First law as applied to control volumes :

The general expression derived as applied to a control volume is as follows :

$$\boxed{\begin{aligned}\frac{dE_{CV}}{dt} = \sum_{in} \dot{m}\left(h + \frac{1}{2}V^2 + gZ\right) - \sum_{out} \dot{m}\left(h + \frac{1}{2}V^2 + gZ\right) \\ + \dot{Q}_{in} - \dot{W}_{out}\end{aligned}}$$

First law as applied to control volumes :

We shall use the first law expression in the box in the last slide for analysis of flow equipments.

Several equipments like pumps, compressors, diffusers, nozzles etc. operate under "steady-flow" conditions.

In "steady-flow" conditions, properties of the fluid may vary in space inside the control volume, however the properties at a given point in space are constant, i.e., do not change with time. For example, the velocity vector is a function of (x,y,z) but NOT time. Similarly, specific internal energy, specific enthalpy, specific volume and density of the fluid are also be functions of (x,y,z) (i.e., coordinates within the control volume) but NOT time.

Thus in "steady flow", properties such as total energy E_{CV}, total mass M_{CV} are constant.

“Steady-flow” conditions :

In “steady-flow” conditions, the first law expression simplifies to :

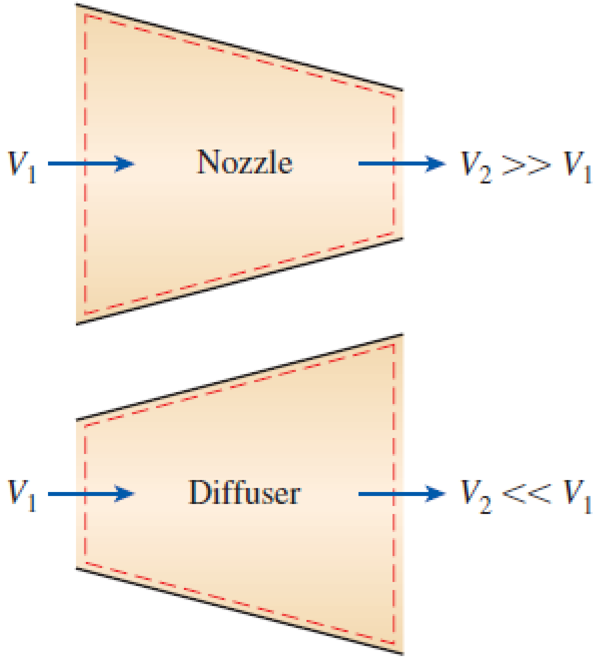
$$\boxed{\sum_{in} \dot{m}\left(h + \frac{1}{2}V^2 \ + \ gZ \right) - \sum_{out} \dot{m}\left(h + \frac{1}{2}V^2 \ + \ gZ \right) + \dot{Q}_{in} \ - \ \dot{W}_{out} \ = \ 0}$$

This is because under steady-flow :

$$\frac{dE_{CV}}{dt} = 0$$

Nozzles and diffusers:

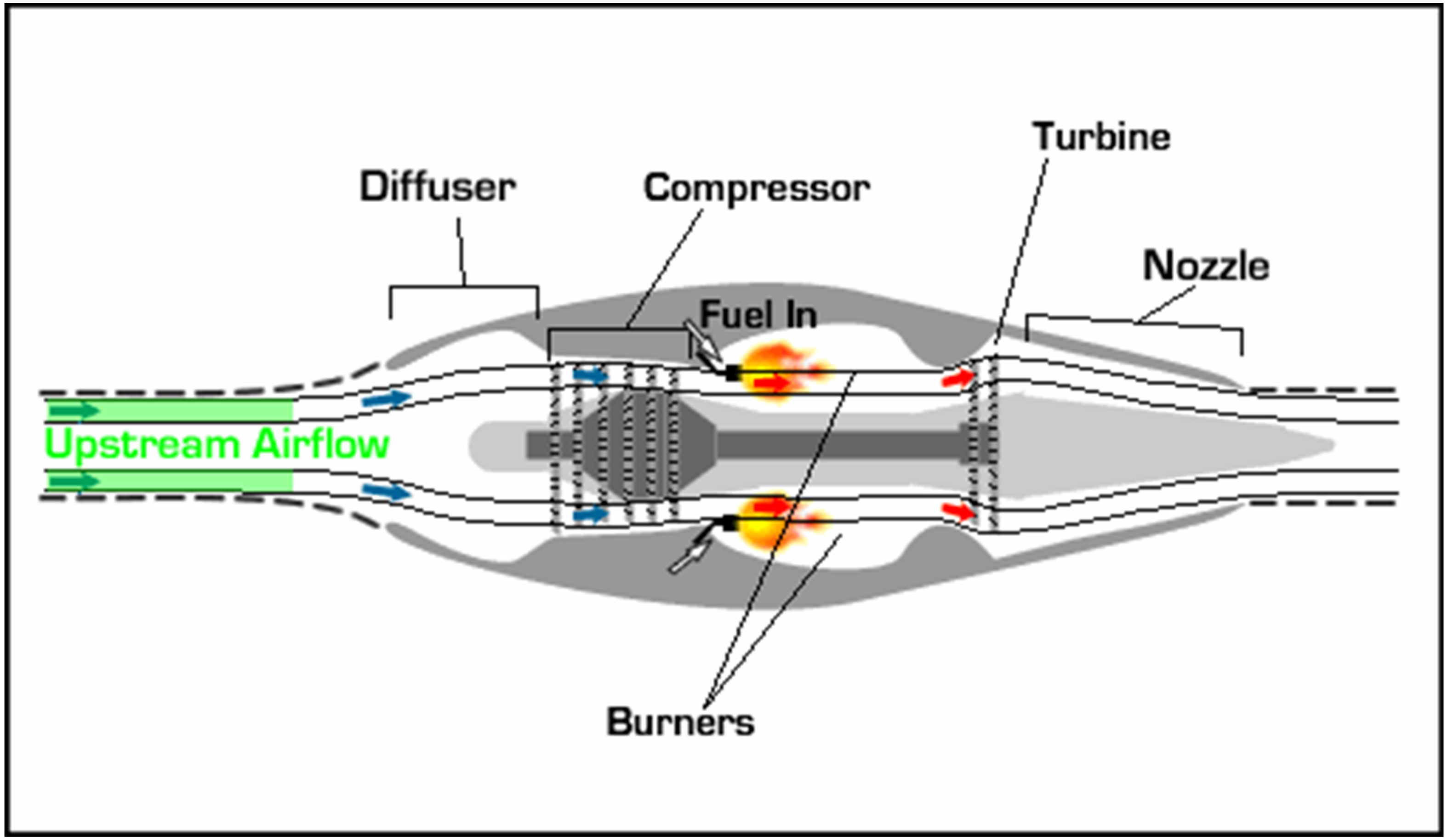
Nozzles and diffusers are commonly utilized in jet engines, rockets, spacecraft, and even garden hoses. A **nozzle** is a device that *increases the velocity of a fluid* at the expense of pressure. A **diffuser** is a device that *increases the pressure of a fluid* by slowing it down. That is, nozzles and diffusers perform opposite tasks.



Use of Nozzles and Diffusers:

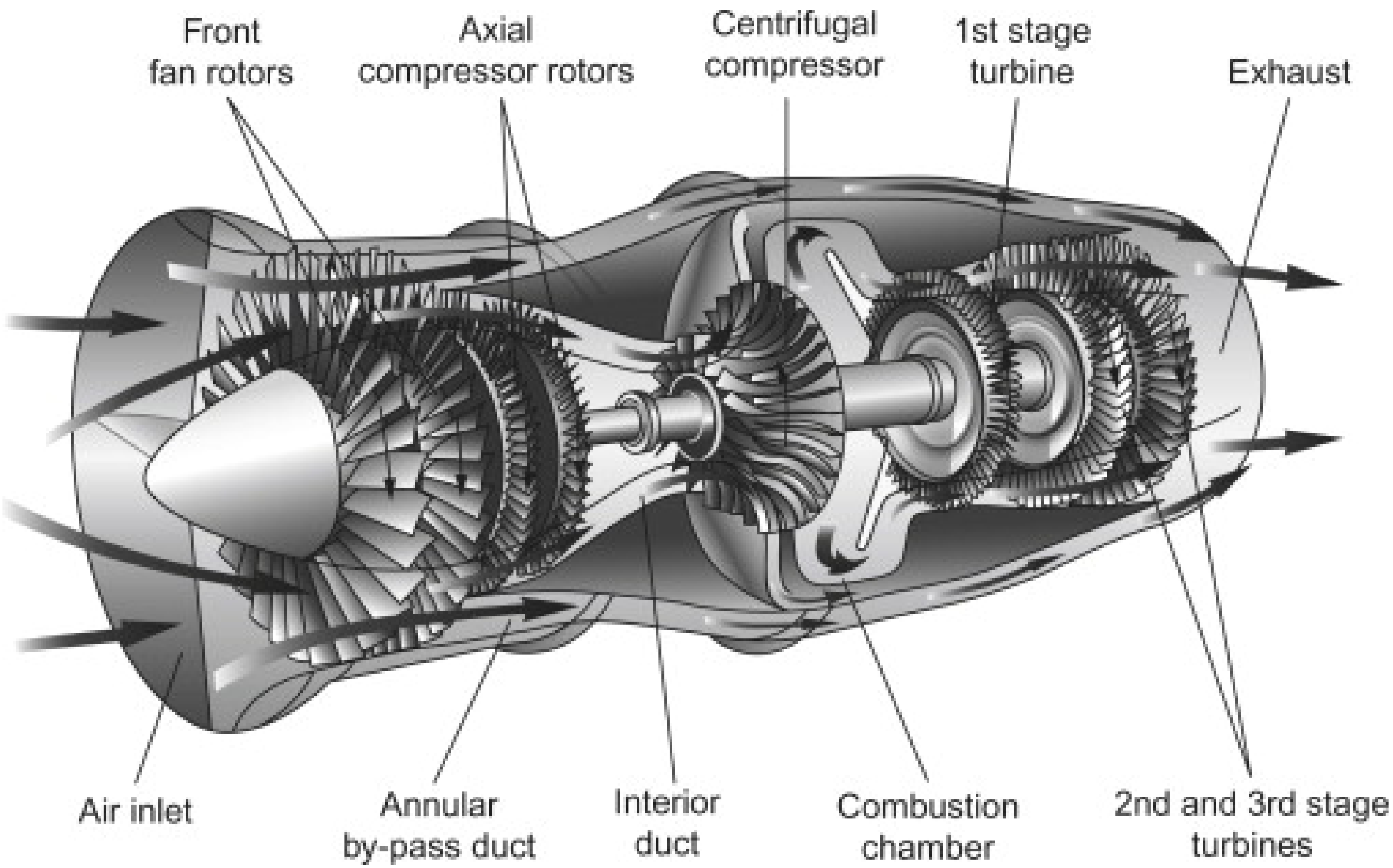
Basic elements of a Jet engine:

Entrance of diffuser	Exit of compressor	Exit of combusition	Exit of turbine
10^0C	450^0C	1600^0C	350^0C
0.75 bar	35 bar	35 bar	0.75 bar



Speed of a commercial plane ≈ 900 km/h = 250 m/s

Design of a Jet engine:



Example: deceleration of air in a diffuser

Air at 10°C and 80 kPa enters the diffuser of a jet engine steadily with a velocity of 200 m/s. The inlet area of the diffuser is 0.4 m^2. The air leaves the diffuser with a velocity that is very small compared with the inlet velocity. Determine (*a*) the mass flow rate of the air and (*b*) the temperature of the air leaving the diffuser.

Solution : (a) To find mass flow rate, we assume that air is an ideal gas. The specific volume can then be obtained as:

$$v_1 = \frac{RT_1}{P_1} = \frac{(0.287\ \text{kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(283\ \text{K})}{80\ \text{kPa}} = 1.015\ \text{m}^3/\text{kg}$$

The volumetric flow rate is the velocity of air at the inlet multiplied by inlet area. Since both of these quantities are given, mass flow rate is obtained by dividing volumetric flow rate by specific volume :

$$\dot{m} = \frac{1}{v_1} V_1 A_1 = \frac{1}{1.015\ \text{m}^3/\text{kg}} (200\ \text{m/s})(0.4\ \text{m}^2) = \mathbf{78.8\ kg/s}$$

