INDIAN INSTITUTE OF TECHNOLOGY KANPUR

ESO 201A: Thermodynamics

(2023-24 I Semester)

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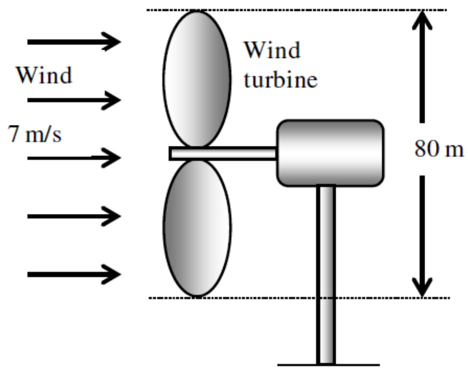
Tutorial 3

Question 1: At a certain location, wind is blowing steadily at 7 m/s. Determine the mechanical energy of air per unit mass and the power generation potential of a wind turbine with 80-m-diameter blades at that location. Also determine the actual electric power generation assuming an overall efficiency of 30 percent. Take the air density to be 1.25 kg/m^3.

Solution:

2-65 Wind is blowing steadily at a certain velocity. The mechanical energy of air per unit mass, the power generation potential, and the actual electric power generation are to be determined.



Assumptions **1** The wind is blowing steadily at a constant uniform velocity. **2** The efficiency of the wind turbine is independent of the wind speed.

Properties The density of air is given to be $\rho = 1.25$ kg/m^3.

Analysis Kinetic energy is the only form of mechanical energy the wind possesses, and it can be converted to work entirely. Therefore, the power potential of the wind is its kinetic energy, which is $V^2/2$ per unit mass, and $\dot{m}V^2/2$ for a given mass flow rate:

$$e_{\text{mech}} = ke = \frac{V^2}{2} = \frac{(7\text{ m/s})^2}{2}\left(\frac{1\text{ kJ/kg}}{1000\text{ m}^2/\text{s}^2}\right) = 0.0245\text{ kJ/kg}$$

$$\dot{m} = \rho VA = \rho V\frac{\pi D^2}{4} = (1.25\text{ kg/m}^3)(7\text{ m/s})\frac{\pi(80\text{ m})^2}{4} = 43{,}982\text{ kg/s}$$

$$\dot{W}_{\max} = \dot{E}_{\text{mech}} = \dot{m}e_{\text{mech}} = (43{,}982\text{ kg/s})(0.0245\text{ kJ/kg}) = \mathbf{1078\text{ kW}}$$

The actual electric power generation is determined by multiplying the power generation potential by the efficiency,

$$\dot{W}_{\text{elect}} = \eta_{\text{wind turbine}}\dot{W}_{\max} = (0.30)(1078\text{ kW}) = \mathbf{323\text{ kW}}$$

Therefore, 323 kW of actual power can be generated by this wind turbine at the stated conditions.

Discussion The power generation of a wind turbine is proportional to the cube of the wind velocity, and thus the power generation will change strongly with the wind conditions.

Question 2: Water is pumped from a lower reservoir to a higher reservoir by a pump that provides 20 kW of shaft power. The free surface of the upper reservoir is 45 m higher than that of the lower reservoir. If the flow rate of water is measured to be 0.03 m^3/s, determine mechanical power that is converted to thermal energy during this process due to frictional effects.

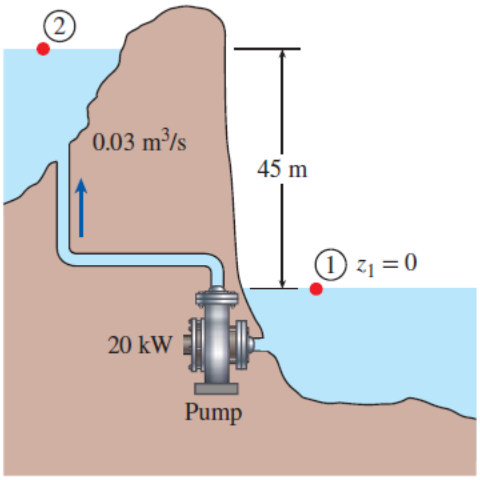
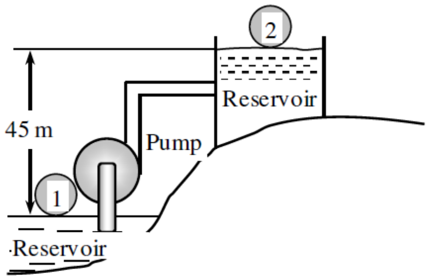


Fig. 1

Solution:

2-67 Water is pumped from a lower reservoir to a higher reservoir at a specified rate. For a specified shaft power input, the power that is converted to thermal energy is to be determined.



Assumptions **1** The pump operates steadily. **2** The elevations of the reservoirs remain constant. **3** The changes in kinetic energy are negligible.

Properties We take the density of water to be $\rho = 1000$ kg/m³.

