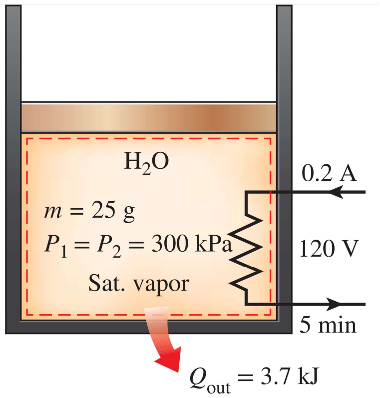
COE-C2007 Thermodynamics, 2022

Learning Exercise 2

The exercise is to be completed independently (do not copy paste from other students) and returned as a single pdf report with appropriate use of pictures and charts, as well as presentation of used equations in possible calculations. Name the uploaded pdf-file so that it tells the course, learning exercise number and your name, like Thermodynamics_LE2_Lastname.pdf
No single question/problem is compulsory, but a minimum of 50 % of points is required in order to pass the exercise. Include also your name and student number on the first page of the report. A proper length of an answer per question would be maximum 1 page. The time for answering this exercise is estimated not to exceed 8 hours, provided that you have attended lectures.

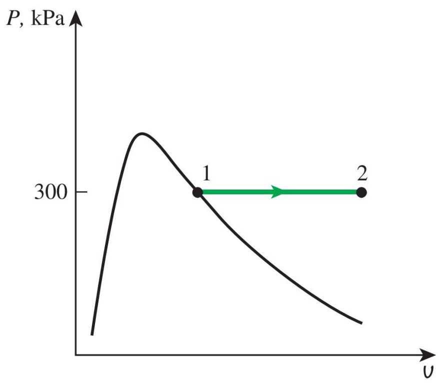
Return DL of LE2: Friday January 28, 2022, 23:55, in MyCourses.

1. A piston–cylinder device contains 25 g of saturated water vapor that is maintained at a constant pressure of 300 kPa. A resistance heater within the cylinder is turned on and passes a current of 0.2 A for 5 min from a 120-V source. At the same time, a heat loss of 3.7 kJ occurs. (a) Show that for a closed system the boundary work Wb and the change in internal energy ΔU in the first-law relation can be combined into one term, ΔH, for a constant-pressure process. (b) Determine the final temperature of the steam.? **(15 Points) (Lecture 3)**



SOLUTION

Saturated water vapor in a piston–cylinder device expands at constant pressure as a result of heating. It is to be shown that ΔU + Wb = ΔH, and the final temperature is to be determined.



Assumptions

1 The cylinder is stationary and thus the kinetic and potential energy changes are zero, ΔKE = ΔPE = 0. Therefore, ΔE = ΔU, and internal energy is the only form of energy of the system that may change during this process.
2 Electrical wires constitute a very small part of the system, and thus the energy change of the wires can be neglected.

Analysis
We take the contents of the cylinder, including the resistance wires, as the system. This is a closed system since no mass crosses the system boundary during the process. We observe that a piston–cylinder device typically involves a moving boundary and thus boundary work Wb. The pressure remains constant during the process and thus P2 = P1. Also, heat is lost from the system and electrical work We is done on the system.
(a) This part of the solution involves a general analysis for a closed system undergoing a quasi-equilibrium constant-pressure process, and thus we consider a general closed system. We take the direction of heat transfer Q to be to the system and the work W to be done by the system. We also express the work as the sum of boundary and other forms of work (such as electrical and shaft). Then, the energy balance can be expressed as:

$$E_{in} - E_{out} = \Delta E_{system}$$
$$Q - W = \Delta U + \Delta KE + \Delta PE$$
$$Q - W_{other} - W_b = U_2 - U_1$$

For a constant-pressure process, the boundary work is given as $W_b = P_0(V_2 - V_1)$. Substituting this into the preceding relation gives

$$Q - W_{oth} \quad - P_0(V_2 - V_1) = U_2 - U_1$$

However,

$$P_0 = P_2 = P_1 \rightarrow Q - W_{oth} \quad = (U_2 + P_2V_2) + (U_1 + P_1V_1)$$