Example: deceleration of air in a diffuser

(b) we neglect changes in potential energy and heat transfer to the diffuser. Also, in the diffuser no work is done. The diffuser operates under steady state. The inlet is denoted as '1' and outlet as '2'. Hence the first Law expression for steady-flow devices simplifies to :

$$\dot{m}\left(h_1 + \frac{V_1^2}{2}\right) = \dot{m}\left(h_2 + \frac{V_2^2}{2}\right)$$

$$h_2 = h_1 - \frac{V_2^2 - V_1^2}{2}$$

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) to be

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

Substituting, we get

$$\begin{aligned} h_2 &= 283.14\ \mathrm{kJ/kg} - \frac{0 - (200\ \mathrm{m/s})^2}{2}\left(\frac{1\ \mathrm{kJ/kg}}{1000\ \mathrm{m^2/s^2}}\right) \\ &= 303.14\ \mathrm{kJ/kg} \end{aligned}$$

Example: deceleration of air in a diffuser

(b)

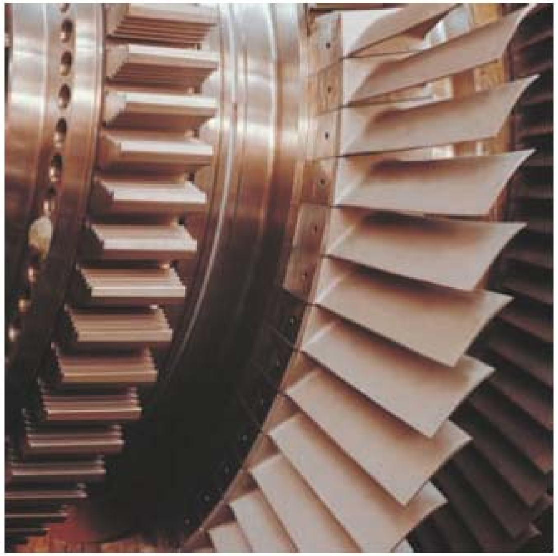
From Table A–17, the temperature corresponding to this enthalpy value is

$$T_2 = \mathbf{303\ K}$$

Discussion This result shows that the temperature of the air increases by about 20°C as it is slowed down in the diffuser. The temperature rise of the air is mainly due to the conversion of kinetic energy to internal energy.

Compressors and Turbines :

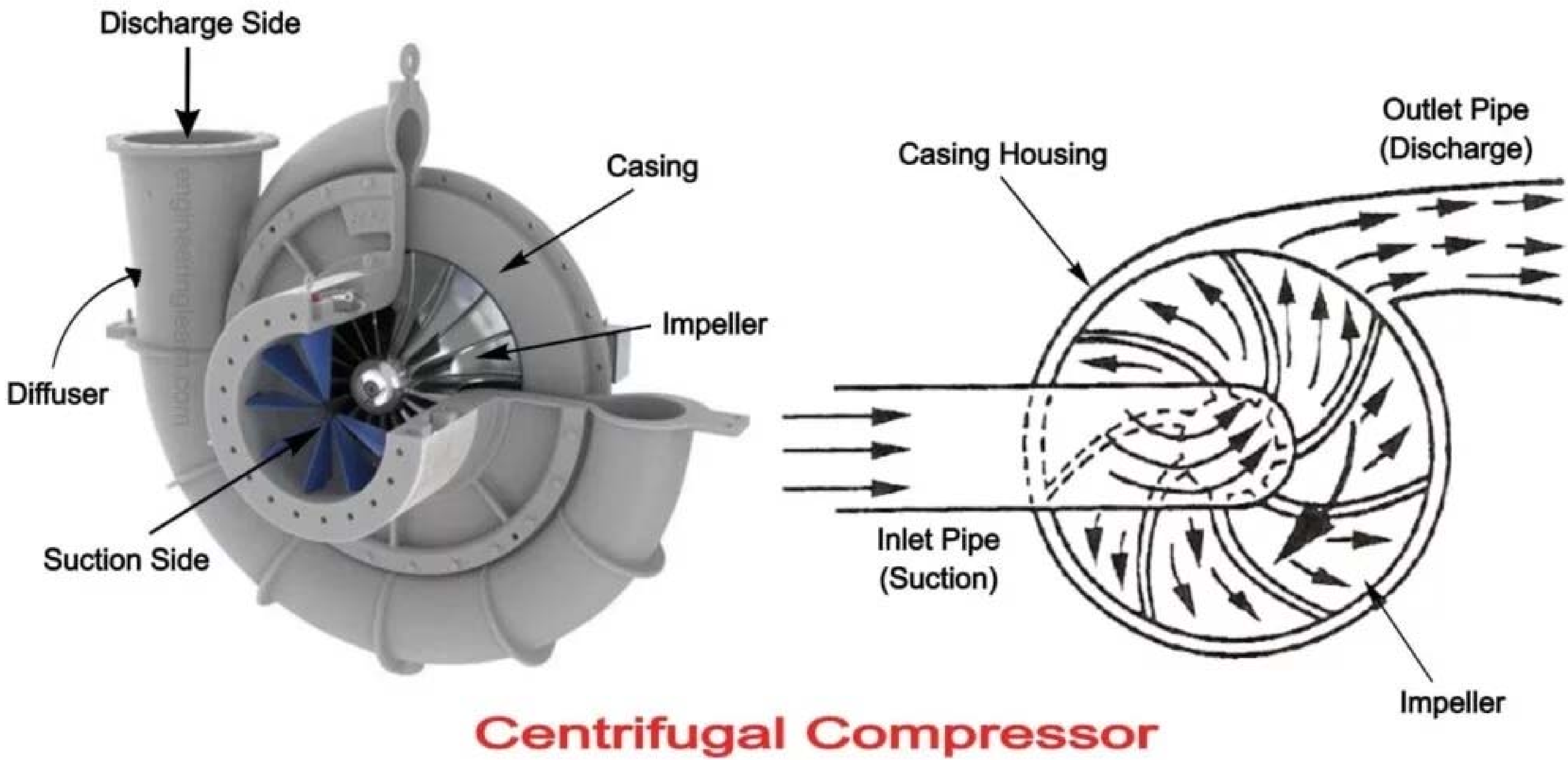
Figure shows the blades on the shaft of a Turbine



