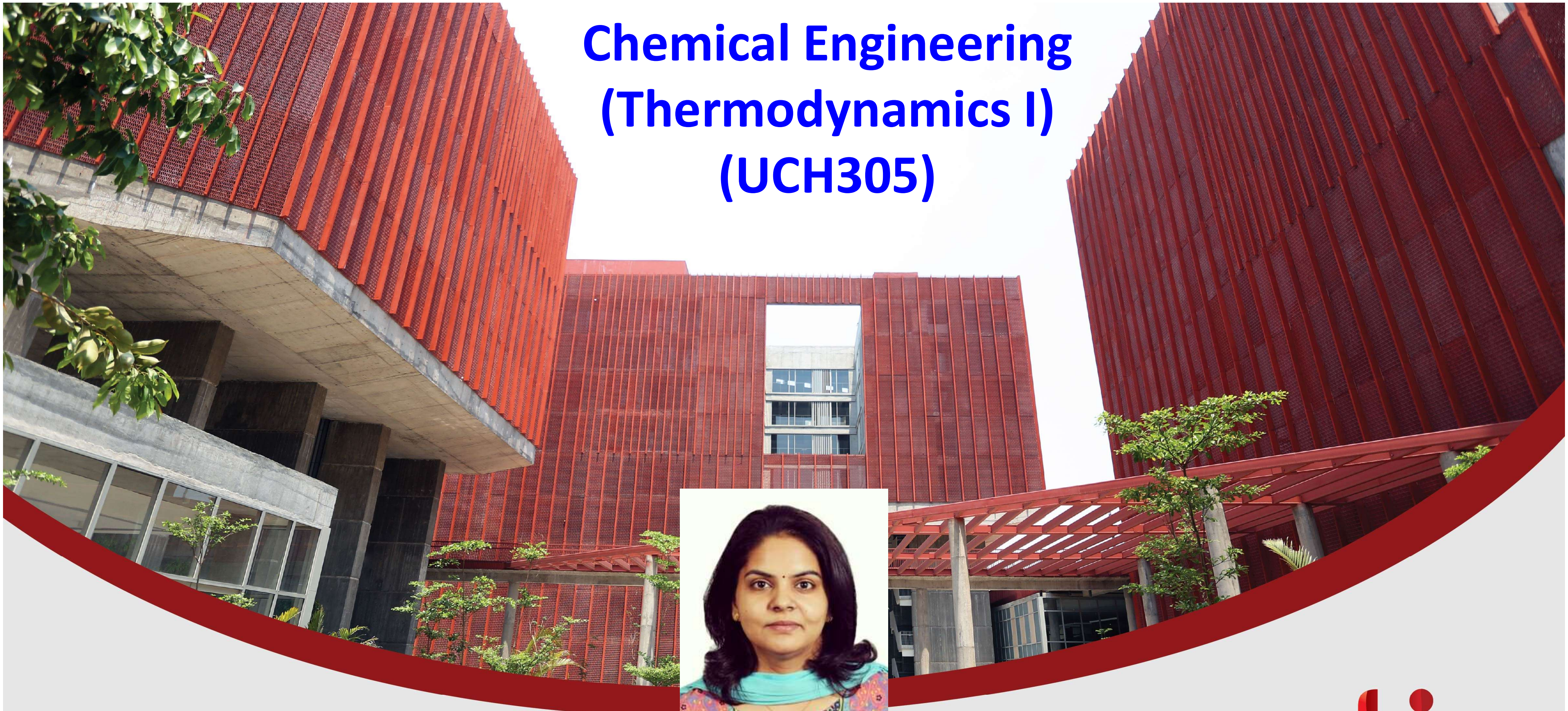
Chemical Engineering (Thermodynamics I) (UCH305)



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Lecture 15

Energy analysis of steady-flow systems

Energy analysis of steady-flow systems

- A large number of engineering devices such as
  - turbines,
  - compressors, and
  - nozzles
    - operate for **long periods of time** under the **same operating conditions**
    - once the ***transient start-up period is completed***, and
    - ***Steady-state operation*** is established.
    - These devices are classified as ***steady-flow devices***.

