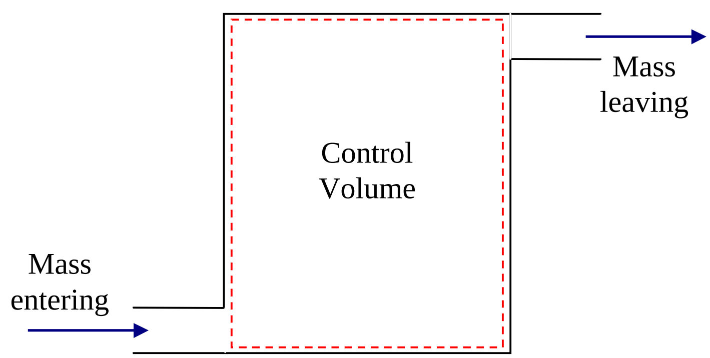
THERMODYNAMICS

FIRST LAW OF THERMODYNAMICS – CONTROL VOLUME

A large number of thermodynamics problems involve mass flow in and out of a system and therefore, are modeled as **control volumes** or **open systems**.



Car radiator, turbine and compressor are examples of control volume systems.

Steady flow implies no change with time and the term **uniform flow** implies no change with location over a specified region.

Conservation of Mass Principle

Mass, like energy, can neither be created nor destroyed.

However mass and energy can be related to each other according to formula

$$E = mc^2$$

Where E in energy, m is mass and c is the speed of light. This equation implies that the mass of a system will change when energy changes.

The conservation of mass principle can be expressed as

$$\sum m_{in} - \sum m_{out} = \Delta m_{system} \qquad \text{(kg)}$$

Or

$$\sum \dot{m}_{in} - \sum \dot{m}_{out} = \Delta \dot{m}_{system} \qquad \text{(kg/s) (mass flow rate)}$$

Mass and Volume Flow Rates

The amount of mass flowing through a cross section per unit time is called the mass flow rate. The mass flow rate of in a pipe or duct is proportional to the cross sectional area A of the pipe or duct, the density ρ, and the velocity C of the fluid.

$$d\dot{m} = \rho C dA$$

For one dimensional flow, the velocity is assumed constant and the mass flow rate can be found by

$$\dot{m} = \rho A C$$

The volume of the fluid flowing through a cross section per unit time is called the volume flow rate and is given by

$$\dot{V} = \int C dA \qquad (\text{m}^3/\text{s})$$

Or

$$\dot{m} = \rho \dot{V}$$

Energy Balance for a Control Volume System

We know that the energy balance is written as

$$E_{in} - E_{out} = \Delta E_{system} \qquad (\text{kJ})$$

or in the rate form

$$\dot{E}_{in} - \dot{E}_{out} = \Delta \dot{E}_{system} \qquad (\text{kW})$$

Mass flow in and out of a system serves as another mechanism to change the energy content of the system. When mass enters a system, it increases the energy in the control volume because the entering mass carries some energy with it. Similarly, when some mass leaves the energy level in the control volume decreases.

The energy required to push fluid into or out of a control volume is called the **flow work**, or **flow energy**. It is considered to be part of the energy transported with the fluid.

Flow work:

To push the entire fluid element into the system, the work done is given by

$$W_{flow} = FL$$

But we know that

$$F = PA$$

Therefore,

$$W_{flow} = FL = PAL \qquad \text{(kJ)}$$
$$W_{flow} = PV$$

In per unit mass basis, flow work is given by

$$w_{flow} = Pv \qquad \text{(kJ/kg)}$$

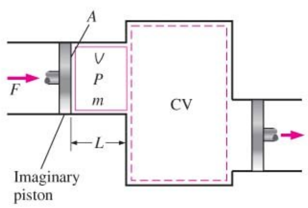


FIGURE 5–11
Schematic for flow work.

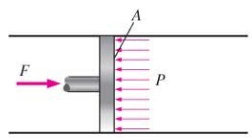


FIGURE 5–12
In the absence of acceleration, the force applied on a fluid by a piston is equal to the force applied on the piston by the fluid.