Also $H = U + PV$, and thus

$$Q - W_{other} = H_2 - H_1 \qquad (kJ)$$

which is the desired relation (Fig. 4–14). This equation is very convenient to use in the analysis of closed systems undergoing a constant-pressure quasi-equilibrium process since the boundary work is automatically taken care of by the enthalpy terms, and one no longer needs to determine it separately.
(b) The only other form of work in this case is the electrical work, which can be determined from

$$W_e = VI\Delta t$$
$$state\ 1: \left.\begin{matrix} P_1 = 300\ kPa \\ Satruation\ vapor \end{matrix}\right\} h_1 = h_{g\ @\ 300\ kPa} \qquad (Table\ A-5)$$

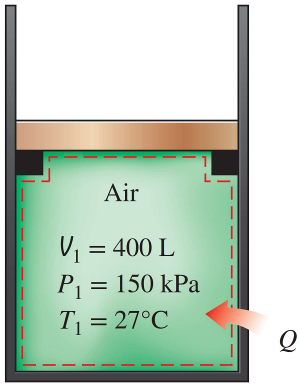
The enthalpy at the final state can be determined directly from Eq. 4–18 by expressing heat transfer from the system and work done on the system as negative quantities (since their directions are opposite to the assumed directions). Alternately, we can use the general energy balance relation with the simplification that the boundary work is considered automatically by replacing ΔU with ΔH for a constant-pressure expansion or compression process:

$$E_{in} - E_{out} = \Delta E_{system}$$
$$W_{e,in} - Q_{out} - W_b = \Delta U$$
$$W_{e,in} - Q_{out} = \Delta H = m(h_2 - h_1) \qquad (since\ P = constant)$$
$$h_2 = ?$$

Now the final state is completely specified since we know both the pressure and the enthalpy. The temperature at this state is

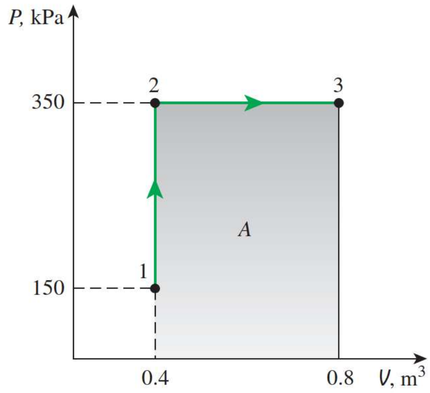
$$state\ 2: \left.\begin{matrix} P_2 = 300\ kPa \\ h_2 = ? \end{matrix}\right\} T_2 = ? \quad (Table\ A-6)$$

2. A piston–cylinder device initially contains air at 150 kPa and 27°C. At this state, the piston is resting on a pair of stops, as shown in Fig. 4–32, and the enclosed volume is 400 L. The mass of the piston is such that a 350-kPa pressure is required to move it. The air is now heated until its volume has doubled. Determine (a) the final temperature, (b) the work done by the air, and (c) the total heat transferred to the air**. (10 Points) (Lecture 3)**



SOLUTION

Air in a piston–cylinder device with a set of stops is heated until its volume is doubled. The final temperature, work done, and the total heat transfer are to be determined.



Assumptions

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

2 The system is stationary and thus the kinetic and potential energy changes are zero, ΔKE = ΔPE = 0 and ΔE = ΔU.

3 The volume remains constant until the piston starts moving, and the pressure remains constant afterwards.

4 There are no electrical, shaft, or other forms of work involved.

Analysis

We take the contents of the cylinder as the system (Fig. 4–32). This is a closed system since no mass crosses the system boundary during the process. We observe that a piston–cylinder device typically involves a moving boundary and thus boundary work, Wb. Also, the boundary work is done by the system, and heat is transferred to the system.

(a) The final temperature can be determined easily by using the ideal-gas relation between states 1 and 3 in the following form:

$$\frac{P_1V_1}{T_1} = \frac{P_3V_3}{T_3} \rightarrow T_3 = ?$$

(b) The work done could be determined by integration, but for this case it is much easier to find it from the area under the process curve on a P-V diagram,

$$A = (V_3 - V_2)P_2 \rightarrow W_{13} = ?$$

The work is done by the system (to raise the piston and to push the atmospheric air out of the way), and thus it is work output.