- The fluid properties can change from point to point within the control volume.
- But at any point of control volume, the fluid properties remain constant during the entire process.
- Remember, *steady* means *no change with time*.
- During a steady-flow process, ***no intensive* or *extensive* properties** *within the control volume* change with time.
- Thus, the volume V, the mass m, and the total energy content E of the control volume remain ***constant***.
- As a result, the boundary work is zero for steady-flow systems

- Then the rate form of the general energy balance reduces for a ***steady-flow*** process to:

$$\begin{pmatrix} \text{Rate of net energy transfer} \\ \text{by heat, work, and mass} \end{pmatrix} = \begin{pmatrix} \text{Rate of change in internal, kinetic,} \\ \text{potential, etc., energies} \end{pmatrix} = 0$$

0 (Steady state)

$$\dot{E}_{in} - \dot{E}_{out} = \frac{dE_{system}}{dt} = 0$$

- or, *Energy balance:*

$$\begin{pmatrix} \text{Rate of energy transfer in} \\ \text{by heat, work, and mass} \end{pmatrix}_{in} = \begin{pmatrix} \text{Rate of energy transfer out} \\ \text{by heat, work, and mass} \end{pmatrix}_{out}$$

$$\dot{E}_{in} = \dot{E}_{out} \qquad (kW)$$

- Note that energy can be transferred by heat, work, and mass only.

- The energy balance for a general steady-flow system can also be written more explicitly as:

$$\dot{Q}_{in} + \dot{W}_{in} + \sum_{in} \dot{m}\,\theta = \dot{Q}_{out} + \dot{W}_{out} + \sum_{out} \dot{m}\,\theta$$

or

$$\dot{Q}_{in} + \dot{W}_{in} + \underbrace{\sum_{in} \dot{m}\left(h + \frac{v^2}{2} + g\,z\right)}_{\textit{for each inlet}} = \dot{Q}_{out} + \dot{W}_{out} + \underbrace{\sum_{out} \dot{m}\left(h + \frac{v^2}{2} + g\,z\right)}_{\textit{for each exit}}$$

- It is common practice to assume heat to be transferred *into the system* (heat input) at a rate of $\dot{Q}$, and work produced *by the system* (work output) at a rate of $\dot{W}$, and then solve the problem.
- The first-law of thermodynamics or energy balance relation in that case for a general steady-flow system becomes:

$$\dot{Q} - \dot{W} = \underbrace{\sum_{out} \dot{m}\left(h + \frac{v^2}{2} + g\,z\right)}_{for\ each\ exit} - \underbrace{\sum_{in} \dot{m}\left(h + \frac{v^2}{2} + g\,z\right)}_{for\ each\ inlet}$$

- For single-stream devices, the steady-flow energy balance equation becomes:

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

- Dividing this equation by $\dot{m}$**,** gives the energy balance on a unit-mass basis as:

$$q - w = \left(h_2 - h_1\right) + \frac{\left(v_2^2 - v_1^2\right)}{2} + g\left(z_2 - z_1\right)$$

- When the fluid experiences negligible changes in its kinetic and potential energies (that is, $\Delta ke \cong 0$, $\Delta pe \cong 0$), the energy balance equation is reduced further to:

$$q - w = h_2 - h_1 = \Delta h$$

- The various terms appearing in the above equations are as follows:

- $\dot{Q}$ **rate of heat transfer between the control volume and its surroundings.**
- When the control volume is losing heat (as in the case of the water heater), $\dot{Q}$ is negative.
- If the control volume is well insulated (i.e., adiabatic), then $\dot{Q} = 0$.

- Then $\dot{W}$ represents the remaining forms of work done per unit time. $\dot{W}$ **= power (kJ/s = kW).**

- For steady-flow devices, the control volume is constant; thus, there is no boundary work involved.

- The work required to push mass into and out of the control volume is also taken care of by using enthalpies for the energy of fluid streams instead of internal energies.

- Many steady-flow devices, such as turbines, compressors, and pumps, transmit power through a shaft, and $\dot{W}$ simply becomes the shaft power for those devices.

- If the control surface is crossed by electric wires (as in the case of an electric motor), $\dot{W}$ represents the electrical work done per unit time.