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

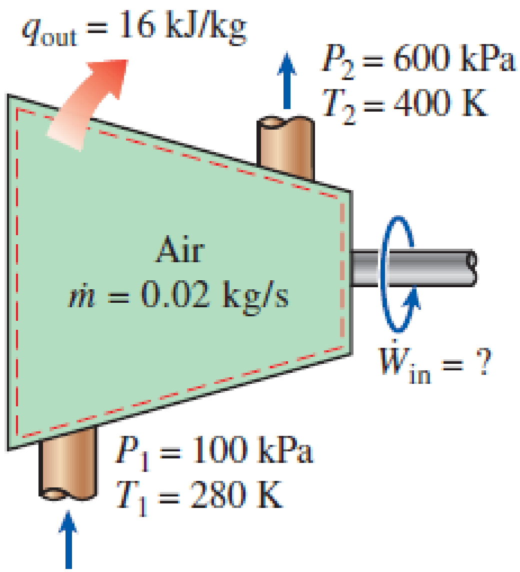
Compressors, as well as pumps and fans, are devices used to increase the pressure of a fluid. Work is supplied to these devices from an external source through a rotating shaft. Therefore, compressors involve work inputs. Even though these three devices function similarly, they do differ in the tasks 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.

Design of a centrifugal compressor



Example : Compressor

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 : We neglect changes in kinetic and potential energies across the compressor. Further, air is considered as an ideal gas. Thus, Table A-17 can be used to find the properties.

Example : Compressor

Since there is only a single inlet and single outlet, the first law equation reduces to : $\dot{m}\left(h_1 - h_2\right) - \dot{Q}_{out} + \dot{W}_{in} = 0$

