DI05019061: Thermal Systems and Energy Efficiency

Complete Lecture Deck

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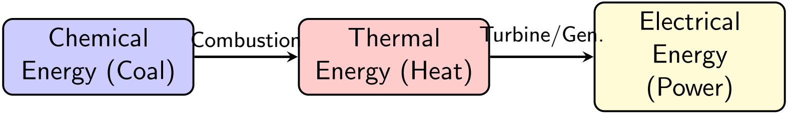
Learning Objectives

- Understand the fundamental definition of energy and its forms.
- Define Energy Conservation clearly.
- Differentiate between Energy Conservation and Energy Efficiency.
- Appreciate the global and national need for energy conservation.
- Understand the economic, environmental, and social significance of saving energy.

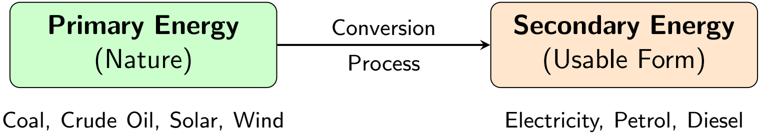
What is Energy?

- Energy is the capacity to do work.
- It is required for almost all activities in modern life: industrial, commercial, and domestic.
- **Law of Conservation of Energy:** Energy can neither be created nor destroyed; it can only be transformed from one form to another.



Primary vs. Secondary Energy

- **Primary Energy Sources:** Extracted directly from nature. (e.g., Coal, crude oil, natural gas, sunlight, wind)
- **Secondary Energy Sources:** Converted from primary sources for easier use. (e.g., Electricity, refined fuels)



What is Energy Conservation?

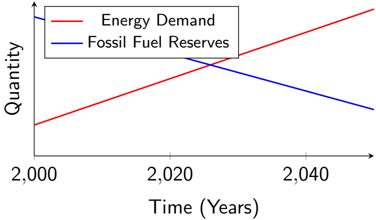
- Energy conservation is the practice of decreasing the quantity of energy used.
- It involves reducing or going without a service to save energy.
- Focuses on behavioral changes and lifestyle modifications.
- **Example:** Turning off lights when leaving a room, or choosing to walk instead of driving.

Energy Conservation vs. Energy Efficiency

Energy Conservation	Energy Efficiency
Reducing energy use by changing behavior or reducing services.	Using technology that requires less energy to perform the same function.
Focus: Behavioral change	**Focus:** Technological change
Example: Turning off the AC when not needed.	**Example:** Replacing a standard AC with an inverter AC.

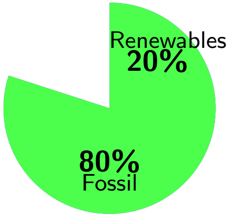
Why Conserve Energy? The Core Issue

- Fossil fuels (coal, oil, gas) are finite and depleting rapidly.
- Energy demand is rising exponentially due to population growth and industrialization.
- Burning fossil fuels is the primary driver of climate change and environmental degradation.
- **Energy security:** Reducing dependence on imported fuels.



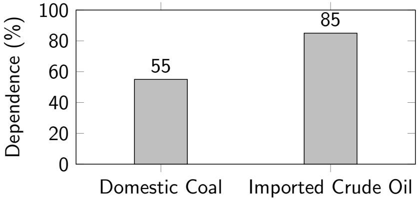
Global Energy Scenario

- Fossil fuels still dominate the global energy mix (approx. 80%).
- Developing nations are experiencing the fastest growth in energy demand.
- Global transition towards renewable energy is accelerating, but not fast enough to meet climate goals without conservation.
- Energy inequality: Significant disparities in per capita energy consumption globally.



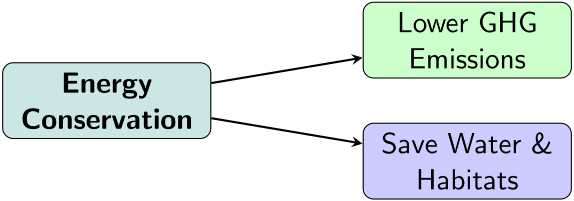
Indian Energy Scenario

- India is the 3rd largest energy consumer globally.
- High dependence on imported crude oil and domestic coal.
- Rapid urbanization and economic growth are driving unprecedented energy demand.
- **Government initiatives:** Energy Conservation Act (2001), Perform Achieve and Trade (PAT) scheme.



Significance 1: Environmental Impact

- Reduces Greenhouse Gas (GHG) emissions, mitigating climate change.
- Lowers air pollution (SOx, NOx, Particulate Matter) improving public health.
- Reduces water consumption and contamination associated with power generation.
- Preserves natural habitats from mining and extraction activities.



Significance 2: Economic Benefits

- **Micro level:** Reduces utility bills for households and operating costs for industries.
- **Macro level:** Reduces a nation's import bill for fossil fuels, strengthening the economy.
- Defers the need for massive capital investments in new power plants and grid infrastructure.
- Increases industrial competitiveness by lowering production costs.

Significance 3: Social & Strategic Importance

- **Enhances Energy Security:** Less reliance on foreign energy sources.
- Promotes sustainable development for future generations.
- Energy saved in urban/industrial areas can be diverted to rural areas lacking access.
- Job creation in energy auditing and energy management sectors.

The 'Hidden' Fuel

The Negawatt Concept

"Energy saved is energy generated."

- It is often cheaper and faster to save a megawatt of electricity than to build a new power plant to generate it.
- This concept is sometimes referred to as a **'Negawatt'**.

Individual & Industrial Roles

Roles in Energy Conservation

Individuals
Turn off appliances, walk/cycle, use natural light

Industries
Optimize processes, stop leaks, energy audits

Policy Makers
Enforce codes, incentivize conservation

Summary & Q&A

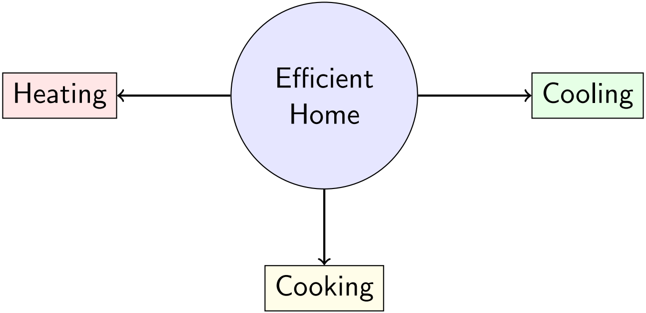
Key Takeaways

- Energy conservation is reducing energy use through behavioral changes.
- It is distinct from, but complementary to, energy efficiency.
- Conservation is crucial for environmental protection, economic stability, and energy security.
- It is the most cost-effective way to bridge the gap between energy supply and demand.

Questions?

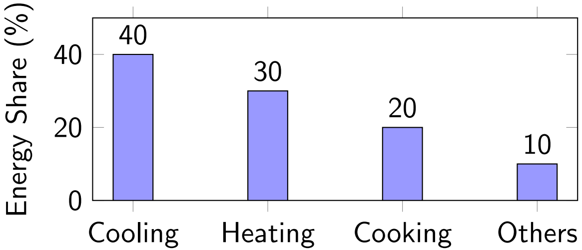
Welcome & Recap

- Welcome to Lecture 2!
- Brief recap of Lecture 1: Significance of energy conservation.
- Today's focus: Energy conservation in domestic applications.



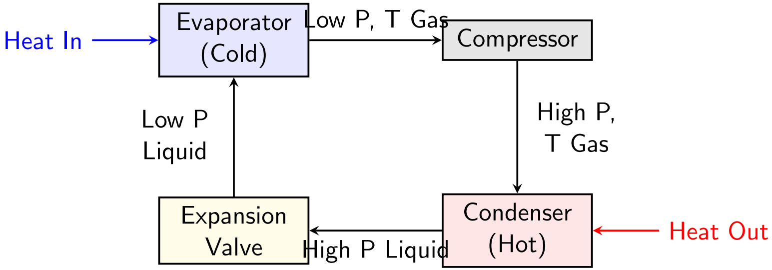
Introduction to Domestic Energy Consumption

- Domestic sector accounts for a major portion of total energy consumption.
- Primary energy consumers: Heating, cooling, and cooking.
- Why focus on domestic energy? Small changes have massive cumulative impact.



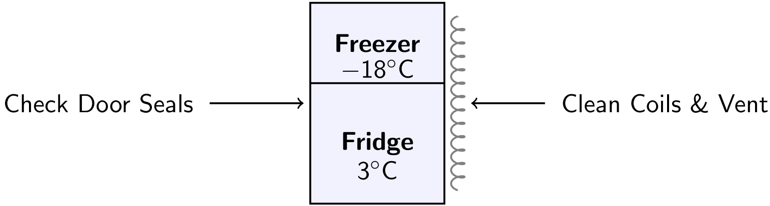
Principles of Cooling Systems

- Both refrigerators and ACs operate on the vapor compression refrigeration cycle.
- They transfer heat from a cooler space to a warmer space using work.
- Efficiency depends on compressor performance, insulation, and ambient temperature.



Energy Efficiency in Refrigerators

- Avoid frequent opening of the refrigerator door.
- Keep coils clean and ensure proper ventilation at the back.
- Set the optimal temperature (e.g., 3-4°C for fridge, −15 to −18°C for freezer).



Understanding Star Ratings

- Bureau of Energy Efficiency (BEE) star ratings guide consumers.
- Higher stars = higher efficiency and lower electricity consumption.
- Inverter technology compressors adjust speed based on load, saving up to 30-50% energy.

Power Savings Guide

★★★★★

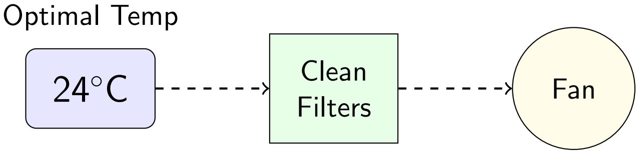
More Stars = More Savings
Consumption: 250 kWh/Year

Energy Conservation in Air Conditioners (ACs)

- ACs are among the highest energy consumers in a typical household.
- Ensure the room is properly sealed (windows, doors) to prevent cool air escape.
- Use curtains or blinds to block direct sunlight and reduce cooling load.

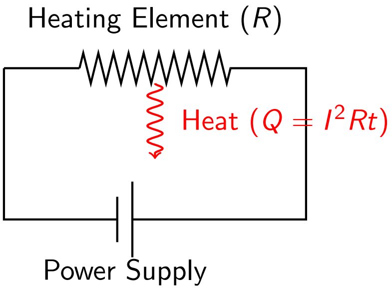
Optimal Settings & Maintenance for ACs

- Set AC temperature to 24-26°C; every degree lower increases consumption by $\sim 6\%$.
- Clean air filters regularly to ensure unrestricted airflow.
- Use ceiling fans alongside ACs to distribute cool air efficiently.



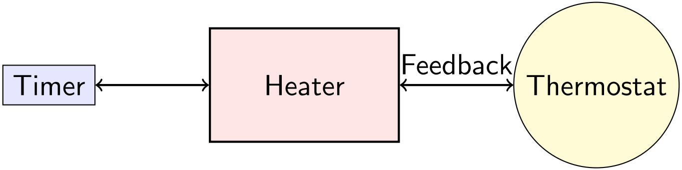
Principles of Electric Heating Systems

- Electric heaters convert electrical energy into heat via Joule heating (I^2R).
- Types include convection heaters, radiant heaters, and oil-filled radiators.
- While 100% efficient in conversion, they are highly energy-intensive compared to heat pumps.



Energy Conservation in Electric Heaters

- Use heaters with thermostats and timers to prevent overheating and wastage.
- Heat only the occupied rooms (zone heating) rather than the whole house.
- Improve room insulation to retain heat longer.



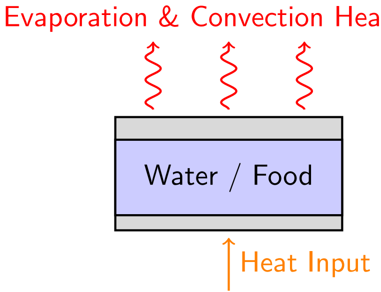
Alternatives to Traditional Heaters

- Consider reverse cycle ACs (heat pumps) for heating.
- Heat pumps provide 3-4 units of heat for every 1 unit of electricity (COP > 1).
- Solar water heaters are excellent alternatives for domestic hot water needs.

Feature	**Electric Heater**	**Heat Pump**
Energy Conversion	1 in $\rightarrow$ 1 out	1 in $\rightarrow$ 3-4 out
Efficiency (COP)	1.0 (100%)	3.0 - 4.0 (300% - 400%)
Operating Cost	High	Low
Dual Use	Heating Only	Heating & Cooling

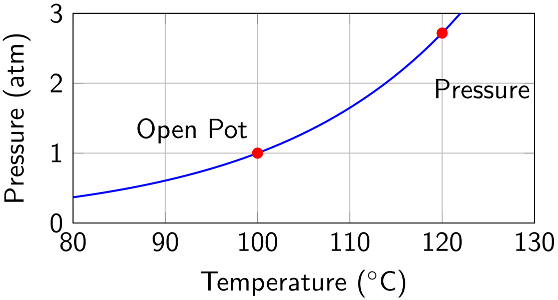
Introduction to Cooking Energy Efficiency

- Cooking consumes significant thermal or electrical energy.
- Methods matter: open vessel cooking loses a lot of heat.
- Choosing the right appliance and vessel size improves heat transfer efficiency.



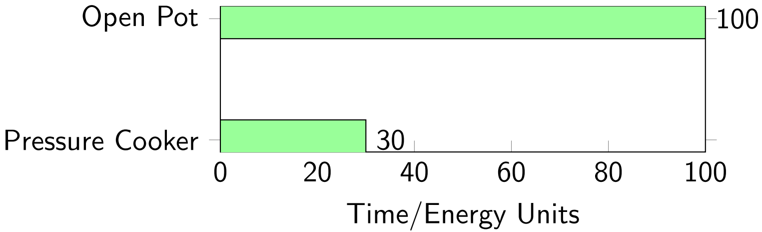
The Science Behind Pressure Cookers

- Pressure cookers trap steam, increasing the internal pressure.
- Higher pressure raises the boiling point of water (up to $\sim 120^{\circ}$C).
- Higher cooking temperatures mean food cooks much faster.



Energy Conservation Benefits of Pressure Cookers

- Reduces cooking time by up to 50-70%.
- Consumes significantly less fuel or electricity compared to open boiling.
- Retains more nutrients in the food due to shorter cooking times.



General Domestic Energy Saving Tips

- Switch off appliances at the plug (avoid standby power consumption).
- Switch to energy-efficient LED lighting.
- Conduct periodic energy audits of household appliances.

Energy Saving Checklist

✓ Unplug unused devices

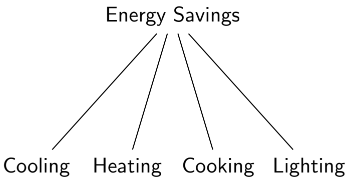
✓ Install LED bulbs

✓ Seal windows & doors

✓ Regular maintenance

Summary & Key Takeaways

- Domestic energy conservation requires efficient appliances and smart user habits.
- Temperature settings, maintenance, and insulation heavily impact cooling/heating energy.
- Tools like pressure cookers utilize thermodynamic principles to save time and energy.

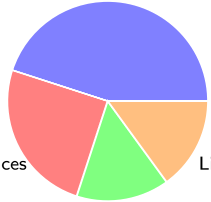


Welcome & Recap

- Course: Thermal Systems and Energy Efficiency
- Lecture Topic: Domestic Energy Conservation
- Focus: Lighting, fans, washing machines, ovens, and televisions

Household Energy Consumption

- Residential sector is a major consumer of electricity.
- Major loads include cooling/heating, lighting, and household appliances.
- Rapid urbanization increases the demand for home appliances.
- Small savings per appliance lead to significant overall energy conservation.



Lighting: Traditional vs. Modern

Type	Characteristics
Incandescent	Convert mostly to heat (inefficient).
CFLs	Use 70% less energy but contain mercury.
LEDs	Highly efficient, long-lasting, and safer.

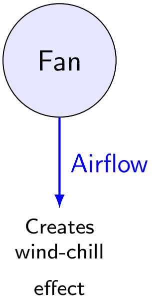
- Switching to LEDs is one of the easiest energy-saving measures.

Lighting: Energy Conservation Tips

- Maximize natural daylight whenever possible.
- Turn off lights when leaving a room.
- Use task lighting instead of whole-room lighting.
- Keep fixtures clean to maximize light output.
- Install motion sensors or timers for outdoor and less used areas.

Ceiling Fans: Energy Usage

- Fans provide thermal comfort by circulating air, not lowering room temperature.
- Conventional fans use induction motors (typically 70-80 watts).
- Running fans in empty rooms wastes electricity.
- Speed regulation methods impact energy consumption.



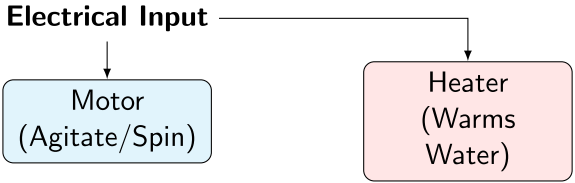
Fans: Efficient Technologies

- BLDC (Brushless Direct Current) motors are highly efficient.
- BLDC fans consume 28-32 watts, saving over 50% energy compared to conventional fans.
- Use electronic regulators instead of conventional resistance regulators.
- Ensure proper blade design and regular cleaning for optimal air delivery.

Feature	**Conventional Fan**	**BLDC Fan**
Power	70-80 W	28-32 W
Efficiency	Low	High

Washing Machines: Energy Basics

- Energy is used by the motor to agitate/spin and the heater to warm water.
- Top-load vs. Front-load: Front-load machines generally use less water and energy.
- Most of the energy (up to 90%) in a hot wash goes toward heating the water.
- Spin drying is energy-intensive if overused.

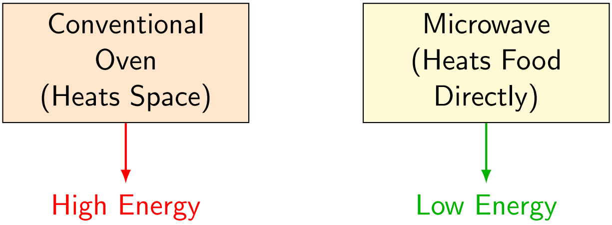


Washing Machines: Conservation Tips

- Wash full loads to maximize efficiency per cycle.
- Use cold water settings for lightly soiled clothes.
- Pre-soak heavily soiled clothes to avoid multiple wash cycles.
- Use optimal amount of detergent to prevent excessive rinsing.
- Sun-dry clothes whenever possible instead of using machine dryers.

Ovens: Conventional vs. Microwave

- Conventional electric ovens heat the entire internal space.
- Microwave ovens heat the food directly using electromagnetic radiation.
- Microwaves are generally more energy-efficient for small to medium portions.
- Preheating is necessary for conventional baking but often unnecessary for microwaves.

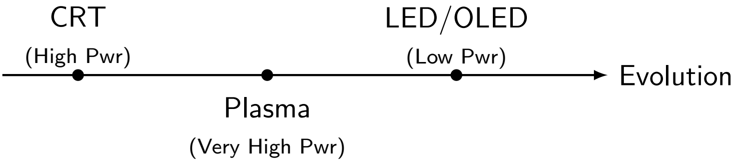


Ovens: Energy Saving Practices

- Don't open the oven door frequently; it drops the temperature significantly.
- Thaw frozen food naturally before cooking or baking.
- Use flat-bottomed pans on electric stovetops for better heat transfer.
- Cook multiple items simultaneously in a conventional oven.

Televisions: Technology Evolution

- CRT (Cathode Ray Tube) TVs were bulky and consumed high power.
- Plasma TVs offered good pictures but were energy hogs.
- LCD/LED TVs are the standard today, offering high efficiency.
- OLED TVs offer deep blacks but power varies with screen brightness.



Televisions: Standby Power (Vampire Load)

- Many TVs and electronics consume power even when turned off (standby mode).
- Used for maintaining settings, remote control sensors, and fast start-up.
- Cumulatively, standby power can account for 5-10% of household electricity.
- Unplugging or using smart power strips eliminates this drain.

Vampire Load

Standby power acts as a silent energy drain. Devices waiting for a remote signal continuously consume electricity over time.

Televisions: Smart Usage Tips

- Turn down screen brightness; higher brightness equals higher power draw.
- Enable 'Energy Saving' mode in TV settings.
- Turn off the TV when no one is watching.
- Consider screen size: larger screens inherently consume more power.

Energy Labels and Standards

- Look for energy rating labels (e.g., BEE star rating in India, Energy Star).
- Higher star ratings indicate higher efficiency.
- Initial cost may be higher, but lifecycle cost is lower due to energy savings.
- Always factor in energy consumption when purchasing new appliances.

5-Star Rating (Highest Efficiency)

Summary & Key Takeaways

- Switch to LED lighting and BLDC fans for immediate energy reductions.
- Operate washing machines with full loads and use cold water when possible.
- Minimize oven heat loss and use microwaves for smaller tasks.
- Eliminate standby power drain from TVs and electronics.

Next Lecture Preview

Introduction to energy conservation in air conditioning and refrigeration systems.

Welcome & Recap

- Welcome to Lecture 4 of Thermal Systems and Energy Efficiency.
- **Recap:** Basic energy concepts, global and Indian energy scenarios.
- **Today's Focus:** Overview of the Energy Conservation Act, 2001.

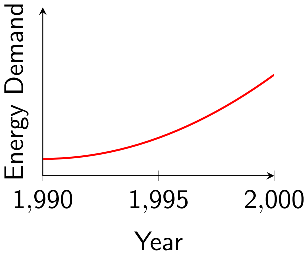
Learning Objectives

- Understand the necessity for an Energy Conservation Act.
- Familiarize with the salient features of the EC Act, 2001.
- Explore the establishment and role of the Bureau of Energy Efficiency (BEE).
- Understand the regulatory mechanisms and designated consumers.

Background and Need for the Act

- Growing energy demand vs. limited resources in India.
- High energy intensity in industrial and commercial sectors.
- Need for a legal framework to promote energy efficiency and conservation.
- Transition towards sustainable development and reduced greenhouse gas emissions.

Demand Trend (pre-2000)



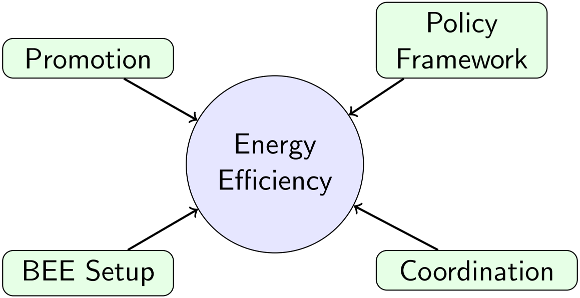
Introduction to Energy Conservation Act, 2001

- Enacted by the Government of India in October 2001.
- Became effective from 1st March 2002.
- Provides the legal framework, institutional arrangement, and a regulatory mechanism.
- Aims to reduce energy intensity of the Indian economy.

Energy Conservation Act, 2001

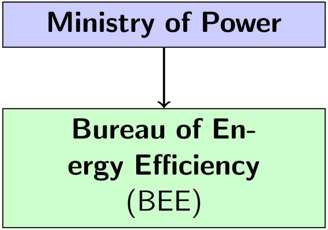
Key Objectives of the EC Act, 2001

- Provide a policy framework and direction for national energy conservation.
- Establish coordination between various entities for energy efficiency.
- Set up the Bureau of Energy Efficiency (BEE) as the nodal agency.
- Promote energy efficiency in all sectors of the economy.



Creation of Bureau of Energy Efficiency (BEE)

- Established on 1st March 2002 under the provisions of the EC Act.
- Statutory body under the Ministry of Power.
- **Mission:** Develop policies and strategies with a thrust on self-regulation and market principles.
- Coordinates with state agencies to implement the EC Act.



Important Features of the EC Act

- Standards and Labeling for equipment and appliances.
- Energy Conservation Building Codes (ECBC) for commercial buildings.
- Identification of Designated Consumers (DCs) in energy-intensive industries.
- Establishment of Energy Conservation Fund at the central and state levels.

Four Pillars of EC Act

S&L   ECBC   DCs   Funds

Standards and Labeling (S&L) Program

- Provides consumers with information on energy performance.
- Helps in making informed purchasing decisions.
- Mandatory and voluntary labeling for various appliances (e.g., ACs, refrigerators).
- Prohibits manufacture/sale of equipment not conforming to standards.

Designated Consumers (DCs)

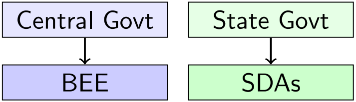
- Energy-intensive industries specified in the Schedule to the Act.
- **Examples:** Aluminum, Cement, Iron & Steel, Thermal Power Stations.
- Required to appoint a certified Energy Manager.
- Must conduct regular energy audits by accredited energy auditors.

Energy Conservation Building Codes (ECBC)

- Sets minimum energy standards for new commercial buildings.
- Applies to buildings having a connected load of 100 kW or contract demand of 120 kVA.
- Focuses on building envelope, HVAC, lighting, and electrical systems.
- Promotes the design of energy-efficient buildings.

Institutional Set-up: Central & State Levels

- **Central Level:** BEE is the nodal agency.
- **State Level:** State Designated Agencies (SDAs) appointed by state governments.
- SDAs coordinate, regulate, and enforce provisions of the Act within the state.
- Central and State Energy Conservation Funds created for promotional activities.



Certification of Energy Managers and Auditors

- The Act mandates the creation of a cadre of professionally qualified energy managers.
- BEE conducts the National Certification Examination for Energy Managers and Auditors.
- Ensures standardized expertise in energy management.
- Only Accredited Energy Auditors can perform statutory audits for DCs.

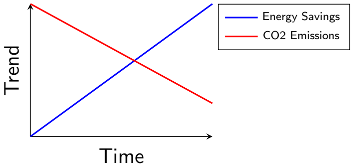
Role	**Key Responsibility**
Energy Manager	Internal energy management (appointed by DCs)
Energy Auditor	Conducts statutory external energy audits

Penalties and Adjudication

- Penalties for non-compliance with the provisions of the EC Act.
- Financial penalties can be levied on entities failing to meet norms.
- Adjudicating officers appointed to hold inquiries and impose penalties.
- Ensures strict enforcement and compliance by designated consumers.

Impact and Success of the EC Act

- Significant savings in electricity consumption nationwide.
- Avoided capacity generation (thousands of MWs saved).
- Reduction in CO_2 emissions, contributing to climate change goals.
- Increased awareness of energy efficiency among industries and citizens.



Summary & Q&A

Summary

- EC Act 2001 provides the legal framework for energy efficiency in India.
- BEE is the central nodal agency for implementation.
- Key provisions include Standards & Labeling, ECBC, and Designated Consumers.

Questions?

Welcome & Recap

- Welcome to Lecture 5: Bureau of Energy Efficiency (BEE) Schemes.
- Recap: The Energy Conservation Act, 2001 established the legal framework for energy efficiency in India.
- Today, we will focus on the specific schemes implemented by BEE under this Act.

Learning Objectives

By the end of this lecture, you will be able to:

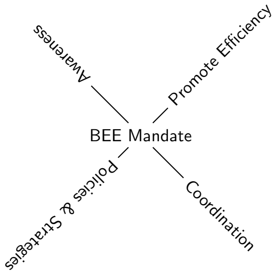
- ✓ Understand the role and mandate of the Bureau of Energy Efficiency (BEE).
- ✓ Identify the major energy conservation schemes introduced by BEE.
- ✓ Explain key schemes like Standards and Labeling, ECBC, and PAT.
- ✓ Analyze the impact of these schemes on overall energy conservation.

Introduction to BEE

- Bureau of Energy Efficiency (BEE) is a statutory body under the Ministry of Power, Government of India.
- Established on 1st March 2002 under the provisions of the Energy Conservation Act, 2001.
- Primary objective: To reduce the energy intensity of the Indian economy.
- Acts as a facilitator and regulator for energy efficiency initiatives.

The Mandate of BEE

- Develop policies with self-regulation.
- Coordinate with designated organizations.
- Promote energy efficiency in various sectors.
- Create awareness.



Major Schemes by BEE - Overview

BEE implements several flagship programs to achieve its objectives:

1. **Standards and Labeling (S&L) Program**
2. **Energy Conservation Building Code (ECBC)**
3. **Perform, Achieve and Trade (PAT) Scheme**
4. **Demand Side Management (DSM) Programs**
5. **Small and Medium Enterprises (SMEs) Program**

Standards and Labeling (S&L) Program

- **Objective:** Provide consumers with informed choices about the energy saving and cost-saving potential of appliances.
- Launched in 2006.
- Involves setting minimum energy performance standards (MEPS).
- Appliances are rated on a scale of 1 to 5 stars.

S&L Program - Impact

- Higher stars indicate better energy efficiency.
- Covers appliances like air conditioners, refrigerators, fans, televisions, etc.
- Has both mandatory and voluntary appliances lists.
- Significant reduction in electricity consumption in the domestic and commercial sectors.

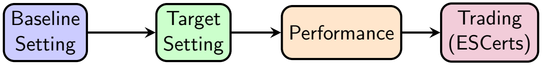
Energy Conservation Building Code (ECBC)

- **Objective:** Establish minimum energy performance standards for new commercial buildings.
- First launched in 2007, updated versions released subsequently (e.g., ECBC 2017).
- Applies to buildings with a connected load of 100 kW or contract demand of 120 kVA and above.
- Focuses on building envelope, HVAC, lighting, and electrical systems.

ECBC - Implementation

- Encourages the use of energy-efficient design and technologies.
- Promotes the integration of renewable energy sources.
- Implementation is primarily the responsibility of State Governments.
- Helps in reducing the carbon footprint of the commercial real estate sector.

- A market-based mechanism to enhance cost-effectiveness of energy efficiency in energy-intensive industries.
- Focuses on 'Designated Consumers' (DCs) - highly energy-intensive units.
- Specific energy consumption (SEC) reduction targets are assigned to DCs.
- Targets are cycle-based (typically 3 years).

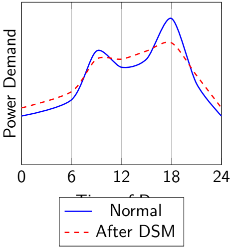


PAT Scheme - Mechanism

- DCs that over-achieve their targets are issued Energy Saving Certificates (ESCerts).
- DCs that under-achieve must buy ESCerts to comply, or face penalties.
- ESCerts can be traded on power exchanges.
- Creates a financial incentive for industries to invest in energy-efficient technologies.

Demand Side Management (DSM)

- **Objective:** Manage consumer demand to optimize power system.
- Reduces peak load and overall consumption.
- Key sectors: Agriculture and Municipalities.
- Examples: Replacing old pumps, upgrading street lighting to LEDs.



SMEs Program & Capacity Building

- **Small and Medium Enterprises (SMEs):** Programs designed to accelerate energy efficiency in industrial clusters.
- Provides technical assistance and creates local energy efficiency hubs.
- **Capacity Building:** Training programs for energy managers, auditors, and professionals.
- Certification examinations for Energy Managers and Energy Auditors.

Impact of BEE Schemes

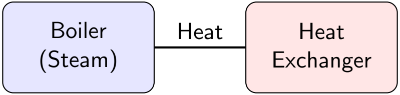
- Avoided massive amounts of planned power generation capacity.
- Significant reduction in greenhouse gas emissions.
- Promoted technological innovation in appliances and industrial equipment.
- Created a new market for energy efficiency services (ESCOs).

Summary & Next Steps

- BEE implements key schemes under the Energy Conservation Act.
- S&L guides consumers; ECBC targets commercial buildings.
- PAT is a market-based scheme for energy-intensive industries.
- **Next Lecture:** We will delve into Energy Audit concepts, types, and methodology.

Welcome & Recap

- **Welcome to Lecture 6!**
- **Course:** Thermal Systems and Energy Efficiency
- **Previous class:** BEE Schemes for energy conservation
- **Today's focus:** Energy Efficiency in Steam Systems & Heat Exchangers

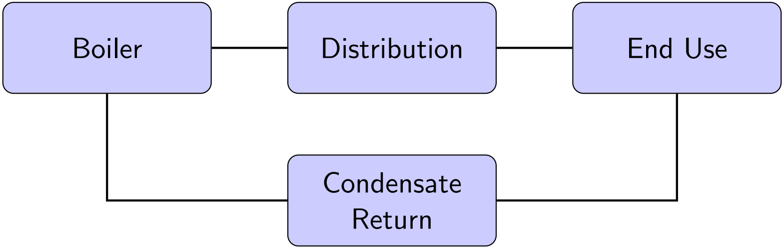


Learning Objectives

- ✓ Understand steam generation principles.
- ✓ Identify efficiency improvement areas in boilers.
- ✓ Understand heat exchanger operation.
- ✓ Learn methods to improve heat transfer efficiency.

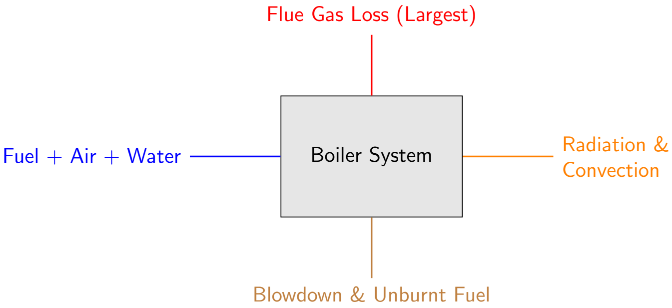
Introduction to Steam Generation Systems

- Steam is a primary energy carrier in industries.
- Used for heating, processing, and power generation.
- Overall system efficiency depends on all these components.



Energy Losses in Boilers

- **Dry flue gas loss:** Largest loss, heat carried away by exhaust.
- **Moisture:** In fuel and combustion air.
- **Unburnt fuel:** In ash (solid fuels).
- **Blowdown loss:** Removing dissolved solids.
- **Radiation and convection:** Losses from boiler surfaces.

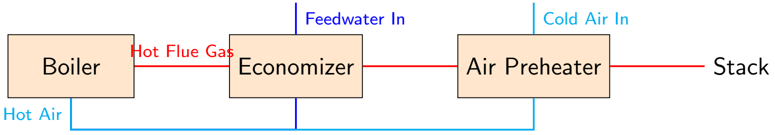


Improving Boiler Efficiency

- **Optimize excess air:** Too much air wastes heat, too little causes unburnt fuel.
- **Reduce flue gas temperature:** Use Economizers and Air Preheaters.
- **Minimize scale and soot:** Regular cleaning of heat transfer surfaces.
- **Optimize blowdown:** Implement automatic blowdown control.
- **Insulate boiler surfaces properly.**

Waste Heat Recovery in Boilers

- **Economizer:** Preheats boiler feedwater using flue gas heat.
- **Air Preheater (APH):** Preheats combustion air using flue gas heat.
- **Benefits:** $\sim 1\%$ efficiency gain for every 22°C drop in flue gas temperature.
- Reduces fuel consumption and emissions.

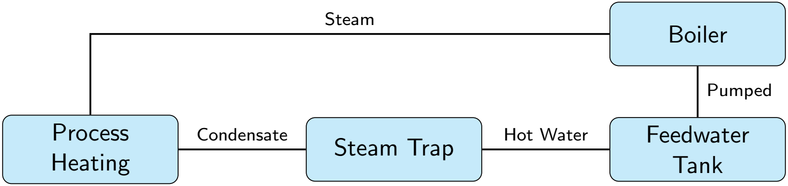


Steam Distribution and Utilization

- **Steam Leaks:** A 3mm leak at 7 kg/cm^2 wastes $\sim$33 tons of coal/year.
- **Insulation:** Bare pipes lose significant heat; proper lagging is critical.
- **Steam Traps:** Remove condensate and non-condensable gases without losing steam.
- **Pressure Optimization:** Distribute at high pressure, utilize at lowest acceptable pressure.

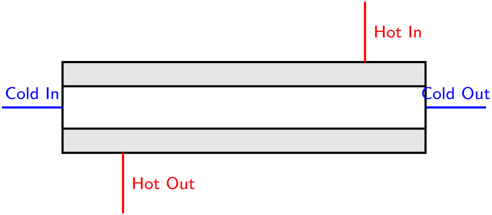
Condensate Recovery

- Condensate contains ∼20% of the original heat of steam.
- Returning condensate saves fuel and treated water.
- Reduces boiler blowdown requirements.
- **Flash Steam Recovery:** Capturing low-pressure steam from high-pressure condensate.



Introduction to Heat Exchangers

- Devices that transfer heat between two or more fluids.
- Fluids are usually separated by a solid wall to prevent mixing.
- **Common Types:** Shell and Tube, Plate Heat Exchangers (PHE), Finned Tube.
- Crucial for waste heat recovery and process temperature control.



Simple Double Pipe Heat Exchanger

- PHEs offer closer approach temperatures (higher efficiency).

- Selection depends on fluid type, pressure, and space available.

Performance of Heat Exchangers

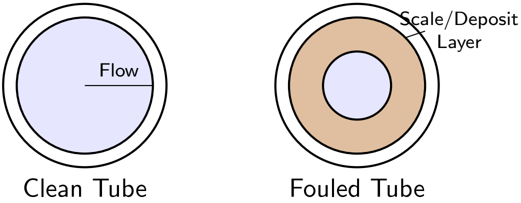
- **Overall Heat Transfer Coefficient (U-value):** Measure of how well heat is transferred.
- **Log Mean Temperature Difference (LMTD):** Driving force for heat transfer.
- **Effectiveness:** Ratio of actual heat transfer to maximum possible heat transfer.
- Higher U-value and effectiveness mean better efficiency.

Heat Transfer Equation

$$Q = U \times A \times \Delta T_{\text{LMTD}}$$

Fouling in Heat Exchangers

- **Fouling:** Accumulation of unwanted material on heat transfer surfaces.
- **Types:** Scaling, particulate, biological, chemical reaction.
- **Impact:** Acts as insulation, drastically reducing heat transfer (U-value).
- Increases pressure drop and pumping power.



Improving Heat Exchanger Efficiency

- **Regular cleaning and maintenance:** To remove fouling deposits.
- **Optimize fluid velocities:** Higher velocity reduces fouling but increases pumping cost.
- **Proper water treatment:** To prevent scaling, biological growth, and corrosion.
- **Use of enhanced surfaces:** (e.g., finned tubes) to increase effective heat transfer area.

Case Study: Heat Exchanger Upgrade

Scenario: Industry replacing an old Shell & Tube with a modern PHE for liquid-liquid cooling.