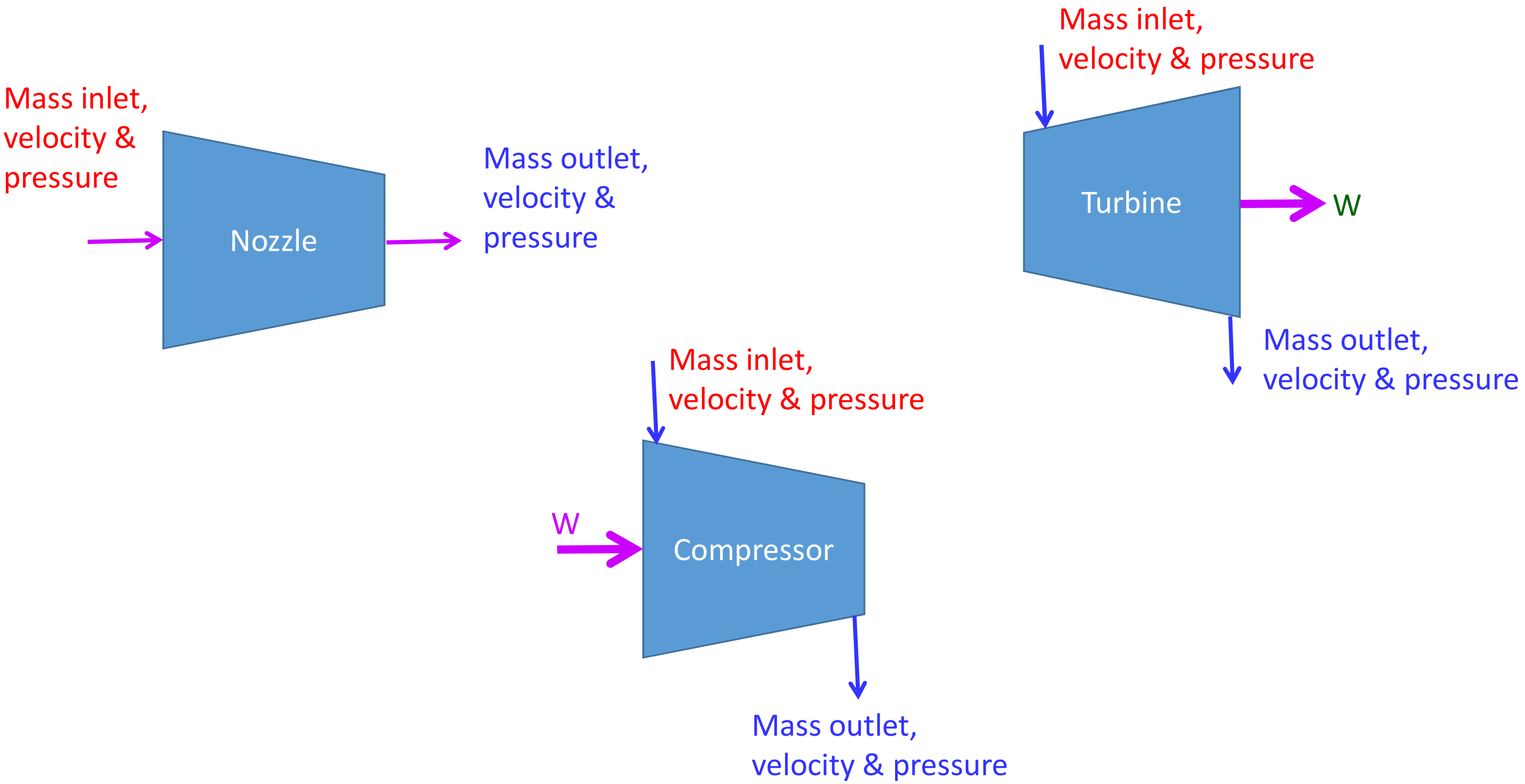
- If neither is present, then $\dot{W} = 0$.

- $\Delta h = (h_2 - h_1)$.

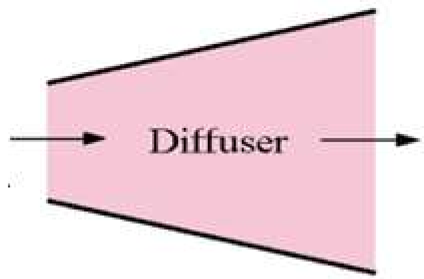
- The enthalpy change (Δh) of a fluid can easily be determined by reading the enthalpy values at the exit (h_2) and inlet (h_1) states from the Enthalpy tables.