Analysis The elevation of water and thus its potential energy changes during pumping, but it experiences no changes in its velocity and pressure. Therefore, the change in the total mechanical energy of water is equal to the change in its potential energy, which is gz per unit mass, and $\dot{m}gz$ for a given mass flow rate. That is,

$$\Delta\dot{E}_{\text{mech}} = \dot{m}\Delta e_{\text{mech}} = \dot{m}\Delta pe = \dot{m}g\Delta z = \rho\dot{V}g\Delta z$$

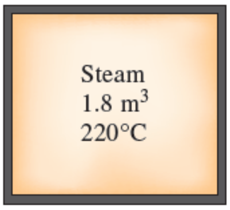
$$= (1000 \text{ kg/m}^3)(0.03 \text{ m}^3/\text{s})(9.81 \text{ m/s}^2)(45 \text{ m})\left(\frac{1 \text{ N}}{1 \text{ kg}\cdot\text{m/s}^2}\right)\left(\frac{1 \text{ kW}}{1000 \text{ N}\cdot\text{m/s}}\right) = 13.2 \text{ kW}$$

Then the mechanical power lost because of frictional effects becomes

$$\dot{W}_{\text{frict}} = \dot{W}_{\text{pump, in}} - \Delta\dot{E}_{\text{mech}} = 20 - 13.2 \text{ kW} = \mathbf{6.8 \text{ kW}}$$

Discussion The 6.8 kW of power is used to overcome the friction in the piping system. The effect of frictional losses in a pump is always to convert mechanical energy to an equivalent amount of thermal energy, which results in a slight rise in fluid temperature. Note that this pumping process could be accomplished by a 13.2 kW pump (rather than 20 kW) if there were no frictional losses in the system. In this ideal case, the pump would function as a turbine when the water is allowed to flow from the upper reservoir to the lower reservoir and extract 13.2 kW of power from the water.

Question 3: A 1.8-m³ rigid tank contains steam at 220°C. One-third of the volume is in the liquid phase and the rest is in the vapor form. Determine (a) the pressure of the steam, (b) the quality of the saturated mixture, and (c) the density of the mixture.



Solution:

3-28 A rigid tank contains steam at a specified state. The pressure, quality, and density of steam are to be determined.

Properties At 220°C $v_f = 0.001190$ m³/kg and $v_g = 0.08609$ m³/kg (Table A-4).

Analysis (*a*) Two phases coexist in equilibrium, thus we have a saturated liquid-vapor mixture. The pressure of the steam is the saturation pressure at the given temperature. Then the pressure in the tank must be the saturation pressure at the specified temperature,

$$P = T_{\text{sat @ 220°C}} = \mathbf{2320\ kPa}$$

(*b*) The total mass and the quality are determined as

$$m_f = \frac{V_f}{v_f} = \frac{1/3 \times (1.8\ \text{m}^3)}{0.001190\ \text{m}^3/\text{kg}} = 504.2\ \text{kg}$$

$$m_g = \frac{V_g}{v_g} = \frac{2/3 \times (1.8\ \text{m}^3)}{0.08609\ \text{m}^3/\text{kg}} = 13.94\ \text{kg}$$

$$m_t = m_f + m_g = 504.2 + 13.94 = 518.1\ \text{kg}$$

$$x = \frac{m_g}{m_t} = \frac{13.94}{518.1} = \mathbf{0.0269}$$

(*c*) The density is determined from

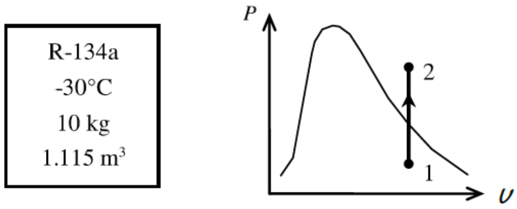
$$v = v_f + x(v_g - v_f) = 0.001190 + (0.0269)(0.08609) = 0.003474\ \text{m}^3/\text{kg}$$

$$\rho = \frac{1}{v} = \frac{1}{0.003474} = \mathbf{287.8\ kg/m^3}$$

Question 4: 10 kg of R-134a fill a 1.115-m³ rigid container at an initial temperature of –30°C. The container is then heated until the pressure is 200 kPa. Determine the final temperature and the initial pressure.

Solution:

3-31 A rigid container that is filled with R-134a is heated. The final temperature and initial pressure are to be determined.



Analysis This is a constant volume process. The specific volume is

$$v_1 = v_2 = \frac{V}{m} = \frac{1.115\ \text{m}^3}{10\ \text{kg}} = 0.1115\ \text{m}^3/\text{kg}$$

The initial state is determined to be a mixture, and thus the pressure is the saturation pressure at the given temperature

$$P_1 = P_{\text{sat @ } -30°\text{C}} = \mathbf{84.43\ kPa}\ \text{(Table A-11)}$$

The final state is superheated vapor and the temperature is determined by interpolation to be

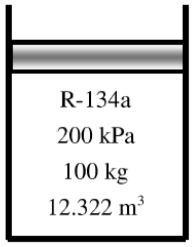
$$\left.\begin{array}{l} P_2 = 200\ \text{kPa} \\ v_2 = 0.1115\ \text{m}^3/\text{kg} \end{array}\right\} T_2 = \mathbf{14.2°C}\ \text{(Table A-13)}$$

Question 5: 100 kg of R-134a at 200 kPa are contained in a piston–cylinder device whose volume is 12.322 m³. The piston is now moved until the volume is one-half its original size. This is done such that the pressure of the R-134a does not change. Determine the final temperature and the change in the total internal energy of the R-134a.

