Lecture 4 Applied Analysis: Pumps, Compressors, and Heat Exchangers

Goal of the lecture: To analyze the working principles, performance characteristics, and thermodynamic efficiency of pumps, compressors, and heat exchangers used in energy and process systems.

Brief lecture notes: This lecture introduces the applied analysis of three fundamental types of thermal and fluid machinery — pumps, compressors, and heat exchangers. These devices are essential components in power generation, refrigeration, and chemical process systems. We will study the energy transformations involved in these machines, their governing equations, efficiency definitions, and practical considerations such as losses, flow characteristics, and performance evaluation. The lecture also emphasizes how the First Law of Thermodynamics is applied to open systems (control volumes) where mass and energy cross the boundaries.

Main part

Pumps, compressors, and heat exchangers are vital components in engineering systems that involve fluid flow and heat transfer. Each of these devices performs a specific thermodynamic function essential to energy conversion and process efficiency. Pumps are used to increase the pressure of liquids, enabling their transport through pipelines or circulation systems. Compressors perform a similar function for gases and vapors, raising their pressure for use in processes such as refrigeration, air compression, and gas transport. Heat exchangers, on the other hand, transfer thermal energy between fluids at different temperatures without allowing them to mix. All three devices operate based on the principle of energy conservation, as expressed by the First Law of Thermodynamics for open systems.

In the analysis of these systems, the energy balance for a steady-flow device plays a fundamental role. For a control volume operating under steady-state conditions, the energy equation can be written as:

$$\dot{Q} - \dot{W} = \dot{m}\left(h_2 - h_1 + \frac{v_2^2 - v_1^2}{2} + g(z_2 - z_1)\right)$$

Here, $\dot{Q}$represents the rate of heat transfer, $\dot{W}$is the rate of work transfer (power input or output), and $\dot{m}$is the mass flow rate of the working fluid. The specific enthalpy $h$accounts for the thermal energy content of the fluid, $v$denotes its velocity, and $z$represents the elevation of the fluid with respect to a reference level. This general energy balance forms the foundation for the performance analysis of pumps, compressors, and heat exchangers, allowing engineers to determine energy transformations and efficiency under various operating conditions.

A pump is a mechanical device that imparts energy to a liquid to increase its pressure or to move it through a hydraulic system. The ideal energy equation for pumps can be expressed as:

$$W_{pump} = \frac{v(P_2 - P_1)}{\eta_p}$$

where η_p is the pump efficiency, P_1 and P_2 are the inlet and outlet pressures, respectively, and v is the specific volume of the liquid. The performance of a pump is generally characterized by several key parameters. The head (H) represents the height to which the pump can raise the fluid and is a measure of the energy per unit weight of fluid imparted by the pump. The flow rate (Q) defines the volumetric quantity of liquid delivered per unit time, reflecting the pump's capacity. Efficiency is another critical factor and is defined as the ratio of the useful hydraulic power output to the total mechanical power input.

In practical applications, pumps are used in a wide range of systems, including water supply networks, chemical processing units, and hydraulic circuits. Their selection depends on the required flow rate, head, type of liquid, and overall system resistance. Understanding the relationship between pressure, flow, and efficiency is essential for optimizing the operation and energy consumption of pumping systems.

Compressors

A compressor performs similar work as a pump but acts on gases. Compression can be isothermal, adiabatic, or polytropic, depending on heat exchange with the surroundings.

For an adiabatic process, the power required is:

$$W = \frac{n}{n-1} RT_1 [(\frac{P_2}{P_1})^{\frac{n-1}{n}} - 1]$$

where n is the polytropic exponent, T_1 and P_1 are inlet temperature and pressure.

Performance indicators:

- Isentropic efficiency (η_s):

$$\eta_s = \frac{(h_2 - h_1)_{is}}{(h_2 - h_1)_{actual}}$$

- Volumetric efficiency — accounts for real gas effects and clearance losses.

Applications: refrigeration cycles, air compression, gas pipelines, and chemical process plants.

Heat Exchangers

A heat exchanger transfers thermal energy between two fluids without direct contact. It operates continuously under steady-flow conditions and obeys the energy balance:

$$\dot{Q} = \dot{m}_h c_{p,h}(T_{h,i} - T_{h,o}) = \dot{m}_c c_{p,c}(T_{c,o} - T_{c,i})$$

where subscripts h and c denote the hot and cold fluids.

Types of heat exchangers:

- Parallel flow — fluids move in the same direction.
- Counter flow — fluids move in opposite directions (higher efficiency).
- Cross flow — fluids intersect perpendicularly.

Overall heat transfer rate:

$$\dot{Q} = UA\Delta T_{lm}$$

where U is the overall heat transfer coefficient, A is the surface area, and ΔT_{lm} is the logarithmic mean temperature difference (LMTD).

Typical System Overview

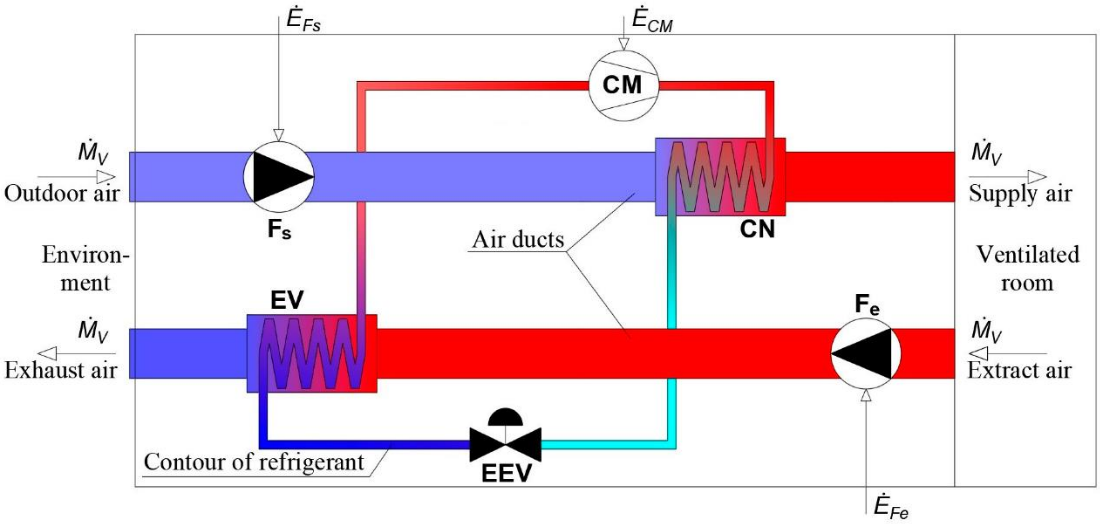

Figure 1. Simplified schematic of pump, compressor, and heat exchanger in a process line.

Comparison of Devices

Device	Working Medium	Energy Type Transferred	Key Parameter	Typical Efficiency
Pump	Liquid	Mechanical (pressure rise)	Head, flow rate	70–90%
Compressor	Gas/vapor	Mechanical + thermal	Pressure ratio	65–85%
Heat Exchanger	Two fluids	Thermal	$U, \Delta T_{lm}$	60–95%

Questions for Self-Control

1. What is the main difference between a pump and a compressor?
2. Write the steady-flow energy equation and explain each term.
3. What parameters determine the performance of a heat exchanger?
4. How is isentropic efficiency defined for a compressor?
5. Why is the counter-flow heat exchanger more efficient than the parallel-flow type?

Literature

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