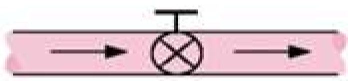
- For ideal gases, it can be approximated by :
  - $\Delta h = c_{p,\text{avg}} (T_2 - T_1)$.

Some Steady-Flow Engineering Devices

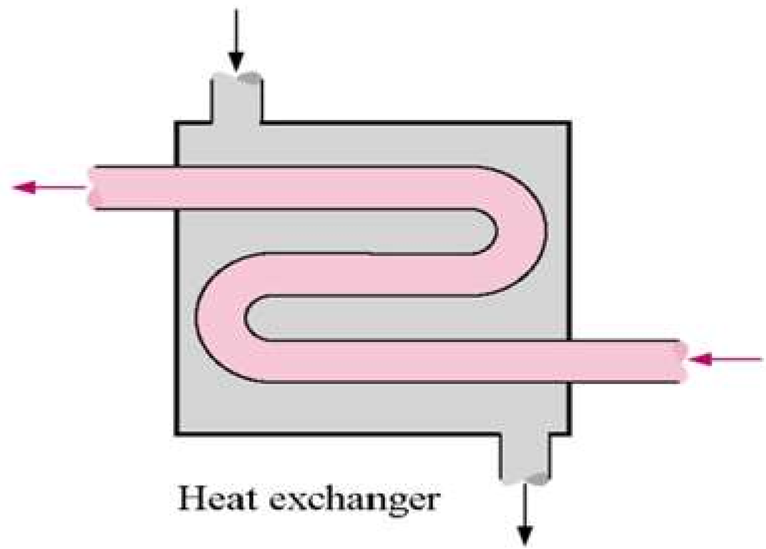


Some Steady-Flow Engineering Devices





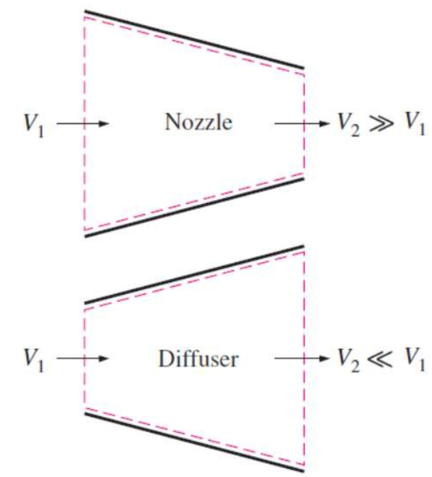
Throttling valve



Heat exchanger

Nozzles and Diffusers

- Nozzles and diffusers are commonly utilized in jet engines, rockets, spacecraft, and even garden hoses.
- The cross-sectional area of a nozzle decreases in the flow direction of flow.
- The reverse is true for diffusers.
- 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* at the expense of velocity.
- That is, nozzles and diffusers perform opposite tasks.



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

- The rate of heat transfer between the fluid flowing through a nozzle or a diffuser and the surroundings is usually very small ($\dot{Q} = 0$).
    - Since the fluid has high velocities, and thus it does not spend enough time in the device for any significant heat transfer to take place.

- Nozzles and diffusers typically involve no work ($\dot{W} = 0$) and any change in potential energy is negligible ($\Delta pe \cong 0$).

- But nozzles and diffusers usually involve very high velocities, and as a fluid passes through a nozzle or diffuser, it experiences large changes in its velocity.

- Therefore, the kinetic energy changes must be accounted for in analyzing the flow through these devices ($\Delta ke \neq 0$).