Parameter	**Old Shell & Tube**	**Modern PHE**
Approach Temperature	5°C	2°C
Cooling Water Flow Rate	High	Significantly Reduced
Pumping Energy	Base	Lower (due to less water)
Maintenance Time	High (Difficult)	Low (Easy to dismantle)

- Energy savings achieved due to reduced cooling water requirement.
- Payback period often **less than a year** for such upgrades.

Summary & Q&A

- **Boiler efficiency** relies on managing air, recovering waste heat (Economizers, APH), and reducing losses.
- **Steam distribution** needs insulation, steam trap maintenance, and leak repair to prevent massive energy waste.
- **Heat exchangers** require optimal selection and proactive fouling management for sustained efficiency.

Any questions?

Welcome & Recap

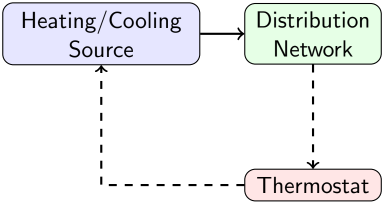
- Welcome to Lecture 7: Introduction to energy efficiency in thermal systems.
- Recap of Lecture 6: Energy conservation in steam systems and heat exchangers.
- Importance of exploring other thermal systems like HVAC, Refrigeration, Compressors, and Pumps.

Learning Objectives

- Understand the basic principles of energy efficiency in HVAC and refrigeration systems.
- Identify energy conservation opportunities in air compressors and pumping systems.
- Evaluate the overall performance of common thermal systems.

Introduction to HVAC Systems

- HVAC stands for Heating, Ventilation, and Air Conditioning.
- Crucial for maintaining indoor air quality and thermal comfort.
- Major energy consumers in commercial and residential buildings.
- Efficiency depends on proper sizing, maintenance, and advanced controls.

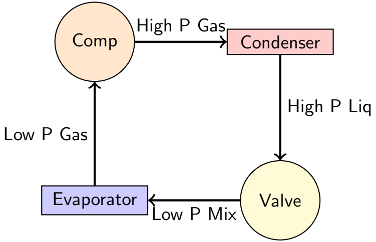


Energy Efficiency in HVAC

- Variable Air Volume (VAV) systems to match load requirements.
- Use of energy recovery ventilators (ERV) to pre-condition incoming fresh air.
- Regular maintenance of filters, coils, and ductwork.
- Smart thermostats and building management systems (BMS) for optimized operation.

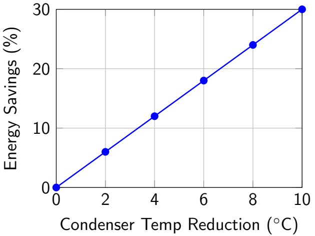
Introduction to Refrigeration Systems

- Used for cooling or freezing applications in industries, food storage, and supermarkets.
- Operates primarily on the Vapor Compression Refrigeration Cycle.
- Key components: Compressor, Condenser, Expansion Valve, and Evaporator.
- Energy usage is heavily dependent on temperature lift (difference between condensing and evaporating temperatures).



Energy Efficiency in Refrigeration

- Optimizing condensing and evaporating temperatures (floating head pressure).
- Use of Variable Frequency Drives (VFDs) on compressors and condenser fans.
- Proper insulation of cold rooms and refrigerant lines.
- Regular defrosting and cleaning of condenser coils.



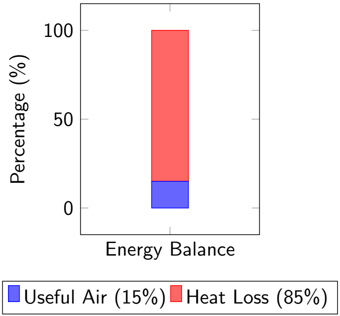
Comparison: HVAC vs. Refrigeration

- Both rely on similar thermodynamic principles but operate under different constraints.
- Energy saving strategies often overlap (e.g., VFDs, regular maintenance).

Aspect	**HVAC**	**Refrigeration**
Primary Focus	Human comfort	Product preservation
Temperature	Higher temperatures	Lower temperatures
Control	Includes humidity control	Primarily temperature

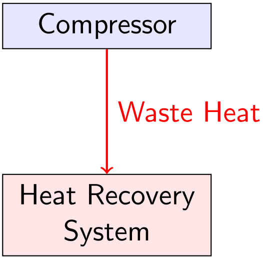
Introduction to Air Compressors

- Air compressors convert electrical energy into potential energy stored in pressurized air.
- Widely used in manufacturing as 'the fourth utility'.
- Inherently inefficient: mostly generates heat, only 10-15% of input energy becomes useful compressed air.
- Proper management is crucial for energy conservation.



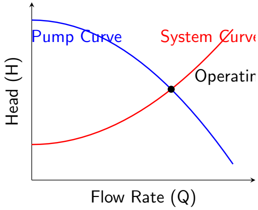
Energy Efficiency in Air Compressors

- Fixing air leaks: Leaks can waste 20-30% of compressor output.
- Reducing operating pressure: A 1 bar reduction saves ∼7% energy.
- Use of VFD compressors to match varying demand profiles.
- Heat recovery: Utilizing compressor waste heat for space or water heating.



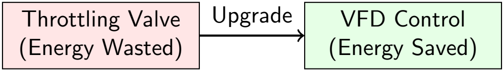
Introduction to Pumping Systems

- Pumps are used to move fluids through piping systems.
- Account for nearly 20% of the world's electrical energy demand.
- Common types: Centrifugal (most common) and Positive Displacement.
- System curve and pump curve intersection determines the operating point.



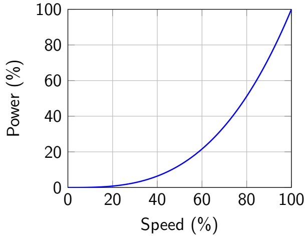
Energy Efficiency in Pumping Systems

- Right-sizing the pump: Avoiding oversized pumps.
- Trimming the impeller if the pump is slightly oversized.
- Using VFDs instead of throttling valves for flow control.
- Maintaining high motor and pump efficiency through regular maintenance.



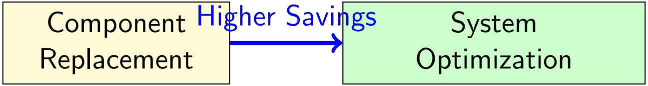
The Role of VFDs across Thermal Systems

- Variable Frequency Drives (VFDs) adjust motor speed to match load.
- Applicable in HVAC fans, Refrigeration compressors, Air compressors, and Pumps.
- Follows affinity laws: Power is proportional to the cube of speed (for centrifugal loads).
- Small reductions in speed lead to large energy savings.



System-Level Approach vs. Component Level

- Component level: Buying a highly efficient motor or compressor.
- System level: Optimizing piping, reducing demand, fixing leaks, improving controls.
- Maximum savings are achieved through a system-level approach.
- An efficient pump in a poorly designed piping system will still waste energy.



Summary of Energy Efficiency Opportunities

Summary Grid

HVAC Smart controls, energy recovery, VAV.	**Refrigeration** Optimized temperatures, insulation, maintenance.
Compressors Leak repair, pressure reduction, heat recovery.	**Pumps** Right-sizing, VFDs instead of throttling.

Q&A and Next Steps

- Any questions on HVAC, Refrigeration, Compressors, or Pumps?
- Next Lecture: Detailed study of performance assessment of specific thermal systems.
- Reading assignment: Chapter on fluid handling and air systems.

?

Next: Performance Assessment

Welcome & Recap

Recap of previous lecture:

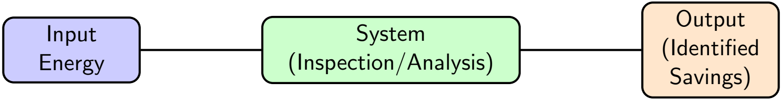
- Basic principles of HVAC (Heating, Ventilation, and Air Conditioning) systems.
- Fundamentals of Refrigeration cycles and applications.
- Types and operation of Compressors.

Today's Focus

Understanding how to systematically assess energy use in such systems through Energy Audits.

What is an Energy Audit?

- An energy audit is a systematic inspection, survey, and analysis of energy flows in a building, process, or system.
- **Objective:** To understand energy dynamics of the system and identify opportunities to reduce the amount of energy input without negatively affecting the output.
- It acts as a fundamental step towards establishing an energy management program.
- An energy audit answers three key questions:
  1. Where is energy being consumed?
  2. How efficiently is it being consumed?
  3. How can energy consumption be reduced?

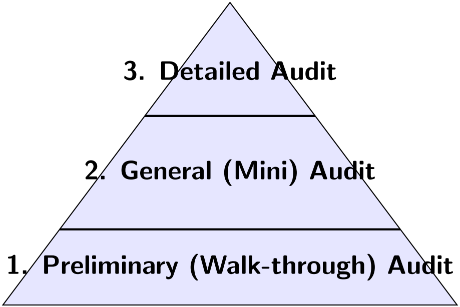


Need for Energy Audits

- **Cost Reduction:** Energy is a major operating cost; reducing it increases profitability.
- **Environmental Impact:** Lower energy consumption means reduced greenhouse gas emissions
  and a smaller carbon footprint.
- **Resource Conservation:** Helps in sustainable utilization of rapidly depleting fossil fuels.
- **System Efficiency:** Identifies maintenance issues and aging equipment, extending equipment lifespan.
- **Compliance:** Helps industries meet government regulations and energy efficiency standards.

Types of Energy Audits

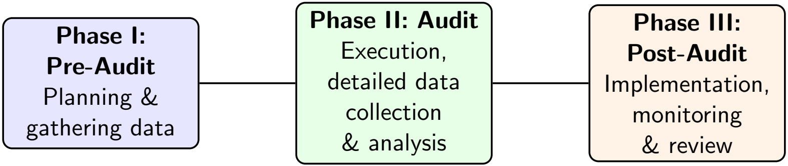
The type of audit depends on the size/type of facility, depth of analysis required, and potential for savings.



- **Preliminary:** Simple, quick, identifies major issues.
- **General:** More detailed, involves some measurement and basic financial analysis.
- **Detailed:** Comprehensive, requires extensive data collection, monitoring, and detailed financial analysis.

Phases of an Energy Audit

A structured energy audit is generally conducted in three phases:



Proper execution of all three phases ensures a successful energy management program.

What is a Walk-through Energy Audit?

- Also known as a **Preliminary Energy Audit**.
- It is the simplest and quickest type of audit.
- Involves brief interviews with site operating personnel and a visual inspection of the facility.
- Relies heavily on visual observation and review of available utility bills and operating data.
- Usually takes only one to two days to complete depending on facility size.

Objectives of a Walk-through Audit

- Establish energy consumption in the organization (Energy Index/Benchmark).
- Estimate the scope for saving energy.
- Identify the most likely areas for attention (the ‘low-hanging fruit’).
- Identify immediate (especially no-cost/low-cost) improvements/savings.
- Set a ‘reference point’ for more detailed audits.

Key Activities in a Walk-through Audit

- **Data Gathering:** Collecting 12-36 months of utility bills (electricity, fuel, water).
- **Facility Tour:** Walking through the plant to observe equipment in operation.
- **Interviews:** Talking to operators and maintenance staff about equipment issues and operating schedules.
- **Visual Inspection:** Checking for obvious energy waste (leaks, uninsulated pipes, lights left on).
- **Brief Report:** Preparing a summary of findings and initial recommendations.

Equipment and Tools Used

Walk-through audits require minimal equipment, mostly for spot checks:

- **Notepad and Camera:** For documentation and recording visual evidence.
- **Lux Meter:** To measure illumination levels in different areas.
- **Infrared Thermometer:** For quick non-contact temperature checks (e.g., finding hot spots on panels or uninsulated pipes).
- **Clamp Meter:** For basic electrical current measurements (if authorized).
- **Tape Measure:** For calculating room dimensions if needed.

Identifying No-Cost / Low-Cost Savings

The primary goal of a walk-through is finding immediate savings that require little to no investment.

No-Cost Measures	**Low-Cost Measures**
Turning off equipment and lights when not in use.	Repairing compressed air leaks or steam leaks.
Optimizing startup and shutdown procedures.	Cleaning heat exchanger surfaces.
Adjusting thermostat settings.	Replacing incandescent bulbs with LEDs.

Common Walk-through Audit Findings

- **Compressed Air Systems:** Audible air leaks (hissing sounds), inappropriate use of compressed air for cleaning.
- **Lighting:** Excessive lighting in unoccupied areas, use of inefficient fixtures, dirty luminaires.
- **Thermal Systems:** Damaged or missing insulation on steam or hot water pipes, visible steam leaks from valves.
- **HVAC:** Clogged air filters, simultaneous heating and cooling, poorly set controls.
- **Motors:** Unusual noise or vibrations, hot to the touch (indicating potential issues).

Benefits of a Walk-through Audit

- **Cost-Effective:** Very low cost to perform.
- **Fast Results:** Immediate identification of quick wins and energy waste.
- **Awareness:** Raises energy awareness among plant personnel during the audit process.
- **Justification:** Provides the necessary preliminary data to justify the cost of a more comprehensive, Detailed Energy Audit.
- **Low Risk:** Excellent starting point for facilities new to energy management.

Limitations of a Walk-through Audit

- **Lack of Detail:** Does not provide an in-depth engineering analysis.
- **Estimation Only:** Savings and costs are based on rough estimates, not precise calculations.
- **Hidden Issues:** Cannot identify inefficiencies that require continuous monitoring or complex data logging.
- **Major Capital Projects:** Insufficient for making decisions on large investments (like replacing a major chiller or boiler).
- **Requires Follow-up:** Often just points to areas that need a more detailed audit.

Summary & Next Steps

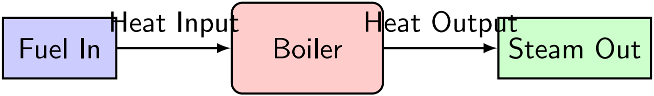
- Energy audits are essential for systematic energy management.
- Walk-through audits are the crucial first step: quick, inexpensive, and focused on low-hanging fruit.
- They rely on visual inspections, basic tools, and utility bill analysis.
- While limited in detail, they pave the way for more comprehensive studies.

Next Lecture

Detailed Energy Audits: Methodology, data logging, and investment grade analysis.

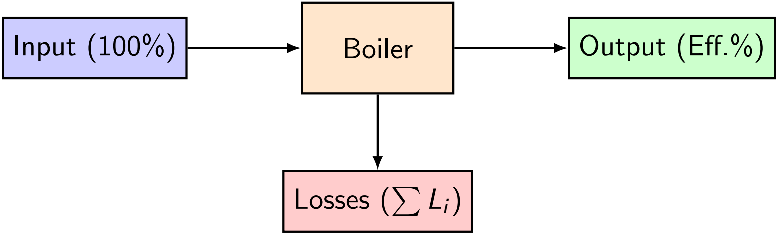
Recap: Direct Method

- Also known as 'Input-Output' method.
- Efficiency $= \left(\frac{\text{Heat Output}}{\text{Heat Input}}\right) \times 100$
- **Heat Output:** Heat gained by the working fluid (water to steam).
- **Heat Input:** Heat available in the fuel.
- **Limitation:** Does not pinpoint specific areas of energy loss.



Introduction to Indirect Method

- Also known as 'Heat Loss' method.
- Efficiency = 100 − (Sum of all heat losses in %).
- Instead of measuring output directly, we measure all the individual losses.
- Provides a detailed breakdown of where energy is wasted.
- Helps in identifying specific areas for performance improvement.



Why Use the Indirect Method?

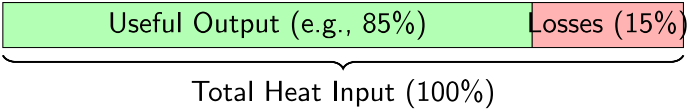
Advantages over direct method:

- ✓ Pinpoints exact sources of heat loss (e.g., flue gas, radiation).
- ✓ Enables targeted corrective actions.
- ✓ Small errors in measurement have less impact on the final efficiency value compared to direct method.
- ✓ Standard practice for large boilers where direct measurement is difficult.

Principle of Indirect Method

The energy balance principle:

- Heat Input = Heat Output + Heat Losses
- Therefore, Heat Output = Heat Input − Heat Losses
- Efficiency (%) = $\frac{\text{Heat Input} - \text{Heat Losses}}{\text{Heat Input}} \times 100$
- Efficiency (%) = $100 - \left(\frac{\text{Heat Losses}}{\text{Heat Input}} \times 100\right)$
- **Efficiency (%) = 100 - (Sum of % Losses)**



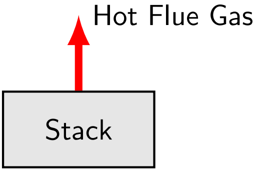
Categories of Heat Losses in a Boiler

Major heat losses include:

- **L1:** Dry flue gas loss
- **L2:** Loss due to hydrogen in fuel
- **L3:** Loss due to moisture in fuel
- **L4:** Loss due to moisture in combustion air
- **L5:** Loss due to carbon monoxide (CO) formation
- **L6:** Loss due to surface radiation and convection
- **L7:** Unburnt losses in fly ash and bottom ash (solid fuels)

L1: Dry Flue Gas Loss

- Usually the **largest single loss** in a boiler.
- Heat carried away by the dry components of the exhaust gases (CO_2, O_2, N_2).
- Depends on:
  1. **Flue gas temperature** (higher temp = higher loss).
  2. **Excess air level** (more air = larger volume of heated gas leaving).
- Minimizing L1 is critical for high efficiency.



$$\uparrow \text{Temp} \implies \uparrow \text{Loss}$$
$$\uparrow \text{Excess Air} \implies \uparrow \text{Loss}$$

L2: Loss Due to Hydrogen in Fuel

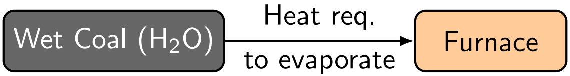
- Hydrogen in fuel reacts with oxygen to form water (H_2O).
- This water immediately turns into steam (superheated vapor) in the combustion zone.
- The heat used to evaporate this water and superheat the steam is lost up the stack.
- Higher hydrogen fuels (like natural gas) have a higher inherent L2 loss compared to coal.
- Unavoidable loss, dependent on fuel composition.

$$2H_2 + O_2 \rightarrow 2H_2O + \text{Heat}$$

(Water vapor absorbs latent heat of vaporization)

L3: Loss Due to Moisture in Fuel

- Fuels often contain inherent or surface moisture (especially coal and biomass).
- Similar to L2, heat is required to evaporate this moisture.
- The water turns to steam and carries latent and sensible heat away in the flue gas.
- Can be reduced by proper fuel storage and drying, but some inherent moisture always exists.

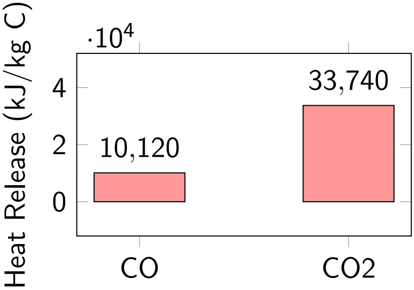


L4: Loss Due to Moisture in Air

- Combustion air drawn from the atmosphere contains water vapor (humidity).
- This moisture enters the furnace, gets heated to the flue gas temperature, and exits the stack.
- Carries away sensible heat.
- Usually a very small loss compared to L1, L2, or L3.
- Dependent on ambient weather conditions.

L5: Loss Due to Carbon Monoxide (CO)

- Result of incomplete combustion.
- Carbon burns to CO instead of CO_2.
- $C + \frac{1}{2}O_2 \rightarrow CO$ (releases much less heat than $C + O_2 \rightarrow CO_2$).
- Indicates poor air-fuel mixing, insufficient excess air, or low furnace temperature.
- A severe penalty on efficiency and a safety/environmental hazard.



L6: Surface Radiation and Convection

- Heat lost from the hot outer surfaces of the boiler to the cooler surrounding environment.
- Depends on:
  1. Surface area of the boiler.
  2. Surface temperature (effectiveness of insulation).
  3. Ambient temperature and air velocity.
- More significant at low loads (as a percentage of input).

L7: Unburnt Losses (Solid Fuels)

- Applicable mainly to coal, biomass, or other solid fuels.
- **Unburnt Carbon in Bottom Ash:** Combustible material that falls through the grate or accumulates at the bottom.
- **Unburnt Carbon in Fly Ash:** Fine combustible particles carried away with the flue gas.
- Causes: Incorrect pulverization, poor grate design, insufficient residence time.
- Represents wasted fuel.

Parameters to Monitor for Indirect Method

To calculate these losses, we need specific measurements:

Category	Specific Measurements
Flue Gas	Analysis (O_2, CO_2, CO % by volume)
Flue Gas	Exit temperature
Ambient Air	Temperature and humidity
Fuel	Ultimate analysis (C, H, O, N, S, Moisture, Ash)
Fuel	Gross Calorific Value (GCV)
Ash	Combustible % in bottom & fly ash (solid fuels)

Preparing for Calculations

- The standard testing code often used is ASME PTC 4.1 or equivalent.
- Requires steady-state operation during the test period.
- Accurate sampling of fuel and ash is critical.
- In the next lecture, we will dive into the specific formulas to calculate L1 through L7.
- We will use a standard reference fuel (e.g., coal or oil) for our examples.

Summary & Q&A

- The indirect method (heat loss method) calculates efficiency by subtracting all % heat losses from 100%.
- It provides a detailed diagnostic of boiler performance.
- Major losses include dry flue gas (L1), hydrogen in fuel (L2), moisture (L3, L4), CO (L5), radiation (L6), and unburnt carbon (L7).
- Accurate measurement of flue gas, fuel, and temperatures is required.
- **Questions?**

Learning Objectives

- Deepen understanding of indirect method calculations
- Analyze practical examples of heat losses
- Apply indirect method to industrial boiler case studies

Focus on practical application
of theory to realistic scenarios

Quick Review: The Indirect Method Equation

Boiler Efficiency Formula

$$\text{Boiler Efficiency} = 100 - (L1 + L2 + L3 + L4 + L5 + L6 + L7 + L8)$$

- $L1$ = Loss due to dry flue gas
- $L2$ = Loss due to hydrogen in fuel
- $L3$ = Loss due to moisture in fuel
- $L4$ = Loss due to moisture in air

Quick Review: Minor Losses

- $L5$ = Loss due to carbon monoxide (CO)
- $L6$ = Loss due to surface radiation and convection
- $L7$ = **Unburnt losses in fly ash (Solid fuels)**
- $L8$ = **Unburnt losses in bottom ash (Solid fuels)**

Note: L7 and L8 are specific to solid fuels like coal or biomass.

Calculating L3: Moisture in Fuel Loss

- Moisture in fuel evaporates, absorbing latent and sensible heat
- This heat is carried away in the flue gas

Formula for L3

$$L3 = \frac{M \times [584 + 0.45 \times (T_f - T_a)]}{GCV} \times 100$$

- M = kg of moisture per kg of fuel
- T_f = Flue gas temperature
- T_a = Ambient temperature

Calculating L4: Moisture in Air Loss

- Air supplied for combustion contains moisture (humidity)
- This moisture is heated from ambient to flue gas temperature
- Usually a very small loss compared to others

Formula for L4

$$L4 = \frac{AAS \times \text{Humidity Factor} \times 0.45 \times (T_f - T_a)}{GCV} \times 100$$

- AAS = Actual Air Supplied
- 0.45 = Specific heat of superheated steam

Calculating L5: Partial Combustion (CO) Loss

- Carbon burning to CO instead of CO_2 releases much less heat
- Indicates incomplete combustion (lack of air or poor mixing)

Formula for L5

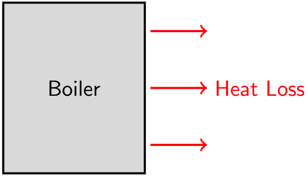
$$L5 = \frac{\%CO}{\%CO_2 + \%CO} \times \frac{C \times 5744}{GCV} \times 100$$

$C \rightarrow CO_2$ $\approx$ 8084 kcal/kg	$C \rightarrow CO$ $\approx$ 2340 kcal/kg

5744 kcal/kg Heat Loss!

Calculating L6: Radiation and Convection Loss

- Heat lost from the hot boiler outer surfaces to the surroundings
- Depends on surface area, insulation thickness/quality, and temp difference
- Often estimated from standard charts (e.g., ABMA chart)
- Typically 1% to 2% for large, well-insulated boilers



Losses specific to Solid Fuels (L7 & L8)

- **L7**: Unburnt carbon in fly ash (carried in flue gas)
- **L8**: Unburnt carbon in bottom ash (drops to ash pit)

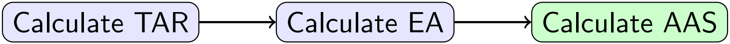
- Formulas depend on total ash content and the % combustible matter in the ash
- Requires lab analysis of ash samples

Case Study Data: Industrial Coal Boiler

Parameter	**Value**
Fuel	Coal
Gross Calorific Value (GCV)	4000 kcal/kg
Carbon Content (C)	41%
Hydrogen Content (H)	2.7%
Moisture Content	10%
Flue Gas Temperature (T_f)	190 °C
Ambient Temperature (T_a)	30 °C
O_2 in flue gas	8%
CO in flue gas	500 ppm (0.05%)

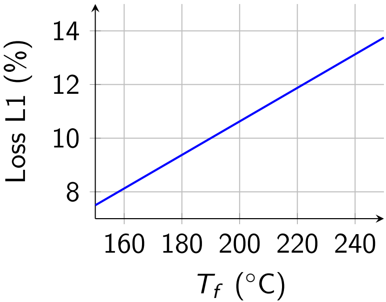
Case Study Calculation: Step 1 (Air Supplied)

- **Theoretical Air Requirement (TAR)** $= \frac{(11.6 \times C) + (34.8 \times (H - O/8)) + (4.35 \times S)}{100}$
- **Excess Air (EA)** $= \frac{O_2}{21 - O_2} \times 100$
- **Actual Air Supplied (AAS)** $= \left(1 + \frac{EA}{100}\right) \times TAR$



Case Study Calculation: Dry Flue Gas Loss (L1)

- Mass of dry flue gas (m) = Mass of combustion products
- $L1 = \frac{m \times C_p \times (T_f - T_a)}{GCV} \times 100$
- This is typically the largest single loss (often 8% to 12%)
- Reducing T_f or excess air reduces this loss



Case Study Calculation: Hydrogen & Moisture Losses

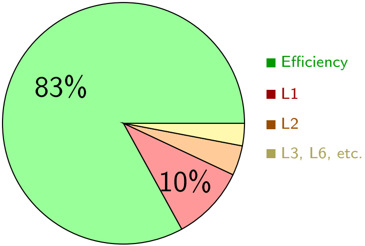
- **Hydrogen (L2)**: Every 1 kg H forms 9 kg H_2O.

$$L2 = \frac{9 \times H_2 \times [584 + 0.45 \times (190 - 30)]}{4000} \times 100$$

- **Moisture (L3)**: Calculated similarly using the 10% moisture figure
- Both losses are inherent to the fuel choice

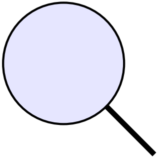
Case Study Results: Typical Breakdown

- L1 (Dry Flue Gas): ∼10%
- L2 (Hydrogen): ∼4%
- L3 (Moisture): ∼1.5%
- L6 (Radiation): ∼1.5%
- **Total Losses = 17%**
- **Indirect Efficiency = 100 - 17 = 83%**



Advantages of the Indirect Method

- Pinpoints exactly WHERE heat is being lost
- Requires only easily measured parameters (Temp, O_2, fuel composition)
- Does not require accurate measurement of fuel or steam flow rates
- Highly useful for routine monitoring and targeting improvements



Diagnostic Nature: Identifies specific losses to fix for better efficiency.

Summary & Q/A

- Indirect method calculates efficiency by summing all losses
- Dry flue gas loss (L1) is usually the largest
- Understanding individual losses allows for targeted efficiency improvements
- Any questions?

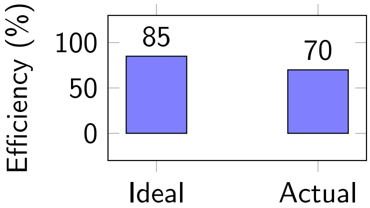
Q & A

Learning Objectives

- Understand the principle of the direct method of evaluating boiler performance.
- Identify the key parameters needed for direct method testing.
- Learn the mathematical formula to calculate efficiency.
- Understand the advantages and limitations of this method.

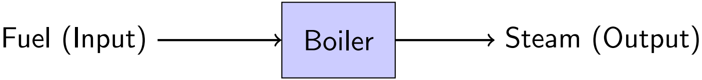
Introduction to Boiler Efficiency

- Boiler efficiency represents the fraction of energy in fuel that is converted into useful steam energy.
- Over time, boiler performance degrades due to poor combustion, heat transfer surface fouling, and poor operation.
- Regular efficiency testing helps identify deviations from the best operating conditions.
- Two main methods for testing boiler efficiency: Direct Method and Indirect Method.



What is the Direct Method?

- Also known as the 'Input-Output Method'.
- It directly compares the energy output of the boiler (in the steam) to the energy input (in the fuel).
- Evaluates the overall efficiency of the boiler.
- Requires only the measurement of fuel consumed and steam generated over a specific time period.



Direct Method: Principle

Basic Formula

$$\text{Efficiency } (\eta) = \left(\frac{\text{Energy Output}}{\text{Energy Input}} \right) \times 100$$

- **Energy Output:** Total heat gained by the working fluid (water/steam).
- **Energy Input:** Total heat supplied by the fuel.
- It treats the boiler as a black box.

Direct Method Formula

$$\text{Boiler Efficiency } (\eta) = \left[\frac{Q \times (H - h)}{q \times \text{GCV}}\right] \times 100$$

Where (Numerator):

- Q = Quantity of steam generated (kg/hr)
- H = Enthalpy of steam (kcal/kg or kJ/kg)
- h = Enthalpy of feedwater (kcal/kg or kJ/kg)

Direct Method Formula (Cont'd)

$$\text{Boiler Efficiency } (\eta) = \left[\frac{Q \times (H - h)}{q \times \text{GCV}}\right] \times 100$$

Where (Denominator):

- q = Quantity of fuel consumed (kg/hr)
- GCV = Gross Calorific Value of fuel (kcal/kg or kJ/kg)

Parameters to be Monitored

To use the Direct Method, specific data must be collected during the test period:

1. Quantity of steam generated (Q)
2. Quantity of fuel consumed (q)
3. Steam pressure and temperature (to find H)
4. Feedwater temperature (to find h)
5. Gross calorific value of fuel (GCV)

Data Collection: Instruments

Parameter to Measure	**Instrument Used**
Quantity of steam (Q)	Steam flow meter
Fuel consumption (q)	Fuel meters / Weighing scales
Steam properties	Pressure gauges / Thermometers
Feedwater properties	Temperature sensors
Gross Calorific Value (GCV)	Laboratory analysis

Enthalpy Determination

- Enthalpy of Steam (H) and Feedwater (h) are crucial.
- Determined using **Steam Tables**.
- Require accurate measurement of pressure and temperature at the boiler outlet and inlet.
- For saturated steam, only pressure or temperature is needed. For superheated steam, both are needed.

Example Calculation

Problem Statement

Given Data:

- Steam generation $(Q) = 10$ TP/hr
- Fuel consumption $(q) = 2.5$ TP/hr
- Steam enthalpy $(H) = 660$ kcal/kg
- Feedwater enthalpy $(h) = 85$ kcal/kg
- Fuel GCV $= 4000$ kcal/kg

Task: Calculate Boiler Efficiency.

Example Solution

Step 1: Convert units to kg/hr

- $Q = 10$ TP/hr $= 10,000$ kg/hr
- $q = 2.5$ TP/hr $= 2,500$ kg/hr

Step 2: Calculate Output and Input Energy

- Output $=$ $Q \times (H - h) = 10,000 \times (660 - 85) = 5,750,000$ kcal/hr
- Input $= q \times \text{GCV} = 2,500 \times 4000 = 10,000,000$ kcal/hr

Step 3: Calculate Efficiency

$$\text{Efficiency} = \left(\frac{\text{Output}}{\text{Input}}\right) \times 100$$
$$= \left(\frac{5,750,000}{10,000,000}\right) \times 100 = 57.5\%$$

Advantages of Direct Method

- Plant personnel can evaluate quickly.
- Requires few parameters for computation.
- Needs few instruments (mainly flow and temperature).
- Easy to compare different boilers using only input and output data.

Disadvantages of Direct Method

- Does not give clues to the operator as to why efficiency of system is lower.
- Does not calculate various losses individually.
- Highly dependent on the accuracy of measuring instruments.
- Any error in measurement directly affects the calculated efficiency.

When to Use Direct Method?

- Useful for routine checks if accurate flow meters are installed.
- Good for establishing a baseline quickly.
- Often used in conjunction with the indirect method (to be covered next) for a comprehensive audit.
- Not ideal for detailed troubleshooting.

Summary & Q&A

Summary

- Direct method measures input vs output energy directly.
- Efficiency $= \left[\frac{Q \times (H-h)}{q \times \text{GCV}}\right] \times 100$
- Simple to calculate but doesn't identify sources of heat loss.

Questions?

Welcome & Recap

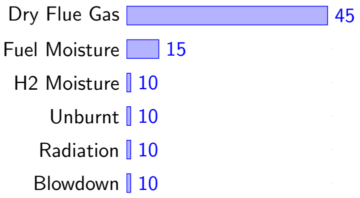
- Course: Thermal Systems and Energy Efficiency
- Topic: Energy Efficiency Measures in Boilers
- Unit 2: Boiler Performance and Steam Distribution Systems
- Recap: Direct Method for evaluating boiler efficiency.

Introduction to Boiler Energy Efficiency

- Boilers are major energy consumers in industries.
- Even a small improvement in efficiency leads to significant fuel savings.
- Efficiency improvements also reduce greenhouse gas emissions.
- Focus on reducing heat losses and optimizing combustion.

Major Areas of Energy Loss in Boilers

- Dry flue gas loss (largest loss).
- Loss due to moisture in fuel and combustion air.
- Loss due to combustion of hydrogen to water.
- Unburnt fuel in ash and carbon in flue gas.
- Radiation and convection losses from boiler casing.
- Blowdown losses.

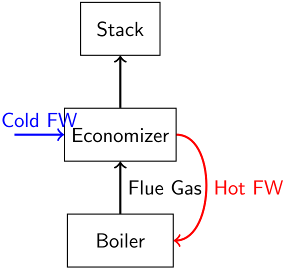


Stack Temperature Reduction

- High stack temperature indicates poor heat transfer or excess air.
- Rule of thumb: 22°C reduction in flue gas temperature increases efficiency by $\sim$1%.
- Methods: Regular cleaning of heat transfer surfaces (soot blowing).
- Limit: Do not reduce below acid dew point to prevent corrosion (typically 120-150°C for sulfur-bearing fuels).

Feed Water Preheating (Economizers)

- Economizers recover heat from flue gases to preheat boiler feed water.
- Rule of thumb: 6°C rise in feed water temperature saves ∼1% fuel.
- Reduces thermal shock to the boiler.
- Cost-effective for most medium to large boilers.



Combustion Air Preheating (Air Heaters)

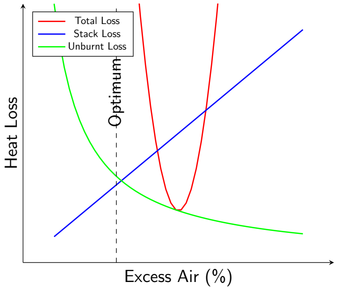
- Air preheaters recover heat from flue gas to preheat combustion air.
- Rule of thumb: 20°C increase in combustion air temperature increases efficiency by ∼1%.
- Improves combustion efficiency, especially for low-grade fuels.
- Usually installed after the economizer.

Minimizing Incomplete Combustion

- Incomplete combustion leads to unburnt carbon (CO in flue gas, carbon in ash).
- Causes: Insufficient air, poor mixing of fuel and air, low furnace temperature.
- Symptoms: Black smoke, high CO levels.
- Solutions: Improve burner design, optimize air-fuel ratio, proper fuel preparation (e.g., coal sizing, oil atomization).

Excess Air Control

- Some excess air is needed for complete combustion, but too much wastes heat.
- Excess air carries useful heat out of the stack.
- Every 10% reduction in excess air increases efficiency by ~1%.
- Use Oxygen/CO trim systems for continuous automatic control.

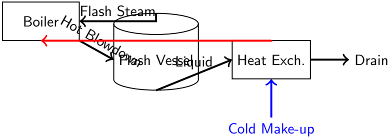


Radiation and Convection Heat Loss Control

- Heat lost from boiler shell to the surroundings.
- Dependent on boiler surface area, temperature, and ambient conditions.
- Usually 1-2% in large boilers, but can be higher in small or poorly insulated ones.
- Solution: Proper maintenance and upgrading of refractory and thermal insulation.

Automatic Blowdown Control

- Blowdown removes dissolved solids (TDS) to prevent scaling.
- Continuous blowdown is more efficient than intermittent manual blowdown.
- Automatic blowdown controls maintain optimal TDS levels, minimizing hot water loss.
- Flash steam recovery and heat exchangers can recover heat from blowdown water.



Reduction of Scaling and Soot Losses

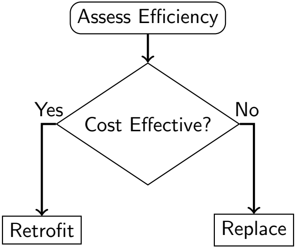
- Scale on water side and soot on fire side act as insulators.
- 1 mm of scale can increase fuel consumption by 5-8%.
- 3 mm of soot can increase fuel consumption by 2.5%.
- Solutions: Proper water treatment (demineralization, softening) and regular soot blowing.

Variable Speed Drives (VSD) for Fans and Pumps

- Boiler loads vary; fans (FD, ID) and feed water pumps often run at part load.
- Damper controls waste energy.
- VSDs match motor speed to the required flow rate.
- Significant electrical energy savings due to the affinity laws (power is proportional to the cube of speed).

Boiler Replacement vs. Retrofitting

- Old, inefficient boilers may need replacement if retrofits are not cost-effective.
- Retrofit options: New high-efficiency burners, adding economizers, improved control systems (PLC/SCADA).
- Consider right-sizing: An oversized boiler running at low load is highly inefficient.



Boiler Maintenance for Efficiency

- Regular tuning of the burner.
- Checking for and repairing air leaks in the boiler casing (tramp air).
- Inspecting steam traps and valves for leaks.
- Routine calibration of instruments (O_2 sensors, temperature gauges).

Case Study / Example

- Plant X had a boiler efficiency of 75%.
- Measures implemented: Economizer installation, automatic blowdown, burner tuning.
- Results: Flue gas temp reduced by 30°C, excess air optimized.