Solution:

3-43 A piston-cylinder device that is filled with R-134a is cooled at constant pressure. The final temperature and the change of total internal energy are to be determined.

Analysis The initial specific volume is

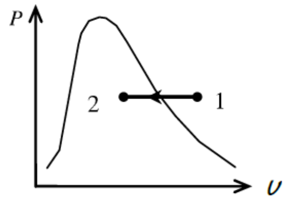


$$v_1 = \frac{V}{m} = \frac{12.322 \text{ m}^3}{100 \text{ kg}} = 0.12322 \text{ m}^3/\text{kg}$$

The initial state is superheated and the internal energy at this state is

$$\left.\begin{array}{l} P_1 = 200 \text{ kPa} \\ v_1 = 0.12322 \text{ m}^3/\text{kg} \end{array}\right\} u_1 = 263.08 \text{ kJ/kg} \text{ (Table A-13)}$$

The final specific volume is



$$v_2 = \frac{v_1}{2} = \frac{0.12322 \text{ m}^3/kg}{2} = 0.06161 \text{ m}^3/\text{kg}$$

This is a constant pressure process. The final state is determined to be saturated mixture whose temperature is

$$T_2 = T_{\text{sat@200 kPa}} = \mathbf{-10.09°C} \text{ (Table A-12)}$$

The internal energy at the final state is (Table A-12)

$$x_2 = \frac{v_2 - v_f}{v_{fg}} = \frac{(0.06161 - 0.0007532) \text{ m}^3/\text{kg}}{(0.099951 - 0.0007532) \text{ m}^3/\text{kg}} = 0.6135$$

$$u_2 = u_f + x_2 u_{fg} = 38.26 + (0.6135)(186.25) = 152.52 \text{ kJ/kg}$$

Hence, the change in the internal energy is

$$\Delta u = u_2 - u_1 = 152.52 - 263.08 = \mathbf{-110.6 \text{ kJ/kg}}$$

Question 6: Water initially at 200 kPa and 300°C is contained in a piston–cylinder device fitted with stops. The water is allowed to cool at constant pressure until it exists as a saturated vapor and the piston rests on the stops. Then the water continues to cool until the pressure is 100 kPa. On the *T-v* diagram, sketch, with respect to the saturation lines, the process curves passing through the initial, intermediate, and final states of the water. Label the *T, P,* and *v* values for end states on the process curves. Find the overall change in internal energy between the initial and final states per unit mass of water.

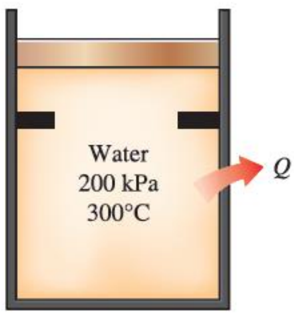


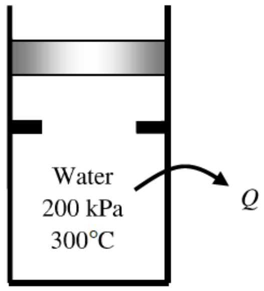
Fig. 3

Solution:

3-44 A piston-cylinder device fitted with stops contains water at a specified state. Now the water is cooled until a final pressure. The process is to be indicated on the T-υ diagram and the change in internal energy is to be determined.

Analysis The process is shown on T-υ diagram. The internal energy at the initial state is

$$\left.\begin{array}{l} P_1 = 200 \text{ kPa} \\ T_1 = 300^\circ\text{C} \end{array}\right\} u_1 = 2808.8 \text{ kJ/kg} \ \ (\text{Table A-6})$$

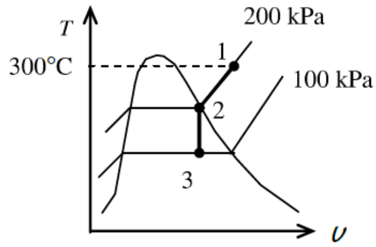


State 2 is saturated vapor at the initial pressure. Then,

$$\left.\begin{array}{l} P_2 = 200 \text{ kPa} \\ x_2 = 1 \text{ (sat. vapor)} \end{array}\right\} \upsilon_2 = 0.8858 \text{ m}^3\text{/kg} \ \ (\text{Table A-5})$$

Process 2-3 is a constant-volume process. Thus,

$$\left.\begin{array}{l} P_3 = 100 \text{ kPa} \\ \upsilon_3 = \upsilon_2 = 0.8858 \text{ m}^3\text{/kg} \end{array}\right\} u_3 = 1508.6 \text{ kJ/kg} \ \ (\text{Table A-5})$$



The overall change in internal energy is

$$\Delta u = u_1 - u_3 = 2808.8 - 1508.6 = \mathbf{1300 \text{ kJ/kg}}$$