- Under stated assumptions and observations, the energy balance for this steady-flow system can be expressed for nozzles and diffusers in the rate form as:

$$\begin{pmatrix} \text{Rate of net energy transfer} \\ \text{by heat, work, and mass} \end{pmatrix} = \begin{pmatrix} \text{Rate of change in internal, kinetic,} \\ \text{potential, etc., energies} \end{pmatrix} = 0$$

$$\dot{E}_{in} - \dot{E}_{out} = \cancel{\frac{dE_{system}}{dt}}^{\text{0 (Steady state}} = 0$$

$$\dot{E}_{in} = \dot{E}_{out} \qquad (kW)$$

$$\dot{Q}_{in} + \dot{W}_{in} + \sum_{in} \dot{m}\left(h + \frac{v^2}{2} + gz\right) = \dot{Q}_{out} + \dot{W}_{out} + \sum_{out} \dot{m}\left(h + \frac{v^2}{2} + gz\right)$$

$$\dot{m}\left(h_1 + \frac{v_1^2}{2}\right) = \dot{m}\left(h_2 + \frac{v_2^2}{2}\right) \quad \left(\text{since} \quad \dot{Q} \cong 0, \dot{W} = 0, \text{ and } \Delta pe = 0\right)$$

$$h_2 = h_1 - \frac{\left(v_2^2 - v_1^2\right)}{2}$$

- The exit velocity of a diffuser is usually small compared with the inlet velocity ($v_2 << v_1$);

- Thus, the kinetic energy at the exit can be neglected.

- The enthalpy of air at the diffuser inlet is determined from the air table (Table A–17 of textbook) to be

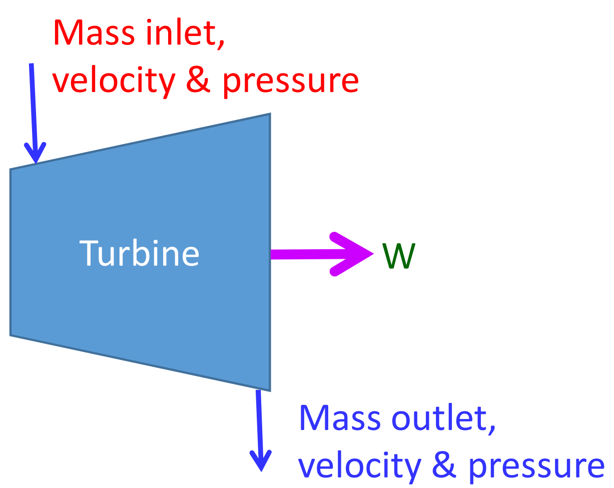
$$h_1 = h_{@\ 283\ \mathrm{K}} = 283.14\ \mathrm{kJ/kg}$$

Turbines and Compressors

- In steam, gas, or hydroelectric power plants, the device that drives the electric generator is the turbine.

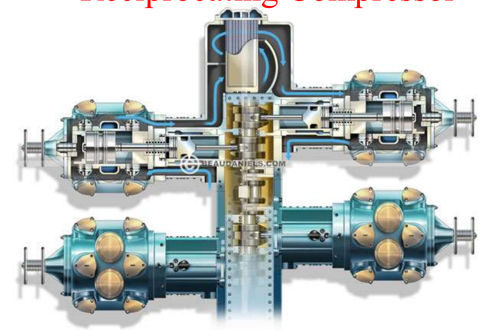
- As the fluid passes through the turbine, work is done against the blades, which are attached to the shaft.

- As a result, the shaft rotates, and the turbine produces work.



- Compressors, as well as pumps and fans, are devices used to increase the pressure of a fluid.
- Work is supplied to these devices from an external source through a rotating shaft.
- Therefore, compressors involve work inputs.
- Even though these three devices function similarly, they do differ in the tasks they perform.
  - A *fan* increases the pressure of a gas slightly and is mainly used to mobilize a gas.
  - A *compressor* is capable of compressing the gas to very high pressures.
  - *Pumps* work very much like compressors except that they handle liquids instead of gases.

Reciprocating Compressor



Pump

Axial Fans

- Note that turbines produce power output, whereas
  - compressors, pumps, and fans require power input.
- Heat transfer from turbines is usually negligible ($\dot{Q} \approx 0$) since they are typically well insulated.
- Heat transfer is also negligible for compressors unless there is intentional cooling.
- Potential energy changes are negligible for all of these devices ($\Delta pe = 0$).
- The velocities involved in these devices, with the exception of turbines and fans, are usually too low to cause any significant change in the kinetic energy ($\Delta ke = 0$).
- The fluid velocities encountered in most turbines are very high, and the fluid experiences a significant change in its kinetic energy.
- However, this change is usually very small relative to the change in enthalpy, and thus it is often disregarded.