Parameter	Before	After
Efficiency	75%	82%
Annual Fuel Savings	-	INR 50 Lakhs
Payback Period	-	1.2 years

Summary & Q&A

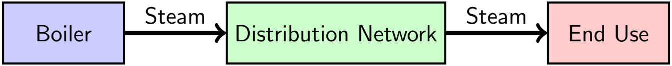
- Energy efficiency in boilers focuses on minimizing losses (stack, radiation, unburnt fuel).
- Key measures: Economizers, Air preheaters, Excess air control, Blowdown heat recovery.
- Regular maintenance and water treatment are crucial.
- Questions?

Welcome & Recap

- Welcome to Lecture 13: Introduction to Steam Distribution Systems.
- Course: Thermal Systems and Energy Efficiency (DI05019061).
- Recap: In the previous lectures, we discussed boiler performance evaluation and various energy efficiency measures for boilers.
- Today, we shift our focus to how steam is transported from the boiler to the point of use.

What is a Steam Distribution System?

- A network of pipes and components designed to transport steam from the boiler to the end-use equipment.
- Acts as the vital link between steam generation and steam utilization.
- Must deliver steam at the correct pressure, temperature, and quality.
- Requires careful design to minimize heat loss and pressure drop.



Purpose of Steam Distribution

- To deliver sufficient quantity of steam to the process.
- To maintain the required pressure and temperature at the point of use.
- To ensure steam is dry and clean.
- To remove air and other incondensable gases from the system.
- To remove condensate safely and efficiently.

Basic Components of a Steam System

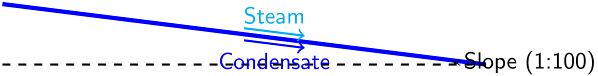
- **Steam Mains:** The primary arteries carrying high-pressure steam.
- **Branch Lines:** Smaller pipes delivering steam to individual equipment.
- **Valves:** Used for isolation, regulation, and pressure reduction.
- **Steam Traps:** Crucial for removing condensate and air without losing steam.
- **Insulation:** Prevents heat loss to the surroundings.

Steam Piping Overview

- Pipes must be appropriately sized based on steam flow rate and allowable pressure drop.
- Oversized pipes lead to excessive heat loss and higher installation costs.
- Undersized pipes result in high steam velocities, excessive pressure drop, and potential noise/erosion.
- Material selection depends on pressure and temperature ratings (e.g., carbon steel is common).

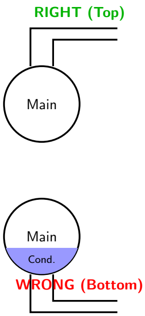
Designing Steam Mains

- Steam mains should be installed with a gradual fall (slope) in the direction of flow.
- Recommended slope is typically 1 in 100 (10 mm per meter).
- This slope allows condensate to drain by gravity towards trapping points.
- Proper support and expansion loops are required to handle thermal expansion.



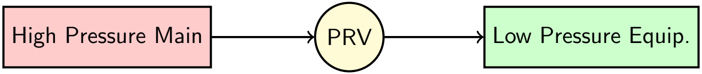
Branch Lines and Take-offs

- Branch lines supply steam to specific applications from the main header.
- Take-offs MUST always be connected to the **TOP** of the steam main.
- Top connections ensure that only dry steam is drawn off.
- Side or bottom connections would draw off condensate along with the steam, reducing quality.



Steam Pressure Reduction

- Steam is often generated and distributed at high pressure.
- High pressure allows smaller pipe sizes, reducing costs and heat loss.
- Pressure Reducing Valves (PRVs) are used locally to step down pressure for specific process equipment.
- Lower pressure at the point of use often provides more latent heat per kg of steam.



The Role of Valves

- **Isolation Valves:** To completely shut off steam flow for maintenance (e.g., Gate or Globe valves).
- **Control Valves:** To regulate the flow rate of steam to maintain process temperature or pressure.
- **Check Valves:** To prevent backflow of steam or condensate.
- **Safety Valves:** Critical for protecting equipment from overpressure.

Introduction to Steam Traps

- A steam trap is an automatic valve that distinguishes between steam and condensate/air.
- It opens to discharge condensate and non-condensable gases.
- It closes tightly to prevent the escape of live steam.
- Proper trapping is essential for system efficiency and preventing waterhammer.

Air Venting in Steam Systems

- Air enters the system when it is shut down.
- Air acts as an insulator; a 1 mm layer of air offers the same resistance to heat transfer as a 15 meter wall of copper.
- Air must be removed automatically using air vents installed at the highest points or ends of mains.
- Failure to vent air leads to slow start-up and reduced plant capacity.

Condensate Recovery Basics

- When steam gives up its latent heat, it turns back into liquid water (condensate).
- Condensate contains valuable sensible heat (up to 20% of the steam's total energy).
- Condensate is also treated, high-quality water.
- Returning it to the boiler feedtank saves fuel, water, and chemical treatment costs.

Insulation of Steam Pipes

- Uninsulated pipes lose massive amounts of heat to the surroundings.
- Proper insulation is the most basic and cost-effective energy saving measure.
- Common materials: Mineral wool, calcium silicate, fiberglass.
- Valves and flanges must also be insulated using removable jackets.

Common Issues: Waterhammer

- Waterhammer occurs when slugs of condensate are picked up by high-velocity steam.
- These water slugs hit fittings, valves, or pipe bends with immense force.
- Can cause severe damage to pipes, fittings, and pose safety risks.
- Caused by poor drainage (lack of traps, incorrect slope, sagging pipes).

Best Practices for Piping Design

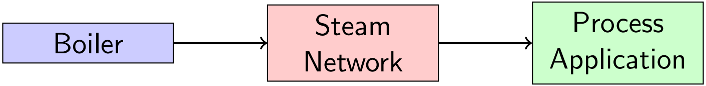
- Always size pipes correctly for the load.
- Ensure proper slope (1:100) towards drain points.
- Install drip legs and steam traps at regular intervals (e.g., every 30-50 meters) and at low points.
- Use top take-offs for branch lines.
- Adequately support pipes and allow for thermal expansion.

Summary & Q&A

- The distribution system is critical for delivering right quality steam.
- Key components include mains, valves, traps, and insulation.
- Proper design (sizing, slope, take-offs) prevents issues like waterhammer.
- Efficient operation requires air venting and condensate recovery.
- Any Questions?

Recap of Previous Lecture

- Discussed steam distribution networks.
- Importance of proper pipe sizing and layout.
- Insulation and its role in minimizing heat loss.
- The problem of condensate formation in steam lines.



Introduction to Steam Traps

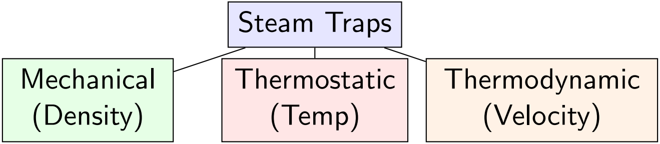
- What is a steam trap?
- An automatic valve that filters out condensate and non-condensable gases.
- Prevents the escape of live steam.
- Crucial for system efficiency and safety.

Why Do We Need Steam Traps?

- To prevent water hammer caused by condensate accumulation.
- To maintain the thermal efficiency of steam-heated equipment.
- To remove air and non-condensable gases that lower steam temperature.
- To protect equipment from corrosion.

Types of Steam Traps

- **Mechanical Traps**: Operate by changes in fluid density (e.g., Float, Inverted Bucket).
- **Thermostatic Traps**: Operate by changes in fluid temperature (e.g., Bimetallic, Balanced Pressure).
- **Thermodynamic Traps**: Operate by changes in fluid dynamics.
- Today's focus: Float and Thermostatic (F&T) Trap - a combination type.

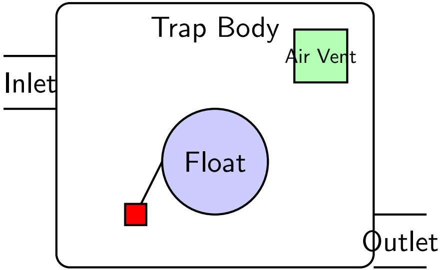


Float and Thermostatic (F&T) Trap: Overview

- Combines two operating mechanisms in one unit.
- **Float Mechanism**: Handles condensate removal based on density.
- **Thermostatic Air Vent**: Handles air and non-condensable gas removal based on temperature.
- Provides continuous discharge of condensate.

Construction of an F&T Trap

- **Trap Body**: Usually cast iron or steel.
- **Float**: A hollow sphere (usually stainless steel).
- **Lever and Valve mechanism**: Connects the float to the discharge valve.
- **Thermostatic Element**: A capsule or bellows located near the top.
- **Inlet and Outlet ports**.



The Float Mechanism

- Operates purely on the density difference between steam and water.
- As condensate enters, the water level rises.
- The buoyant float rises with the water level.
- This movement opens the main discharge valve via the lever.

The Thermostatic Air Vent

- Contains a fluid mixture with a specific boiling point.
- At start-up (cold state), the vent is fully open.
- Allows rapid discharge of initial air.
- Closes when heated by the arrival of hot steam.

Working Principle: Start-up

- System is cold; large amounts of air are present.
- Thermostatic vent is wide open, discharging air.
- Cold condensate arrives and begins to fill the trap.
- Float rises, opening the main valve to discharge cold condensate.

Working Principle: Normal Operation

- Hot steam reaches the trap, causing the thermostatic vent to close tight.
- Steam cannot escape through the top.
- Condensate continues to enter and is discharged continuously by the float valve.
- Maintains a water seal over the main valve to prevent steam loss.

Advantages of F&T Steam Traps

- Continuous discharge of condensate at steam temperature.
- Excellent air venting capability (critical for fast start-ups).
- High capacity for their size.
- Responds well to sudden and large fluctuations in load.

Disadvantages and Limitations

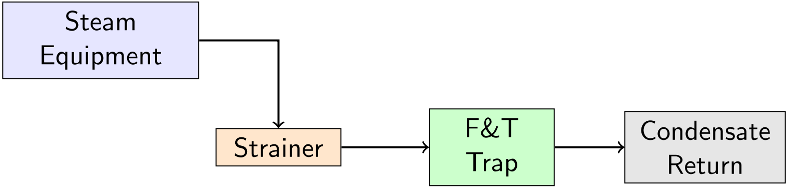
- Susceptible to damage from water hammer.
- Float can be damaged by freezing (if installed outdoors in cold climates).
- Cannot handle superheated steam effectively.
- Orientation specific: Must be installed horizontally (usually) to work.

Applications of F&T Traps

- Heat exchangers and calorifiers.
- Air heating coils and AHU batteries.
- Jacketed pans and boiling pans.
- Any application requiring continuous, immediate condensate removal.

Installation and Maintenance

- Must be installed below the equipment being drained.
- Requires a strainer upstream to prevent dirt from jamming the valves.
- Regular inspection of the float for punctures.
- Checking the thermostatic element for failure.



Summary & Q/A

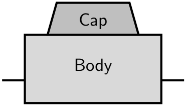
- F&T traps combine mechanical and thermostatic principles.
- They offer continuous condensate discharge and excellent air venting.
- Ideal for process applications with varying loads.
- Questions?

Welcome & Recap

- Welcome to Lecture 15: Thermodynamic Steam Traps
- Recap: Mechanical Traps (Float) operate on density difference
- Recap: Thermostatic Traps operate on temperature difference
- Today we focus on traps that operate on velocity/dynamic principles

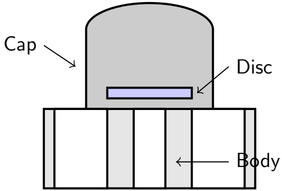
Introduction to Thermodynamic Steam Traps

- Also known as disc traps.
- Operate on the dynamic principles of fluid flow (Bernoulli's principle).
- Rely on the difference in velocity and pressure between steam and condensate.
- Characterized by an extremely robust, simple, and compact design.



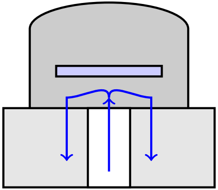
Basic Components of a Thermodynamic Trap

- **Body**: Usually made of stainless steel or carbon steel.
- **Cap** (Control Chamber): The top cover creating a pressure chamber.
- **Disc**: The only moving part in the trap.
- **Seat**: Consists of an inner ring (inlet) and outer ring (outlet).



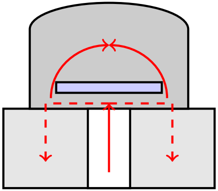
Working Principle - Phase 1: Startup

- On startup, system pressure forces the disc upwards.
- Cold condensate and air enter through the inner ring.
- They flow under the disc and exit through the outer ring.
- The trap is fully open, discharging large volumes of condensate.



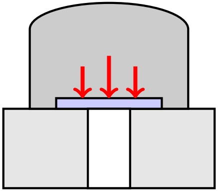
Working Principle - Phase 2: Closing

- As hot condensate reaches the trap, it passes through the narrow gap under the disc.
- The sudden drop in pressure causes hot condensate to flash into steam.
- Flash steam flows at high velocity, creating a low-pressure area under the disc (Bernoulli effect).
- Simultaneously, some flash steam enters the control chamber above the disc.



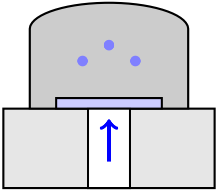
Working Principle - Phase 3: Closed

- The pressure in the control chamber (above the disc) equals the static pressure of the flash steam.
- However, the area above the disc is greater than the inlet area below it.
- This creates a net downward force, snapping the disc tightly onto the seat rings.
- The trap is now closed, preventing live steam from escaping.



Working Principle - Phase 4: Re-opening

- The trap remains closed as long as the pressure in the control chamber is maintained.
- Eventually, the flash steam in the control chamber cools and condenses.
- The pressure above the disc drops.
- Inlet pressure overcomes the reduced downward force, lifting the disc to discharge condensate again.



The Role of Flash Steam

Dual Role of Flash Steam

- Flash steam is crucial for the operation of a thermodynamic trap.
- It provides the high velocity needed to lower the pressure under the disc.
- It provides the pressure in the control chamber to hold the disc closed.
- Without flash steam, the trap would simply act as a continuous flow valve.

Advantages of Thermodynamic Traps

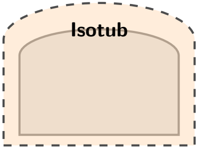
- Can operate across their entire working range without adjustment.
- Compact, simple, lightweight, and have a large condensate capacity for their size.
- Highly resistant to waterhammer, vibration, and corrosive condensate.
- Can be used on high-pressure and superheated steam.
- Do not freeze when installed vertically discharging to atmosphere.

Disadvantages / Limitations

- Can be noisy in operation (distinct 'clicking' sound).
- Not suitable for very low differential pressures.
- Can discharge large quantities of air on startup if pressure builds up too quickly (air binding).
- Operation can be affected by heavy rain or cold winds (rapid cooling of the cap).
- Provide a cyclic, rather than continuous, discharge of condensate.

Installation Best Practices

- Cold winds or rain can cause the steam in the control chamber to condense too rapidly.
- This leads to rapid cycling, increasing wear on the disc and seat.
- Solution: Install an **'isotub'** or insulating cover over the cap.
- An isotub provides an air-filled insulating chamber, slowing heat loss and stabilizing operation.



Typical Applications

- Steam mains drainage.
- Tracer lines (steam tracing).
- Small process equipment with constant loads.
- Applications involving superheated steam.
- Outdoor installations where freezing is a concern.

Maintenance and Troubleshooting

- **Failure Modes**: Often fail open due to wear on the disc or seat.
- **Inspection**: Listen for the distinct 'click' - rapid clicking indicates a problem or low load.
- **Maintenance**: The disc and seat can usually be cleaned or replaced without removing the body from the line.
- **Air Binding**: If the trap is air bound, a separate air vent may be required.

Comparison with Mechanical Traps

cc

Feature	Thermodynamic	Mechanical (Float)
Discharge	Cyclic	Continuous
Size	Very compact	Larger
Air Handling	May struggle with rapid air buildup	Often have built-in thermostatic air vents
Robustness	Handles waterhammer much better	Susceptible to waterhammer damage

Comparison with Thermostatic Traps

cc

Feature	Thermodynamic	Thermostatic
Principle	Velocity/pressure	Temperature
Discharge Temp	Close to steam temperature	Sub-cooled condensate
Response Time	Responds rapidly to load changes	Can be slower
Superheat	Handles superheat well	Some can be damaged by it

Summary & Q&A

- Thermodynamic traps operate on dynamic principles of fluid flow and flash steam.
- They are compact, robust, and handle high pressures and waterhammer exceptionally well.
- Operation is cyclic, characterized by a distinct snapping action.
- Ideal for mains drainage and tracer lines, but not for applications requiring continuous discharge or very low pressures.

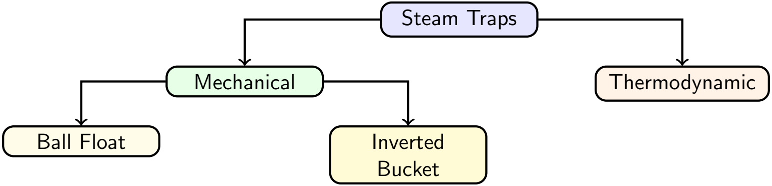
Questions?

1. Welcome & Recap

- Welcome to Lecture 16 of Thermal Systems and Energy Efficiency.
- Today's topic: Inverted Bucket Steam Traps.
- Recap: Thermodynamic steam traps operate based on the difference in dynamic pressure of steam and condensate.

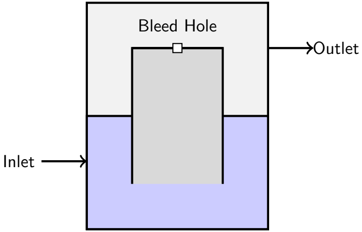
2. Introduction to Mechanical Traps

- Mechanical steam traps operate on the principle of specific gravity difference between steam and condensate.
- They use a float mechanism to actuate a valve.
- Two main types: Ball Float and Inverted Bucket.
- Inverted Bucket is one of the most robust mechanical traps available.



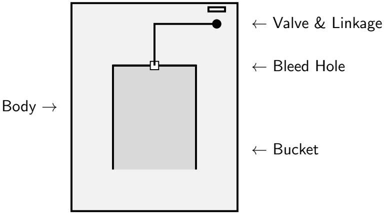
3. What is an Inverted Bucket Trap?

- A mechanical steam trap that uses an inverted bucket as a float.
- The bucket floats when steam reaches the trap and sinks when condensate fills the body.
- Known for its rugged construction and long service life.
- Can handle water hammer and high pressures effectively.



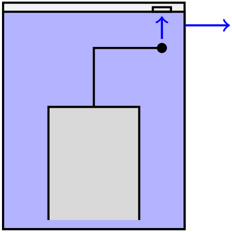
4. Main Components

- **Body and Cover:** Houses the internal mechanisms.
- **Inverted Bucket:** The float element, open at the bottom, with a small bleed hole at the top.
- **Valve and Seat:** Controls the discharge of condensate.
- **Leverage System:** Connects the bucket to the valve, multiplying the lifting force.



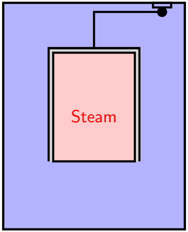
5. Operating Principle: Start-up

- On start-up, the trap is cold and empty (or full of water).
- The inverted bucket rests at the bottom of the trap body.
- The valve is fully open in this position.
- Initial air and cold condensate flow freely through the open valve into the return line.



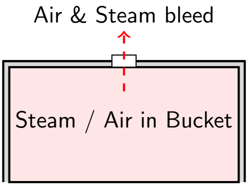
6. Operating Principle: Steam Arrival

- As steam enters the trap, it flows up into the inverted bucket.
- The steam displaces the condensate inside the bucket, making it buoyant.
- The bucket floats upwards, pulling the valve towards the seat via the linkage.
- The valve closes tightly, preventing steam loss.



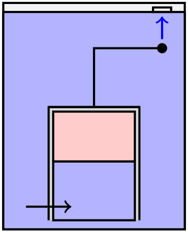
7. The Role of the Bleed Hole

- A small vent hole at the top of the bucket allows trapped air and gases to escape.
- It also allows a small amount of steam to bleed through.
- This bled steam condenses in the cooler space above the bucket.
- Essential for preventing air binding and allowing the trap to cycle.



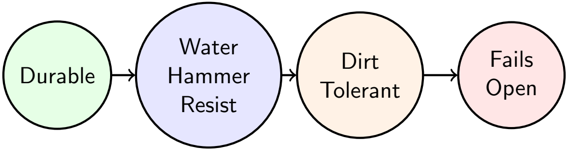
8. Operating Principle: Condensate Discharge

- As more condensate enters, it fills the trap body and displaces steam in the bucket.
- Steam also bleeds out of the top vent hole.
- The bucket loses buoyancy and sinks due to its own weight.
- The sinking bucket pulls the valve open, discharging the accumulated condensate.



9. Advantages of Inverted Bucket Traps

- Extremely rugged and durable; can withstand water hammer.
- Resistant to wear and corrosion.
- Tolerates dirt and scale better than many other trap types.
- Fails in the OPEN position (usually), ensuring continuous drainage.

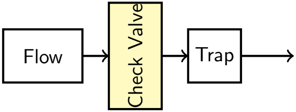


10. Disadvantages and Limitations

- Slow to discharge air on start-up (bleed hole is small).
- Must maintain a prime (water seal) to operate; can lose prime if steam is superheated or pressure fluctuates rapidly.
- If prime is lost, steam will blow straight through.
- Not suitable for applications requiring continuous, immediate discharge (it operates intermittently).

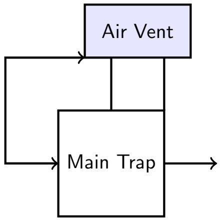
11. Loss of Prime: Causes and Solutions

- **Causes:** Sudden pressure drops, superheated steam, or very light loads.
- **Effect:** Bucket stays down, valve stays open, steam is wasted.
- **Solutions:** Install a check valve ahead of the trap to prevent backflow.
- Ensure trap is appropriately sized for the application.



12. Air Venting Limitations

- The small bleed hole limits the rate at which air can be vented.
- In systems with large amounts of air on start-up, this can significantly delay heating.
- **Solution:** Parallel installation of a separate thermostatic air vent.
- Some modern inverted bucket traps include integral thermostatic air vents.



13. Typical Applications

- Steam mains drainage.
- Steam tracing lines.
- Laundry equipment.
- Heat exchangers where intermittent discharge is acceptable.
- Applications where water hammer is a known issue.

- Determine the required condensate discharge capacity (load).
- Determine the differential pressure across the trap (Inlet - Outlet pressure).
- Select a trap with a safety factor (typically 2 to 3 times the actual load).
- Ensure the trap's pressure rating exceeds the maximum system pressure.

Parameter	**Consideration**
Load	Base load + Startup load
Differential Pressure	$P_{inlet} - P_{outlet}$
Safety Factor	2 to 3 times depending on application
Pressure Rating	Must exceed Max Allowable Working Pressure

15. Maintenance and Troubleshooting

- **Trap blowing live steam:** Check for loss of prime, dirt holding valve open, or worn valve/seat.
- **Trap fails to discharge:** Check if pressure is too high, or if the bleed hole is plugged.
- **Sluggish heating:** Often due to slow air venting or an undersized trap.
- Regular inspection of internal mechanisms is recommended.

16. Summary & Q&A

- Inverted bucket traps are mechanical traps using a floating bucket.
- They are robust, handle water hammer well, and fail open.
- They require a water seal (prime) to operate and vent air slowly.
- Ideal for mains drainage and demanding industrial applications.
- **Questions?**

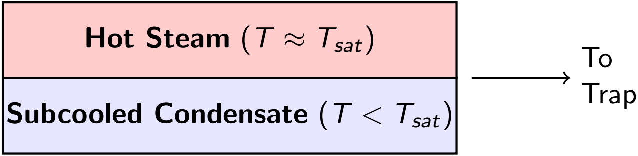
Key Takeaways

- Operate on density difference.
- Highly durable and water hammer resistant.
- Prime and bleed hole are critical.

- Welcome to Lecture 17: Thermostatic & Bimetallic Steam Traps
- Course: Thermal Systems and Energy Efficiency (DI05019061)
- **Recap:** In the previous lecture, we discussed Inverted Bucket Steam Traps, a type of mechanical trap relying on density differences.

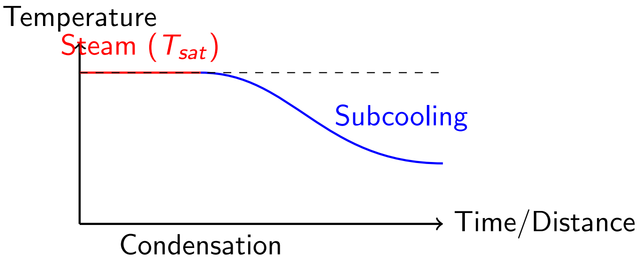
Introduction to Thermostatic Steam Traps

- Thermostatic steam traps operate based on the temperature difference between steam and condensate.
- Steam has a higher temperature than the cooled condensate.
- These traps contain a temperature-sensing element that opens the valve when cooler condensate is present and closes it when hot steam reaches the trap.
- They are excellent for air venting at startup because air is cooler than steam.



Principle of Operation: Thermostatic Action

- The core principle is the response to temperature changes.
- As steam gives up its latent heat, it condenses into water at steam temperature.
- Before thermostatic traps can discharge it, the condensate must subcool (drop below steam temperature).
- The thermal element senses this temperature drop to actuate the valve.



The Concept of Subcooling

- Subcooling is the cooling of condensate below the saturation temperature of steam at a given pressure.
- Thermostatic traps require a certain amount of subcooling to operate.
- **Advantage:** Uses sensible heat of condensate, increasing overall energy efficiency.
- **Disadvantage:** Condensate backs up in the system to cool, which may not be suitable for processes requiring dry steam immediately.

Main Types of Thermostatic Traps

There are two primary types of thermostatic traps used in industry:

1. Balanced Pressure (Bellows or Capsule) Traps

Uses a liquid mixture with a boiling point lower than water.

2. Bimetallic Traps

Uses a bimetallic strip that bends with temperature changes.

Both rely on thermal elements to control the valve.

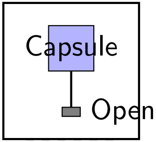
Balanced Pressure (Bellows) Steam Traps

- The operating element is a capsule or bellows filled with a liquid/alcohol mixture.
- The fill liquid has a boiling point lower than that of water.
- The capsule expands when heated (vaporizing the liquid) and contracts when cooled.
- **Self-adjusting to pressure:** The boiling point of the fill mixture rises with system pressure, keeping a constant operating temperature difference.

How Bellows Traps Work: Startup vs Operation

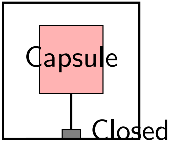
Startup (Cold)

- System is cold.
- Liquid in capsule condensed.
- Valve wide open.
- Air and cold condensate freely discharged rapidly.



Operation (Hot)

- Hot condensate/steam arrive.
- Liquid boils, generating internal pressure.
- Bellows expands.
- Valve closes, preventing steam loss.



Advantages & Limitations: Balanced Pressure Traps

Advantages

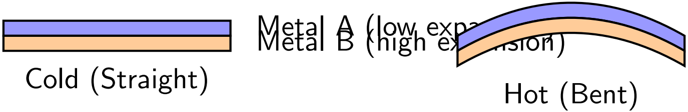
- Excellent air venting capacity at startup.
- Self-adjusting to variations in steam pressure.
- Compact size with a large discharge capacity relative to their size.
- Unlikely to freeze if installed to discharge vertically downwards to atmosphere.

Limitations

- Susceptible to waterhammer, which can damage the delicate bellows.
- Older corrugated bellows designs were prone to corrosion (modern uses SS).
- Cannot be used on superheated steam (permanently closed or ruptures).
- Condensate must subcool (slight waterlogging).

Bimetallic Steam Traps

- Operate using bimetallic elements (two dissimilar metals welded together).
- Metals have different coefficients of thermal expansion.
- When heated, one metal expands more than the other, causing the element to bend or bow.
- This bending action provides the mechanical force to open or close the valve.



How Bimetallic Traps Work

- **Cold Startup:** The bimetallic element is relaxed, the valve is open, discharging air and cold condensate.
- **Heating up:** As hot condensate reaches the trap, the element heats up and begins to bend.
- **Closing:** The bending force pulls the valve onto the seat against the system pressure, closing it before steam arrives.
- Operating force is a balance between steam pressure (trying to open the valve) and bimetal pull (trying to close it).

Advantages & Limitations: Bimetallic Steam Traps

Advantages

- Very robust and can withstand waterhammer.
- Can handle high pressures and superheated steam.
- Can discharge a large amount of cold condensate at startup.
- Wide open when cold, making them freeze-proof if installed correctly.
- Extracts sensible heat from condensate (energy savings).

Limitations

- Sluggish response to changes in pressure and temperature.
- Do not respond quickly to load changes.
- Significant subcooling is required (often backing up condensate).
- Not suitable for applications needing immediate condensate removal.

Comparison: Bellows vs. Bimetallic

Feature	Balanced Pressure (Bellows)	Bimetallic
Response Time	Relatively fast	Sluggish
Waterhammer Resistance	Vulnerable	Very robust
Superheated Steam	Cannot be used	Well-suited
Subcooling Requirement	Required (moderate)	Required (significant)
Air Venting	Excellent	Excellent

Summary & Q&A

Key Takeaways

- Thermostatic traps use temperature differences to operate, requiring condensate subcooling.
- Balanced pressure (bellows) traps are compact, self-adjusting, but delicate and vulnerable to waterhammer.
- Bimetallic traps are robust, handle superheat, but are slow to respond and back up more condensate.
- Both are excellent for tracing lines and air venting but poor for fast-response heat exchangers.

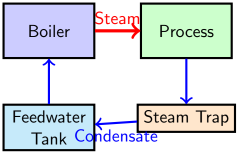
Questions?

Welcome & Recap

- Course: Thermal Systems and Energy Efficiency
- Unit 2: Boiler Performance and Steam Distribution Systems
- Lecture 18: Energy Conservation in Steam Distribution
- Recap: Different types of steam traps.

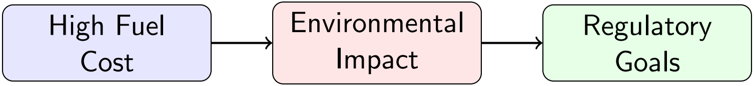
Introduction to Steam Distribution

- Transports steam from the boiler to the end-use equipment.
- Must deliver steam at the correct pressure and temperature.
- Needs to be clean, dry, and free of air/incondensable gases.
- Inefficiencies in distribution lead to significant energy losses.



Importance of Energy Conservation

- Steam generation is energy-intensive and expensive.
- Losses in distribution increase overall fuel consumption.
- Conservation directly impacts the bottom line and environmental footprint.
- Regulatory compliance and sustainability goals require efficient operations.



Key Areas of Energy Loss

- Uninsulated or poorly insulated pipes and valves.
- Steam leaks from joints, valves, and traps.
- Failure to recover condensate.
- Venting of flash steam to the atmosphere.
- Incorrect steam pressure for the application.

Uninsulated Pipes	Steam Leaks	Condensate Loss	Flash Steam Venting	Wrong Pressure

Steam Leaks: Identification

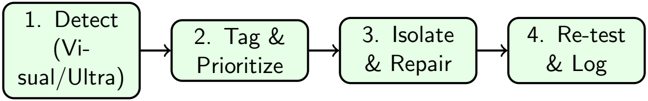
- Leaks can occur at flanges, valves, pipe joints, and failed traps.
- A 3mm hole can waste thousands of rupees worth of steam annually.
- Visual inspection often reveals plumes of steam.
- Ultrasonic leak detectors are used for hidden or internal leaks.

Impact of a 3mm Leak (Example @ 7 bar)

Loss $\approx$ 15 kg/hr of steam
Annual Loss $\approx$ 130 tonnes/year
Massive financial and energy drain!

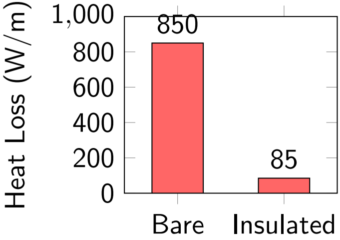
Steam Leaks: Repair and Prevention

- Implement a routine leak detection and repair program.
- Prioritize repairing larger, continuous leaks immediately.
- Use appropriate gaskets and sealants for steam applications.
- Ensure proper pipe alignment and support to reduce stress on joints.



Insulation of Steam Pipes

- Bare pipes lose heat continuously to the surroundings.
- Insulation reduces heat loss by up to 90%.
- Reduces condensation inside the pipe, improving steam quality.
- Improves safety by protecting personnel from hot surfaces.



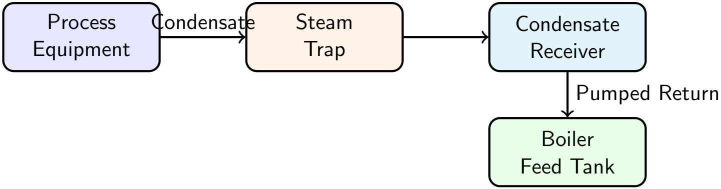
Insulation: Types and Selection

- Common materials: Mineral wool, fiberglass, calcium silicate.
- Selection depends on operating temperature, environment, and cost.
- Don't forget to insulate valves, flanges, and fittings (removable jackets).
- Economic thickness of insulation (ETI) balances insulation cost vs. energy savings.

Material	**Typical Application**
Mineral Wool	High temperature steam lines
Fiberglass	Low to medium pressure lines
Calcium Silicate	Very high temp, mechanical strength needed
Removable Jackets	Valves, Flanges, Steam Traps

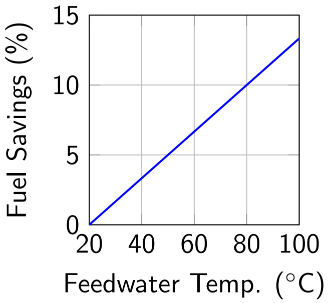
Condensate Recovery: Overview

- Condensate is hot, treated water containing valuable heat.
- Returning condensate to the boiler saves fuel and water.
- Reduces the need for chemical water treatment.
- Lowers effluent discharge and associated costs.



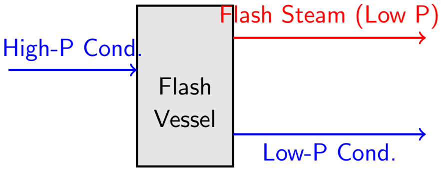
Condensate Recovery: Economic Benefits

- Can contain up to 20% of the energy of the original steam.
- For every 6°C rise in feedwater temperature, fuel savings are $\approx 1\%$.
- Reduces boiler blowdown requirements.
- Payback period for condensate recovery systems is usually very short.



Flash Steam Recovery

- Flash steam is generated when high-pressure condensate drops to a lower pressure.
- Contains significant latent heat.
- Can be recovered using a flash vessel and used for low-pressure applications.
- Commonly used for space heating or preheating process water.



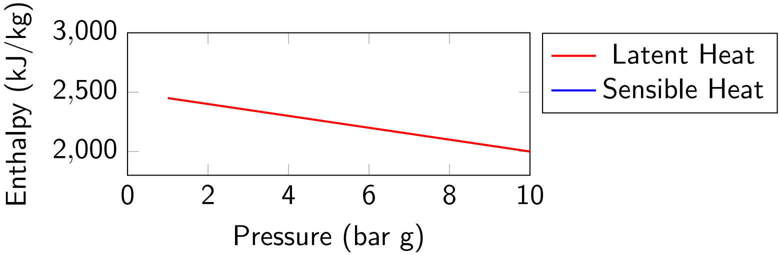
Steam Trap Maintenance

- Failed-open traps blow live steam into the condensate return.
- Failed-closed traps cause waterhammer and poor heating.
- Regular testing (visual, thermal, ultrasonic) is necessary.
- Replace or repair faulty traps immediately to prevent energy loss.

Failure Mode	**Consequence**	**Symptom**
Failed Open	Wastes live steam	High condensate temp, steam plume
Failed Closed	Condensate backup	Cold pipe, poor heat transfer

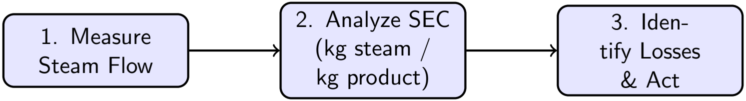
Optimizing Steam Pressure

- Generate steam at the highest required pressure, distribute at needed pressure.
- Reducing pressure using PRVs at the point of use reduces distribution losses.
- Lower pressure steam has higher latent heat.
- Avoid supplying higher pressure than the equipment requires.



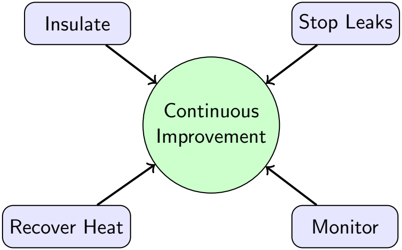
Monitoring and Metering

- You cannot manage what you do not measure.
- Install steam meters at departmental or key equipment levels.
- Track steam consumption against production output (specific energy consumption).
- Identify sudden spikes or gradual increases indicating problems.



Best Practices Summary

- Insulate all hot surfaces, including flanges and valves.
- Fix leaks promptly and implement a steam trap testing routine.
- Maximize condensate and flash steam recovery.
- Optimize operating pressures and meter your usage.
- Train personnel on energy-efficient practices.



Summary & Q/A

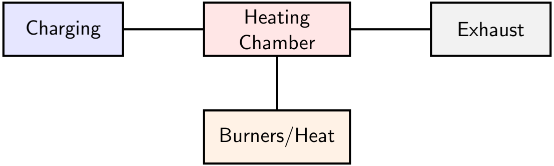
- Energy conservation in steam systems offers massive cost savings.
- Key areas: leaks, insulation, condensate, and traps.
- Proactive maintenance is essential.
- Questions?

Introduction to Furnaces

- A furnace is an equipment used to melt metals for casting or to heat materials to change their shape or properties.
- Since industrial furnaces perform many functions, there is a wide variety of shapes and sizes.
- Primary purpose: To release heat from a fuel and transfer it to a material (charge).
- Key requirement is achieving the desired temperature efficiently.

Key Components of a Furnace

- While designs vary, most furnaces share common structural elements.
- Heating chamber or enclosure (combustion chamber).
- Burners or heating elements.
- Refractory lining and insulation.
- Flue or exhaust system for removing waste gases.
- Material handling or charging mechanism.



1. The Heating Chamber

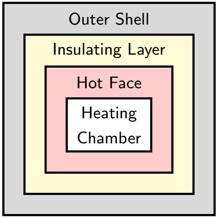
- Also known as the combustion chamber in fuel-fired furnaces.
- The space where the charge is placed and heated.
- Designed to maximize heat transfer to the charge.
- Its shape and size depend on the type and volume of material being processed.
- Must contain the high temperatures and pressures generated during combustion.