Note that $\dot{Q}_{in} = -\dot{Q}_{out}$ and $-\dot{W}_{out} = \dot{W}_{in}$

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

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

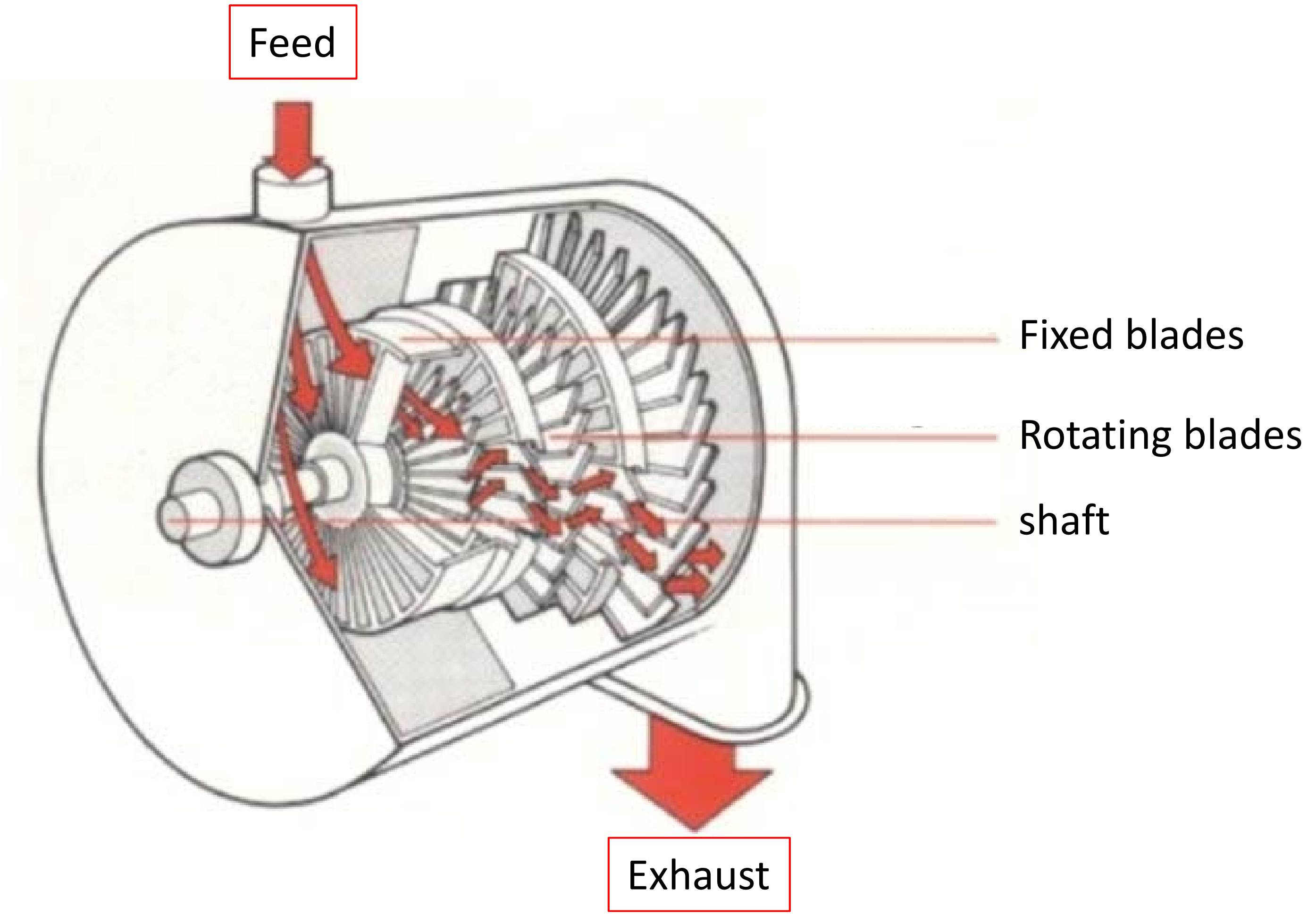
$$h_1 = h_{@\,280\text{ K}} = 280.13\text{ kJ/kg}$$
$$h_2 = h_{@\,400\text{ K}} = 400.98\text{ kJ/kg}$$

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

$$\begin{aligned}\dot{W}_{in} &= (0.02\text{ kg/s})(16\text{ kJ/kg}) + (0.02\text{ kg/s})(400.98 - 280.13)\text{ kJ/kg}\\ &= \mathbf{2.74\text{ kW}}\end{aligned}$$

Discussion Note that the mechanical energy input to the compressor manifests itself as a rise in enthalpy of air and heat loss from the compressor.