Compressor

Problem:

Air at 100 kPa and 280 K is compressed steadily to 600 kPa and 400 K. The mass flow rate of the air is 0.02 kg/s, and a heat loss of 16 kJ/kg occurs during the process. Assuming the changes in kinetic and potential energies are negligible, determine the necessary power input to the compressor?

Solution: Air is compressed steadily by a compressor to a specified temperature and pressure. The power input to the compressor is to be determined.

Assumptions:

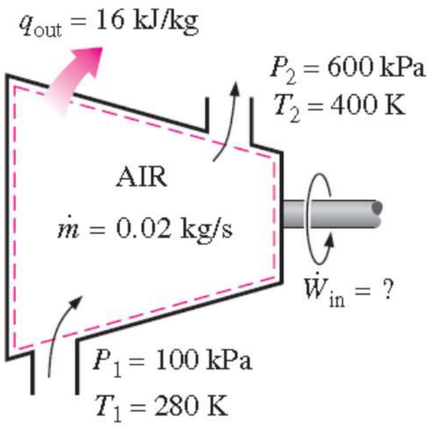
1 This is a steady-flow process since there is no change with time at any point and thus $\Delta m_{CV} = 0$ and $\Delta E_{CV} = 0$.

2 Air is an ideal gas since it is at a high temperature and low pressure relative to its critical-point values.

3 The kinetic and potential energy changes are zero, $\Delta ke = \Delta pe = 0$.

Analysis:

- We take the *compressor* as the system (Fig.).
- This is a *control volume* since mass crosses the system boundary during the process.
- We observe that there is only one inlet and one exit and thus $\dot{m}_1 = \dot{m}_2 = \dot{m}$.
- Also, heat is lost from the system and work is supplied to the system.



- The energy balance for turbine/compressor at steady-flow system can be expressed in the rate form as:

$$\begin{pmatrix} \text{Rate of net energy transfer} \\ \text{by heat, work, and mass} \end{pmatrix} = \begin{pmatrix} \text{Rate of change in internal, kinetic,} \\ \text{potential, etc., energies} \end{pmatrix} = 0$$

$$\dot{E}_{in} - \dot{E}_{out} = \cancel{\frac{dE_{system}}{dt}}^{\text{0 (Steady state}} = 0$$

$$\dot{E}_{in} = \dot{E}_{out} \qquad (kW)$$

$$\dot{W}_{in} + \dot{m}h_1 = \dot{Q}_{out} + \dot{m}h_2 \qquad (\text{since} \quad \Delta ke = 0, \text{and } \Delta pe = 0)$$

$$\dot{W}_{in} = \dot{m}q_{out} + \dot{m}(h_2 - h_1)$$

- The enthalpy of an ideal gas depends on temperature only, and the enthalpies of the air at the specified temperatures are determined from the air table (Table A–17) to be:

$$h_1 = h_{@\,280\text{ K}} = 280.13\text{ kJ/kg}$$

$$h_2 = h_{@\,400\text{ K}} = 400.98\text{ kJ/kg}$$

- Substituting, the power input to the compressor is determined to be:

$$\dot{W}_{\text{in}} = (0.02\text{ kg/s})\,(16\text{ kJ/kg}) + (0.02\text{ kg/s})\,(400.98 - 280.132)\text{ kJ/kg}$$

$$= \boldsymbol{2.74\ kW}$$

Throttling Valves

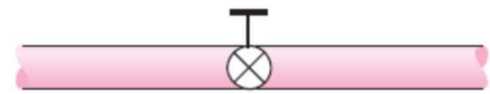
- Throttling valves are *any kind of flow-restricting devices* that cause a *significant pressure drop* in the fluid.

- Some familiar examples are ordinary adjustable valves, porous plugs, and capillary tubes (Fig.).

- Unlike turbines, they produce a pressure drop without involving any work.

- The pressure drop in the fluid is often accompanied by a *large drop in temperature*, and for that reason throttling devices are commonly used in refrigeration and air-conditioning applications.

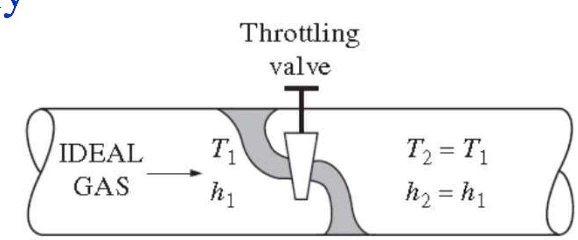
- The magnitude of the temperature drop (or, sometimes, the temperature rise) during a throttling process is governed by a property called the *Joule-Thomson coefficient*.