2. Burners and Heat Sources

- The heat source provides the energy required for the process.
- **Fuel-Fired Furnaces**: Use burners to combust gas, oil, or solid fuels.
- **Electric Furnaces**: Use electrodes or heating elements.
- Burners must ensure proper mixing of fuel and air for efficient combustion.
- Placement of burners is critical for uniform heat distribution.

3. Refractory Lining - Purpose

- The inner lining of the heating chamber.
- Primary function: To contain the heat within the furnace.
- Protects the outer steel shell from high temperatures and thermal damage.
- Must withstand chemical attack from the charge or combustion gases.
- Crucial for maintaining energy efficiency by reducing heat loss.



Refractory Lining - Materials

- Made from high-temperature resistant materials.
- Common materials: Fireclay, high alumina, silica, magnesite.
- Selection depends on the operating temperature and chemical environment.
- Often consists of multiple layers: a dense hot face layer and a porous insulating layer behind it.

4. The Outer Shell

- The structural framework that holds the furnace together.
- Typically made of steel plates and structural shapes (beams, channels).
- Provides mechanical strength to support the refractory, burners, and charge.
- Must be robust enough to withstand thermal expansion and contraction.
- Often painted with heat-resistant paint to prevent corrosion.

5. Exhaust and Flue System

- Necessary in fuel-fired furnaces to remove combustion products.
- Includes the flue duct, chimney (stack), and sometimes draft control dampers.
- Proper drafting is required to maintain the correct pressure in the combustion chamber.
- Flue gases carry away a significant amount of heat, which is a major source of energy loss.
- Waste heat recovery systems are often integrated here.

6. Charging and Discharging Mechanisms

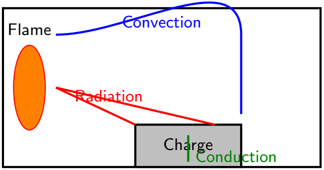
- Systems used to load the material (charge) and remove the heated product.
- Can be manual in small furnaces, but mostly automated in industrial setups.
- **Batch Furnaces**: Use doors, bogies (cars), or pushers.
- **Continuous Furnaces**: Use conveyors, walking beams, or rotary hearths.
- Proper design minimizes heat loss when doors are open.

7. Control Systems and Instrumentation

- Modern furnaces rely heavily on automation.
- **Sensors**: Thermocouples for temperature, pressure sensors, gas analyzers.
- **Controllers**: Adjust fuel/air ratio to maintain temperature and combustion efficiency.
- Safety interlocks to shut down the system in case of flame failure or over-temperature.
- Crucial for both product quality and energy efficiency.

Heat Transfer in a Furnace

- Understanding how heat moves is vital to furnace design.
- **Radiation**: The primary mode of heat transfer at high temperatures (from flame and hot refractory to the charge).
- **Convection**: Heat transfer from hot combustion gases sweeping over the charge.
- **Conduction**: Heat transfer within the charge itself as it heats up.
- Furnace structure is designed to maximize radiation and convection to the charge.



Furnace Atmospheres

- The environment inside the heating chamber is important for the product.
- Furnace structure must be sealed if a specific controlled atmosphere is required.

Atmosphere Type	Characteristics / Application
Oxidizing	Excess air, used when oxidation is not an issue.
Reducing	Lack of oxygen, prevents oxidation of the charge (e.g., in metallurgy).
Neutral	Perfect stoichiometric combustion, rare in practice.

Design Considerations for Efficiency

- The structure directly impacts energy efficiency.
- Optimizing the chamber size to the charge to reduce empty space.
- High-quality, thick insulation to minimize casing heat losses.
- Well-fitting doors and seals to prevent cold air infiltration.
- Aerodynamic internal design to improve convective heat transfer.

Summary of Furnace Structure

- A furnace is a complex system, not just a hot box.
- Key structural elements: Shell, Refractory, Burners, Flue, Charging system.
- The design must balance structural integrity at high temperatures with maximum thermal efficiency.
- Understanding these components is the first step in analyzing furnace performance.

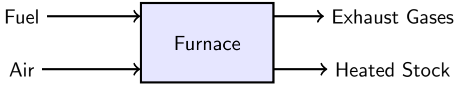
Q&A and Next Steps

- Any questions on the general structure of a furnace?
- **Next Lecture**: Classification of Furnaces.
- We will explore the different types of furnaces based on their operation and heat source.

Preview: Furnace Types
Batch vs Continuous
Fuel-fired vs Electric

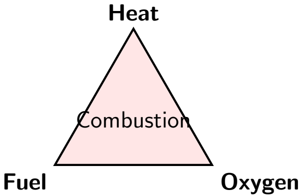
Introduction to Working Principle

- A furnace is a device used for high-temperature heating.
- Primary function: Extract heat from a fuel source and transfer it to a material/stock.
- Relies on the fundamental principles of thermodynamics, heat transfer, and combustion.
- General phases: Combustion of fuel, heat transfer to the stock, and exhaust of flue gases.



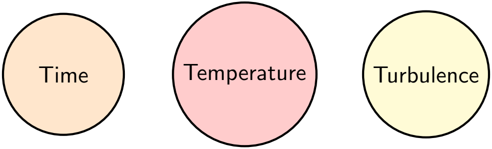
The Combustion Process

- Combustion is an exothermic chemical reaction between a fuel and an oxidant (usually oxygen in the air).
- Produces heat, light, and combustion products (flue gases).
- Complete combustion is desired to maximize heat release and minimize unburnt fuel losses.
- Requires proper mixing, adequate oxygen, and sufficient temperature to ignite and sustain the flame.



The 3 T's of Combustion

Efficient combustion relies on the '3 T's'.



- **Time**: Sufficient residence time for the combustion reaction to complete.
- **Temperature**: High enough temperature to ignite and maintain the reaction.
- **Turbulence**: Good mixing of fuel and air to ensure all fuel molecules find oxygen.

Time in Combustion

- Combustion is not instantaneous; it requires time.
- **Residence time**: The time the fuel-air mixture spends in the combustion chamber.
- If time is too short, unburnt fuel escapes through the exhaust.
- Furnace volume must be large enough to allow sufficient residence time for the specific fuel.

Temperature in Combustion

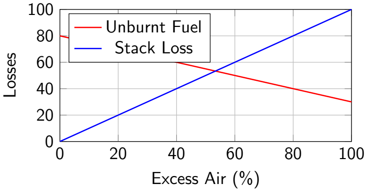
- A minimum ignition temperature is required to start the reaction.
- The chamber must maintain a high temperature to sustain continuous combustion.
- Pre-heating combustion air can significantly increase the furnace temperature and efficiency.
- If temperature drops too low, combustion may become unstable or extinguish.

Turbulence in Combustion

- Turbulence ensures intimate mixing of fuel particles/droplets with oxygen molecules.
- Poor mixing leads to localized rich (too much fuel) and lean (too much air) zones.
- Rich zones cause soot and carbon monoxide formation.
- Burner design plays a critical role in creating the necessary turbulence.

Air-Fuel Ratio and Excess Air

- **Stoichiometric (theoretical) air**: The exact amount of air needed for complete combustion.
- In reality, perfect mixing is impossible, so **Excess Air** is supplied.
- Excess Air ensures all fuel burns but introduces a penalty: heating extra nitrogen.
- Optimization is required: Too little air causes unburnt fuel loss; too much air causes heat loss to stack.



Heat Transfer Mechanisms

- Once heat is generated, it must be transferred to the stock.
- Furnaces rely on all three modes of heat transfer: Conduction, Convection, and Radiation.
- In high-temperature furnaces, **Radiation** is the dominant mode.
- **Convection** is significant for transferring heat from flue gases to the stock and furnace walls.

Radiation Heat Transfer

- Transfer of heat via electromagnetic waves.
- Proportional to the fourth power of absolute temperature (T^4).
- Highly effective at the high temperatures found in furnaces.
- Heat radiates directly from the flame and from the hot refractory walls to the stock.

Convection Heat Transfer

- Transfer of heat by the physical movement of the hot flue gases.
- Depends on gas velocity, surface area, and temperature difference.
- Crucial in lower temperature zones of the furnace or in specific furnace designs.
- Forced circulation (using fans) can enhance convective heat transfer.

Draft Systems in Furnaces

- Draft is the pressure difference that causes air to flow into the furnace and flue gases to exhaust.
- Essential for supplying combustion air and removing the products of combustion.
- Can be Natural Draft or Mechanical Draft.
- Proper draft maintains the correct pressure inside the furnace chamber.

Natural vs. Mechanical Draft

- **Natural Draft**: Created by the density difference between hot exhaust gases in the chimney and cold outside air.
- **Mechanical Draft**: Created using fans or blowers.
- **Forced Draft (FD) fans**: Push air into the furnace.
- **Induced Draft (ID) fans**: Pull exhaust gases out of the furnace.

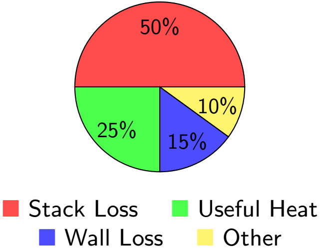
Feature	**Natural Draft**	**Mechanical Draft**
Creation Method	Chimney (Density diff.)	Fans or blowers (FD, ID)
Control	Weather dependent	Highly controllable
Efficiency	Lower	Higher

Exhaust Mechanisms and Flue Gases

- Flue gases are the byproducts of combustion (CO_2, H_2O, N_2, sometimes SO_x, NO_x).
- They carry away a significant amount of sensible heat (stack loss).
- Heat recovery systems (recuperators, regenerators) are often used to extract this waste heat.
- Proper exhaust design minimizes environmental impact and improves overall efficiency.

Heat Losses in a Furnace

- **Stack loss**: Heat carried away by hot flue gases (largest loss).
- **Wall loss**: Heat conducted through furnace walls and roof.
- **Opening loss**: Radiation loss through open doors or viewing ports.
- **Unburnt fuel loss**: Due to incomplete combustion.



Summary & Q&A

- Furnace working principle involves combustion, heat transfer, and exhaust.
- The 3 T's (Time, Temp, Turbulence) are crucial for complete combustion.
- Radiation and convection are the primary modes of heat transfer to the stock.
- Proper draft and excess air control are necessary for optimal operation.
- Any questions?

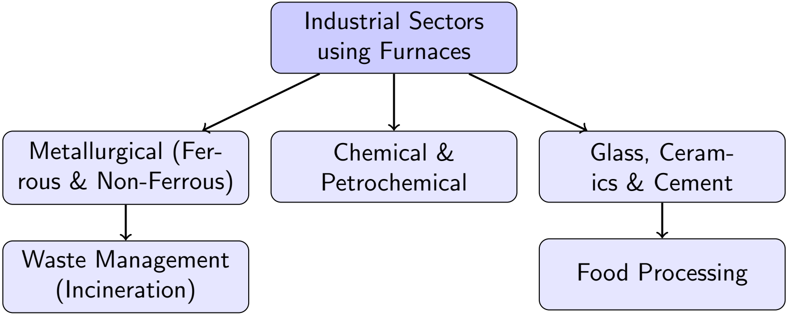
Welcome & Recap

- Course: Thermal Systems and Energy Efficiency
- Unit 3: Furnace Systems and Energy Efficiency
- Lecture 21: Industrial Applications of Furnaces
- Recap: Working principles of general industrial furnaces.

Introduction to Industrial Applications

- Furnaces are the heart of many industrial processes.
- They provide the high temperatures required for chemical reactions, melting, and material transformation.
- Applications range from heavy metallurgy to specialized chemical processing.
- The choice of furnace is highly dependent on the specific industrial application.

Major Industrial Sectors



Metallurgical Applications: Iron and Steel

Furnace Type	Primary Application
Blast Furnaces	Primary smelting to produce pig iron from iron ore.
Basic Oxygen Furnaces (BOF)	Converting pig iron into steel.
Electric Arc Furnaces (EAF)	Melting scrap steel for recycling.
Reheating Furnaces	Heating steel billets/slabs prior to rolling.

Metallurgical Applications: Non-Ferrous

Industry	Furnace / Application
Aluminum Industry	Hall-Héroult smelting pots (electrolytic furnaces) and reverberatory melting furnaces.
Copper Production	Flash smelting furnaces and converters.
Zinc and Lead Smelting	Roasting furnaces and blast furnaces.
Crucible Furnaces	Used for smaller scale melting of non-ferrous alloys (e.g., brass, bronze).

Glass Industry Applications

- Glass Melting Furnaces: Continuous tank furnaces for large-scale production.
- High temperatures (1500°C - 1600°C) required to melt silica sand, soda ash, and limestone.
- Annealing Lehrs: Long, continuous furnaces used to slowly cool glass products to relieve internal stresses.
- Regenerative furnaces are common for energy efficiency.

Ceramic & Refractory Industries

- Kilns (Tunnel Kilns, Shuttle Kilns): Used for firing ceramics, bricks, and tiles.
- Firing process involves heating the shaped clay/ceramic body to achieve desired physical properties.
- Refractory Firing: Very high-temperature kilns for producing heat-resistant bricks used in other furnaces.
- Precise temperature control is vital for product quality.

Chemical Industry Applications

- Process Heaters: Furnaces used to heat fluids in tubes for chemical reactions.
- Cracking Furnaces: Used in thermal cracking of hydrocarbons (e.g., producing ethylene).
- Steam Reformers: Reacting steam and natural gas to produce synthesis gas (hydrogen and carbon monoxide).
- Calcination Furnaces: Used for thermal decomposition of ores or chemicals (e.g., calcining limestone to quicklime).

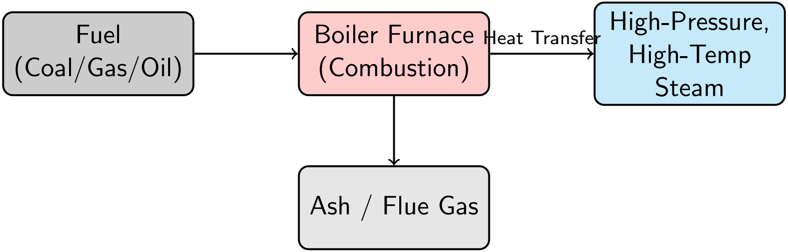
Petrochemical: Crackers & Reformers

- Ethylene Crackers: Highly specialized furnaces where steam and hydrocarbons pass through tubes at high temperatures (up to 850°C) for short residence times.
- Catalytic Reformers: Furnaces heating naphtha before passing it over catalysts to increase octane rating.
- Crucial for producing building blocks for plastics, synthetic fibers, and fuels.
- Strict control of tube skin temperatures is required.

Cement Manufacturing: Rotary Kilns

- Rotary Kilns: Massive, slightly inclined rotating cylinders.
- Raw materials (limestone, clay) are fed at the upper end and move downwards.
- Burner at the lower end provides heat (up to 1450°C material temperature).
- Process produces cement clinker, which is then ground into cement.
- Highly energy-intensive process.

Thermal Power Plants & Boilers



- Types: Pulverized coal furnaces, fluidized bed combustion (FBC) furnaces.
- Focus is on maximum heat transfer to water/steam tubes.

Waste Incineration

- Incinerators: Specialized furnaces for burning municipal, hazardous, or medical waste.
- Volume Reduction: Significantly reduces the volume of solid waste.
- Energy Recovery (Waste-to-Energy): Heat generated can be used to produce steam for electricity.
- Strict emission control systems are required to handle toxic flue gases.

Food Processing Applications

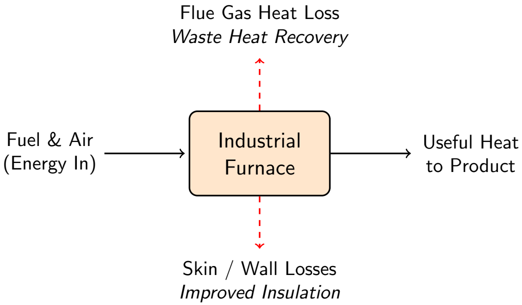
- Industrial Ovens: Used for baking (bread, biscuits), roasting (coffee, nuts), and drying.
- Operate at lower temperatures compared to metallurgical furnaces.
- Types: Tunnel ovens (continuous), batch ovens.
- Focus on uniform temperature distribution and hygiene.

Furnace Selection Criteria

Key Parameters for Furnace Selection

- **Temperature:** Operating Temperature required by the process.
- **Charge:** Nature of the Charge (solid, liquid, corrosive, etc.).
- **Capacity:** Production Capacity (Batch vs. Continuous).
- **Fuel:** Fuel Availability and Cost.
- **Atmosphere:** Atmosphere Requirements (oxidizing, reducing, inert).
- **Regulations:** Environmental Regulations.

Energy Efficiency Considerations



- **Combustion Optimization:** Maintaining proper air-fuel ratios.
- **Process Integration:** Optimizing the whole plant's energy flow.

Summary & Q/A

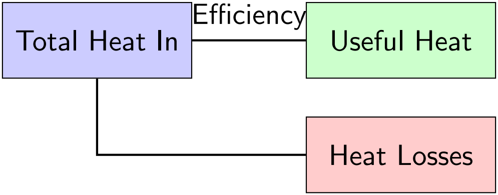
- Furnaces have diverse applications across metallurgy, glass, ceramics, chemicals, and power generation.
- Each industry uses specialized furnace designs tailored to its specific process requirements.
- The choice of furnace depends on temperature, capacity, and the nature of the material processed.
- Energy efficiency remains a common and critical goal across all industrial furnace applications.

Welcome & Recap

- Welcome to Lecture 22.
- Course: Thermal Systems and Energy Efficiency.
- Recap: Industrial applications and types of furnaces.
- Today's Focus: Parameters Influencing Furnace Efficiency.

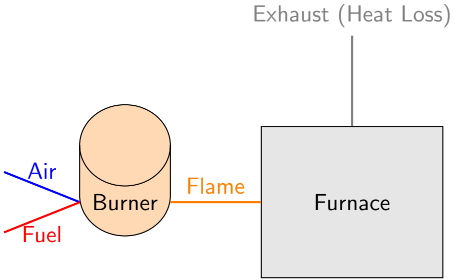
Introduction to Furnace Efficiency

- Furnace efficiency is the ratio of useful heat to total heat input.
- It directly impacts fuel consumption and operating costs.
- Optimizing efficiency reduces greenhouse gas emissions.
- Efficiency is not static; it depends on multiple operational parameters.



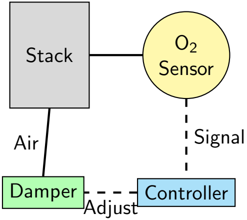
Key Parameter 1: Excess Air

- Combustion requires air, but too much air (excess air) wastes heat.
- Excess air absorbs heat and carries it out through the chimney.
- Maintaining the correct air-to-fuel ratio is critical.
- Every 10% reduction in excess air can significantly save fuel.



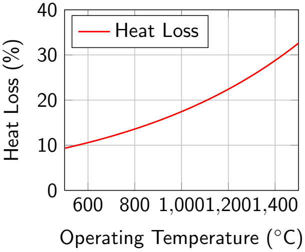
Controlling Excess Air

- Use oxygen or carbon dioxide sensors in the flue gas.
- Implement automatic damper controls for air intake.
- Regularly check and calibrate burners.
- Minimize air infiltration through furnace leaks.



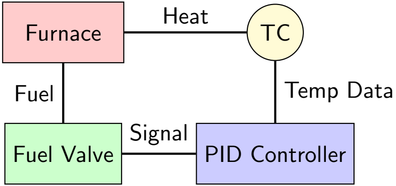
Key Parameter 2: Operating Temperature

- Higher operating temperatures increase heat loss through walls and roof.
- Operate at optimum temperature for the process.
- Operating above required temp wastes fuel, damages refractories.
- Temperature control systems are essential.



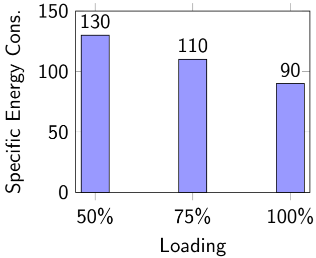
Temperature Control Strategies

- Use accurate and properly placed thermocouples.
- Implement PID controllers for precise burner modulation.
- Avoid frequent temperature cycling if possible.
- Insulate properly for high-temperature processes.



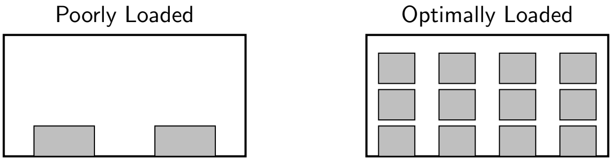
Key Parameter 3: Furnace Loading

- Furnaces are most efficient when operated at design capacity.
- Under-loading: higher % of heat goes to losses rather than product.
- Over-loading: incomplete heating, increased rejection rates.
- Optimal loading maximizes useful heat transfer.



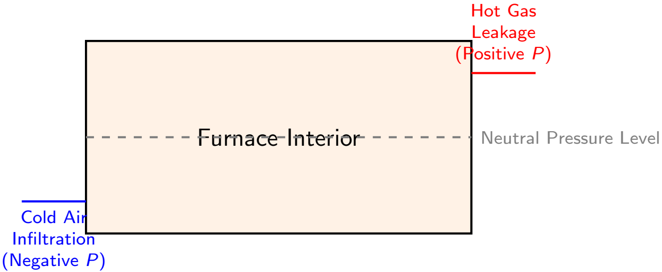
Optimizing Furnace Loading

- Schedule production to ensure furnace runs at full capacity.
- Consolidate smaller batches into larger ones when feasible.
- Ensure proper arrangement of charge to maximize heat transfer.
- Avoid running empty or on standby for long periods.



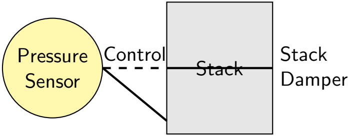
Key Parameter 4: Draft Control

- Draft is the pressure difference that moves gases through the furnace.
- Negative pressure can pull in cold outside air (infiltration).
- Positive pressure can push hot gases out through cracks.
- A slight positive pressure at hearth level is usually ideal.



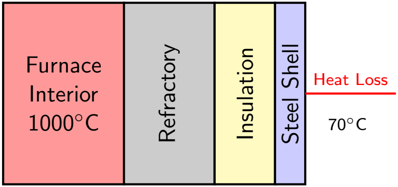
Managing Furnace Draft

- Use pressure sensors to monitor draft continuously.
- Adjust stack damper to control internal pressure.
- Seal doors, viewing ports, and expansion joints to prevent leaks.
- Maintain proper pressure for uniform temperature.



Key Parameter 5: Heat Losses (Wall & Roof)

- Heat conducts through refractory lining and radiates from outer shell.
- Deteriorated refractory increases these losses significantly.
- Proper insulation thickness is required based on internal temp.
- High shell temperatures indicate poor insulation.



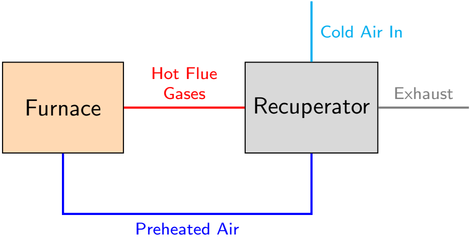
Minimizing Wall and Roof Losses

- Use high-quality refractory bricks or ceramic fiber linings.
- Perform regular maintenance to repair cracks and fallen refractory.
- Apply low-emissivity coatings on exterior shell.
- Use thermal imaging to detect hidden insulation failures.

Insulation Material	**Thermal Cond. (W/mK)**	**Max Temp (°C)**
Firebrick	1.2 – 1.5	1400
Insulating Brick	0.3 – 0.4	1300
Ceramic Fiber	0.1 – 0.2	1200

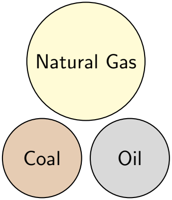
Key Parameter 6: Waste Heat Recovery

- Significant portion of heat leaves furnace via flue gases.
- Waste heat can be recovered to preheat combustion air.
- Can also be used to preheat the charge (material).
- Recuperators and regenerators are common recovery devices.



Key Parameter 7: Fuel Quality

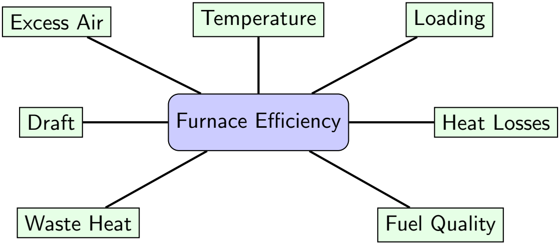
- Calorific value and composition affect efficiency.
- Moisture in fuel absorbs heat for vaporization.
- Impurities cause fouling/scaling on burners and recuperators.
- Consistent fuel quality ensures stable combustion.



Purity / Combustion Efficiency
Gas > Oil > Coal

Summary of Efficiency Parameters

- Optimum excess air minimizes stack losses.
- Strict operating temperature control prevents wasteful heating.
- Maximum furnace loading ensures heat goes into product.
- Proper draft and good insulation minimize physical heat losses.



Summary & Q&A

- Today we covered the key parameters that influence furnace efficiency.
- Understanding these factors is crucial for energy conservation.
- Next lecture: Calculation of furnace efficiency (Direct and Indirect Methods).
- Are there any questions?

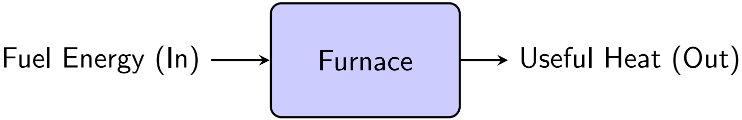
Questions?

Objectives & Recap

- **Recap:** Various parameters influence furnace efficiency (draft, fuel properties, excess air).
- **Objective 1:** Understand the input-output method of efficiency calculation.
- **Objective 2:** Calculate furnace efficiency using the direct method.
- **Objective 3:** Identify limitations of the direct method.

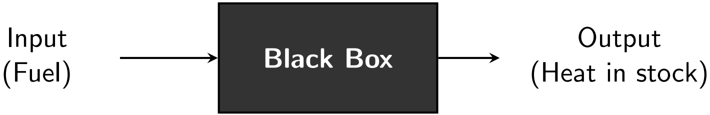
Introduction to Furnace Efficiency

- Furnace efficiency determines how effectively fuel energy is converted into useful heat.
- High efficiency means lower fuel consumption and reduced emissions.
- Two main methods to calculate efficiency:
  1. Direct Method (Input-Output Method)
  2. Indirect Method (Heat Loss Method)



Concept of Direct Method

- Also known as the Input-Output Method.
- Evaluates efficiency based on the useful heat transferred to the stock (material) versus the energy supplied by the fuel.
- Treats the furnace as a 'black box'.
- Only considers what goes in (fuel energy) and what comes out (useful heat in stock).



The Direct Method Equation

- Simple, straightforward mathematical relationship.

Direct Method Efficiency

$$\text{Efficiency } (\eta) = \left(\frac{\text{Heat Output}}{\text{Heat Input}}\right) \times 100$$

- **Heat Output:** Useful heat transferred to the material (stock).
- **Heat Input:** Total heat supplied by the fuel.

Heat Output Calculation

Useful Heat Output Equation

$$Q_{\text{out}} = m \times C_p \times (T_2 - T_1)$$

Where:

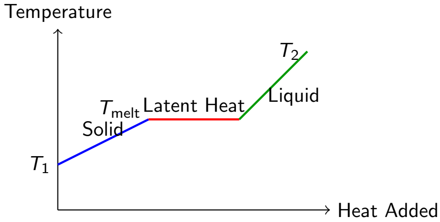
- m = Mass of the stock heated (kg)
- C_p = Specific heat of the stock (kCal/kg°C or kJ/kg°C)
- T_1 = Initial temperature of the stock (°C)
- T_2 = Final temperature of the stock (°C)

Heat Output - Phase Change

- If the material undergoes a phase change (e.g., melting), latent heat must be added.
- Crucial for melting furnaces (e.g., induction furnaces, cupolas).

$$Q_{out} = m\left[C_{p,s}(T_{melt} - T_1) + h_{fg} + C_{p,l}(T_2 - T_{melt})\right]$$

$$L = \text{Latent heat of fusion}$$



Heat Input Calculation

Heat Input Equation

$$Q_{\text{in}} = \text{Quantity of fuel consumed} \times \text{GCV of fuel}$$

- **Fuel quantity:** Measured in kg (for solids/liquids) or m^3 (for gases).
- **GCV:** Gross Calorific Value (kCal/kg or kJ/kg).
- Must ensure fuel consumption is measured over the same time period as stock heating.

Required Parameters for Measurement

To use the Direct Method, you need precise measurements of:

Parameter	**Measurement Device/Source**
1. Weight of the stock processed	Weighbridge or scales
2. Initial and final temperature	Pyrometers or thermocouples
3. Fuel consumption during batch	Flow meters or weight scales
4. GCV of the specific fuel batch	Laboratory analysis report

Advantages of Direct Method

- **Simplicity:** Easy to understand and calculate.
- **Quick Assessment:** Provides a rapid overall efficiency figure.
- **Fewer Parameters:** Requires fewer parameters to measure compared to the indirect method.
- **Baseline:** Good for establishing baseline performance of the furnace.

Disadvantages / Limitations

- **Lack of Detail:** Does not identify WHERE heat is lost (e.g., flue gas, radiation, openings).
- **No Actionable Data:** Provides no actionable data for specific improvements or troubleshooting.
- **Error Sensitivity:** Highly sensitive to measurement errors (e.g., incorrect stock weight or fuel flow).
- **Applicability:** Difficult to apply in continuous furnaces with varying loads.

Example Problem - Statement

Problem Statement

A reheating furnace heats 10 tonnes of steel per hour from 30°C to 1200°C.

- The furnace consumes 600 kg of fuel oil per hour.
- Specific heat of steel = 0.12 kCal/kg°C.
- Gross Calorific Value of fuel oil = 10,000 kCal/kg.

Calculate the efficiency of the furnace.

Example Problem - Calculation

Step 1: Calculate Heat Output (Q_{out})

- Mass (m) = 10,000 kg (since 10 tonnes = 10,000 kg)
- $\Delta T = 1200 - 30 = 1170°C$

$$Q_{out} = m \times C_p \times \Delta T$$

$$Q_{out} = 10,000 \times 0.12 \times 1170$$

$$Q_{out} = 1,404,000 \text{ kCal/hr}$$

Example Problem - Calculation (Cont.)

Step 2: Calculate Heat Input (Q_{in})

- Fuel consumed $= 600$ kg/hr
- $Q_{in} = 600 \times 10,000 = 6,000,000$ kCal/hr

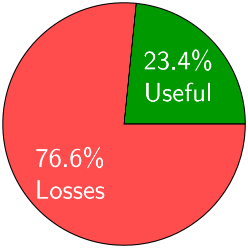
Step 3: Calculate Efficiency (η)

$$\eta = \left(\frac{Q_{out}}{Q_{in}}\right) \times 100$$

$$\eta = \left(\frac{1,404,000}{6,000,000}\right) \times 100 = \mathbf{23.4\%}$$

Interpretation of Results

- The calculated efficiency is 23.4%.
- This means 76.6% of the energy supplied by the fuel is lost.
- Typical reheating furnace efficiencies range from 20% to 40%.
- To improve this, we would need to use the Indirect Method to find out where the 76.6% went.



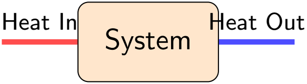
Summary & Q&A

- Direct Method evaluates efficiency by comparing useful heat output to total fuel heat input.
- It treats the furnace as a ‘black box’.
- It is simple but fails to identify sources of heat loss.

Questions?

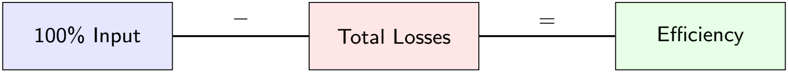
Welcome & Recap

- Course: Thermal Systems and Energy Efficiency (DI05019061)
- Lecture 24: Furnace Efficiency - Indirect Method
- Unit 3: Furnace Systems and Energy Efficiency
- Recap: Direct method evaluated efficiency by comparing heat output to heat input directly.



Introduction to the Indirect Method

- Also known as the Heat Loss Method.
- Efficiency is calculated by subtracting heat losses from 100%.
- More accurate than the direct method for large furnaces.
- Helps pinpoint areas where energy is being wasted.



Why Use the Indirect Method?

- ✓ Highlights specific areas of energy waste.
- ✓ Provides actionable insights for energy conservation.
- ✓ Crucial for process optimization.
- ✓ Often easier to measure losses accurately than total output.

Principle of Indirect Efficiency

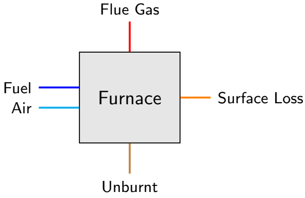
Fundamental Equation

$$\text{Efficiency (\%)} = 100\% - \text{Total Losses (\%)}$$

- Total Heat Input = Sensible heat + Heat from fuel combustion.
- Losses are expressed as a percentage of total heat input.
- Requires comprehensive measurement of all outgoing energy streams.

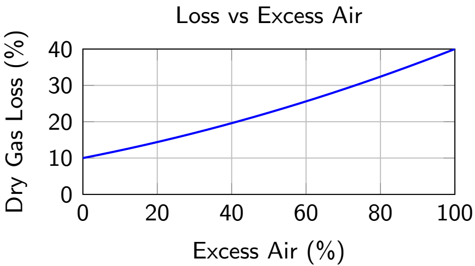
Major Heat Losses in a Furnace

1. Dry flue gas loss
2. Loss due to moisture in fuel
3. Loss due to hydrogen in fuel
4. Loss from moisture in combustion air
5. Wall / surface heat losses
6. Unburnt losses



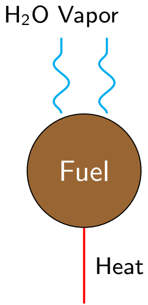
1. Dry Flue Gas Loss

- Often the largest source of heat loss (10-30%).
- Occurs due to the sensible heat carried away by hot exhaust gases.
- Depends on flue gas temperature and excess air level.
- Calculation requires measuring flue gas temperature and composition (O_2/CO_2).



2. Loss Due to Moisture in Fuel

- Moisture in fuel absorbs heat to vaporize.
- This latent and sensible heat goes up the stack.
- High moisture content significantly reduces furnace efficiency.
- Common in biomass or low-grade coal.



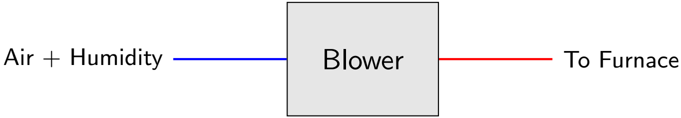
3. Loss Due to Hydrogen in Fuel

- Hydrogen in fuel combusts to form water vapor (H_2O).
- This water vapor absorbs latent heat of vaporization.
- Heat is lost when the vapor exits through the chimney.
- Higher in gaseous and liquid fuels compared to solid fuels.

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O + \text{Heat}$$

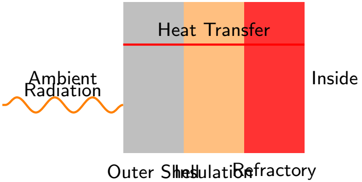
4. Loss Due to Moisture in Combustion Air

- Ambient air contains humidity (water vapor).
- This moisture enters the furnace and must be heated to the exhaust temperature.
- Generally a small loss compared to dry flue gas.
- Increases in highly humid climates or seasons.



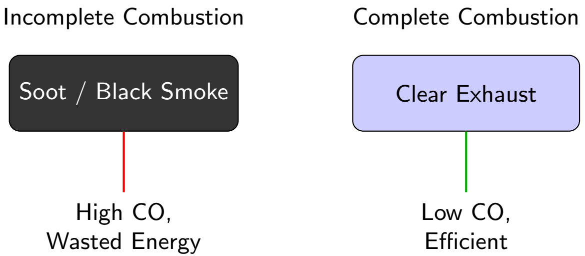
5. Wall and Surface Heat Losses

- Heat lost from furnace casing to the surroundings.
- Occurs via radiation and convection.
- Depends on surface area, surface temperature, and ambient conditions.
- Minimized by proper refractory and insulation.



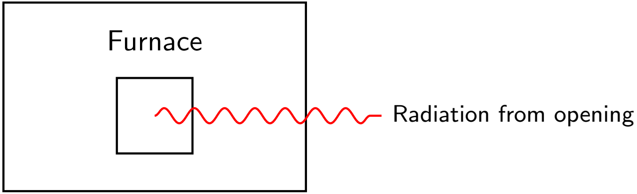
6. Unburnt Fuel Losses

- Incomplete combustion leads to unburnt fuel.
- Can be solid (carbon in ash) or gaseous (CO in flue gas).
- Indicates poor mixing, insufficient air, or inadequate residence time.
- Represents wasted chemical energy.



Other Minor Losses

- Heat loss through openings (doors, ports).
- Heat carried away by cooling water systems.
- Heat stored in fixtures or conveyors (in continuous furnaces).
- Often grouped together or estimated if small.



Data Required for Indirect Method

- ✓ Fuel analysis (Ultimate analysis: C, H, O, N, S, Moisture, Ash).
- ✓ Gross Calorific Value (GCV) of the fuel.
- ✓ Flue gas temperature and ambient temperature.
- ✓ Flue gas analysis (O_2 or CO_2 percentage).
- ✓ Surface temperatures of the furnace.

Calculating Efficiency: Step-by-Step

Step 1: Gather all measured data and fuel properties.

Step 2: Calculate theoretical air requirement.

Step 3: Calculate actual mass of dry flue gas.

Step 4: Calculate individual percentage losses ($L_1, L_2, \ldots$).

Step 5: Sum all losses and subtract from 100%.

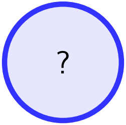
Direct vs. Indirect Method Comparison

- Direct: Simpler, requires fewer measurements, but doesn't show WHERE heat is lost.
- Indirect: Complex, needs many measurements, but pinpoints specific losses.
- Indirect is preferred for auditing and improving efficiency.
- Both should ideally yield similar results.

Feature	**Direct Method**	**Indirect Method**
Complexity	Low	High
Measurements	Few	Many
Pinpoints Losses	No	Yes
Best For	Quick checks	Auditing & Optimization

Summary & Q&A

- Indirect method evaluates efficiency by quantifying heat losses.
- Major losses include dry flue gas, moisture, hydrogen, and surface radiation.
- Understanding losses is the first step to optimizing furnace operation.
- Questions?