Having said that,

The forms of energy which can be associated with the moving fluid mass entering and leaving the system are

- Internal energy, U
- Kinetic energy, KE
- Potential energy, PE
- Flow work, PV

Hence

$$E_{in} = U_{in} + (PV)_{in} + KE_{in} + PE_{in}$$
$$E_{out} = U_{out} + (PV)_{out} + KE_{out} + PE_{out}$$

Or

$$E_{in} = H_{in} + KE_{in} + PE_{in}$$
$$E_{out} = H_{out} + KE_{out} + PE_{out}$$

Steady Flow Process

During a steady flow process, the total amount of mass contained within a control volume does not change with time. Hence

$$\sum \dot{m}_{in} - \sum \dot{m}_{out} = \Delta \dot{m}_{system}$$
$$\sum \dot{m}_{in} - \sum \dot{m}_{out} = 0 \qquad \text{(kg/s)}$$
$$\sum \dot{m}_{in} = \sum \dot{m}_{out}$$

Also, during a steady flow process, the total energy content of a control volume does not change with time. Hence

$$\dot{E}_{in} - \dot{E}_{out} = \Delta \dot{E}_{system}$$
$$\dot{E}_{in} - \dot{E}_{out} = 0$$
$$\dot{E}_{in} = \dot{E}_{out}$$

Noting that energy can be transferred by heat, work and mass only, the energy balance for a steady flow system can be expressed as

$$\dot{Q}_{in} + \dot{W}_{in} + \sum \dot{m}_{in}\left(h_{in} + ke_{in} + pe_{in}\right) = \dot{Q}_{out} + \dot{W}_{out} + \sum \dot{m}_{out}\left(h_{out} + ke_{out} + pe_{out}\right)$$

As it is common practice to assume heat to be transferred into the system and power is produced by the system

$$\dot{Q} - \dot{W} = \sum \dot{m}_{out}\left(h_{out} + ke_{out} + pe_{out}\right) - \sum \dot{m}_{in}\left(h_{in} + ke_{in} + pe_{in}\right)$$

For a single steam (one-inlet-one-exit) system, $\dot{m}_{in} = \dot{m}_{out} = \dot{m}$, the energy balance can be written as (subscripts 1 and 2 denote *in* and *out*)

$$\dot{Q} - \dot{W} = \dot{m}\left(h_2 - h_1 + ke_2 - ke_1 + pe_2 - pe_1\right)$$
$$\dot{Q} - \dot{W} = \dot{m}\left(h_2 - h_1 + \frac{1}{2}\left(V_2^2 - V_1^1\right) + g\left(z_2 - z_1\right)\right)$$

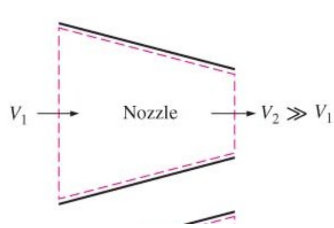
This equation is called the steady flow energy equation (SFEE).
For a system which experiences negligible kinetic and potential energies the

$$\dot{Q} - \dot{W} = \dot{m}\left(h_2 - h_1\right)$$
$$\dot{q} - \dot{w} = \Delta h$$

Some Steady Flow Engineering Devices

<u>Nozzles and diffusers</u>

A **nozzle** is a device that increases the velocity of a fluid at the expense of pressure.
A **diffuser** is a device that increases the pressure of a fluid by slowing it down.



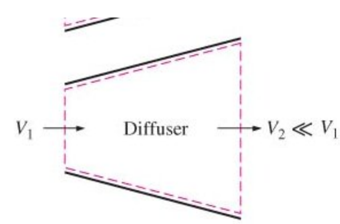


FIGURE 5–25
Nozzles and diffusers are shaped so that they cause large changes in fluid velocities and thus kinetic energies.

Questions

1. Air enters an adiabatic nozzle steadily at 300 kPa, 200 °C, and 30 m/s and leaves at 100 kPa and 180 m/s. The inlet area of the nozzle is 80 cm^2. Determine (a) the mass flow rate through the nozzle, (b) the exit temperature of the air, and (c) the exit area of the nozzle.

Answers: 0.5304 kg/s, 184.60 °C and 38.7 cm^2

2. Carbon dioxide enters an adiabatic nozzle steadily at 1 MPa and 500 °C with a mass flow rate of 6000 kg/h and leaves at 100 kPa and 450 m/s. The inlet area of the nozzle is 40 cm2. Determine: (a) the inlet velocity, and (b) the exit temperature.

Answers: 60.8 m/s and 685.8 K

3. Air at 600 kPa and 500 K enters an adiabatic nozzle that has an inlet-to-exit area ration of 2:1 with a velocity of 120 m/s and leaves with a velocity of 380 m/s. Determine (a) the exit temperature, and (b) the exit pressure.

Answers: 436.5 K and 330.8 kPa

Throttling Valves

Throttling valves are any kind of flow restricting devices that causes a significant pressure drop in the fluid. In this device:

$$h_2 = h_1 \qquad \text{(kJ/kg)}$$

Turbines and Compressors

A turbine is a device that produces work. As fluid passes through the turbine, work is done against the blades, which are attached to the shaft causing the shaft to rotate.