(*a*) An adjustable valve

(*b*) A porous plug

(*c*) A capillary tube



- Throttling valves are usually small devices, and the flow through them may be assumed to be adiabatic ($q \cong 0$) since there is neither sufficient time nor large enough area for any effective heat transfer to take place.

- Also, there is no work done ($w = 0$), and the change in potential energy, if any, is very small ($\Delta pe \cong 0$).

- Even though the exit velocity is often considerably higher than the inlet velocity, in many cases, the increase in kinetic energy is insignificant ($\Delta ke \cong 0$).

- Then the conservation of energy equation for this single-stream steady-flow device reduces to:

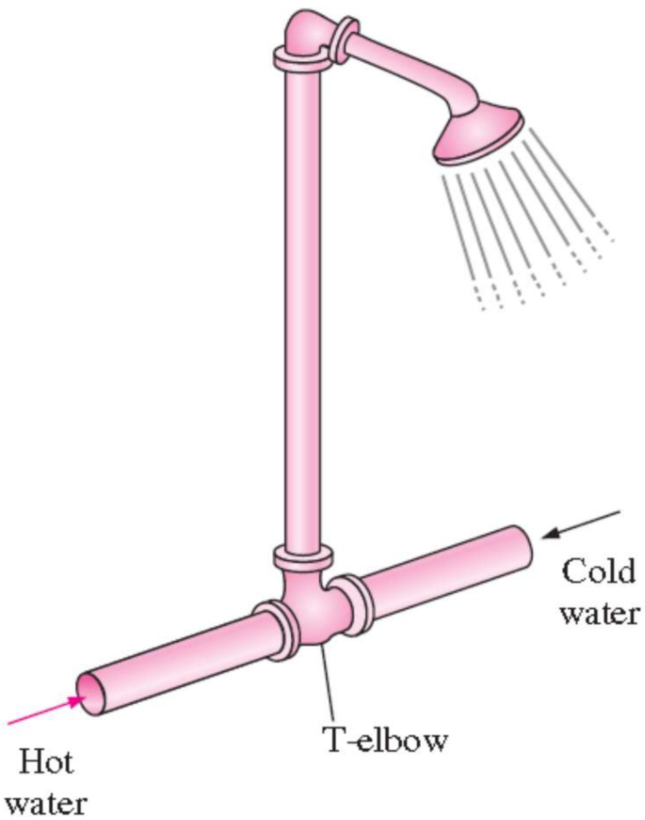
$$h_2 \cong h_1 \qquad \text{kJ/kg}$$

- That is, enthalpy values at the inlet and exit of a throttling valve are the same.

- For this reason, a throttling valve is sometimes called an *isenthalpic device*.

Mixing Chambers

- In engineering applications, mixing two streams of fluids is not a rare occurrence.
- The section where the mixing process takes place is commonly referred to as a **mixing chamber**.
- The mixing chamber does not have to be a distinct "chamber."
- An ordinary T-elbow or a Y-elbow in a shower, for example, serves as the mixing chamber for the cold- and hot-water streams (Fig.)



- Mixing chambers are usually well insulated ($q \cong 0$) and usually do not involve any kind of work ($w = 0$).

- Also, the kinetic and potential energies of the fluid streams are usually negligible ($\Delta ke \cong 0$, $\Delta pe \cong 0$).

- Then all there is left in the energy equation is the total energies of the incoming streams and the outgoing mixture.

- The conservation of energy principle requires that these two equal each other.

- Therefore, the conservation of energy equation becomes analogous to the conservation of mass equation for this case.

EXAMPLE: Mixing of Hot and Cold Waters in a Shower

Consider an ordinary shower where hot water at 140°F is mixed with cold water at 50°F. If it is desired that a steady stream of warm water at 110°F be supplied, determine the ratio of the mass flow rates of the hot to cold water. Assume the heat losses from the mixing chamber to be negligible and the mixing to take place at a pressure of 20 psia.

Solution:

In a shower, cold water is mixed with hot water at a specified temperature.