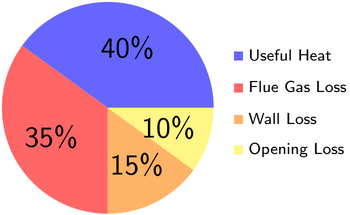


Welcome & Recap

- Welcome to Lecture 25: Energy conservation techniques in furnaces.
- Course: Thermal Systems and Energy Efficiency (DI05019061).
- Recap: Indirect Method for determining furnace efficiency.
- Today's focus: Practical methods to conserve energy and improve efficiency in industrial furnaces.

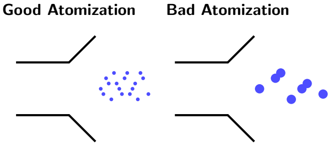
Introduction to Energy Conservation in Furnaces

- Furnaces are major energy consumers in industries like steel, glass, and ceramics.
- Significant portion of heat is lost through flue gases, walls, and openings.
- Energy conservation aims to maximize the heat transfer to the stock.
- Reduces fuel consumption, lowering operational costs and emissions.



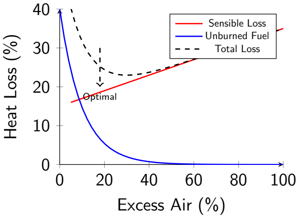
Strategy 1: Complete Combustion

- Unburned fuel represents a direct energy loss (chemical heat loss).
- Causes: Poor atomization, incorrect air-fuel ratio, inadequate mixing.
- Solutions: Regular burner maintenance, correct fuel oil temperature.
- Ensure proper atomizing steam/air pressure for liquid fuels.



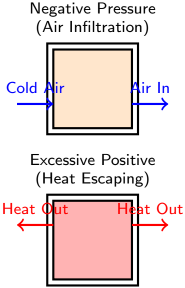
Strategy 2: Controlling Excess Air

- Excess air is needed for complete combustion but too much is wasteful.
- Extra air gets heated and carries sensible heat away up the chimney.
- Optimal excess air varies by fuel: ∼10-15% for natural gas, ∼15-20% for oil.
- Use Oxygen or CO_2 analyzers in the stack for continuous monitoring and control.



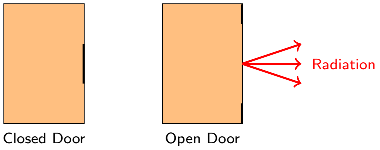
Strategy 3: Proper Draft Control

- Furnaces should operate at a slight positive pressure (e.g., +1 to +2 mm of WC) at the hearth level.
- Negative pressure causes cold air infiltration through doors and cracks.
- Cold air absorbs heat, reducing furnace temperature and efficiency.
- Excessive positive pressure causes flame roll-out and heat loss to surroundings.



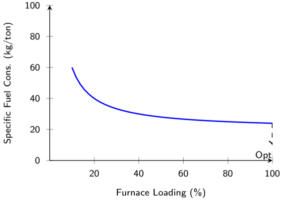
Strategy 4: Minimizing Opening Losses

- Heat radiates out when furnace doors are opened.
- Loss depends on opening size, furnace temperature, and time kept open.
- Keep doors closed as much as possible.
- Use properly sized doors; minimize the size of inspection or charging ports.



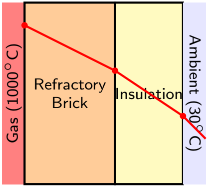
Strategy 5: Optimum Capacity Utilization

- Furnaces are most efficient at their design capacity.
- Under-loading increases the specific fuel consumption (fuel per ton of product).
- Wall losses and flue gas losses occur regardless of the load.
- Plan production schedules to run furnaces continuously at full load.



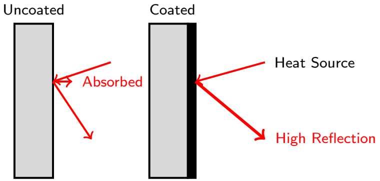
Strategy 6: Insulation and Refractories

- Heat is lost through conduction from the furnace interior to the outer skin.
- Improve insulation to reduce skin temperature.
- Use High Alumina bricks or Ceramic Fiber linings where appropriate.
- Ceramic fiber has low thermal mass, reducing heat storage losses during start-up/shut-down.



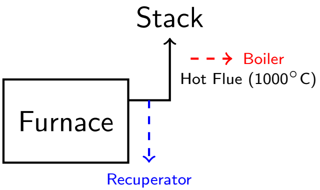
Strategy 7: High Emissivity Coatings

- Applied to the interior refractory surfaces of the furnace.
- Increases the emissivity of the walls, improving radiant heat transfer to the load.
- Allows the furnace to operate at a lower set temperature for the same heating rate.
- Protects refractory from thermal shock and chemical attack.



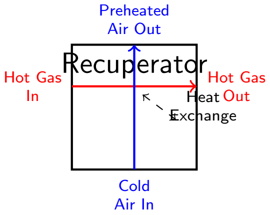
Strategy 8: Waste Heat Recovery (Flue Gases)

- Flue gases leave the furnace at very high temperatures (up to 1000°C+).
- This is the largest single source of heat loss in most furnaces.
- Recovering this heat is critical for significant energy savings.
- Used for: Preheating combustion air, preheating stock, or generating steam.



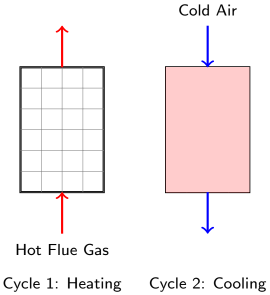
Waste Heat Recovery: Recuperators

- Continuous heat exchangers (typically cross-flow).
- Hot flue gases flow through or around tubes, while cold combustion air flows on the other side.
- Preheating combustion air directly reduces fuel consumption.
- Types: Metallic recuperators (for temps up to $\sim 800^\circ$C) and Ceramic (for higher temps).



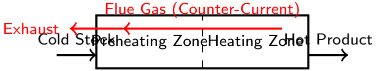
Waste Heat Recovery: Regenerators

- Cyclic heat exchangers using a thermal storage medium (checkerwork bricks).
- Cycle 1: Hot flue gas heats the bricks.
- Cycle 2: Flow is reversed; cold combustion air passes through and absorbs heat.
- Common in high-temperature applications like glass melting furnaces.



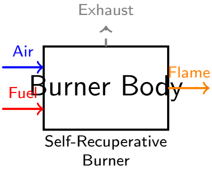
Waste Heat Recovery: Stock Preheating

- Using flue gas heat to warm the raw material (stock) before it enters the high-temperature zone.
- Very common in continuous furnaces (e.g., tunnel kilns, pusher furnaces).
- Reduces the heat duty required in the main heating zone.
- Highly efficient way to utilize lower-grade waste heat.



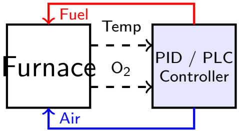
Strategy 9: Advanced Burners

- Upgrading to modern, highly efficient burners.
- Regenerative Burners: Have built-in heat storage, offering extreme efficiency.
- Self-Recuperative Burners: Incorporate a recuperator inside the burner body.
- Low NO_x Burners: Designed to maintain efficiency while reducing harmful emissions.



Strategy 10: Automation and Control

- Replacing manual control with automated systems.
- PID controllers or PLCs for precise temperature control.
- Automated Air-Fuel ratio controllers linked to oxygen sensors.
- Supervisory Control and Data Acquisition (SCADA) for monitoring efficiency in real-time.



Summary & Q&A

- Energy conservation in furnaces is achieved by minimizing various heat losses.
- Key methods: controlling excess air, optimizing draft, and maximizing capacity.
- Insulation and proper refractories minimize skin losses.
- Waste Heat Recovery (recuperators, regenerators) offers the largest potential for savings.

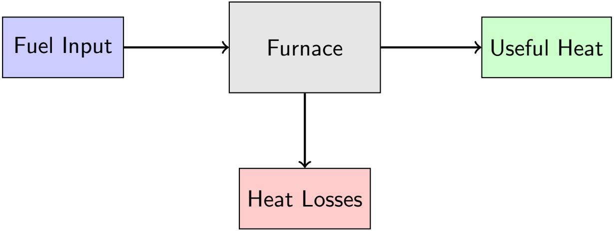
Questions?

Welcome & Recap

- Welcome to Lecture 26: Methods to improve fuel efficiency
- Unit 3: Furnace Systems and Energy Efficiency
- Recap: General energy conservation techniques in furnaces explored previously.
- Today's Focus: Specific methods and operational strategies to maximize fuel utilization.

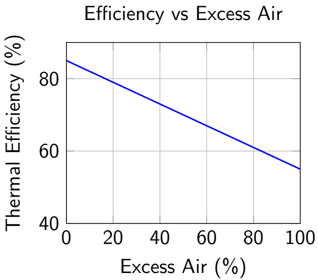
Introduction to Fuel Efficiency

- Fuel efficiency is the ratio of useful energy output to the total energy input from fuel.
- In industrial furnaces, improving this means getting more product heating for less fuel.
- Primary goal: Ensure complete combustion while minimizing heat losses.
- Even small percentage improvements can lead to significant cost savings.



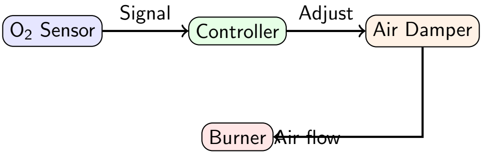
Importance of Excess Air Control

- Complete combustion requires air, but too much air carries heat away up the stack.
- Controlling excess air is the most effective way to improve fuel efficiency.
- Every 10% reduction in excess air can yield approximately 1% saving in fuel.
- Requires continuous monitoring of O_2 or CO levels in the flue gas.



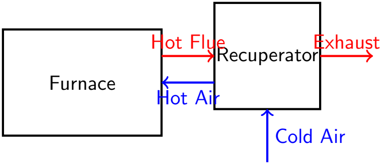
Determining Optimum Air-Fuel Ratio

- The optimum ratio depends on the fuel type and burner design.
- Natural gas typically requires 5-10% excess air, while liquid fuels might need more.
- Automated trim control systems use O_2 sensors to adjust air dampers in real-time.
- Prevents both unburned fuel (CO) and excessive stack heat loss.



Preheating Combustion Air

- Combustion air can be preheated using waste heat from the flue gases.
- Preheating air increases the flame temperature and overall thermal efficiency.
- For every 20°C increase in combustion air temperature, fuel savings of roughly 1% can be achieved.
- Recuperators and regenerators are commonly used for this purpose.



Importance of Burner Design

- The burner is the heart of the combustion system.
- A good design ensures proper mixing of fuel and air for complete combustion.
- Key factors: Atomization (for liquids), flame shape, and turndown ratio.
- Old, inefficient burners should be evaluated for replacement.

High-Efficiency Burner Technologies

- High-Velocity Burners: Promote rapid mixing and better heat transfer through convection.
- Low-NOx Burners: Designed to reduce emissions while maintaining high efficiency.
- Regenerative Burners: Pair burners with heat storage beds for extreme air preheating.
- Flat Flame Burners: Provide uniform radiant heat across the furnace roof or walls.

Minimizing Heat Losses from Openings

- Furnace doors and viewing ports are significant sources of heat loss.
- Radiation loss increases rapidly with the size of the opening and furnace temperature.
- Air infiltration through openings cools the furnace and wastes fuel.
- Solutions: Keep doors closed when possible, use proper seals, minimize opening sizes.

Controlling Furnace Draft and Pressure

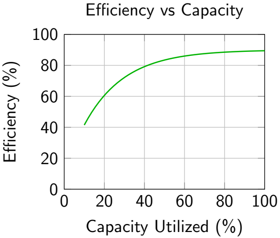
- Furnaces should operate at a slight positive pressure near the hearth.
- Negative pressure (strong draft) pulls in cold ambient air, causing severe efficiency drops.
- Excessive positive pressure forces hot gases out through seals and doors.
- Automatic draft control dampers in the flue are essential for maintaining proper pressure.

Upgrading Insulation and Refractories

- Wall and roof heat losses can account for 10-20% of fuel input.
- Upgrading to low thermal mass materials (like ceramic fibers) reduces heat storage losses.
- Adding additional insulation layers to existing walls lowers the outer skin temperature.
- Regular maintenance to repair cracked or fallen refractories is vital.

Capacity Utilization and Scheduling

- Furnaces are most efficient when operating at or near their designed full load.
- Operating at partial loads significantly drops efficiency due to fixed baseline losses.
- Batch furnaces should be scheduled to minimize idle time at high temperatures.
- Continuous furnaces should maintain a steady, optimal throughput.



Minimizing Dead Weight (Fixtures)

- Heating trays, baskets, and fixtures consumes fuel without adding value to the product.
- This is known as ‘tare weight’ or ‘dead weight’.
- Use lightweight, high-strength alloys or ceramics for fixtures.
- Redesigning fixtures to reduce weight can yield substantial, immediate fuel savings.

Maintaining Clean Heat Transfer Surfaces

- Soot on the fireside or scale on the product side acts as an insulator.
- Even a 1mm layer of soot can reduce heat transfer efficiency significantly.
- Regular cleaning and maintenance of radiant tubes and heat exchangers is required.
- Proper combustion control minimizes soot formation in the first place.

Instrumentation and Monitoring

- "You cannot manage what you do not measure."
- Key instruments: Fuel meters, O_2/CO analyzers, temperature sensors (thermocouples).
- Continuous monitoring allows for immediate correction of inefficiencies.
- Data logging helps identify trends and evaluate the success of efficiency upgrades.

Summary of Fuel Saving Potential

Method	Potential Savings
Air-Fuel Ratio Control	5-20%
Waste Heat Recovery	10-30%
Improved Insulation	2-10%
Better Capacity Utilization	5-15%

Combined, these methods can drastically reduce fuel consumption and operating costs.

Summary & Q&A

- Controlling excess air and upgrading burners are critical for complete combustion.
- Waste heat recovery and improved insulation significantly reduce thermal losses.
- Operational practices, like optimizing capacity and scheduling, are equally important.
- Continuous monitoring ensures sustained fuel efficiency.

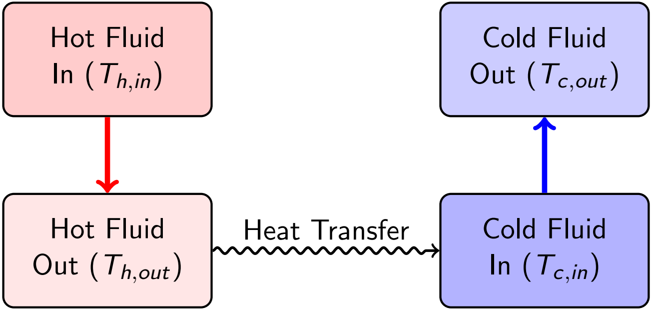
Any questions?

Welcome & Recap

- Welcome to Lecture 27: Energy Saving Techniques in Heat Exchangers.
- Recap: In the previous lecture, we discussed furnace fuel efficiency methods.
- Today's focus: Maximizing efficiency and saving energy in heat exchangers.

Introduction to Heat Exchangers (HEX)

- Devices designed to transfer heat between two or more fluids.
- Crucial in industrial processes, HVAC, power plants, and chemical engineering.
- Energy efficiency in HEX directly impacts overall plant efficiency and operational costs.

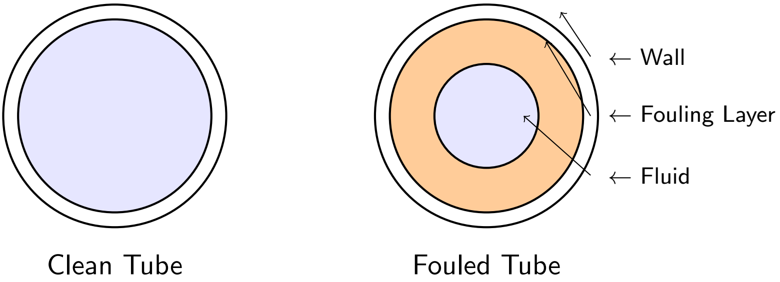


Why Energy Efficiency Matters in HEX

- Reduces fuel consumption and greenhouse gas emissions.
- Lowers operational and maintenance costs.
- Improves process throughput and product quality.
- Extends the lifespan of the equipment.

Technique 1: Mitigation of Fouling

- Fouling is the accumulation of unwanted materials on heat transfer surfaces.
- It acts as an insulator, significantly reducing heat transfer rates.
- Increases pressure drop, requiring more pumping power.
- Regular monitoring of fouling resistance is essential.

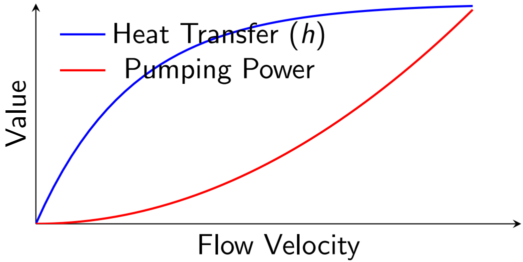


Fouling Control Methods

- Implement regular and scheduled cleaning (mechanical or chemical).
- Use anti-fouling coatings on heat transfer surfaces.
- Maintain appropriate fluid velocities to minimize deposition.
- Install online cleaning systems (e.g., sponge ball systems).

Technique 2: Flow Rate Optimization

- Optimize fluid flow rates to balance heat transfer and pressure drop.
- Higher velocities increase heat transfer but also increase pumping energy.
- Use Variable Frequency Drives (VFDs) on pumps to adjust flow based on demand.
- Avoid excessive flow rates that don't yield proportional heat transfer gains.



Technique 3: Enhancing Heat Transfer

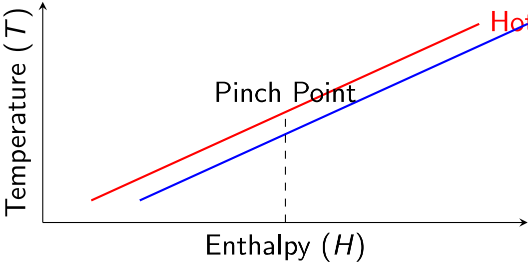
- Use extended surfaces (fins) to increase heat transfer area.
- Install tube inserts (turbulators) to promote turbulent flow.
- Corrugated tubes can significantly improve heat transfer coefficients.
- Evaluate the trade-off with increased pressure drop when adding enhancements.

Technique 4: Proper Insulation

- Insulate the outer shell and associated piping to prevent heat loss to the surroundings.
- Essential for high-temperature and cryogenic applications.
- Regularly inspect insulation for damage or degradation (e.g., CUI - Corrosion Under Insulation).
- Use economic thickness of insulation calculations to determine optimal insulation.

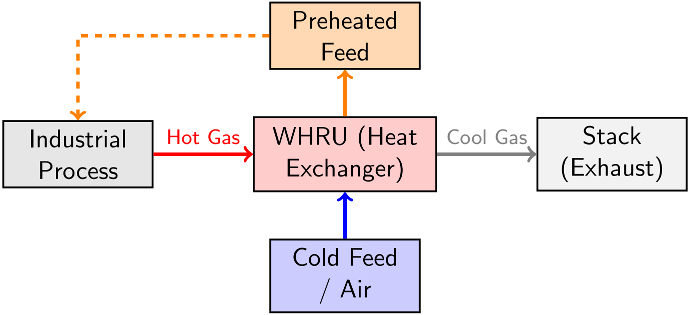
Technique 5: Pinch Analysis Integration

- Use pinch analysis to optimize Heat Exchanger Networks (HEN).
- Maximize heat recovery between hot and cold streams within the process.
- Minimize the need for external heating (utilities) and cooling.
- Can lead to significant overall energy savings in complex plants.



Technique 6: Waste Heat Recovery

- Utilize heat exchangers to recover waste heat from exhaust gases or hot effluents.
- Preheat incoming feed streams or combustion air.
- Commonly used in boilers, furnaces, and HVAC systems (e.g., economizers, air preheaters).
- Directly offsets primary fuel consumption.



Technique 7: Addressing Bypassing and Leakages

- Ensure proper baffle spacing and tight tolerances to minimize fluid bypassing.
- Bypassing reduces the effective heat transfer area.
- Regularly check for internal leaks between hot and cold streams.
- Fixing leaks improves thermal efficiency and prevents product contamination.

Technique 8: Material Selection and Upgrades

- Select materials with high thermal conductivity where appropriate.
- Use corrosion-resistant materials to prevent degradation and fouling over time.
- Consider upgrading older, inefficient heat exchangers to modern designs.

Feature	Shell & Tube HEX	Plate & Frame HEX
Footprint	Large	Compact (Small)
Efficiency / U-value	Moderate	High
Maintenance/Cleaning	Difficult (Pulling bundle)	Easy (Can be disassembled)
Max Pressure/Temp	Very High	Moderate

Table: Comparison for Potential Upgrades

Technique 9: Automation and Control Systems

- Implement advanced control systems to maintain optimal temperature differences.
- Use sensors to continuously monitor inlet and outlet temperatures and flow rates.
- Automated controls can react to process variations faster than manual adjustments.
- Helps in maintaining operation close to the design efficiency point.

Monitoring and Performance Evaluation

- Regularly calculate Log Mean Temperature Difference (LMTD) and Effectiveness.
- Track the Overall Heat Transfer Coefficient (U-value) over time.
- A declining U-value is a strong indicator of fouling or other performance issues.
- Establish a baseline and set alerts for deviation from expected performance.

Case Study: Energy Savings in Industrial HEX

Scenario and Actions

- **Scenario:** A chemical plant upgraded from shell & tube to plate heat exchangers.
- **Action:** Implemented automated cleaning and optimized flow rates with VFDs.

Results

- **Result:** Achieved a 20% reduction in heating utility costs and increased throughput.
- **Payback period:** Less than 18 months due to significant energy savings.

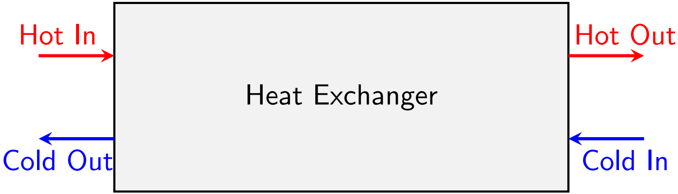
Summary & Q&A

- Fouling mitigation and proper maintenance are critical for HEX efficiency.
- Flow optimization and heat transfer enhancement offer significant savings.
- System-level approaches like Pinch Analysis and Waste Heat Recovery maximize overall plant efficiency.

Questions?

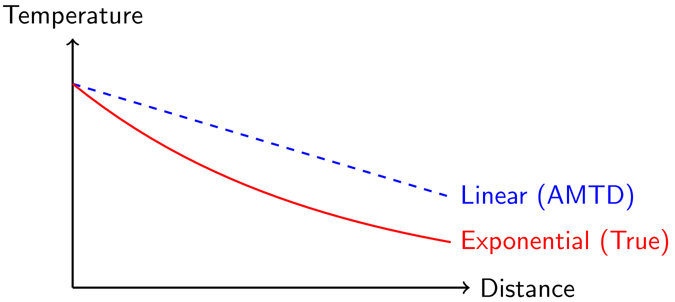
Introduction to Heat Transfer in Exchangers

- Heat exchangers facilitate heat transfer between two fluids.
- The driving force for heat transfer is the temperature difference (ΔT).
- In a heat exchanger, the temperatures of both fluids typically change as they flow.
- Therefore, ΔT is not constant throughout the exchanger.



Why Simple Average Temperature Difference is Inadequate

- Using a simple arithmetic mean temperature difference (AMTD) is inaccurate.
- Temperature changes in fluids are generally exponential, not linear.
- AMTD overestimates the actual driving force for heat transfer.
- A more accurate mathematical representation is required.



What is LMTD?

- LMTD stands for **Logarithmic Mean Temperature Difference**.
- It is the appropriate average temperature difference to use in heat exchanger analysis.
- LMTD accurately accounts for the exponential temperature profiles of the fluids.
- It is used to calculate the total heat transfer rate:

Heat Transfer Rate Equation

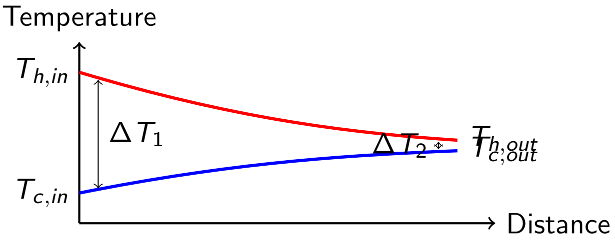
$$Q = U \cdot A \cdot \text{LMTD}$$

Assumptions in LMTD Derivation

- The overall heat transfer coefficient (U) is constant.
- Specific heats of the fluids (C_p) are constant.
- Heat exchange with the surroundings is negligible (adiabatic system).
- Kinetic and potential energy changes are negligible.
- Flow is steady and one-dimensional.

Temperature Profiles: Parallel Flow

- Both hot and cold fluids enter at the same end and flow in the same direction.
- Large initial temperature difference (ΔT_1) at the inlet.
- Temperature difference gradually decreases towards the outlet (ΔT_2).
- Cold fluid outlet temperature can never exceed the hot fluid outlet temperature.



LMTD Formula for Parallel Flow

- $\Delta T_1 = T_{h,in} - T_{c,in}$ (Temperature difference at inlet)
- $\Delta T_2 = T_{h,out} - T_{c,out}$ (Temperature difference at outlet)

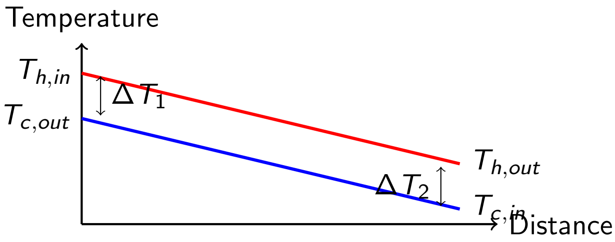
LMTD Formula

$$\text{LMTD} = \frac{\Delta T_1 - \Delta T_2}{\ln\left(\frac{\Delta T_1}{\Delta T_2}\right)}$$

- **Note:** It doesn't matter if you swap ΔT_1 and ΔT_2 in the numerator and denominator.

Temperature Profiles: Counter Flow

- Fluids enter at opposite ends and flow in opposite directions.
- More uniform temperature difference along the length of the exchanger.
- Cold fluid outlet temperature *can* be higher than the hot fluid outlet temperature.
- Generally more efficient than parallel flow.



LMTD Formula for Counter Flow

- $\Delta T_1 = T_{h,in} - T_{c,out}$ (Temperature difference at one end)
- $\Delta T_2 = T_{h,out} - T_{c,in}$ (Temperature difference at the other end)

LMTD Formula

$$\text{LMTD} = \frac{\Delta T_1 - \Delta T_2}{\ln\left(\frac{\Delta T_1}{\Delta T_2}\right)}$$

- The formula structure is identical, but the definitions of ΔT_1 and ΔT_2 change based on the physical arrangement.

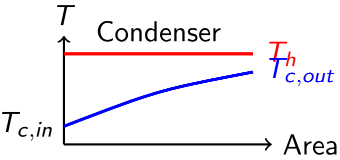
Comparing Parallel and Counter Flow LMTD

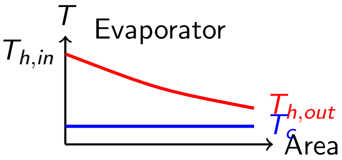
- For the same inlet and outlet temperatures, $\text{LMTD}_{\text{counter}} > \text{LMTD}_{\text{parallel}}$.
- A larger LMTD means a higher driving force for heat transfer.
- Therefore, for a given heat duty (Q) and U, a counter flow exchanger requires less surface area (A).
- Counter flow is more compact and economical.

Parameter	**Parallel Flow**	**Counter Flow**
LMTD	Lower	Higher
Required Area (A)	Larger	Smaller
Compactness	Lower	Higher
Efficiency	Lower	Higher

Special Case: Constant Temperature (Phase Change)

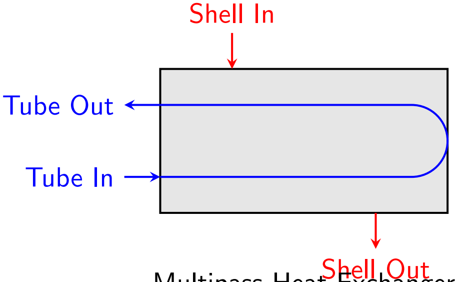
- Occurs in condensers (hot fluid condenses) and evaporators/boilers (cold fluid boils).
- One fluid remains at a constant temperature throughout the exchanger.
- In this case, $\text{LMTD}_{\text{parallel}} = \text{LMTD}_{\text{counter}}$.
- Flow direction (parallel or counter) does not affect the heat transfer performance.





Multipass and Cross-Flow Heat Exchangers

- Pure parallel or counter flow is rare in complex industrial exchangers.
- Shell-and-tube (multipass) and cross-flow (e.g., car radiators) are common.
- The flow in these is a mix of parallel, counter, and cross flow.
- The simple LMTD formula needs a correction factor.



Multipass Heat Exchanger

LMTD Correction Factor (F)

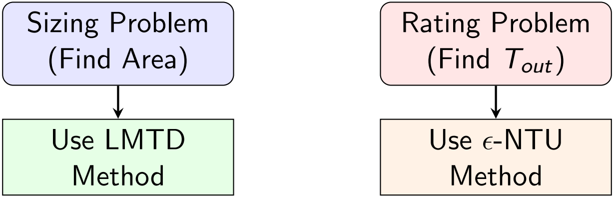
- Actual heat transfer equation:

Corrected Heat Transfer Equation

$$Q = U \cdot A \cdot (F \cdot \text{LMTD}_{\text{counter\_flow}})$$

- F is a correction factor, where $0 < F \leq 1$.
- F accounts for the deviation from pure counter flow.
- F is determined from charts based on temperature ratios (P and R).

- LMTD is excellent for sizing (finding Area) when all inlet and outlet temperatures are known.
- It is cumbersome for performance rating (finding outlet temperatures given Area).
- Rating problems require iterative trial-and-error calculations with LMTD.
- The Effectiveness-NTU (ϵ-NTU) method is preferred for rating problems.



Practical Significance for Energy Efficiency

- Maximizing LMTD minimizes the required heat transfer area, reducing capital costs.
- Ensuring counter-flow arrangement wherever possible improves efficiency.
- Monitoring temperature profiles helps identify fouling (which reduces U and affects overall performance).
- Proper understanding of LMTD is crucial for optimizing heat recovery systems.

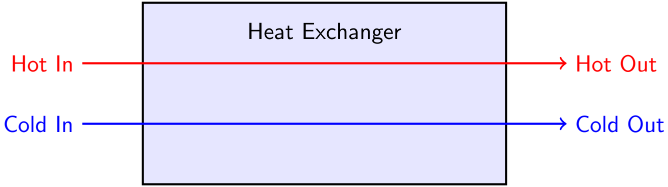
Summary & Q&A

- LMTD is the appropriate average temperature difference for heat exchangers.
- Calculated differently for parallel and counter flow.
- Counter flow provides a higher LMTD and is more efficient.
- Correction factor F is used for complex flow arrangements.

Questions?

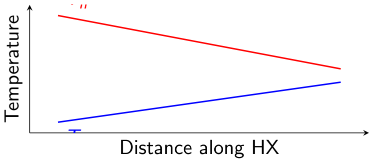
Welcome & Recap

- Welcome to Lecture 29: Calculation of LMTD
- Unit 4: Energy Efficiency in Heat Exchangers and Compressed Air Systems
- Recap: In the previous lecture, we introduced the concept of Log Mean Temperature Difference (LMTD) and its significance in heat exchanger analysis.



Introduction to LMTD Calculation

- LMTD is used to determine the temperature driving force for heat transfer in flow systems.
- It provides a more accurate representation of the average temperature difference across the heat exchanger.
- Today, we will focus solely on the calculation and application of the LMTD formula.
- We will not cover the mathematical derivation in this course.



The General LMTD Formula

- The Log Mean Temperature Difference (LMTD or ΔT_{lm}) is given by:

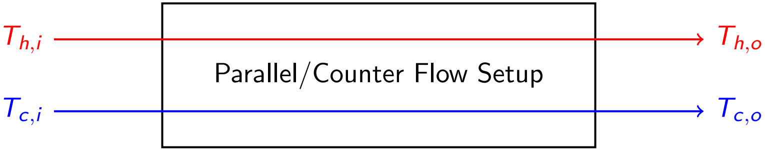
LMTD Formula

$$\Delta T_{lm} = \frac{\Delta T_1 - \Delta T_2}{\ln(\Delta T_1/\Delta T_2)}$$

- Where ΔT_1 and ΔT_2 are the temperature differences at the two ends of the heat exchanger.
- The specific definitions of ΔT_1 and ΔT_2 depend on the flow arrangement (parallel or counter-flow).

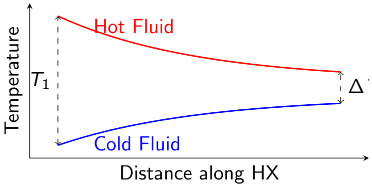
Temperature Definitions

- To use the LMTD formula, we need four temperatures:
  - $T_{h,i}$: Hot fluid inlet temperature
  - $T_{h,o}$: Hot fluid outlet temperature
  - $T_{c,i}$: Cold fluid inlet temperature
  - $T_{c,o}$: Cold fluid outlet temperature



LMTD for Parallel Flow Heat Exchangers

- In a parallel flow arrangement, both fluids enter at the same end and flow in the same direction.
- $\Delta T_1 = T_{h,i} - T_{c,i}$ (Temperature difference at inlet)
- $\Delta T_2 = T_{h,o} - T_{c,o}$ (Temperature difference at outlet)



Parallel Flow: Example Setup

- Consider a parallel flow heat exchanger with:
- Hot fluid entering at 100°C and leaving at 60°C.
- Cold fluid entering at 20°C and leaving at 40°C.
- Let's identify ΔT_1 and ΔT_2.

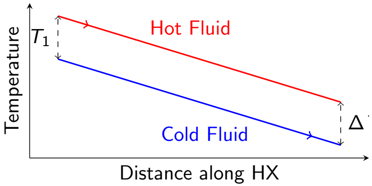
Fluid	**Inlet Temp. (°C)**	**Outlet Temp. (°C)**
Hot	100	60
Cold	20	40

Parallel Flow: Example Calculation

- $\Delta T_1 = 100 - 20 = 80°\text{C}$
- $\Delta T_2 = 60 - 40 = 20°\text{C}$
- $\Delta T_{lm} = \frac{80-20}{\ln(80/20)}$
- $\Delta T_{lm} = \frac{60}{\ln(4)} = \frac{60}{1.386} \approx 43.3°\text{C}$

LMTD for Counter-Flow Heat Exchangers

- In a counter-flow arrangement, fluids enter at opposite ends and flow in opposite directions.
- $\Delta T_1 = T_{h,i} - T_{c,o}$ (Temperature difference at hot fluid inlet end)
- $\Delta T_2 = T_{h,o} - T_{c,i}$ (Temperature difference at hot fluid outlet end)



Counter-Flow: Example Setup

- Let's use the same temperatures, but assume counter-flow:
- Hot fluid: inlet 100°C, outlet 60°C.
- Cold fluid: inlet 20°C, outlet 40°C.
- Let's identify ΔT_1 and ΔT_2.

Fluid	**Inlet Temp. (°C)**	**Outlet Temp. (°C)**
Hot (Left to Right)	100	60
Cold (Right to Left)	20	40

Counter-Flow: Example Calculation

- $\Delta T_1 = T_{h,i} - T_{c,o} = 100 - 40 = 60°\text{C}$
- $\Delta T_2 = T_{h,o} - T_{c,i} = 60 - 20 = 40°\text{C}$
- $\Delta T_{lm} = \frac{60-40}{\ln(60/40)}$
- $\Delta T_{lm} = \frac{20}{\ln(1.5)} = \frac{20}{0.405} \approx 49.3°\text{C}$

Comparison: Parallel vs. Counter-Flow

- For the same inlet and outlet temperatures, the LMTD for a counter-flow heat exchanger is always greater than or equal to that of a parallel-flow heat exchanger.
- $\Delta T_{lm,\text{counter}} \geq \Delta T_{lm,\text{parallel}}$
- A higher LMTD means a larger driving force for heat transfer.
- Therefore, counter-flow heat exchangers are generally more efficient and require less surface area for the same heat duty.

Flow Arrangement	**Calculated LMTD**
Parallel Flow	43.3°C
Counter Flow	49.3°C

Special Case: $\Delta T_1 = \Delta T_2$

- What happens if $\Delta T_1 = \Delta T_2$?
- The formula $\frac{\Delta T_1 - \Delta T_2}{\ln(\Delta T_1 / \Delta T_2)}$ results in $0/0$, which is indeterminate.
- In this specific case, by applying L'Hôpital's rule, it can be shown that:

$$\Delta T_{lm} = \Delta T_1 = \Delta T_2$$

Important Considerations

- The LMTD method is most straightforward when all inlet and outlet temperatures are known.
- If some temperatures are unknown, solving for them using LMTD may require iterative (trial-and-error) procedures.
- The formula assumes constant specific heats and a constant overall heat transfer coefficient (U) throughout the exchanger.

Practice Problem 1

- **Problem**: A counter-flow heat exchanger cools oil from 85°C to 55°C using water which enters at 25°C and leaves at 45°C.
- Calculate the LMTD.
- Identify: $T_{h,i}$, $T_{h,o}$, $T_{c,i}$, $T_{c,o}$
- Calculate ΔT_1 and ΔT_2

Practice Problem 1: Solution

- $T_{h,i} = 85°C, \ T_{h,o} = 55°C$
- $T_{c,i} = 25°C, \ T_{c,o} = 45°C$
- Counter-flow:
- $\Delta T_1 = T_{h,i} - T_{c,o} = 85 - 45 = 40°C$
- $\Delta T_2 = T_{h,o} - T_{c,i} = 55 - 25 = 30°C$
- $\Delta T_{lm} = \frac{40-30}{\ln(40/30)} = \frac{10}{\ln(1.333)} \approx 34.8°C$

Summary & Q&A

- LMTD is the appropriate average temperature difference to use for heat exchanger analysis.
- The formula is $\Delta T_{lm} = \frac{\Delta T_1 - \Delta T_2}{\ln(\Delta T_1 / \Delta T_2)}$.
- Definitions of ΔT_1 and ΔT_2 depend on whether flow is parallel or counter-flow.
- Counter-flow typically yields a higher LMTD.
- **Questions?**

Welcome & Recap

- Welcome to Lecture 30: Parallel & Cross Flow Heat Exchangers
- Course: Thermal Systems and Energy Efficiency
- Previous class: LMTD Calculations
- Today's focus: Flow arrangements and their impact on efficiency

Learning Objectives

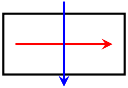
- Understand the fundamental concept of flow arrangements in heat exchangers.
- Differentiate between parallel flow and cross flow configurations.
- Analyze the temperature profiles of different flow types.
- Select the appropriate flow arrangement based on application requirements.