Compressors are devices used to increase the pressure of the fluid. Work is supplied to these devices from an external source through a rotating shaft.

Questions

4. Air enters the compressor of a gas-turbine plant at ambient conditions of 100 kPa and 25°C with low velocity and exits at 1 MPa and 347°C with a velocity of 90 m/s. The compressor is cooled at a rate of 1500 kJ/min, and the power input to the compressor is 250 kW. Determine the mass flow rate of air through the compressor.

Answer: 0.680 kg/s

5. Carbon dioxide enters an adiabatic compressor at 100 kPa and 450 K at a rate of 0.5 kg/s and leaves at 600 kPa and 450 K. Neglecting kinetic energy changes, determine (a) the volume flow rate of the carbon dioxide at the compressor inlet and (b) the power input to the compressor.

Answer: 0.28 m^3/s and 68.8 kW

6. Steam flows steadily through an adiabatic turbine. The inlet conditions of the steam are 10 MPa, 450 °C, and 80 m/s, and the exit conditions are 10 kPa, 92 percent quality, and 50 m/s. The mass flow rate of the steam is 12 kg/s. Determine (a) the change n kinetic energy, (b) the power output, and (c) the turbine inlet area.

Answer: -1.95 kJ/kg, 10.2 MW and (c) 0.00446m^2

7. Steam enters an adiabatic turbine at 10 MPa and 500 °C at a rate of 3 kg/s and leaves at 20 kPa. If the power output of the turbine is 2MW, determine the temperature of the steam at the turbine exit. Neglect kinetic energy changes.

Answer: 110.8 °C

Pipe and Duct Flow

Flow through a pipe or duct usually satisfies the steady flow conditions where

$$Q \neq 0,$$
$$W \neq 0,$$
$$\Delta KE = 0$$
$$\Delta PE \neq 0$$

Questions

8. An electric heating system used in many houses consists of a simple duct with resistance wires. Air is heated as it flows over resistance wires. Consider a 15 kW electric heating system. Air enters the heating section at 100 kPa and 17 ºC with a volume flow rate of 150 m3/min. If heat is lost from the air in the duct to the surroundings at a rate of 200 W, determine the exit temperature.

Answer: 21.9 ºC

Mixture Chamber

A mixing chamber refers to a mixing process between two fluid streams. It does not have to be a distinct 'chamber' an ordinary T-elbow or a Y-elbow can serve the purpose. Its main function is to regular temperature of the fluid leaving the chamber.

Questions

9. A hot-water stream at 80°C enters a mixing chamber with a mass flow rate of 0.5 kg/s where it is mixed with a stream of cold water at 20°C. If it is desired that the mixture leave the chamber at 42°C, determine the mass flow rate of the cold-water stream. Assume all the streams are at a pressure of 250 kPa.

Answer: 0.864 kg/s

10. In steam power plants, open feedwater heaters are frequently utilized to heat the feedwater by mixing it with steam bled off the turbine at some intermediate stage. Consider an open feedwater heater that operates at a pressure of 800 kPa. Feedwater at 50°C and 800 kPa is to be heated with superheated steam at 200°C and 800 kPa. In an ideal feedwater heater the mixture leaves the heater as saturated liquid at the feedwater pressure. Determine the ratio of the mass flow rates of the feedwater and the superheated vapor for this case.

Answer: 4.14

Heat Exchanger

Heat exchanger are devices where two moving fluid streams exchange heat without mixing. The simplest form of heat exchanger is the double pipe heat exchanger. One fluid flows in the inner pipe and the outer in the annular space between the two pipes. Under steady operation the mass flow rate of each fluid stream flowing through a heat exchanger remains constant.

Questions

11. Refrigerant-134a at 1 MPa and 80°C is to be cooled to 1 MPa and 30°C in a condenser by air. The air enters at 100 kPa and 27°C with a volume flow rate of 800 m3/min and leaves at 95 kPa and 60°C. Determine the mass flow rate of the refrigerant.

Answer: 139 kg/min

12. Steam enters a condenser of a steam power plant at 20 kPa and a quality of 95 percent with a mass flow rate of 20,000 kg/hr. It is to be cooled by water from a nearby river by circulating the water through the tubes within the condenser. To prevent thermal pollution, the river water is not allowed to experience a temperature rise above 10°C. If the steam is to leave the condenser as saturated liquid at 20 kPa, determine the mass flow rate of the cooling water required.

Answer: 17866 kg/min