For a specified mixture temperature, the ratio of the mass flow rates of the hot to cold water is to be determined.

Assumptions

1. This is a steady-flow process since there is no change with time at any point and thus $\Delta m_{CV} = 0$ and $\Delta E_{CV} = 0$.

2. The kinetic and potential energies are negligible, $\Delta ke = \Delta pe = 0$.

3. Heat losses from the system are negligible and thus $\dot{Q} = 0$.

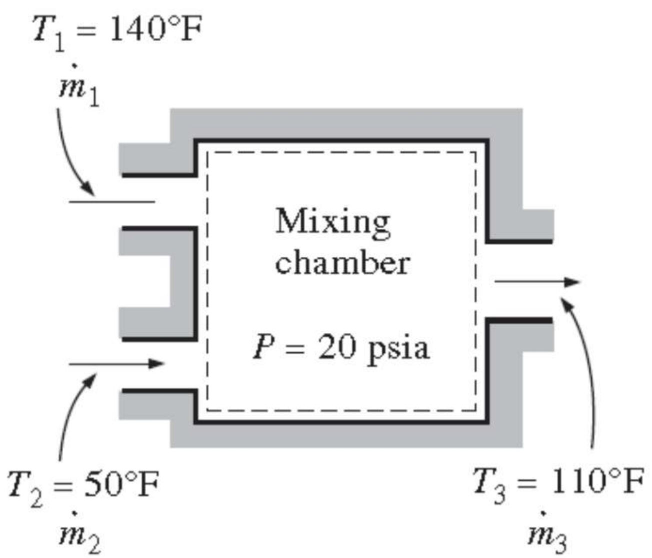
4. There is no work interaction involved.

Analysis

1. We take the *mixing chamber* as the system (Fig.).

2. This is a *control volume* since mass crosses the system boundary during the process.

3. We observe that there are two inlets and one exit.



- Under the stated assumptions and observations, the mass and energy balances for this steady-flow system can be expressed in the rate form as follows:

- Mass balance: $$\dot{m}_{in} - \dot{m}_{out} = \cancel{\frac{dm_{system}}{dt}}^{\,0 \text{ steady}} = 0$$

$$\dot{m}_{in} = \dot{m}_{out} \rightarrow \dot{m}_1 + \dot{m}_2 = \dot{m}_3$$

- Energy balance: $$\dot{E}_{in} - \dot{E}_{out} = \cancel{\frac{dE_{system}}{dt}}^{\,0 \text{ (Steady state)}} = 0$$

$$\dot{E}_{in} = \dot{E}_{out} \qquad (kW)$$

$$\dot{m}_1 h_1 + \dot{m}_2 h_2 = \dot{m}_3 h_3 \quad \left(\text{since} \quad \dot{Q} = 0, \dot{W} = 0, \Delta ke = 0, \text{and } \Delta pe = 0 \right)$$

- Combining the mass and energy balances, gives:

$$\dot{m}_1 h_1 + \dot{m}_2 h_2 = \left(\dot{m}_1 + \dot{m}_2 \right) h_3$$

- Dividing this equation by $\dot{m}_2$ yields:

$$y\, h_1 + h_2 = \left(y + 1 \right) h_3$$

- where $y = \dot{m}_1 / \dot{m}_2$ is the desired mass flow rate ratio.

- The saturation temperature of water at 20 psia is 227.92°F.

- Since the temperatures of all three streams are below this value ($T < T$sat), the water in all three streams exists as a compressed liquid (Fig. 5–34).

- A compressed liquid can be approximated as a saturated liquid at the given temperature.

Thus:

$h_1 = h_{f @ 140°F} = 107.99$ Btu/lbm

$h_2 = h_{f @ 50°F} = 18.07$ Btu/lbm

$h_3 = h_{f @ 110°F} = 78.02$ Btu/lbm

Solving for y and substituting yields:

$$\boxed{y = \frac{(h_3 - h_2)}{(h_1 - h_3)} = \frac{78.02 - 18.07}{107.99 - 78.02} = \frac{59.95}{29.97} = 2.0003337 \approx 2.0}$$

- Note that the mass flow rate of the hot water must be twice the mass flow rate of the cold water for the mixture to leave at 110°F.

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Thank you for your Patience