Introduction to Flow Arrangements

- The direction of fluid flow relative to each other significantly affects heat transfer.
- Primary types of flow arrangements:
  - Parallel Flow (Co-current)
  - Counter Flow
  - Cross Flow
- Today we focus specifically on Parallel and Cross Flow arrangements.

Parallel

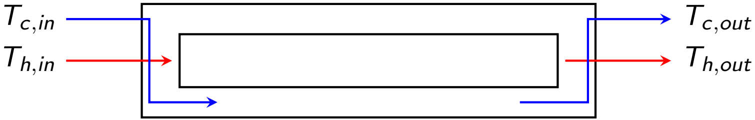
Counter



Cross

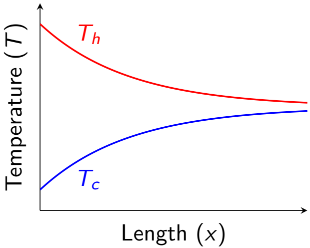
Parallel Flow Heat Exchangers

- Also known as co-current flow heat exchangers.
- Both the hot fluid and the cold fluid enter the heat exchanger at the same end.
- They travel through the exchanger in the same direction.
- They exit at the same end.



Temperature Profile: Parallel Flow

- Maximum temperature difference (driving force) occurs at the inlet.
- The temperature difference decreases rapidly along the length of the exchanger.
- The cold fluid exit temperature can NEVER exceed the hot fluid exit temperature.
- Thermal stresses are highest at the inlet due to the large initial temperature difference.



Advantages of Parallel Flow

- Useful when two fluids need to be brought to nearly the same temperature.
- Helps prevent the cold fluid from exceeding a specific maximum temperature.
- Provides a rapid initial rate of heat transfer.
- Can be beneficial for viscous fluids where a rapid temperature increase decreases viscosity quickly.

Disadvantages of Parallel Flow

- Lowest thermal efficiency among the main flow arrangements.
- Requires a larger surface area to transfer the same amount of heat compared to counter flow.
- High thermal stresses at the inlet can lead to material fatigue or failure in extreme cases.

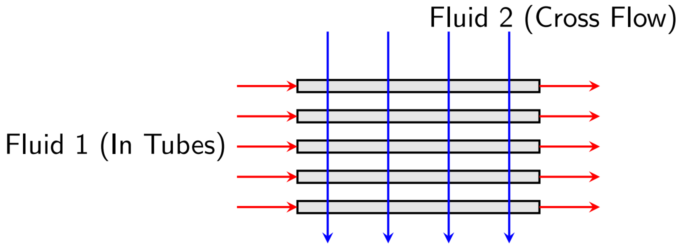
Feature	**Parallel Flow Comparison**
Efficiency	Lower than Counter Flow
Area Required	Larger for same duty
Thermal Stress	High at inlet

Applications of Parallel Flow

- Handling heat-sensitive materials (e.g., food processing, pharmaceuticals).
- Situations where rapid heating or cooling is required initially.
- When it is desired to have a uniform temperature for both fluids at the exit.

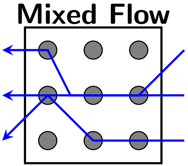
Cross Flow Heat Exchangers

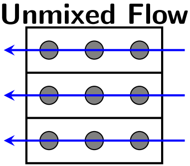
- Fluids flow perpendicular (at right angles) to each other.
- Commonly used when one fluid is a gas (like air) and the other is a liquid.
- Extensively used in HVAC systems and automobile radiators.



Cross flow heat exchangers are categorized by fluid mixing:

- **Unmixed Fluid:** Fluid is forced to flow in separate channels (e.g., inside tubes or between fins) and cannot mix in the transverse direction.
- **Mixed Fluid:** Fluid is free to move transversely and mix as it flows over the tubes.





Combinations of Mixed/Unmixed

- **Both fluids unmixed:** Common in finned-tube exchangers (e.g., car radiator).
- **One fluid mixed, one unmixed:** E.g., air flowing over bare tubes (air is mixed, fluid in tubes is unmixed).
- **Both fluids mixed:** Less common, but possible in certain designs without guides or fins.

Configuration	**Typical Example**
Both Unmixed	Car Radiator (finned tubes)
One Mixed / One Unmixed	Bare Tube Bank in Cross Flow
Both Mixed	Rare, open flow geometries

Temperature Profile & Effectiveness

- Temperature profile is complex; it varies in two dimensions (x and y).
- Effectiveness is intermediate: Better than parallel flow, but generally less than true counter flow.
- The LMTD correction factor (F) must be applied when calculating heat transfer:

$$\dot{Q} = U \cdot A \cdot F \cdot \Delta T_{lm,CF}$$

Where $\Delta T_{lm,CF}$ is the LMTD for counter flow arrangement.

Advantages of Cross Flow

- Compact design, especially when using fins to increase surface area.
- Excellent for liquid-to-gas heat transfer.
- Relatively simple construction for certain applications (like air conditioning coils).

Comparison: Parallel vs. Cross Flow

cc

Feature	**Parallel Flow**	**Cross Flow**
Efficiency	Lowest	Intermediate ($>$ Parallel)
Footprint	Often requires more length	Can be made very compact
Application	Temp limits, rapid initial heat	Gas/liquid combinations (HVAC)
Thermal Stress	High at inlet	Distributed differently

Real-World Example: Car Radiator

- A classic cross flow heat exchanger (both fluids unmixed).
- Hot engine coolant flows through tubes (unmixed).
- Ambient air is forced across the tubes by a fan and vehicle motion.
- Fins guide the air, keeping it unmixed and increasing heat transfer area.

Summary & Q&A

- Parallel flow: same direction, rapid initial heat transfer, limits max cold fluid temperature.
- Cross flow: perpendicular flow, excellent for gas-liquid heat exchange, categorized by mixing.
- Selection depends on efficiency needs, physical space, and fluid properties.

Questions?

Objectives of the Lecture

- Evaluate heat exchanger performance.
- Understand the concept and application of Logarithmic Mean Temperature Difference (LMTD).
- Use LMTD to determine the required heat transfer area.
- Analyze the impact of fouling on heat exchanger performance.

Introduction to Heat Exchanger Performance

- Performance analysis determines how effectively a heat exchanger transfers heat.
- Governing Equation:

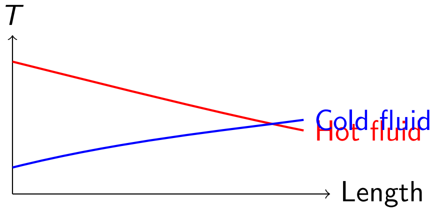
Basic Heat Transfer Equation

$$Q = U \cdot A \cdot \Delta T_m$$

- Where Q is the total heat transfer rate.
- U is the overall heat transfer coefficient.
- A is the heat transfer area.
- ΔT_m is the appropriate mean temperature difference.

Temperature Variation in Heat Exchangers

- Temperatures of hot and cold fluids vary as they flow through the heat exchanger.
- Therefore, the temperature difference ΔT is not constant.
- A simple arithmetic mean temperature difference is often inaccurate.
- A mathematically derived mean is required for accurate design and analysis.



Logarithmic Mean Temperature Difference (LMTD)

- LMTD is the correct average temperature difference to use in the heat transfer equation.
- It accounts for the logarithmic temperature profile along the length of the heat exchanger.

$$\Delta T_{lm} = \frac{\Delta T_1 - \Delta T_2}{\ln(\Delta T_1 / \Delta T_2)}$$

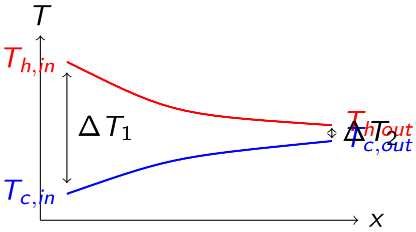
- ΔT_1 and ΔT_2 are the temperature differences at the two ends of the exchanger.

Assumptions in LMTD Derivation

- Steady-state operating conditions.
- Overall heat transfer coefficient (U) is constant.
- Specific heats (C_p) of both fluids are constant.
- No phase change occurs (except for isothermal condensation/boiling).
- No heat loss to the surroundings.

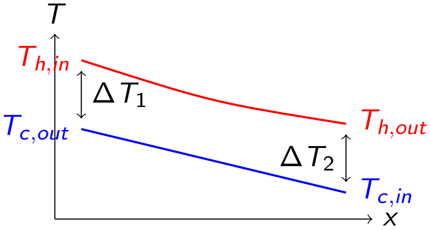
LMTD for Parallel Flow

- Both fluids enter at the same end and flow in the same direction.
- At inlet (End 1): $\Delta T_1 = T_{h,in} - T_{c,in}$
- At outlet (End 2): $\Delta T_2 = T_{h,out} - T_{c,out}$
- The temperature difference decreases rapidly at first, then more slowly.



LMTD for Counter Flow

- Fluids enter at opposite ends and flow in opposite directions.
- At one end: $\Delta T_1 = T_{h,in} - T_{c,out}$
- At the other end: $\Delta T_2 = T_{h,out} - T_{c,in}$
- Provides a more uniform temperature difference along the length.



Comparison: Parallel vs. Counter Flow

- For the same inlet and outlet temperatures, LMTD for counter flow is always greater than LMTD for parallel flow.
- $\Delta T_{lm,counter} > \Delta T_{lm,parallel}$
- Consequently, counter flow requires less surface area (A) for the same heat transfer rate (Q).
- Counter flow is generally more efficient.

Feature	Parallel Flow	Counter Flow
LMTD	Lower	Higher
Area Required	Larger	Smaller
Efficiency	Lower	Higher

Multipass and Cross Flow Heat Exchangers

- Pure parallel or counter flow is rare in large industrial applications.
- Shell-and-tube (multipass) and cross flow exchangers have complex flow paths.
- The basic LMTD formula assumes pure parallel or counter flow.
- A correction factor is needed for these complex configurations.

LMTD Correction Factor (F)

- The modified heat transfer equation:

$$Q = U \cdot A \cdot F \cdot \Delta T_{lm,CF}$$

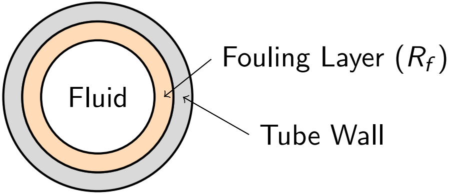
- F is the correction factor ($0 < F < 1$).
- $\Delta T_{lm,CF}$ is the LMTD calculated assuming pure counter flow.
- F depends on the geometry of the heat exchanger and the inlet/outlet temperatures.

Determining the Correction Factor

- F is typically determined from standard charts.
- Charts use two dimensionless parameters: P (temperature ratio) and R (capacity ratio).
- $P = \frac{t_2 - t_1}{T_1 - t_1}$ (effectiveness of the cold fluid)
- $R = \frac{T_1 - T_2}{t_2 - t_1}$ (ratio of mass flow $\times$ specific heat products)

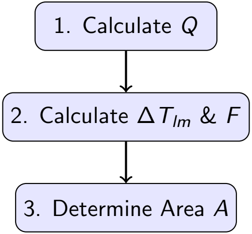
Impact of Fouling on Performance

- Over time, deposits (scale, dirt, rust) form on heat transfer surfaces.
- This is called fouling, and it adds thermal resistance.
- Fouling decreases the overall heat transfer coefficient (U).
- $\frac{1}{U_{dirty}} = \frac{1}{U_{clean}} + R_f$ (Where R_f is the fouling factor).



Designing with the LMTD Method

- The LMTD method is ideal when all inlet and outlet temperatures are known or can be easily found.
- Steps:



Limitations of the LMTD Method

- What if only inlet temperatures and flow rates are known?
- Finding outlet temperatures requires iterative calculation using LMTD.
- This makes LMTD cumbersome for performance evaluation (rating) problems.
- The Effectiveness-NTU (ϵ-NTU) method is preferred for such cases.

Summary & Next Lecture

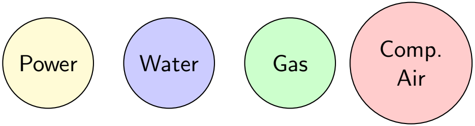
- LMTD correctly averages the varying temperature difference in a heat exchanger.
- Counter flow is generally more efficient than parallel flow.
- Correction factor F is used for complex flow arrangements.
- Fouling reduces performance over time.
- **Next Lecture:** Heat exchanger performance using Effectiveness-NTU method.

What is an Air Compressor?

- A device that converts power (using an electric motor, diesel or gasoline engine, etc.) into potential energy stored in pressurized air.
- Forces more and more air into a storage tank, increasing the pressure.
- When tank pressure reaches its engineered upper limit, the compressor shuts off.
- The compressed air, then, is held in the tank until called into use.

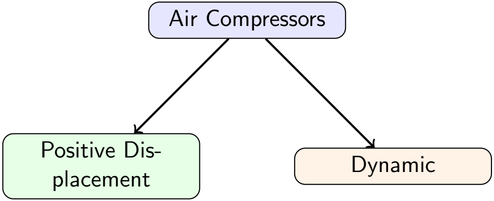
Why Use Compressed Air?

- Considered the "Fourth Utility" in industries (after electricity, water, and gas).
- Used extensively for pneumatic tools, material handling, painting, and automation.
- Essential for operations requiring clean, safe, and reliable power sources.
- **Warning:** Compressed air systems consume a significant portion of industrial electricity (often 10-30%).



Types of Air Compressors

- Classification is generally based on the working principle.
- **Positive Displacement Compressors:** Increase pressure by reducing the volume of the air.
- **Dynamic Compressors:** Increase pressure by imparting velocity to the air and converting it into pressure.



Positive Displacement Compressors

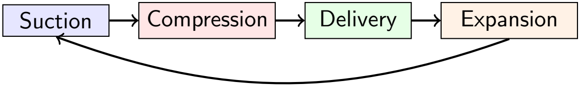
- Work by filling a chamber with air and then mechanically reducing the chamber's volume.
- **Reciprocating (piston) compressors:** Use pistons driven by a crankshaft.
- **Rotary compressors:** Use rotating elements like screws, vanes, or lobes.
- Generally provide higher pressures but have lower flow rates compared to dynamic types.

Dynamic Compressors

- Impart kinetic energy (velocity) to continuously flowing air by means of impellers rotating at high speeds.
- The velocity energy is then converted into pressure energy in a diffuser.
- **Centrifugal compressors:** Radial flow.
- **Axial flow compressors:** Flow parallel to the axis.
- Provide very high flow rates but lower pressure ratios per stage.

Reciprocating Compressor Working

- **Suction Stroke:** Piston moves down, drawing ambient air into the cylinder through the intake valve.
- **Compression Stroke:** Intake valve closes, piston moves up, compressing the trapped air.
- **Delivery Stroke:** When internal pressure exceeds receiver pressure, the discharge valve opens and air is expelled.
- Operates cyclically.

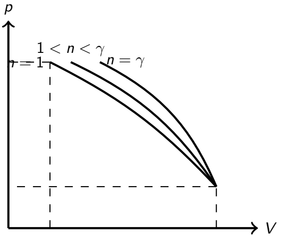


The Indicator Diagram ($p - V$ Diagram)

- Graphical representation of pressure (p) vs. volume (V) during the compression cycle.
- Suction occurs at constant atmospheric pressure.
- Compression can be polytropic ($pV^n = C$), isothermal ($pV = C$), or isentropic ($pV^\gamma = C$).
- Delivery occurs at constant discharge pressure.
- The area enclosed by the $p - V$ diagram represents the work done per cycle.

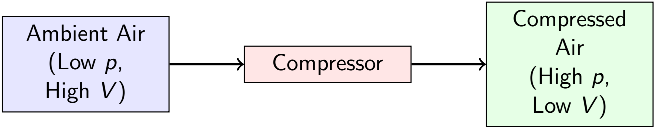
Work Required for Compression

- **Isothermal ($n = 1$):**
  Minimum theoretical work.
  Heat entirely removed.
- **Isentropic ($n = \gamma$):**
  Adiabatic, no heat transfer.
  Maximum work.
- **Polytropic ($1 < n < \gamma$):**
  Actual process.
- Cooling systems aim to move closer to isothermal.



What is Free Air Delivery (FAD)?

- FAD is the actual quantity of compressed air delivered by the compressor at its discharge, but expressed in terms of ambient (free air) conditions.
- "Free air" refers to the air at the specific temperature, pressure, and humidity of the compressor inlet.
- Commonly measured in cubic feet per minute (cfm), liters per second (l/s), or cubic meters per minute (m^3/min).



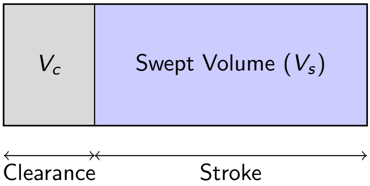
FAD: Output referenced back to Inlet Conditions

Why is FAD Important?

- FAD is the standard measure of a compressor's actual output capacity.
- It allows for fair comparison of different compressors regardless of their operating discharge pressure.
- Crucial for correctly sizing a compressor to meet the actual pneumatic load requirements of a plant.
- Ensures you are buying the right amount of 'air delivery' rather than just a motor size.

FAD vs Piston Displacement

- **Piston Displacement (Swept Volume):** The theoretical volume the piston sweeps during the suction stroke.
- FAD is ALWAYS less than the swept volume.
- Why? Due to clearance volume expansion, heating of incoming air, valve pressure drops, and internal leakage.



Understanding Volumetric Efficiency

- Volumetric Efficiency $= \frac{\text{Free Air Delivered}}{\text{Piston Swept Volume}}$
- It is a measure of how effectively the compressor uses its displacement.
- Typically ranges from 60% to 85% for reciprocating compressors.
- Decreases as the delivery pressure ratio increases because clearance air expands more.

Volumetric Efficiency (η_{vol})

$$\eta_{vol} = \frac{\text{Actual Volume of Air Drawn In}}{\text{Swept Volume}} = 1 + C - C\left(\frac{P_2}{P_1}\right)^{\frac{1}{n}}$$

Factors Influencing Output capacity

- **Suction Temperature:** Hotter inlet air is less dense, reducing the mass flow rate of air delivered.
- **Suction Pressure:** Lower atmospheric pressure (e.g., at higher altitudes) decreases inlet density and FAD.
- **Humidity:** Water vapor displaces dry air in the intake, slightly reducing the effective air delivery.
- **Maintenance:** Worn piston rings or leaky valves will significantly drop the actual FAD.

How is FAD Measured?

- Standard laboratory tests use orifice plates or nozzles to accurately measure FAD.
- In the field, a **Pump-up (Receiver capacity) test** is a simple method to estimate FAD.
- Pump-up test: Measure the time taken to fill a receiver of known volume from a lower pressure (P_1) to a higher pressure (P_2).
- Calculation uses the ideal gas law to convert the mass of air added to the tank back to inlet free air volume.

Summary & Questions

- Compressors are vital but energy-intensive.
- Positive displacement and dynamic are main types.
- FAD represents the actual delivered volume referenced to inlet conditions.
- FAD is the standard metric for capacity and is crucial for selection and efficiency.

Any questions?

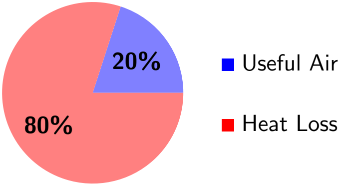
Welcome & Recap

- Welcome to Lecture 33: Energy Conservation in Compressed Air
- Recap of Lecture 32: Compressor basics, Types, and Free Air Delivery (FAD)
- Today's Focus: Practical measures to save energy in compressed air systems

Modern Air Compressor System

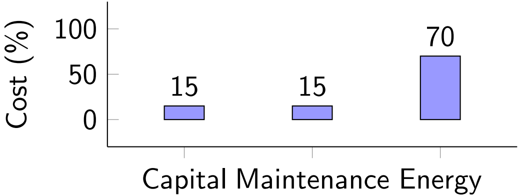
Why Energy Conservation in Compressed Air?

- Compressed air is often called the ‘Fourth Utility’ in industries.
- It is one of the most expensive forms of energy in a plant.
- Only about 10–20% of electrical energy input is converted to useful compressed air.
- The remaining 80–90% is lost as heat.
- Huge potential for cost savings and energy efficiency.



Lifecycle Cost of a Compressor

- Initial Capital Cost: ∼10–15%
- Maintenance Cost: ∼10–15%
- Energy Cost: ∼70–80% over its 10-year lifespan.
- Conclusion: Energy is the dominant cost factor, not the equipment price.
- Focusing on efficiency yields the highest return on investment.

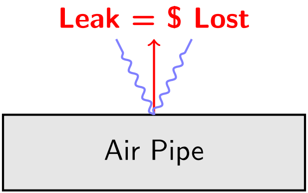


Major Areas for Energy Conservation

1. Minimizing Air Leaks
2. Optimizing Generation / Delivery Pressure
3. Improving Intake Air Quality (Cool & Clean)
4. Reducing Pressure Drops in Piping
5. Compressor Controls and Variable Speed Drives (VFD)
6. Waste Heat Recovery
7. Avoiding Misuse of Compressed Air

1. Minimizing Air Leaks

- Leaks are the largest single source of energy loss (can be 20–30% of total capacity).
- Common leak points: joints, flanges, valves, hoses, couplings, and thread sealants.
- Even small leaks (e.g., 1 mm hole) can cost thousands of rupees annually.
- A continuous leak acts like a compressor running uselessly 24/7.

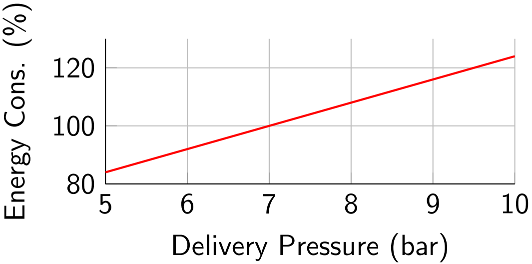


Leak Detection and Repair Strategies

- Ultrasonic Acoustic Detectors: Best for finding high-frequency leaks in noisy plants.
- Soap Water Test: Simple, traditional method for accessible joints.
- Leak Tagging System: Identify, tag, and schedule repairs.
- Conduct periodic leak audits (e.g., every 6 months).
- Objective: Keep total leakage below 5% of total capacity.

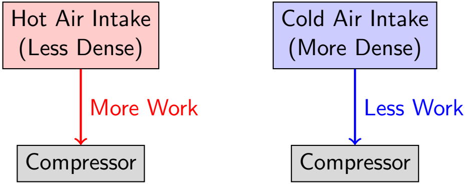
2. Optimizing Delivery Pressure

- Rule of Thumb: A reduction of 1 bar (14.5 psi) in delivery pressure saves ∼6–10% in energy consumption.
- Higher pressure increases leak rates and artificial demand.
- Artificial Demand: Using air at a higher pressure than necessary.
- Action: Gradually lower the compressor set pressure until the most critical end-use is just satisfied.
- Use pressure regulators at end-use points.



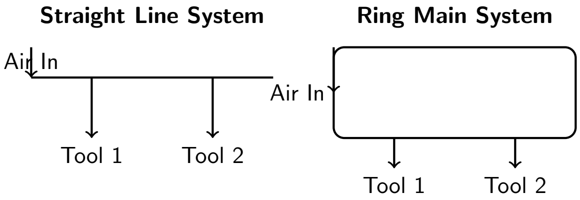
3. Intake Air Temperature and Quality

- Cold Air Intake: Colder air is denser.
- Rule of Thumb: Every 4°C drop in intake air temperature saves ∼1% in energy.
- Draw air from outside (cooler) rather than inside a hot compressor room.
- Clean Air Filter: Dirty filters increase pressure drop.
- Rule of Thumb: Every 250 mmWC pressure drop across the filter reduces efficiency by ∼2%.



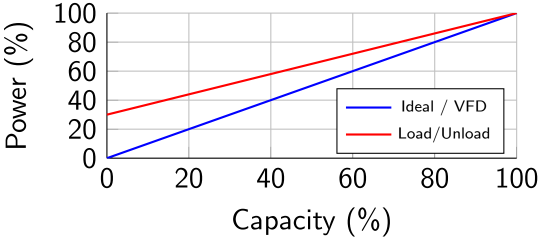
4. Minimizing Pressure Drop in Piping

- Pressure drop occurs due to friction in pipes, bends, and fittings.
- High pressure drop forces the compressor to generate air at a much higher pressure than needed at the tool.
- Solutions: Properly size (upsize) the main distribution pipes.
- Use smooth inner surface pipes (e.g., aluminum, stainless steel).
- Design in a closed-loop (ring main) system to equalize pressure.



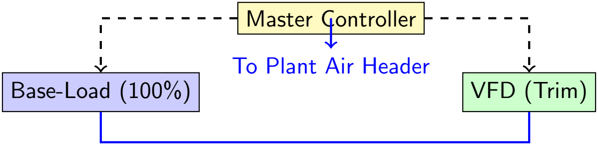
5. Compressor Controls

- Compressors rarely run at 100% full load all the time.
- Load/Unload Controls: Compressor idles when pressure is reached. But idling still consumes 20–30% of full load power!
- Modulation Control: Throttles the inlet. Highly inefficient at partial loads.
- Variable Frequency Drives (VFD): Adjusts motor speed to exactly match the air demand.
- VFDs eliminate unload running and save significant energy.



Right-Sizing and Multi-Compressor Sequencing

- Avoid using one giant compressor for small loads.
- Use a mix of base-load (constant speed) and trim (VFD) compressors.
- Base-load compressors run at 100% efficiency.
- The VFD compressor handles the fluctuating demand.
- Use Master Controllers to sequence compressors optimally and prevent multiple compressors from running at partial load.



- As discussed, ∼80% of input energy becomes heat.
- This heat is usually blown away by cooling fans or cooling water.
- Recovery: Heat exchangers can recover this heat to produce hot water (up to 70–80°C).
- Applications for recovered heat: Boiler make-up water, space heating, washing, and process heating.
- Can recover up to 70% of the input electrical energy as useful heat.

7. Avoiding Misuses of Compressed Air

- Compressed air should ONLY be used when no other alternative exists.
- Common misuses: Sweeping floors, cooling personnel, drying parts, agitating liquids.
- Alternatives: Use brooms or vacuums, electric fans, blowers, or mechanical agitators.
- A low-pressure electric blower is 10x more efficient than using compressed air for blowing/drying.

✗ **Misuse** Air nozzles for cleaning	✓ **Better Practice** Vacuum or electric blower

Condensate Drain Management

- Moisture in air condenses during compression and cooling.
- Manual valves: Often left slightly open, causing continuous air leak.
- Timer drains: Open periodically, but often blow out good air after the water is gone.
- Zero-Loss Drain Valves: Use a float or sensor to discharge ONLY water, no air loss.
- Upgrading to zero-loss drains is a fast payback measure.

Zero-Loss Drain Valve Benefits:

- Senses condensate level
- Opens only when water is present
- Closes before compressed air escapes

Regular Maintenance and Monitoring

- Clean intake filters regularly to reduce pressure drop.
- Check and clean intercoolers and aftercoolers.
- Monitor the Specific Energy Consumption (SEC) - kW/CFM.
- Install flow meters and power meters to track efficiency continuously.
- Good maintenance prevents efficiency degradation over time.

Flow Rate	**Power Draw**
500 CFM	**75 kW**

SEC: **0.15 kW/CFM**

Summary & Q&A

- Energy is the largest cost in a compressor's lifecycle (80%).
- Fix leaks, lower pressure, and draw cool air.
- Use VFDs for varying loads and sequence compressors.
- Recover waste heat and stop the misuse of compressed air.
- Questions?

Q & A

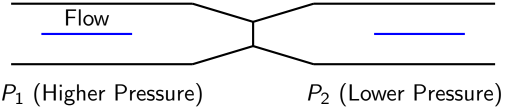
Recap: Compressed Air Systems

- Compressed air is widely used but often inefficient.
- Accurate measurement of capacity (FAD) is critical.
- Receiver method is simple but has limitations.
- For continuous and accurate measurement, standardized methods like Nozzle Method are used.

Introduction to Nozzle Method

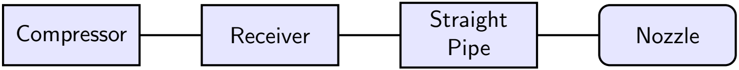
- A standardized test method for measuring compressor capacity.
- Involves discharging compressed air through a precisely machined nozzle.
- Governed by standards like IS 5456 or ASME PTC 9.
- Provides accurate and continuous flow measurement.

- Based on fluid mechanics principles (Bernoulli's equation).
- Flow restriction (nozzle) causes a pressure drop.
- By measuring this pressure drop, temperature, and atmospheric pressure, flow rate can be calculated.
- The nozzle is typically installed in the discharge pipeline.



Test Setup Requirements

- Compressor discharging into a receiver/pulsation damper.
- A straight length of pipe before the nozzle.
- The measuring nozzle fitted at the end of the pipe or in-line.
- Instruments for measuring pressure, temperature, and humidity.



Key Instruments Used

- **Barometer:** To measure atmospheric pressure.
- **Thermometers/Thermocouples:** To measure ambient and nozzle temperatures.
- **Pressure Gauges/Manometers:** To measure pressure before the nozzle.
- **Hygrometer:** To measure relative humidity (for precise calculations).

The Measuring Nozzle

- Precisely machined internal profile.
- Designed to minimize friction and turbulence.
- Has a known coefficient of discharge (C_d).
- Different sizes available depending on expected flow rate.

Calculation Parameters

- d = Diameter of the nozzle throat (m).
- h = Pressure drop across the nozzle (mm of water).
- T = Absolute temperature of air before the nozzle (K).
- P = Absolute pressure of air before the nozzle (Pa).

General Flow Equation

- Where Q is the volume flow rate.
- K is a constant depending on units, nozzle coefficient, and gas properties.
- This formula derives from fundamental flow dynamics.

Flow Equation

$$Q = K \cdot d^2 \cdot \sqrt{\frac{h}{T}}$$

Converting to Free Air Delivery (FAD)

- Calculated flow Q is at nozzle conditions.
- Must be converted to inlet (ambient) conditions to find FAD.
- Use ideal gas law:

$$\frac{P_{\text{nozzle}} \cdot Q_{\text{nozzle}}}{T_{\text{nozzle}}} = \frac{P_{\text{ambient}} \cdot \text{FAD}}{T_{\text{ambient}}}$$

$$\text{FAD} = Q_{\text{nozzle}} \cdot \left(\frac{P_{\text{nozzle}}}{P_{\text{ambient}}} \right) \cdot \left(\frac{T_{\text{ambient}}}{T_{\text{nozzle}}} \right)$$

Advantages of Nozzle Method

- High accuracy (typically within ± 1 to 2%).
- Continuous measurement capability.
- Standardized and widely accepted by manufacturers and auditors.
- Suitable for medium to large compressors.

Limitations and Challenges

- Requires specific setup and straight pipe lengths.
- More complex and expensive than the receiver method.
- Needs precise calibration of instruments.
- Flow must be steady; pulsation can cause significant errors.

Comparison: Receiver vs. Nozzle Method

cc

Feature	Receiver Method	Nozzle Method
Complexity	Simple, cheap setup	Complex setup
Accuracy	Lower accuracy	Highly accurate
Application	Field tests on small units	Standard performance testing
Measurement	Average flow over time	Instantaneous flow

Practical Application (Energy Audit)

- Used during detailed energy audits to verify manufacturer's FAD claims.
- Helps in establishing baseline performance of aging compressors.
- Identifies capacity loss due to wear and tear over time.
- Crucial for calculating exact specific power consumption (kW/CFM).

Example Problem Concept

Given: Nozzle diameter, pressure drop (mm WC), temperatures, atmospheric pressure.

Step 1: Flow at nozzle using standard formula

Step 2: Apply correction factors

Step 3: Convert to FAD using inlet P & T

Summary & Q&A

- Nozzle method provides precise, continuous FAD measurement.
- Relies on pressure drop across a standard restriction.
- Requires careful setup and accurate instruments.
- Essential for determining true compressor efficiency in audits.

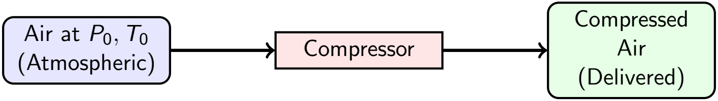
Questions?

Welcome & Recap

- Welcome to Lecture 35.
- Today's topic: FAD Measurement using the Pump-up Method.
- Recap: In the previous lecture, we discussed the Nozzle Method for measuring Free Air Delivery (FAD).
- We will now explore an alternative, practical approach suitable for field testing.

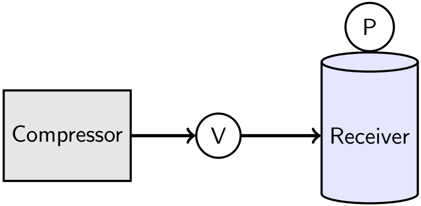
Introduction to FAD Measurement

- FAD (Free Air Delivery) is the actual quantity of compressed air delivered by the compressor.
- Expressed in CFM (Cubic Feet per Minute) or m^3/min.
- Measured at free air conditions (inlet pressure and temperature).
- Accurate FAD measurement is crucial for evaluating compressor efficiency and capacity.



What is the Pump-up Method?

- Also known as the 'Receiver Capacity Method' or 'Fill Test'.
- A practical, field-level test to estimate compressor capacity.
- Involves measuring the time taken to pump up an air receiver from a lower pressure to an upper pressure.
- Does not require complex instrumentation like orifice plates or nozzles.



Principle of the Pump-up Method

- Based on the Ideal Gas Law: $P \times V = m \times R \times T$.
- The volume of the receiver is constant and known.
- By measuring the change in pressure over a specific time interval, we can calculate the volume of air delivered.
- The calculated volume is then converted to free air conditions (inlet conditions).

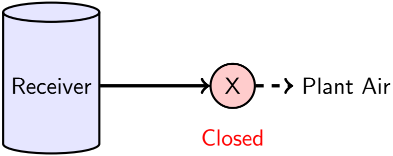
$$P \cdot V = m \cdot R \cdot T$$

Key Requirements for the Test

- The exact volume of the air receiver must be known (V).
- The volume of connecting pipes from compressor to receiver should be included (if significant).
- Accurate pressure gauges are required.
- A stopwatch to precisely measure the time taken to build pressure.

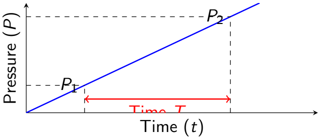
Step-by-Step Procedure: Preparation

- Isolate the compressor and receiver from the plant air distribution system.
- Ensure there is no air demand or leakage during the test.
- Empty the receiver completely to atmospheric pressure (0 barg).
- Close the receiver drain valve securely.



Step-by-Step Procedure: Execution

- Start the compressor and allow it to run at full load.
- Begin timing when the receiver pressure reaches a defined lower limit (e.g., $P_1 = 0.5$ kg/cm^2 or half the working pressure).
- It's better not to start timing from 0 pressure to allow the compressor to reach stable operating speed.
- Continue timing until the pressure reaches the normal operating limit (e.g., $P_2 = 7.0$ kg/cm^2).



Step-by-Step Procedure: Data Recording

- Record the initial pressure (P_1) and final pressure (P_2).
- Record the time taken (T) to reach P_2 from P_1.
- Note the atmospheric pressure (P_0) at the site.
- Record the inlet air temperature (t_1) and the compressed air temperature (t_2) in the receiver.

Calculation Methodology: Formula

- The standard formula for FAD using the pump-up method is:

$$\text{FAD (m}^3\text{/min)} = \frac{(P_2 - P_1) \times V}{P_0 \times T}$$

- Temperature Correction Factor is sometimes applied: $\frac{273+t_1}{273+t_2}$
- Corrected FAD:

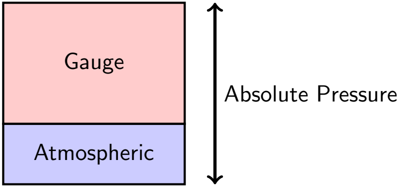
$$\text{FAD}_{corr} = \frac{(P_2 - P_1) \times V \times (273 + t_1)}{P_0 \times T \times (273 + t_2)}$$

Calculation Methodology: Variables Explained

- V = Volume of the receiver (in cubic meters, m^3)
- P_1 = Initial pressure (absolute, in kg/cm^2a or bar(a))
- P_2 = Final pressure (absolute, in kg/cm^2a or bar(a))
- P_0 = Atmospheric pressure (absolute, in kg/cm^2a or bar(a))
- T = Time taken to pump up (in minutes)
- t_1 = Inlet air temperature ($^\circ$C), t_2 = Receiver air temperature ($^\circ$C)

Important Note on Pressures

- Pressure gauges read Gauge Pressure (barg or psig).
- Absolute Pressure = Gauge Pressure + Atmospheric Pressure.
- Atmospheric Pressure is typically 1.013 bar or 1.033 kg/cm^2 at sea level.
- Always convert P_1, P_2, and P_0 to absolute units before using the formula.



Example Calculation

- Given: Receiver Volume $(V) = 3\ \text{m}^3$, Atm Pressure $(P_0) = 1.013$ bar(a)
- Initial Pressure $(P_1) = 2.0$ barg (3.013 bar(a))
- Final Pressure $(P_2) = 7.0$ barg (8.013 bar(a))
- Time Taken $(T) = 2.5$ minutes (Ignoring temperature correction)

$$\text{FAD} = \frac{(8.013 - 3.013) \times 3}{1.013 \times 2.5}$$

$$\text{FAD} = \frac{5.0 \times 3}{2.5325} = 5.92\ \text{m}^3/\text{min}$$

Advantages of Pump-up Method

- **Simplicity:** Easy to perform in the field without breaking pipework.
- **Cost-effective:** No expensive flow meters or nozzles required.
- **Speed:** Can be conducted quickly during a short production shutdown.
- Provides a good baseline for assessing compressor wear over time.

Limitations of Pump-up Method

- **Accuracy:** Less accurate than the nozzle method (typically $\pm 5\%$ to $\pm 10\%$ error).
- **Volume Errors:** Difficult to accurately account for the volume of connecting pipes.
- **Temperature Variations:** Rapid filling causes temperature rise in the receiver, which is hard to measure accurately immediately.
- **Leakage:** Any internal leakage (e.g., drain valves) skews results.

Comparison: Pump-up vs. Nozzle Method

Feature	Pump-up Method	Nozzle Method (ISO 1217)
Accuracy	Moderate ($\pm$5% to 10%)	High
Setup	Simple, field-friendly	Complex, specialized equipment
Cost	Low	High
Nature	Dynamic (pressure changes)	Steady-state
Best For	Routine checks	Acceptance testing

Summary & Q/A

- FAD represents the actual output capacity of a compressor.
- The Pump-up method is a practical field test using receiver volume and time.
- Accuracy depends on precise knowledge of volume, pressures, and temperatures.
- Absolute pressure must always be used in FAD calculations.