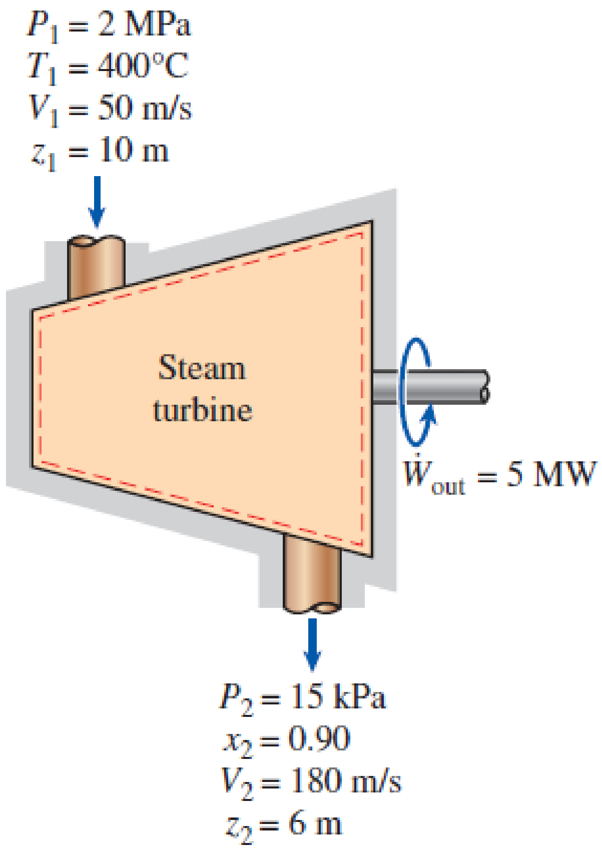
Design of a steam turbine



Example : Turbine

The power output of an adiabatic steam turbine is 5 MW, and the inlet and the exit conditions of the steam are as indicated in Fig.

(*a*) Compare the magnitudes of Δh, Δke, and Δpe.
(*b*) Determine the work done per unit mass of the steam flowing through the turbine.
(*c*) Calculate the mass flow rate of the steam.



Example : Turbine

(*a*) At the inlet, steam is in a superheated vapor state, and its enthalpy is

$$\left.\begin{aligned} P_1 &= 2\text{ MPa} \\ T_1 &= 400^\circ\text{C} \end{aligned}\right\} \quad h_1 = 3248.4\text{ kJ/kg} \qquad \text{(Table A–6)}$$

At the turbine exit, we obviously have a saturated liquid–vapor mixture at 15-kPa pressure. The enthalpy at this state is

$$h_2 = h_f + x_2 h_{fg} = [225.94 + (0.9)(2372.3)]\text{ kJ/kg} = 2361.01\text{ kJ/kg}$$

Then

$$\Delta h = h_2 - h_1 = (2361.01 - 3248.4)\text{ kJ/kg} = \mathbf{-887.39\ kJ/kg}$$

$$\Delta \text{ke} = \frac{V_2^2 - V_1^2}{2} = \frac{(180\text{ m/s})^2 - (50\text{ m/s})^2}{2}\left(\frac{1\text{ kJ/kg}}{1000\text{ m}^2/\text{s}^2}\right) = \mathbf{14.95\ kJ/kg}$$

$$\Delta \text{pe} = g(z_2 - z_1) = (9.81\text{ m/s}^2)[(6 - 10)\text{ m}]\left(\frac{1\text{ kJ/kg}}{1000\text{ m}^2/\text{s}^2}\right) = \mathbf{-0.04\ kJ/kg}$$

Example : Turbine

(*b*) The energy balance for this steady-flow system can be expressed in the rate form as

$$\dot{m}\left(h_1 + \frac{V_1^2}{2} + gz_1\right) = \dot{W}_{\text{out}} + \dot{m}\left(h_2 + \frac{V_2^2}{2} + gz_2\right) \quad (\text{since } \dot{Q} = 0)$$

Dividing by the mass flow rate $\dot{m}$ and substituting, the work done by the turbine per unit mass of the steam is determined to be

$$w_{\text{out}} = -\left[(h_2 - h_1) + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)\right] = -(\Delta h + \Delta \text{ke} + \Delta \text{pe})$$

$$= -[-887.39 + 14.95 - 0.04] \text{ kJ/kg} = \mathbf{872.48 \text{ kJ/kg}}$$

(*c*) The required mass flow rate for a 5-MW power output is

$$\dot{m} = \frac{\dot{W}_{\text{out}}}{w_{\text{out}}} = \frac{5000 \text{ kJ/s}}{872.48 \text{ kJ/kg}} = \mathbf{5.73 \text{ kg/s}}$$

Example : Turbine

Discussion Two observations can be made from these results. First, the change in potential energy is insignificant in comparison to the changes in enthalpy and kinetic energy. This is typical for most engineering devices. Second, as a result of low pressure and thus high specific volume, the steam velocity at the turbine exit can be very high. Yet the change in kinetic energy is a small fraction of the change in enthalpy (less than 2 percent in our case) and is therefore often neglected.