Any questions?

Welcome & Recap

- Welcome to Lecture 36: Intro to HVAC & Refrigeration
- Unit 5: HVAC and Refrigeration Systems energy efficiency
- Recap: Key concepts from compressed air systems

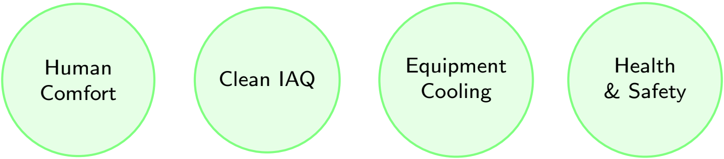
What is HVAC?

- **HVAC** stands for Heating, Ventilation, and Air Conditioning.

Heating	Ventilation	Air Conditioning
Raising temp. of a space	Providing fresh air, removing stale	Cooling and humidity control

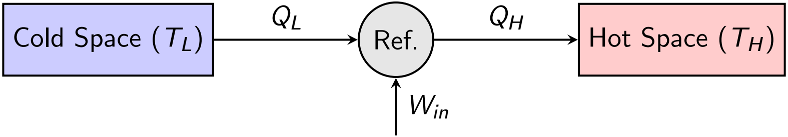
Purpose and Importance of HVAC

- **Human Comfort:** Maintaining optimal temperature and humidity.
- **Indoor Air Quality (IAQ):** Filtering air and maintaining oxygen levels.
- **Equipment Protection:** Cooling servers and industrial machinery.
- **Health and Safety:** Preventing mold growth and removing contaminants.



What is Refrigeration?

- Refrigeration is the process of cooling a space, substance, or system.
- It involves transferring heat from a lower-temperature region to a higher-temperature region.
- Requires work input (usually mechanical or electrical) to operate against the natural flow of heat.



Applications of Refrigeration

Sector	**Examples**
Domestic	Refrigerators and freezers
Commercial	Supermarket display cases, cold storage
Industrial	Chemical processing, liquefaction of gases
Comfort AC	Building cooling systems

Thermodynamics in HVAC&R

First Law of Thermodynamics

Energy cannot be created or destroyed, only transferred. ($Q_H = Q_L + W_{in}$)

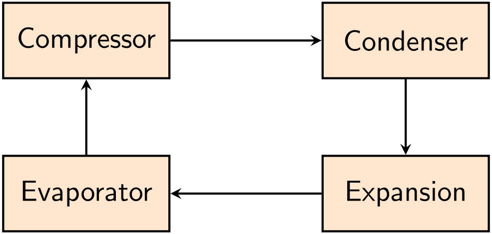
Second Law of Thermodynamics

Heat naturally flows from hot to cold; work is needed to reverse this.

- Refrigeration systems operate as reverse heat engines (heat pumps or refrigerators).

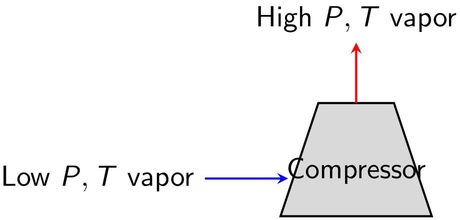
Vapor Compression Refrigeration Cycle

- The most common type of refrigeration system.
- Uses a circulating liquid refrigerant as the medium which absorbs and removes heat.
- Consists of four main processes:



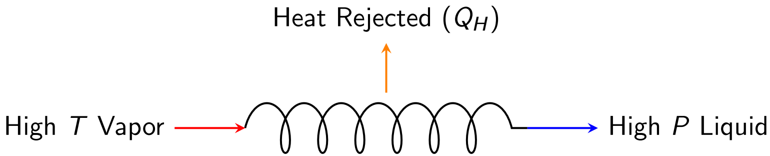
Component 1: Compressor

- The 'heart' of the system.
- Draws in low-pressure, low-temperature refrigerant vapor.
- Compresses it to a high-pressure, high-temperature vapor.
- Provides the driving force for refrigerant circulation.



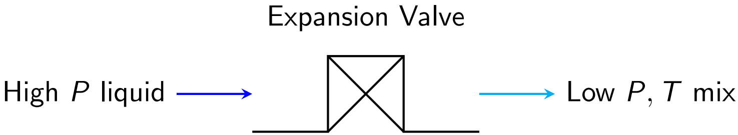
Component 2: Condenser

- A heat exchanger where the refrigerant rejects heat to the surroundings.
- High-temperature vapor enters and condenses into a high-pressure liquid.
- Cooling medium can be air or water.



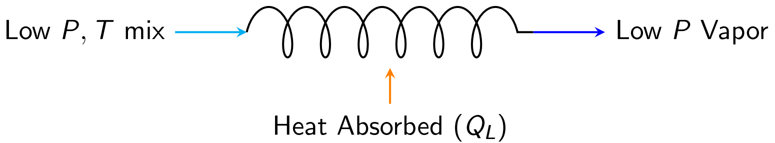
Component 3: Expansion Device

- Reduces the pressure of the liquid refrigerant.
- Causes a sudden drop in temperature (throttling process).
- Regulates the flow of refrigerant into the evaporator.



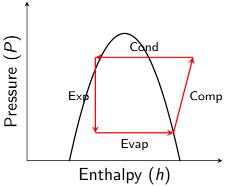
Component 4: Evaporator

- A heat exchanger where the refrigerant absorbs heat from the space to be cooled.
- Low-pressure, low-temperature liquid boils and turns into a vapor.
- Produces the desired cooling effect.



The P-h Diagram

- Pressure-Enthalpy (P-h) diagram analyzes cycles.
- Plots pressure (y) vs. enthalpy (x).
- Shows refrigerant state at any point.
- Calculates cooling capacity and compressor work.



Refrigerants

- The working fluid in the refrigeration cycle.
- Must have favorable thermodynamic properties (e.g., low boiling point).
- Environmental concerns: Ozone Depletion Potential (ODP) and Global Warming Potential (GWP).
- Transitioning to eco-friendly refrigerants.

Type	**Examples**	**ODP**	**GWP**
CFCs (Older)	R-11, R-12	High	High
HCFCs	R-22	Low	High
HFCs	R-134a, R-410A	Zero	High
Natural / HFOs	Ammonia, R-1234yf	Zero	Low/Zero

Performance Metrics: COP

- **Coefficient of Performance (COP)** measures efficiency.
- Higher COP indicates a more efficient system.
- Related to Energy Efficiency Ratio (EER).

COP Formula

$$\text{COP} = \frac{\text{Desired Output (Cooling Effect, } Q_L\text{)}}{\text{Required Input (Compressor Work, } W_{in}\text{)}}$$

Introduction to Air Conditioning Systems

- AC systems use refrigeration cycles to cool air.
- Also involves managing humidity (dehumidification during cooling).
- Proper sizing and maintenance are key for energy efficiency.

Type	**Description**	**Use Case**
Window AC	Single unit housing all components	Single rooms
Split AC	Separate indoor & outdoor units	Homes, offices
Central AC	Centralized cooling via ducts	Large buildings

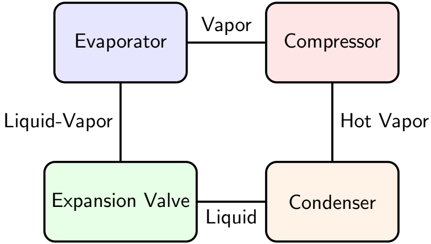
Summary & Q&A

- HVAC controls temperature, humidity, and air quality.
- Refrigeration transfers heat from cold to hot using work input.
- The Vapor Compression Cycle has four main parts: Compressor, Condenser, Expansion Valve, Evaporator.
- COP is the primary measure of refrigeration efficiency.

Questions?

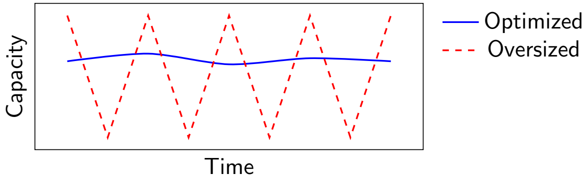
Introduction to Refrigeration Systems

- Refrigeration is the process of removing heat from an enclosed space or substance to lower its temperature.
- Essential for various sectors: HVAC, food preservation, chemical processing, and medical.
- Vapor Compression and Vapor Absorption are the two primary types of systems.
- Selecting the right system is crucial for performance and energy efficiency.

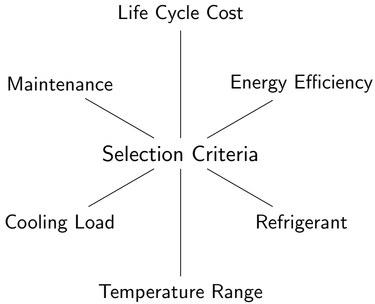


Why Do We Need Selection Criteria?

- No single refrigeration system is suitable for all applications.
- Mismatched systems lead to poor efficiency and high energy bills.
- Oversized systems suffer from frequent cycling and wear.
- Undersized systems fail to meet cooling demands during peak loads.

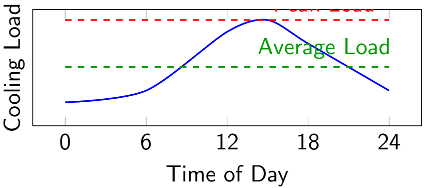


Primary Selection Criteria Overview



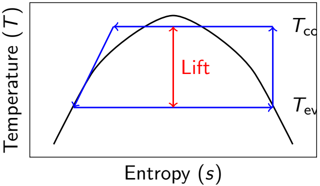
Cooling Load and Capacity Requirements

- Determined by the maximum heat that must be removed per unit time.
- Must account for sensible heat (temperature change) and latent heat (phase change).
- **Peak Load:** The maximum demand the system will face.
- **Average Load:** Normal operating conditions over a given period.
- Systems must handle peak loads but operate efficiently at average/part loads.



Operating Temperature Range

- **Evaporating Temperature:** Determines the lowest temperature the system can achieve.
- **Condensing Temperature:** Depends on the ambient environment (air or water available for cooling).
- Large temperature lifts (difference between condensing and evaporating temps) reduce efficiency.
- Cryogenic applications require multi-stage or cascade refrigeration systems.



Refrigerant Selection: Environmental Impact

- **Ozone Depletion Potential (ODP):** Must be zero (e.g., phase-out of CFCs and HCFCs).
- **Global Warming Potential (GWP):** Preference for low-GWP refrigerants.
- Regulatory Compliance: Montreal Protocol and Kigali Amendment.
- Natural refrigerants like Ammonia, CO_2, and Hydrocarbons are gaining popularity.

Type	**Refrigerant**	**ODP**	**GWP**
CFC	R-12	1.0	10,900
HCFC	R-22	0.05	1,810
HFC	R-134a	0	1,430
Natural	NH_3 (R-717)	0	0
Natural	CO_2 (R-744)	0	1

Refrigerant Selection: Safety & Properties

- **Toxicity:** Safe for human exposure in case of leaks (ASHRAE safety group A vs B).
- **Flammability:** Class 1 (no flame propagation) to Class 3 (higher flammability).
- **Thermodynamic Properties:** High latent heat of vaporization preferred.
- **Chemical Stability:** Must not react with system materials or compressor oil.

Flammability	Lower Toxicity (A)	Higher Toxicity (B)
High (3)	A3 (Hydrocarbons)	B3
Low (2)	A2	B2
Low (2L)	A2L (HFOs)	B2L
None (1)	A1 (R-134a, CO_2)	B1

Energy Efficiency and COP

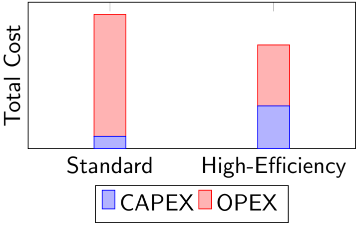
- **Coefficient of Performance (COP):** Ratio of cooling effect to work input.
- Higher COP means lower energy consumption.

$$\text{COP} = \frac{\text{Cooling Effect (kW)}}{\text{Work Input (kW)}}$$

- **Part-Load Efficiency:** Systems rarely run at full load; part-load performance is critical.
- **Integrated Part Load Value (IPLV):** A more accurate measure of seasonal efficiency.
- Variable Frequency Drives (VFDs) improve part-load efficiency.

Initial Cost vs. Operating Cost

- **Capital Expenditure (CAPEX):** Initial purchase and installation costs.
- **Operational Expenditure (OPEX):** Energy, maintenance, and refrigerant replacement.
- **Life Cycle Cost Analysis (LCCA):** Evaluates the total cost of ownership over lifespan.
- High-efficiency systems have higher CAPEX but lower OPEX, yielding a faster payback.



Space and Weight Constraints

- **Footprint:** The physical floor space required by the equipment.
- Weight considerations for rooftop installations.
- **Indoor vs. Outdoor Units:** Depending on available space and noise restrictions.
- Compact systems (like plate heat exchangers) are preferred in space-constrained areas.

Maintenance and Reliability

- **System Complexity:** More complex systems require highly skilled technicians.
- **Availability of Spare Parts:** Ensure local availability for quick repairs.
- **Maintenance Frequency:** Systems that need frequent cleaning or oil changes increase downtime.
- **Reliability** is critical for continuous processes (e.g., pharmaceutical storage, data centers).

Type of Application

- **Commercial HVAC:** Focus on human comfort, noise levels, and part-load efficiency.
- **Industrial Process Cooling:** Demands robust equipment, steady low temperatures, and high reliability.
- **Cold Storage:** Requires excellent insulation and uniform temperature distribution.
- **Transport Refrigeration:** Must withstand vibrations, varying ambient conditions, and have independent power.

Environmental and Ambient Conditions

- **Ambient Temperature:** Affects the heat rejection capability of the condenser.
- High ambient regions require larger condensers or water-cooling.
- **Water Availability:** Water-cooled condensers are efficient but require a steady water supply and water treatment.
- **Corrosive Environments:** Coastal areas need corrosion-resistant coatings (e.g., epoxy coated coils).

Emerging Technologies and Trends

- **Smart Controls and IoT:** Predictive maintenance and real-time optimization.
- **Magnetic Refrigeration:** Uses magnetocaloric effect, eliminating traditional refrigerants.
- **Solar-Powered Refrigeration:** Combining solar PV or thermal with refrigeration to reduce grid reliance.
- **Advanced Heat Exchangers:** Microchannel coils for better heat transfer and reduced refrigerant charge.

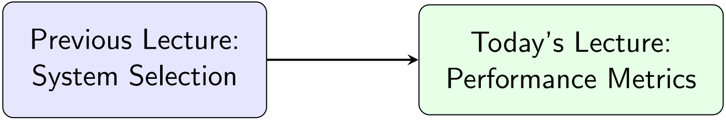
Summary & Q&A

- Proper selection balances capacity, efficiency, cost, and environmental impact.
- Refrigerant choice is heavily influenced by ODP, GWP, and safety regulations.
- Life Cycle Cost Analysis is more important than just initial capital cost.
- Application type and ambient conditions heavily dictate system design.

Any questions?

Welcome & Recap

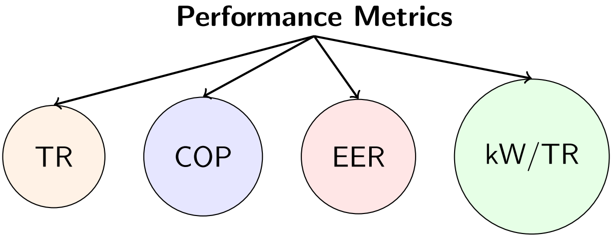
- Welcome to Lecture 38: Performance Metrics: TR, COP, EER.
- **Recap:** In the last lecture, we discussed refrigeration system selection criteria.



Introduction to Refrigeration Performance Metrics

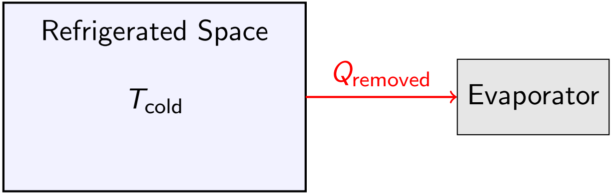
Why do we need performance metrics?

- To evaluate the cooling effect relative to energy input.
- To compare different systems and technologies.
- Key metrics: Net Refrigerating Capacity, TR, COP, EER, and kW/TR.



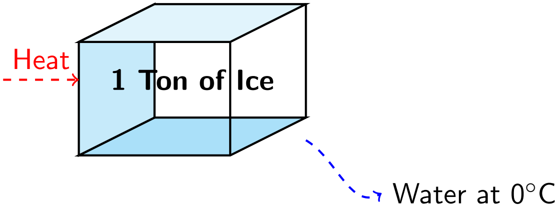
Net Refrigerating Capacity

- **Definition:** The actual rate at which heat is removed from the refrigerated space.
- Expressed in watts (W), kilowatts (kW), or Btu/hr.
- Determines the size or capacity of the cooling equipment needed.
- Depends on the mass flow rate of the refrigerant and the enthalpy change in the evaporator.



Concept of Ton of Refrigeration (TR)

- **Historical origin:** The cooling effect produced by melting 1 ton (2000 lbs) of pure ice at 0°C (32°F) in 24 hours.
- Latent heat of fusion of ice = 144 Btu/lb.
- Cooling effect = 2000 lbs × 144 Btu/lb = 288,000 Btu/24 hours.
- Standard unit for large commercial HVAC and refrigeration systems.



Ton of Refrigeration (TR) - Conversions

1 TR Equivalent Values

- 1 TR = 288,000 Btu / 24 hours.
- 1 TR = 12,000 Btu/hr.
- 1 TR = 200 Btu/min.
- **In SI Units:** 1 TR = 3.516 kW (or approx. 3.5 kW).

Unit System	**Value of 1 TR**
British (Btu/hr)	12,000
SI (kW)	3.516

Example Calculation: Cooling Load in TR

Problem: A room requires 70,320 W of cooling. Find the capacity in TR.

- **Step 1:** Convert W to kW:

$$70,320\text{ W} = 70.32\text{ kW}$$

- **Step 2:** Formula:

$$\text{TR} = \frac{\text{Cooling Load in kW}}{3.516}$$

- **Step 3:** Calculation:

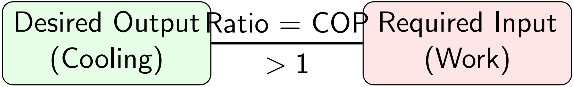
$$\text{TR} = \frac{70.32}{3.516} = 20\text{ TR}$$

Coefficient of Performance (COP)

- **Definition:** Ratio of the desired output to the required input.
- For a refrigerator:

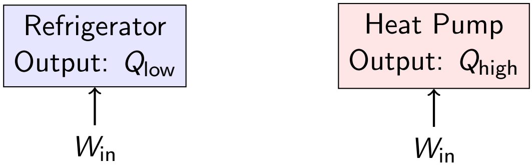
$$\text{COP} = \frac{\text{Cooling Effect}}{\text{Work Input}}$$

- $\text{COP} = \frac{\text{Net Refrigerating Capacity (kW)}}{\text{Compressor Power (kW)}}$
- It is a dimensionless number, generally greater than 1.



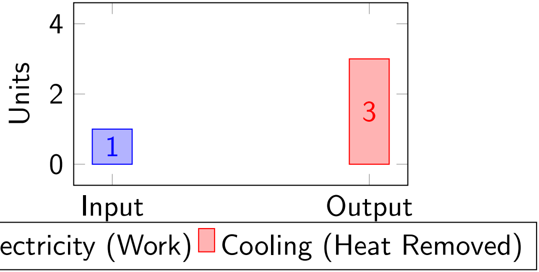
COP: Refrigerator vs Heat Pump

- **Refrigerator COP:** Focuses on cooling. $\text{COP}_R = \frac{Q_{\text{low}}}{W_{\text{in}}}$
- **Heat Pump COP:** Focuses on heating. $\text{COP}_{HP} = \frac{Q_{\text{high}}}{W_{\text{in}}}$
- **Relationship:** $\text{COP}_{HP} = \text{COP}_R + 1$
- Higher COP means a more efficient system.



Significance of COP in Energy Efficiency

- COP directly impacts operating costs.
- A system with COP $= 3$ produces 3 units of cooling for every 1 unit of electricity.
- Increasing evaporator temperature or decreasing condenser temperature improves COP.
- Design goal: Maximize COP within economic and physical constraints.



Energy Efficiency Ratio (EER)

- **Definition:** Ratio of cooling capacity in Btu/hr to electrical input in Watts.
- **Formula:**

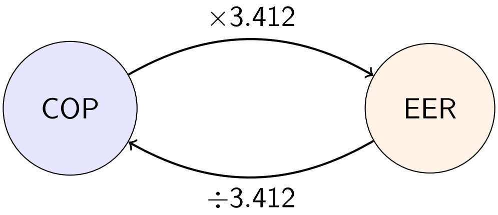
$$\text{EER} = \frac{\text{Cooling Capacity (Btu/hr)}}{\text{Power Input (W)}}$$

- Commonly used for smaller room ACs and split units.
- Higher EER indicates a more efficient cooling system.

EER is effectively a mixed-unit version of COP.

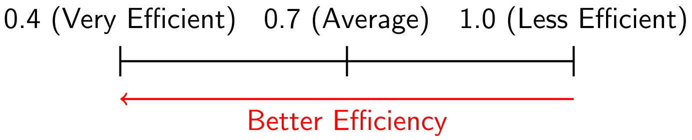
EER vs COP: Key Differences

- **COP** uses consistent units (kW/kW or W/W).
- **EER** uses mixed units (Btu/hr / W).
- **Conversion:** $\text{EER} = \text{COP} \times 3.412$
- **Example:** If COP is 3.0, $\text{EER} = 3.0 \times 3.412 = 10.236$.



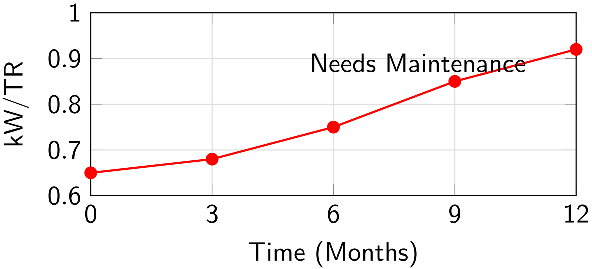
kW/TR (Kilowatt per Ton of Refrigeration)

- **Definition:** Electrical power (kW) required to produce 1 Ton of Refrigeration.
- Commonly used metric for large central chiller plants.
- **Inverse relationship:** *Lower* kW/TR means *higher* efficiency.
- Typical values: 0.55 to 0.8 kW/TR for modern efficient chillers.



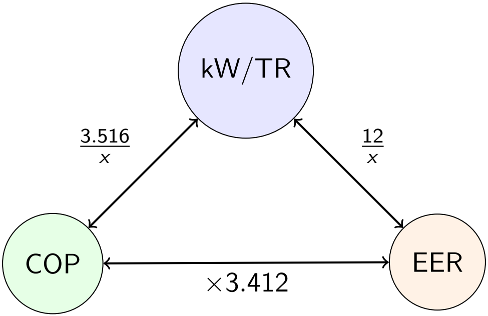
kW/TR and System Efficiency

- kW/TR provides a quick snapshot of chiller power consumption.
- Useful for calculating total power:
  Total kW = System TR × (kW/TR).
- Helps facility managers monitor performance degradation over time.
- Affected by part-load conditions and ambient temperatures.



Relationship Between kW/TR, COP, and EER

- Recall: 1 TR = 3.516 kW.
- COP $= \frac{3.516}{\text{kW/TR}}$
- EER $= \frac{12}{\text{kW/TR}}$
- **Example:** A chiller with 0.6 kW/TR has a COP of $3.516/0.6 = 5.86$.



Summary of Performance Metrics

Metric	Measures	Units	Goal
TR	Cooling Capacity	1 TR = 3.516 kW	-
COP	Efficiency	Dimensionless	**Higher**
EER	Efficiency	Btu/hr per W	**Higher**
kW/TR	Energy Consumption	kW per TR	**Lower**

Key Takeaways

- 1 TR is equivalent to 3.516 kW of cooling capacity.
- COP and EER are efficiency metrics where higher values mean better efficiency.
- kW/TR is an energy consumption metric where lower values mean better efficiency.

Q&A and Next Steps

- **Questions** on TR, COP, EER, or kW/TR?
- **Next Lecture:** Vapor Compression Refrigeration Cycle (VCC).
- **Assignment:** Practice converting between COP, EER, and kW/TR.

Next Up: Vapor Compression Cycle

Learning Objectives & Recap

Learning Objectives:

- Apply formulas to calculate Coefficient of Performance (COP).
- Solve problems related to Energy Efficiency Ratio (EER).
- Perform calculations involving power per ton of refrigeration (kW/TR).

Recap of Previous Lecture:

- Defined Tons of Refrigeration (TR): 1 TR = 3.517 kW.
- Understood COP for cooling and heating.
- Discussed EER and its significance in HVAC.

Essential Formulas Reference

Coefficient of Performance (COP)

$$\text{COP}_{\text{cooling}} = \frac{\text{Refrigerating Effect (kW)}}{\text{Work Input (kW)}}$$

$$\text{COP}_{\text{heating}} = \frac{\text{Heating Effect (kW)}}{\text{Work Input (kW)}} = \text{COP}_{\text{cooling}} + 1$$

Energy Efficiency Ratio (EER)

$$\text{EER} = \frac{\text{Cooling Capacity (Btu/hr)}}{\text{Power Input (Watts)}}$$

Relation: $\text{EER} \approx 3.412 \times \text{COP}$

Power per Ton (kW/TR)

$$\text{kW/TR} = \frac{\text{Power Input (kW)}}{\text{Cooling Capacity (TR)}}$$

Relation: $\text{kW/TR} = \frac{3.517}{\text{COP}}$

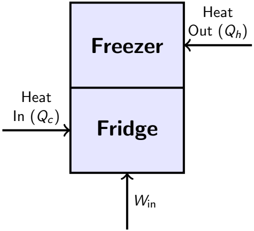
Example 1: Basic COP Calculation

Problem Statement:

- A refrigeration system provides a cooling effect of 50 kW.
- The compressor requires an electrical power input of 15 kW.

Determine:

1. The Coefficient of Performance (COP).
2. The cooling capacity in Tons of Refrigeration (TR).



Solution 1: Basic COP Calculation

1. Calculating COP:

- Given: Refrigerating Effect (Q_c) = 50 kW
- Given: Work Input (W_{in}) = 15 kW

$$\text{COP} = \frac{Q_c}{W_{\text{in}}}$$

$$\text{COP} = \frac{50}{15} = \mathbf{3.33}$$

2. Calculating Capacity in TR:

- Conversion factor: 1 TR = 3.517 kW

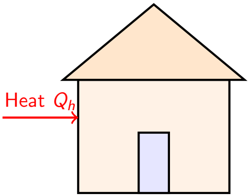
$$\text{Capacity (TR)} = \frac{Q_c}{3.517}$$

$$\text{Capacity (TR)} = \frac{50}{3.517} = \mathbf{14.22\ TR}$$

Example 2: Heat Pump Application

Problem Statement:

- A heat pump is used to maintain a room at a warm temperature during winter.
- It delivers heat at a rate of 25 kW to the room.
- The compressor consumes 6 kW of electrical power.



Determine:

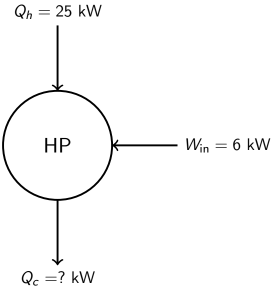
1. The COP of the heat pump.
2. The amount of heat extracted from the cold outside environment.

Solution 2: Heat Pump Application

1. Calculating COP of Heat Pump:

- Given: Heating Effect (Q_h) = 25 kW
- Given: Work Input (W_{in}) = 6 kW

$$COP_{hp} = \frac{Q_h}{W_{in}}$$
$$COP_{hp} = \frac{25}{6} = \mathbf{4.17}$$



2. Heat Extracted from Outside (Q_c):

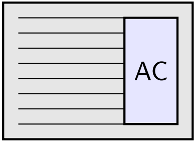
- Energy Balance: $Q_h = Q_c + W_{in}$

$$Q_c = Q_h - W_{in}$$
$$Q_c = 25 \text{ kW} - 6 \text{ kW} = \mathbf{19 \text{ kW}}$$

Example 3: EER Calculation

Problem Statement:

- A window air conditioning unit has a rated cooling capacity of 18,000 Btu/hr.
- The unit consumes 1,600 Watts of electrical power during steady operation.



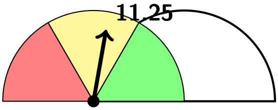
Determine:

1. The Energy Efficiency Ratio (EER) of the unit.
2. Is this EER considered efficient by modern standards?

Solution 3: EER Calculation

1. Calculating EER:

- Given: Cooling Capacity = 18,000 Btu/hr
- Given: Power Input = 1,600 W



$$\text{EER} = \frac{\text{Capacity (Btu/hr)}}{\text{Power Input (W)}}$$

$$\text{EER} = \frac{18{,}000}{1{,}600}$$

$$\text{EER} = \mathbf{11.25}$$

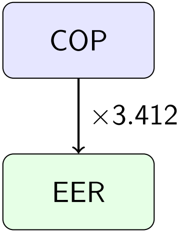
2. Discussion: An EER of 11.25 is reasonably efficient for standard window units, though high-efficiency models can reach 12 to 15 or higher.

Problem Statement:

- An industrial chiller has a specified COP of 4.5.

Determine:

1. The equivalent Energy Efficiency Ratio (EER).
2. If the chiller provides 100 TR of cooling, what is the power consumption in kW?



Solution 4: Converting COP to EER

1. **Equivalent EER:**
   - Given: COP $= 4.5$
   - Formula: EER $\approx 3.412 \times$ COP

$$\text{EER} = 3.412 \times 4.5$$
$$\text{EER} = \mathbf{15.35}$$

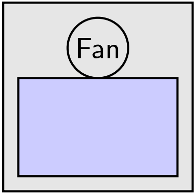
2. **Power Consumption:**
   - Given: Capacity $= 100$ TR
   - Convert TR to kW: $Q_c = 100 \times 3.517 = 351.7$ kW
   - Use COP formula: COP $= \frac{Q_c}{W_{\text{in}}}$

$$W_{\text{in}} = \frac{Q_c}{\text{COP}}$$
$$W_{\text{in}} = \frac{351.7}{4.5} = \mathbf{78.16\ kW}$$

Example 5: Specific Power (kW/TR)

Problem Statement:

- A central air conditioning plant consumes 250 kW of electrical power.
- The plant has a cooling load capacity of 300 TR.



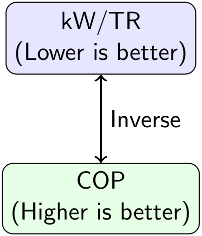
Determine:

1. The specific power consumption in kW/TR.
2. The COP of the plant.
3. Evaluate if the kW/TR value is indicative of a highly efficient system.

1. Calculating kW/TR:

- Given: Power Input = 250 kW
- Given: Capacity = 300 TR

$$\text{kW/TR} = \frac{250}{300} = \mathbf{0.833\ kW/TR}$$



2. Calculating COP:

- Relation: $\text{kW/TR} = \frac{3.517}{\text{COP}} \implies \text{COP} = \frac{3.517}{\text{kW/TR}}$

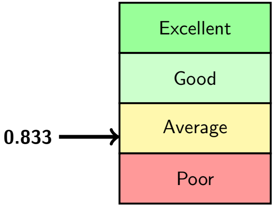
$$\text{COP} = \frac{3.517}{0.833} = \mathbf{4.22}$$

3. Evaluating Efficiency based on kW/TR:

- Calculated kW/TR = 0.833

General Benchmarks for Water-Cooled Chillers:

- **Excellent:** < 0.60 kW/TR
- **Good:** 0.60 – 0.70 kW/TR
- **Average:** 0.70 – 0.85 kW/TR
- **Poor:** > 0.85 kW/TR



Conclusion:

- The system operates at an **average** efficiency level and may benefit from maintenance or optimization.

Common Pitfalls in Numerical Problems

Unit Mismatches:

- Mixing kW with Btu/hr or Watts without proper conversion.

Confusing Heating vs. Cooling COP:

- Using Refrigerating Effect instead of Heating Effect when analyzing a Heat Pump.

Inverting Ratios:

- **Remember:** COP and EER = Output / Input (Higher is better).
- **Remember:** kW/TR = Input / Output (Lower is better).

Summary & Q&A

Key Takeaways:

- COP relates heating/cooling effect directly to work input (dimensionless).
- EER evaluates cooling capacity (Btu/hr) per electrical input (Watts).
- kW/TR is a practical metric for large plants, inversely related to COP.
- Consistent unit conversion is critical for accurate calculations.

Questions?

Welcome & Recap

Course: Thermal Systems and Energy Efficiency
Unit 5: HVAC and Refrigeration Systems energy efficiency
Today's Topic: Heat Load Estimation & Psychrometrics
Recap: Recall our previous discussion on calculating COP and EER for refrigeration systems.

Learning Objectives & Outline

Objectives:

- Read and interpret a psychrometric chart.
- Estimate heat load using enthalpy difference.
- Solve simple heat load numericals.

Outline:

- Introduction to Heat Load
- Basics of Psychrometrics
- Enthalpy and Heat Load Equation
- Numerical Problem Solving

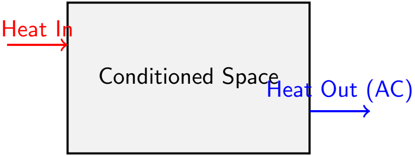
Introduction to Heat Load Estimation

What is Heat Load?

- The amount of heat energy that needs to be added or removed from a space to maintain desired conditions (temperature and humidity).

Why is it important?

- Crucial for selecting the right size (capacity) of HVAC equipment.
- Undersized units won't cool properly.
- Oversized units waste energy and fail to dehumidify properly.



What is a Psychrometric Chart?

Definition:

- A graphical representation of the physical and thermal properties of moist air at a constant pressure.

Purpose in HVAC:

- Used to visualize air conditioning processes.
- Helps determine changes in moisture and heat content.

State Point:

- Any point on the chart represents a specific state of air (defined by two independent properties).

Key Properties on the Psychrometric Chart

- **Dry-Bulb Temperature (DBT):** True air temperature, read on the horizontal axis.
- **Wet-Bulb Temperature (WBT):** Lowest temp achieved by evaporation, read on slanted lines.
- **Relative Humidity (RH):** Percentage of moisture air can hold, shown as curved lines.
- **Specific Humidity/Moisture Content (W):** Actual mass of water vapor, read on the right vertical axis.
- **Dew Point Temperature (DPT):** Temp at which condensation begins, read horizontally to the saturation curve.

Understanding Enthalpy (h)

What is Enthalpy?

- The total heat content of the air-water vapor mixture.
- Measured in kJ/kg of dry air.

Where is it on the chart?

- Enthalpy scales are located outside the main body of the chart, on the top-left slanted axis.
- Lines of constant enthalpy run diagonally downwards from left to right (almost parallel to WBT lines).

Sensible Heat vs. Latent Heat

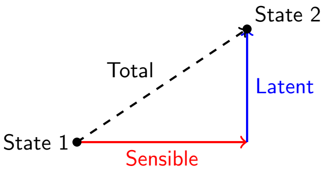
Sensible Heat:

- Changes temperature, not moisture.
- Horizontal movement on chart.

Latent Heat:

- Changes moisture, not temperature.
- Vertical movement on chart.

Total Heat = Sensible + Latent



The Concept of Enthalpy Difference (Δh)

Process Analysis:

- Air conditioning involves changing air from an initial state (State 1) to a final state (State 2).

Enthalpy Difference (Δh):

- $\Delta h = h_1 - h_2$ (for cooling) or $h_2 - h_1$ (for heating).
- It represents the exact amount of total heat energy added or removed per kg of dry air.
- This is the foundation of estimating the required cooling or heating capacity.

Basic Heat Load Equation

The Formula

$$Q = m \times \Delta h$$

Where:

- Q = Total heat load or capacity (kW or kJ/s)
- m = Mass flow rate of air (kg/s)
- Δh = Enthalpy difference ($h_1 - h_2$) in kJ/kg

Conversion note:

- If volume flow rate (V, m^3/s) is given, $m = \frac{V}{v}$
- Where v = specific volume (m^3/kg), read from the psychrometric chart.

Steps for Estimating Heat Load

Step 1: Identify given conditions (e.g., initial and final T and RH).

↓

Step 2: Locate State Point 1 and State Point 2 on the psychrometric chart.

↓

Step 3: Read enthalpy h_1 for State 1 and h_2 for State 2 from the chart.

↓

Step 4: Calculate the enthalpy difference, $\Delta h = |h_1 - h_2|$.

↓

Step 5: Determine mass flow rate (m) if not directly given.

↓

Step 6: Calculate total heat load $Q = m \times \Delta h$.

Simple Numerical Problem - Statement

Problem:

- Air at 35°C DBT and 60% RH is to be cooled to 20°C DBT and 50% RH.
- The mass flow rate of air is 2 kg/s.
- Determine the cooling capacity (total heat load) required in kW.

Given:

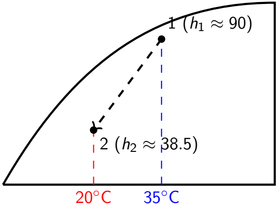
- State 1: $T_1 = 35°\text{C}$, $RH_1 = 60\%$
- State 2: $T_2 = 20°\text{C}$, $RH_2 = 50\%$
- $m = 2$ kg/s

Locating State 1 (35°C DBT, 60% RH):

- Find 35°C on the bottom axis.
- Follow it up to intersect the 60% RH curve.
- Read enthalpy $h_1 \approx 90$ kJ/kg.

Locating State 2 (20°C DBT, 50% RH):

- Find 20°C on the bottom axis.
- Follow it up to intersect the 50% RH curve.
- Read enthalpy $h_2 \approx 38.5$ kJ/kg.



Step 1: Calculate Enthalpy Difference (Δh)

- $\Delta h = h_1 - h_2$
- $\Delta h = 90 - 38.5 = 51.5$ kJ/kg

Step 2: Calculate Total Heat Load (Q)

- $Q = m \times \Delta h$
- $Q = 2$ kg/s $\times$ 51.5 kJ/kg
- $Q = 103$ kW

Result:

- The required cooling capacity is **103 kW**.

Practical Applications in HVAC

Equipment Sizing:

- The calculated Q (kW) directly determines the required capacity of the Chiller, AHU, or VRF system.

Tonnage Calculation:

- 1 Ton of Refrigeration (TR) $= 3.517$ kW.
- For our problem: $103 \text{ kW}/3.517 \approx 29.3$ TR.

Energy Audits:

- Used to check if existing equipment is appropriately sized for the current building loads.

Impact of Accurate Estimation:

- Accurate Δh estimation prevents oversizing.
- Oversized compressors cycle on and off frequently, reducing efficiency and lifespan.

Optimizing the Process:

- Understanding the state points allows engineers to select optimal supply air temperatures.
- Minimizes unnecessary latent cooling (over-dehumidification), saving significant energy.

Summary & Q&A

Summary:

- Psychrometric charts map moist air properties.
- Enthalpy (h) represents total heat content.
- Heat load is calculated using $Q = m \times \Delta h$.
- Accurate estimation is key for energy efficiency.

Questions?

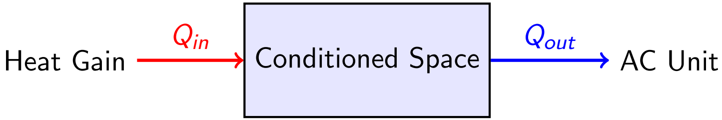
- Feel free to ask about chart reading or calculations.

Welcome & Recap

- Welcome to Lecture 41: Basic Concept of Cooling Load
- Course: Thermal Systems and Energy Efficiency (DI05019061)
- Recap: Psychrometric charts and air conditioning processes

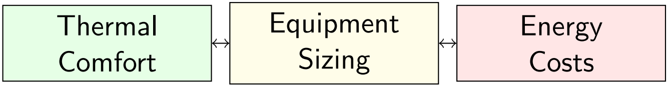
What is Cooling Load?

- It is the rate at which heat energy must be removed from a space to maintain a specific temperature and humidity.
- Measured in Watts (W), Kilowatts (kW), or Tons of Refrigeration (TR).
- Essential for sizing HVAC equipment accurately.



Purpose of Cooling Load Calculations

- Ensure thermal comfort for occupants.
- Select appropriately sized HVAC equipment.
- Avoid **oversized** equipment (leads to inefficiency and poor humidity control).
- Avoid **undersized** equipment (fails to maintain desired conditions).
- Estimate energy consumption and operating costs.

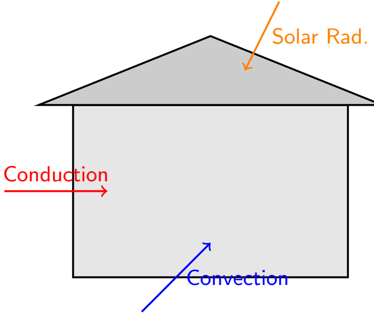


Heat Transfer in Buildings

Heat enters a building through various mechanisms:

- **Conduction:** Through solid boundaries like walls, roof, and glass.
- **Convection:** Heat transfer via air movement.
- **Radiation:** Direct solar heat gain through transparent surfaces.

Understanding these modes is key to analyzing cooling loads.



Sensible vs. Latent Heat Loads

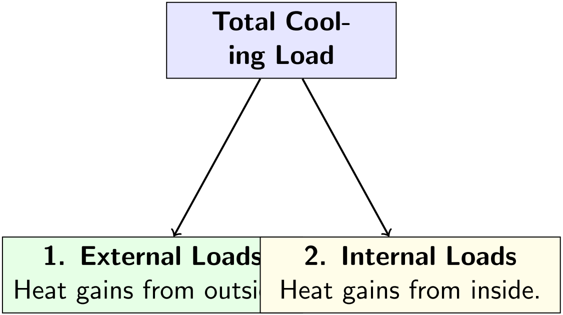
Total Cooling Load

Total Cooling Load = Sensible Load + Latent Load

- **Sensible Heat Load:** Heat addition that causes a rise in dry-bulb temperature.
- **Latent Heat Load:** Heat addition associated with the addition of moisture (water vapor) to the space.

HVAC systems must handle both to maintain comfort (temperature and humidity).

Cooling loads are generally divided into two main categories:



Both contribute to the total heat that must be removed.

External Cooling Load Components

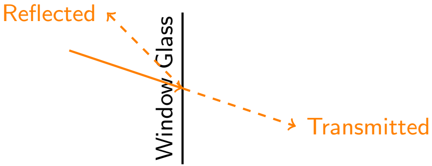
- Solar heat gain through glass (windows, skylights).
- Heat conduction through opaque surfaces (exterior walls, roof).
- Heat conduction through partitions, ceilings, and floors adjacent to unconditioned spaces.
- Heat gain from ventilation air (outside air brought in deliberately).
- Heat gain from infiltration (unintentional air leakage).

Internal Cooling Load Components

- Heat generated by occupants (people).
- Heat generated by lighting systems.
- Heat generated by appliances and equipment (computers, machinery, ovens).
- These loads can be a significant portion of the total load, especially in commercial buildings.

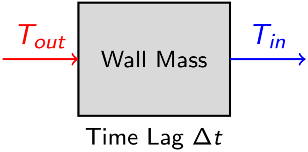
Solar Radiation through Glass

- Often the largest and most variable cooling load component.
- Depends heavily on window orientation (East/West vs. North/South), time of day, and season.
- Transmitted directly into the space, warming interior surfaces instantly.
- Can be mitigated using shading devices (blinds, overhangs) or special glazing (Low-E glass).



Heat Conduction through Walls and Roofs

- Driven by the temperature difference between outside and inside air.
- Also driven by solar radiation absorbed by the exterior surface (Sol-air temperature).
- Thermal mass of the building causes a **time lag**; heat absorbed during the day may enter the space hours later.
- Insulation (U-value) is critical for reducing this load.



Heat Gains from Occupants

- Human bodies constantly release heat and moisture.
- Provides both sensible heat (body temperature) and latent heat (respiration, perspiration).
- The amount varies significantly with activity level.
- Crucial in crowded spaces like theaters or gymnasiums.

Activity Level	**Typical Application**	**Sensible (W)**	**Latent (W)**
Seated at rest	Theater, office	65	30
Standing, light work	Retail store	75	55
Heavy work	Factory, gym	170	255

Heat Gains from Lighting and Appliances

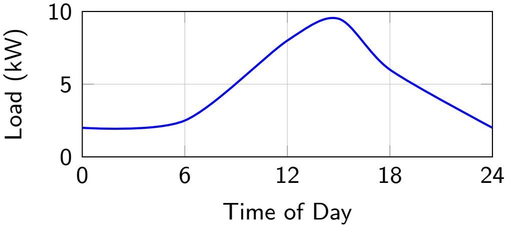
- **Lighting:** Converts electrical power into light and heat. Nearly all energy consumed by indoor lighting becomes a sensible heat load.
- **Appliances/Equipment:** Computers, printers, motors, cooking equipment.
- Can produce sensible heat, and sometimes latent heat (e.g., cooking, coffee makers).
- Energy efficient lighting (LEDs) significantly reduces this cooling load.

Ventilation and Infiltration

- **Ventilation:** Intentional introduction of outdoor air for indoor air quality (IAQ).
- **Infiltration:** Unintentional leakage of outdoor air through cracks and doors.
- Outdoor air brings both sensible heat (if hotter outside) and latent heat (if more humid outside).
- A major component in hot and humid climates.

Peak Cooling Load vs. Average Load

- **Peak Cooling Load:** The maximum load that occurs under design conditions. Used to **size** the HVAC equipment.
- **Average/Part Load:** The typical load during operation. Used to **estimate** energy consumption.
- Equipment rarely operates at peak load; efficiency at part-load is very important.



Factors Affecting Cooling Load

- **Building Design:** Orientation, glazing area, shading, insulation levels.
- **Usage Profile:** Occupancy schedules, lighting schedules, equipment use.
- **Climate/Location:** Solar intensity, outdoor temperature, and humidity patterns.
- **Indoor Design Conditions:** The desired temperature and humidity setpoints.

Accurate load calculation requires detailed information on all these factors.

Summary & Q/A

- Cooling load is the rate of heat removal required for comfort.
- Total load = Sensible Load (temperature) + Latent Load (moisture).
- Comprises external loads (solar, conduction) and internal loads (people, equipment).
- Accurate calculations are essential for proper HVAC sizing and energy efficiency.

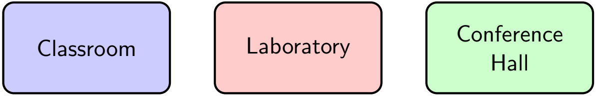
Questions?

Welcome & Recap

- Course: Thermal Systems and Energy Efficiency
- Unit 5: HVAC and Refrigeration Systems energy efficiency
- Lecture 42: Cooling Load Estimation for Specific Spaces
- Recap: Basic concepts of cooling load, sensible and latent heat.

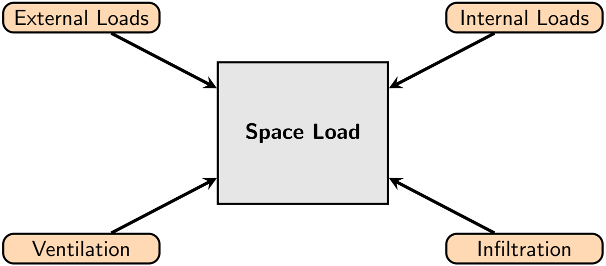
Introduction to Space-Specific Load

- Different spaces have vastly different thermal requirements.
- Load estimation must be tailored to the primary function of the room.
- Key variables include occupancy density, equipment usage, and operating hours.
- We will examine three distinct environments: Classrooms, Laboratories, and Conference Halls.



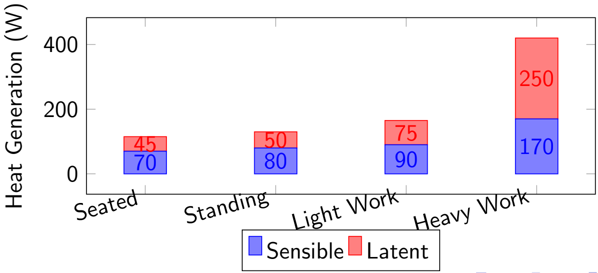
General Components of Space Load

- External Loads: Heat transfer through walls, roof, and glass (conduction and radiation).
- Internal Loads: People, lighting, and appliances/equipment.
- Ventilation Loads: Fresh air intake required for indoor air quality (IAQ).
- Infiltration: Unintended outside air entering the space.



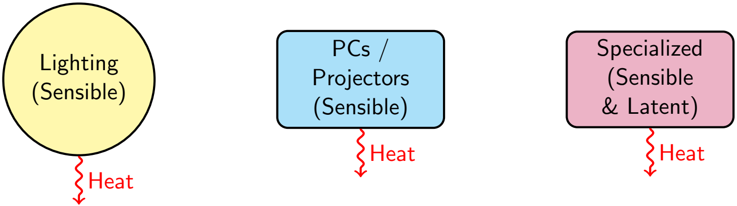
The Impact of Occupancy

- People generate both sensible (temperature) and latent (moisture) heat.
- The activity level directly affects the heat output.
- Sedentary activities (listening, working) produce less heat than active movement.
- High-density spaces require significant latent load management.



Lighting and Equipment Loads

- Lighting: Converts electrical power mostly into sensible heat.
- Equipment (PCs, Projectors): Steady sources of sensible heat.
- Specialized Equipment: Can produce massive sensible or latent loads depending on the process.
- Diversity Factor: Not all equipment or lights are on simultaneously.



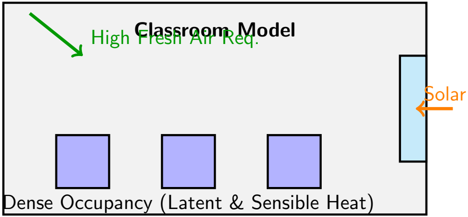
Case 1: The Classroom Environment

- Primary characteristics: Moderate to high occupancy density.
- Activity level: Mostly sedentary (sitting, listening, occasional movement).
- Operating hours: Typically intermittent, following a fixed timetable.
- Equipment: Relatively low (lighting, a projector, a few computers).

Classroom Profile
High Density — Sedentary Activity —
Intermittent Usage — Low Equipment

Classroom Load Estimation Factors

- High fresh air requirement (ventilation) due to high occupancy.
- Significant latent load from the number of students.
- Lighting and solar load (through windows) are standard components.
- Rapid load changes during class changeovers.



Case 2: The Laboratory Environment

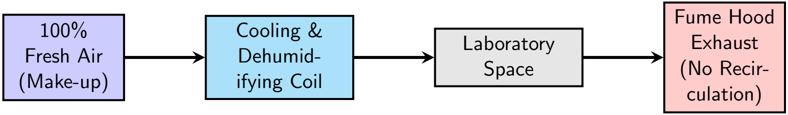
- Primary characteristics: Low to moderate occupancy, highly specialized.
- Equipment: Extensive and varied (ovens, computers, specialized machinery).
- Ventilation: Often requires 100% outside air (no recirculation) for safety.
- Exhaust: Fume hoods and localized exhaust systems dictate airflow.

Laboratory Profile

Low Occupancy — High Equipment Load — 100% Fresh Air — Fume Hoods

Laboratory Load Estimation Factors

- Equipment heat gain is often the dominant internal load.
- Make-up air (replacing exhausted air) represents a massive sensible and latent load.
- Strict temperature and humidity control may be required for experiments.
- Diversity factor for equipment usage is critical for accurate sizing.



Case 3: The Conference Hall

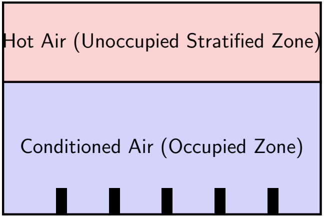
- Primary characteristics: Very high occupancy density during events.
- Usage pattern: Highly intermittent and unpredictable peaks.
- Volume: Typically features high ceilings and large open volumes.
- Equipment: High-intensity lighting, heavy AV equipment.

Conference Hall Profile

Peak Occupancy — High Volume — AV Loads — Intermittent Use

Conference Hall Load Estimation Factors

- Massive latent and sensible loads from dense crowds.
- Pre-cooling strategies are often employed before an event begins.
- Stratification: High ceilings allow heat to rise above the occupied zone.
- High ventilation requirements during peak occupancy.



Comparison of Space Loads

- Classroom: Driven by occupancy and steady ventilation.
- Laboratory: Driven by equipment heat and exhaust/make-up air requirements.
- Conference Hall: Driven by extreme, intermittent occupancy peaks and high volume.
- Each requires a different approach to HVAC system design and control.

Feature	**Classroom**	**Laboratory**	**Conference Hall**
Occupancy	Moderate-High	Low-Moderate	Very High (Peaks)
Equipment Load	Low	High	Moderate (AV/Lights)
Ventilation	Steady	100% Fresh Air	Demand Controlled
Key Challenge	Latent Loads	Make-up Air	Stratification & Peaks

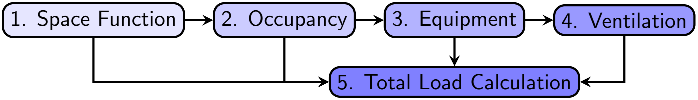
Conceptual Data Sheet Usage

- Engineers use standard tables (e.g., ASHRAE Fundamentals) for estimation.
- Tables provide typical heat gain values per person based on activity.
- Equipment data sheets provide wattage and heat dissipation rates.
- Standard tables dictate required ventilation rates (CFM/person).

Degree of Activity	**Sensible Heat (W)**	**Latent Heat (W)**
Seated at theater	65	30
Seated, very light work	70	45
Standing, light work	75	55
Heavy work	170	250

Applying Data to Estimation

- Step 1: Identify space function and dimensions.
- Step 2: Estimate maximum occupancy and activity level.
- Step 3: Inventory equipment and apply diversity factors.
- Step 4: Calculate ventilation requirements using standards.
- Step 5: Sum sensible and latent loads separately.



Energy Efficiency Implications

- Accurate load estimation prevents oversizing HVAC equipment.
- Oversized equipment cycles frequently, reducing efficiency and lifespan.
- Understanding space usage allows for smart controls (e.g., CO2 sensors for ventilation).
- Tailoring the system to the space is the first step in energy-efficient design.

Oversized System	**Correctly Sized**
Frequent Cycling	Longer Runtimes
High Energy Use	Lower Energy Use
Poor Humidty Control	Better Comfort

Summary & Q&A

- Different spaces (Classrooms, Labs, Halls) have unique thermal profiles.
- Occupancy, equipment, and ventilation dictate the cooling load.
- Accurate load estimation is crucial for efficient HVAC design.
- Any questions?

Q & A

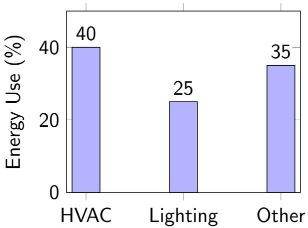
Welcome & Recap

- Welcome to Lecture 43: Energy Efficiency Improvement Measures.
- Recap of previous lecture: Space load estimation.
- Focus today: Practical measures to improve efficiency in HVAC&R systems.

Goal: Optimize performance while minimizing energy consumption.

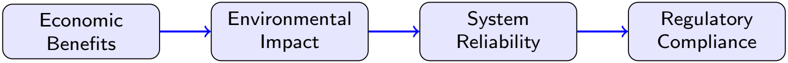
Introduction to Energy Efficiency in HVAC&R

- HVAC systems are major energy consumers in commercial and industrial buildings.
- Energy efficiency reduces operational costs and environmental impact.
- Measures can be categorized into design, equipment upgrades, and operational controls.



Importance of Energy Efficiency

- **Economic Benefits:** Significant reduction in electricity bills.
- **Environmental Impact:** Lower greenhouse gas emissions and smaller carbon footprint.
- **System Reliability:** Efficient systems often undergo less stress, increasing lifespan.
- **Regulatory Compliance:** Meeting modern building codes and energy standards.



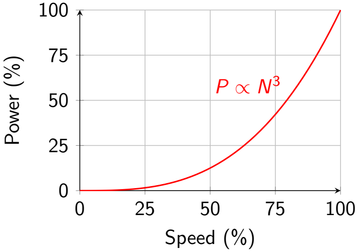
Improving Efficiency in Compressors

- Compressors consume the most energy in refrigeration cycles.
- Use of high-efficiency compressors (e.g., scroll or screw compressors).
- Part-load performance optimization is crucial since systems rarely run at full load.
- Implementing multi-stage compression for large systems.

Compressor Type	**Typical Use**	**Efficiency (Part-Load)**
Reciprocating	Small/Medium	Moderate
Scroll	Medium	Good
Screw	Large	Very Good
Centrifugal	Very Large	Excellent (with VFD)

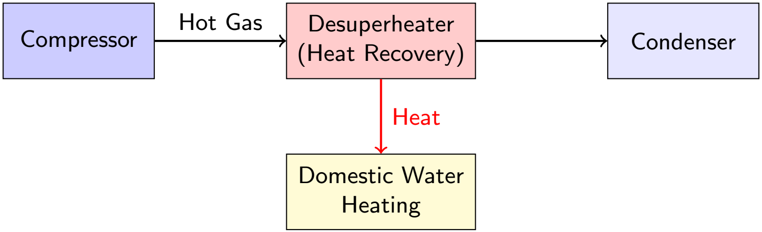
Variable Frequency Drives (VFDs)

- VFDs adjust motor speed to match the actual load demand.
- Applicable to fans, pumps, and compressors.
- Energy savings follow the Affinity Laws ($P \propto N^3$).
- Reduces wear and tear on motors through soft starting.



Heat Recovery Systems

- Capture waste heat from the condenser for other uses (e.g., water heating).
- Air-to-air heat exchangers (Heat Recovery Wheels) in ventilation systems.
- Reduces the load on both heating and cooling equipment.
- Improves overall system COP (Coefficient of Performance).



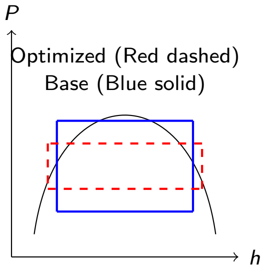
Economizers and Free Cooling

- **Air-side Economizers:** Use outside air for cooling when outdoor temperature and humidity are favorable.
- **Water-side Economizers:** Use cooling towers directly to cool chilled water loops without running the compressor.
- Significantly reduces compressor run hours.
- Requires proper sensor maintenance for reliable operation.

Mode	**Outdoor Conditions**	**Compressor Status**
Full Free Cooling	Cool & Dry	OFF
Partial Free Cooling	Mild	Part-Load
Mechanical Cooling	Hot & Humid	ON (Full Load)

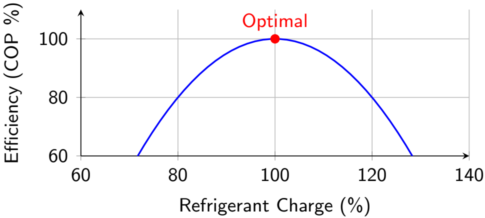
Condenser and Evaporator Optimization

- Lowering condensing temperature increases efficiency (reduces compressor lift).
- Raising evaporator temperature increases efficiency.
- Rule of thumb: 1°C change in evaporator/condenser temp changes efficiency by $\sim 2-3\%$.
- Regular cleaning of coils prevents efficiency degradation.



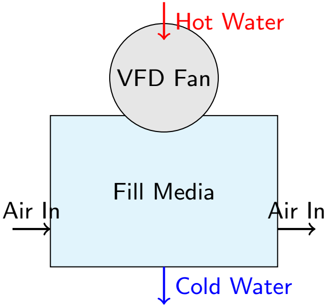
Refrigerant Selection and Management

- Using refrigerants with favorable thermodynamic properties.
- Ensuring correct refrigerant charge; both undercharging and overcharging decrease efficiency.
- Regular leak detection and repair.
- Transition to low-GWP (Global Warming Potential) refrigerants often comes with efficiency upgrades.



Cooling Tower Efficiency Measures

- Implement VFDs on cooling tower fans.
- Optimize water treatment to prevent scaling, which acts as an insulator.
- Use high-efficiency fill media to maximize heat transfer area.
- Lowering the cooling water supply temperature when ambient conditions allow.



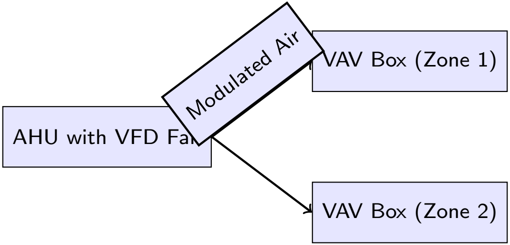
Pumping Systems Optimization

- Shift from constant flow to variable primary flow (VPF) chilled water systems.
- Use two-way valves instead of three-way bypass valves.
- Right-sizing pumps to avoid throttling losses.
- Regular maintenance of pump seals and bearings.

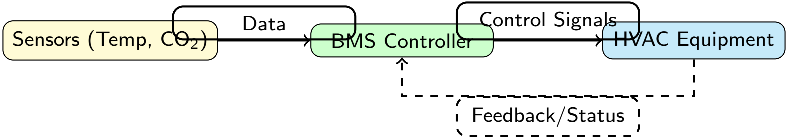
Feature	**Constant Volume (CV)**	**Variable Flow (VPF)**
Pump Operation	Runs at constant speed	Speed varies with load
Valves Used	3-way bypass valves	2-way modulating valves
Energy Consumption	High (always full flow)	Low (optimized flow)

Air Distribution System Optimization

- Implement Variable Air Volume (VAV) systems instead of Constant Air Volume (CAV).
- Seal ductwork to prevent conditioned air leakage.
- Optimize duct design to minimize static pressure drops.
- Use high-efficiency air filters and replace them regularly to reduce fan energy.



- Centralized control of HVAC, lighting, and other systems.
- Implement scheduling: Setbacks during unoccupied hours.
- Demand Control Ventilation (DCV) using CO_2 sensors.
- Continuous monitoring and fault detection.



Maintenance and Insulation

- Predictive and preventive maintenance schedules.
- Insulate chilled water pipes and refrigerant suction lines to prevent heat gain.
- Insulate ductwork passing through unconditioned spaces.
- Clean heat exchanger surfaces regularly to maintain U-values.

Maintenance Impact

Regular maintenance ensures equipment operates at design efficiency, preventing the 10-20% degradation often seen in neglected systems.

Insulation Impact

Missing or damaged insulation can lead to significant thermal losses and condensation issues, reducing overall system capacity.

Case Study / Example

- **Example:** A commercial building upgrades to VFDs on chilled water pumps and installs an air-side economizer.
- **Result:** Pumping energy reduced by 40% (Affinity Laws).
- **Result:** Compressor run-time reduced by 20% due to free cooling.
- Overall HVAC energy consumption dropped by 25%, paying back the investment in 2 years.

Metric	**Before Upgrade**	**After Upgrade**
Annual Energy Cost	$100,000	$75,000
Compressor Hours	4,000 hrs	3,200 hrs
Pumping Power	100%	60%
Savings	**$25,000 / year (2-year ROI)**	

Summary & Q&A

- Energy efficiency in HVAC involves equipment upgrades, intelligent controls, and rigorous maintenance.
- Key technologies include VFDs, Heat Recovery, and Economizers.
- Optimizing system operating temperatures (condenser/evaporator) is critical.

Questions?

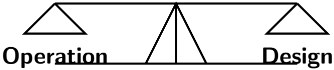
Learning Objectives

- Differentiate between operational and design-level conservation.
- Apply operational strategies to reduce energy consumption.
- Integrate energy-efficient design principles into HVAC & R systems.

Energy Conservation in HVAC&R can be broadly classified into two categories:

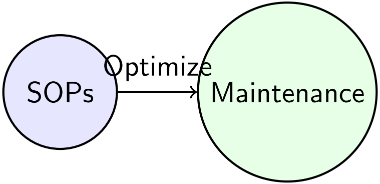
1. **Operational Techniques:** Actions taken during the day-to-day running of existing systems.
2. **Design-Level Techniques:** Decisions made during the system's conceptualization and installation.

Both are essential for achieving optimal energy efficiency.



What is Operational Conservation?

- Focuses on optimizing the performance of existing equipment.
- Involves zero or low capital investment.
- Relies on standard operating procedures (SOPs) and maintenance.
- Yields immediate energy savings when implemented correctly.



Operational Conservation: Preventive Maintenance

- Regular servicing prevents performance degradation.
- Includes checking refrigerant charge: undercharged systems run longer and consume more power.
- Lubrication of moving parts to reduce friction losses.
- Calibration of sensors and thermostats for accurate control.

Operational Conservation: Setpoint Optimization

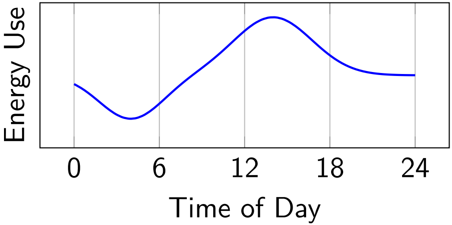
- Adjusting temperature setpoints based on actual needs.
- **Cooling:** Raising the chilled water setpoint slightly can improve chiller COP.
- **Heating:** Lowering the hot water setpoint saves boiler fuel.
- Implementing deadbands to prevent rapid cycling of equipment.

Operational Conservation: Cleaning & Inspection

- Fouled heat exchangers drastically reduce heat transfer efficiency.
- Regularly clean evaporator and condenser coils.
- Replace or clean air filters to maintain proper airflow.
- Check for and repair duct leaks to prevent conditioned air loss.

Operational Conservation: Load Management

- Scheduling equipment operation to match building occupancy.
- Using Building Management Systems (BMS) for automated control.
- Night setback strategies: reducing HVAC operation during unoccupied hours.
- Demand limiting during peak electrical tariff periods.

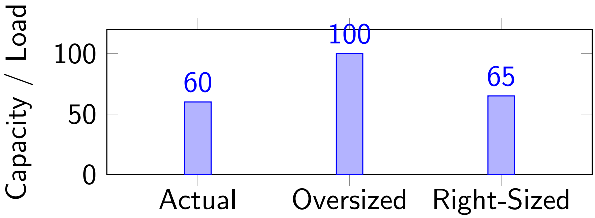


What is Design-Level Conservation?

- Strategies implemented during the initial planning or major retrofits.
- Requires capital investment but offers significant long-term savings.
- Dictates the maximum potential efficiency of the system.
- Involves technology selection, system sizing, and architectural integration.

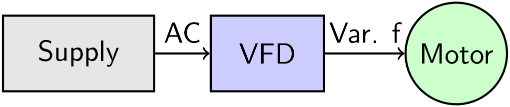
Design-Level Conservation: Right-Sizing

- Accurate calculation of cooling and heating loads.
- Avoiding aggressive 'safety factors' that lead to oversized equipment.
- Oversized equipment cycles frequently, reducing efficiency and lifespan.
- Right-sized systems operate closer to their optimal full-load efficiency.



Design-Level Conservation: VFDs

- Variable Frequency Drives (VFDs) control the speed of motors.
- Applied to fans, pumps, and compressors.
- Allows the system to match part-load conditions efficiently.
- Power consumption is proportional to the cube of the speed (Affinity Laws).



Design-Level Conservation: Heat Recovery

- Capturing waste heat and reusing it elsewhere.
- **Desuperheaters:** Using heat from refrigeration condensers for domestic hot water.
- **Energy Recovery Ventilators (ERVs):** Pre-conditioning fresh air using exhaust air.
- Significantly reduces the primary energy required for heating.

Design-Level Conservation: Insulation & Envelope

- Improving the building envelope reduces the overall HVAC load.
- High-quality insulation on chilled water pipes and air ducts.
- Prevents thermal losses during distribution.
- Using reflective roofing or high-performance glazing.

Comparing Operational vs. Design Strategies

- **Operational:** Low cost, immediate impact, requires continuous effort.
- **Design:** High initial cost, sets the baseline, requires proper planning.
- **Synergy:** A high-efficiency design requires good operational practices to realize its potential.
- Best practice combines both approaches.

Feature	Operational	Design-Level
Capital Cost	Low / Zero	High
Implementation Time	Immediate	Long-term
Impact Scope	Existing Potential	Maximum Potential
Requirement	Continuous SOPs	Upfront Planning

Case Study: Combined Approach

- **Scenario:** Commercial office building upgrading its chiller plant.
- **Design Action:** Installed a high-efficiency variable-speed magnetic bearing chiller.
- **Operational Action:** Implemented a chilled water reset schedule based on outside air temperature.
- **Result:** 40% reduction in annual cooling energy consumption.

Summary & Q&A

- Operational conservation focuses on running existing equipment optimally (maintenance, scheduling).
- Design conservation focuses on selecting the right equipment and architecture (VFDs, heat recovery, sizing).
- Both are critical for maximizing energy efficiency in HVAC&R systems.

Questions?

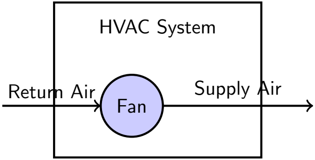
Welcome & Recap

- Welcome to Lecture 45: Fan Pressure, Power & Efficiency.
- Course: Thermal Systems and Energy Efficiency (DI05019061).
- Recap: In the previous lecture, we discussed operational and design conservation in HVAC systems.

Goal: Deep dive into fan performance parameters (Pressure, Power, and Efficiency)

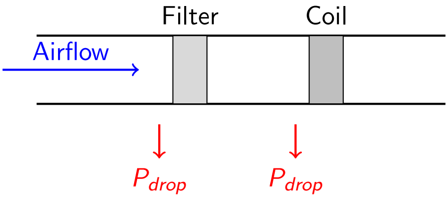
Introduction to Fans in HVAC

- Fans are critical components in HVAC systems, responsible for moving air.
- They overcome system resistance to deliver the required airflow.
- Understanding fan performance is key to energy efficiency.
- Main parameters: Pressure, Power, and Efficiency.



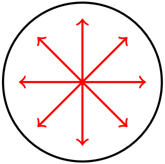
Fan Pressure Basics

- Fan pressure is the energy imparted to the air by the fan.
- It is required to overcome the friction and resistance of ductwork, filters, and coils.
- Expressed typically in Pascals (Pa) or millimeters of water gauge (mmWG).
- Consists of Static Pressure and Velocity Pressure.



Static Pressure (SP)

The outward push of air against duct walls (potential energy).



Balloon analogy

Velocity Pressure (VP)

The pressure caused by the movement of air (kinetic energy).

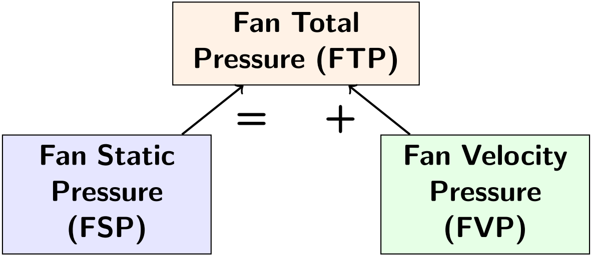
Formula:

$$\text{VP (mmWG)} = \left(\frac{\text{Velocity}}{4.04}\right)^2$$

Both are crucial for complete fan performance analysis.

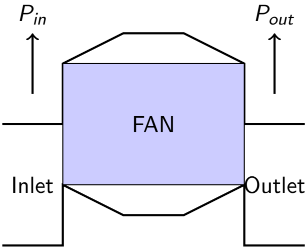
Total Pressure in Fan Systems

- **Fan Total Pressure (FTP)** is the sum of Static Pressure and Velocity Pressure.
- FTP = Fan Static Pressure (FSP) + Fan Velocity Pressure (FVP).
- Represents the total energy added to the air by the fan.
- Used for accurate fan selection and efficiency calculations.



Determination of Fan Pressure

- Fan pressure is determined by measuring pressure at the fan inlet and outlet.
- Fan Total Pressure = Total Pressure at Outlet - Total Pressure at Inlet.
- Fan Static Pressure = Fan Total Pressure - Fan Velocity Pressure at Outlet.
- Measurements must be taken accurately using standardized procedures.



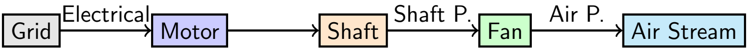
Measurement Instruments

Instrument	**Application**
Pitot Tube	Used with a manometer to measure static, velocity, and total pressure.
Manometer	U-tube, inclined, or digital devices for reading pressure differences.
Anemometer	Measures air velocity directly, which can be used to find VP.

- Proper placement (e.g., pitot tube traverses) is essential for accurate readings.

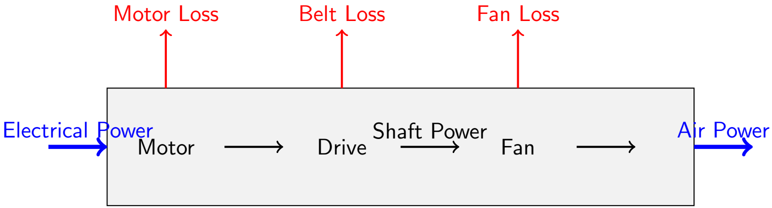
Introduction to Fan Power Input

- Power is the rate at which energy is consumed by the fan.
- **Air Power:** The useful power delivered to the air stream.
- **Shaft Power (Brake Horsepower):** The power required at the fan shaft.
- **Electrical Power:** The total power drawn by the motor from the grid.



Shaft Power vs. Electrical Power

- Shaft Power is greater than Air Power due to fan aerodynamic and mechanical losses.
- Electrical Power is greater than Shaft Power due to motor and transmission (belt) losses.
- Understanding these differences is vital for identifying energy-saving opportunities.
- Motor efficiency and drive efficiency play significant roles.



Calculating Fan Power Input

Important Formulas

$$\text{Air Power (kW)} = \frac{Q(\text{m}^3/\text{s}) \times \text{Total Press. (mmWC)}}{102}$$

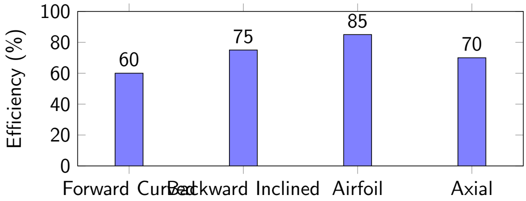
$$\text{Shaft Power (kW)} = \frac{\text{Air Power}}{\text{Fan Efficiency}}$$

$$\text{Elec. Power (kW)} = \frac{\text{Shaft Power}}{\text{Motor Eff.} \times \text{Drive Eff.}}$$

- Direct measurement of electrical power can be done using a power analyzer.

Introduction to Fan Efficiency

- Efficiency indicates how well a fan converts mechanical power into air power.
- Higher efficiency means lower energy consumption for the same airflow.
- Typically ranges from 40% to 85% depending on fan type and design.
- Crucial metric for selecting energy-efficient HVAC equipment.



Static Efficiency vs. Total Efficiency

Total Efficiency

$$\eta_{\text{total}} = \frac{\text{Air Power (Total)}}{\text{Shaft Power}}$$

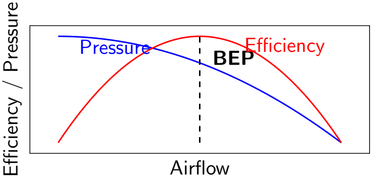
Static Efficiency

$$\eta_{\text{static}} = \frac{\text{Air Power (Static)}}{\text{Shaft Power}}$$

- Static Efficiency is always lower than Total Efficiency.
- Static efficiency is often used because velocity pressure is sometimes not useful in the specific application.

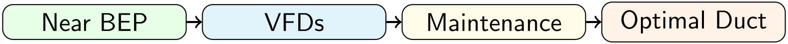
Factors Affecting Fan Efficiency

- Blade design and fan aerodynamics.
- Clearances between the impeller and the casing.
- Operating point on the fan curve (efficiency is highest at the Best Efficiency Point - BEP).
- System effect: Poor duct design at inlet/outlet degrades field efficiency.



Energy Efficiency in Fan Operation

- Select fans that operate near their Best Efficiency Point (BEP).
- Use Variable Frequency Drives (VFDs) for part-load conditions instead of dampers.
- Regular maintenance: cleaning blades, checking belt tension.
- Optimize ductwork to minimize system resistance and Fan Total Pressure requirement.



Case Study / Numerical Example

Given:

- Flow rate = 5 m^3/s
- Total Pressure = 1000 Pa
- Shaft Power = 7.5 kW

Calculations:

1. **Calculate Air Power:**

$$\frac{5 \times 1000}{1000} = 5.0 \text{ kW}$$

2. **Calculate Fan Total Efficiency:**

$$\frac{5.0 \text{ kW}}{7.5 \text{ kW}} = 66.7\%$$

3. **If Motor Efficiency is 90% and Drive is direct (100%):**

$$\text{Electrical Power} = \frac{7.5}{0.9 \times 1.0} = 8.33 \text{ kW}$$

Summary & Q&A

Key Takeaways

- Fan pressure includes both static and velocity components.
- Understanding the differences between air, shaft, and electrical power is crucial.
- Fan efficiency measures the conversion of mechanical to fluid energy.
- Operating fans near their BEP and reducing system resistance saves energy.

Questions?