(c) Under the stated assumptions and observations, the energy balance on the system between the initial and final states (process 1–3) can be expressed as

$$E_{in} - E_{out} = \Delta E_{system}$$

$$Q_{in} - W_{b,out} = \Delta U = m(u_3 - u_1)$$

The mass of the system can be determined from the ideal-gas relation:

$$m = \frac{P_1 V_1}{RT_1} = ?$$

The internal energies are determined from the air table (Table A–17) to be

$$u_1 = u_{@\,300K} = ?$$

$$u_3 = u_{@\,1400K} = ?$$

Thus, according to the following equation, we get Q_{in}

$$Q_{in} - W_{b,out} = \Delta U = m(u_3 - u_1)$$

3. Determine the enthalpy of liquid water at 100°C and 15 MPa (a) by using compressed liquid tables, (b) by approximating it as a saturated liquid, and (c) by using the correction given by $h_{@P,T} \cong h_{f\,@\,T} + v_{f\,@\,T}(P - P_{sat\,@\,T})$. **(15 Points) (Lecture 3)**

SOLUTION

The enthalpy of liquid water is to be determined exactly and approximately.

Analysis

At 100°C, the saturation pressure of water is 101.42 kPa, and since P > Psat, the water exists as a compressed liquid at the specified state.

(a) From compressed liquid tables, we read

$$\left.\begin{aligned} P &= 15\ MPa \\ T &= 100\ oC \end{aligned}\right\} \rightarrow h = ? \quad (Table\ A - 7)$$

This is the exact value.

(b) Approximating the compressed liquid as a saturated liquid at 100°C, as is commonly done, we obtain

$$h \cong h_{f\,@\,100\,oC} = ?$$

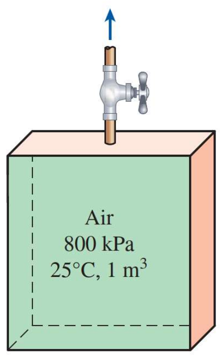
(c) From equation: $h_{@P,T} \cong h_{f\,@\,T} + v_{f\,@\,T}(P - P_{sat\,@\,T})$., we easily can calculate the $h_{@P,T}$

4. A tank with an internal volume of 1 m3 contains air at 800 kPa and 25°C. A valve on the tank is opened, allowing air to escape, and the pressure inside quickly drops to 150 kPa, at which point the valve is closed. Assume there is negligible heat transfer from the tank to the air left in the tank.

(a) Using the approximation $h_e \approx constant = h_{e,avg} = 0.5(h_1 + h_2)$, calculate the mass withdrawn during the process.

(b) Consider the same process but broken into two parts. That is, consider an intermediate state at $P_2 = 400kPa$, calculate the mass removed during the process from $P_1 = 800kPa$ to P_2 and then the mass removed during the process from P_2 to $P_3 = 150kPa$, using the type of approximation used in part (a), and add the two to get the total mass removed.

(c) Calculate the mass removed if the variation of he is accounted for. **(15 Points) (Lecture 4)**



Solution

The air in a tank is released until the pressure in the tank reduces to a specified value. The mass withdrawn from the tank is to be determined for three methods of analysis.

Assumptions

1 This is an unsteady process since the conditions within the device are changing during the process, but it can be analyzed as a uniform-flow process.

2 Air is an ideal gas with constant specific heats.

3 Kinetic and potential energies are negligible.

4 There are no work or heat interactions involved.

Properties

The gas constant of air is 0.287 kPa·m3/kg·K (Table A-1). The specific heats of air at room temperature are cp = 1.005 kJ/kg·K and cv = 0.718 kJ/kg·K. Also k = 1.4 (Table A-2a).

Analysis

(a) We take the tank as the system, which is a control volume since mass crosses the boundary. Noting that the microscopic energies of flowing and nonflowing fluids are represented by enthalpy h and internal energy u, respectively, the mass and energy balances for this uniform-flow system can be expressed as

Mass balance:

$$m_{in} - m_{out} = \Delta m_{system}$$
$$-m_e - m_2 - m_1$$

Energy balance:

$$E_{in} - E_{out} = \Delta E_{system}$$
$$-m_e h_e = m_2 u_2 - m_1 u_1$$
$$-m_e c_p T_e = m_2 c_v T_2 - m_1 c_v T_1$$

combine the two balances:

$$0 = m_2 c_v T_2 - m_1 c_v T_1 + (m_2 - m_1) c_p T_e$$

The initial and final mass are given by:

$$m_1 = \frac{P_1 V}{R T_1} = ?$$
$$m_2 = \frac{P_2 V}{R T_2} = ?$$

The temperature of air leaving the tank changes from the initial temperature in the tank to the final temperature during the discharging process. We assume that the temperature of the air leaving the tank is the average of initial and final temperatures in the tank. Substituting into the energy balance equation gives

$$0 = m_2 c_v T_2 - m_1 c_v T_1 + (m_2 - m_1) c_p T_e$$

whose solution is $T_2 = ?$

Substituting, the final mass is

$$m_2 = \frac{P_2 V}{RT_2} = ?$$

and the mass withdrawn is

$$m_e = m_2 - m_1$$

(b) Considering the process in two parts, first from 800 kPa to 400 kPa and from 400 kPa to 150 kPa, the solution will be as follows:

From 800 kPa to 400 kPa:

$$m_2 = \frac{P_2 V}{RT_2} = ?$$

$$0 = m_2 c_v T_2 - m_1 c_v T_1 + (m_2 - m_1) c_p T_e$$

$$m_{e,1} = m_1 - m_2$$

From 400 kPa to 150 kPa:

$$m_2 = \frac{P_2 V}{RT_2} = ?$$

$$0 = m_2 c_v T_2 - m_1 c_v T_1 + (m_2 - m_1) c_p T_e$$

$$m_{e,2} = m_1 - m_2$$

The total mass withdrawn is

$$m_e = m_{e,1} + m_{e,2}$$

(c) The mass balance may be written as

$$\frac{dm}{dt} = -\dot{m}_e$$

When this is combined with the ideal gas equation of state, it becomes

$$\frac{V}{R}\frac{d(P/T)}{dt} = -\dot{m}_e$$

since the tank volume remains constant during the process. An energy balance on the tank gives

$$\frac{d(mu)}{dt} = -h_e \dot{m}_e$$

$$c_v \frac{d(mT)}{dt} = c_p T \frac{dm}{dt}$$

$$c_v \frac{V}{R}\frac{d(P)}{dt} = c_p T \frac{V}{R}\frac{d(P/T)}{dt}$$

$$c_v \frac{dP}{dt} = c_p \left(\frac{dP}{dt} - \frac{P}{T}\frac{dT}{dt}\right)$$

When this result is integrated, it gives

$$T_2 = T_1 \left(\frac{P_2}{P_1}\right)^{(k-1)/k} = ?$$

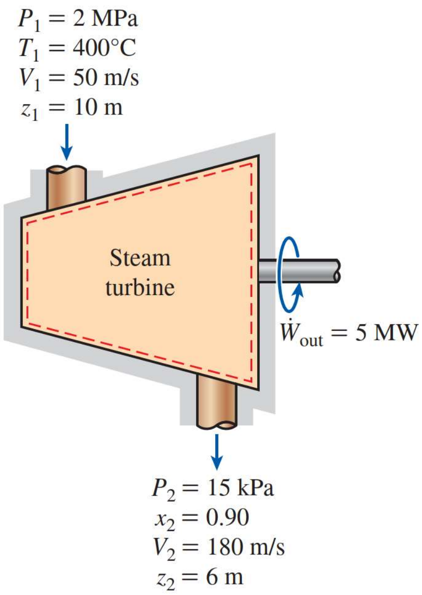
The final mass is

$$m_2 = \frac{P_2 V}{RT_2} = ?$$

and the mass withdrawn is

$$m_e = m_2 - m_1$$

5. 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. 5–31. (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. **(20 Points) (Lecture 4)**



SOLUTION

The inlet and exit conditions of a steam turbine and its power output are given. The changes in kinetic energy, potential energy, and enthalpy of steam, as well as the work done per unit mass and the mass flow rate of steam are to be determined.

Assumptions

1 This is a steady-flow process since there is no change with time at any point and thus ΔmCV = 0 and ΔECV = 0.

2 The system is adiabatic and thus there is no heat transfer.

Analysis

We take the turbine as the system. 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, work is done by the system. The inlet and exit velocities and elevations are given, and thus the kinetic and potential energies are to be considered.

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

$$\left.\begin{matrix} P_1 = 2\ MPa \\ T_1 = 400\ oC \end{matrix}\right\} \rightarrow h_1 =? \quad (Table\ A-6)$$

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

$$h_2 = h_f + x_2 h_{fg} =?$$

then

$$\Delta h = h_2 - h_1 =?$$

$$\Delta ke = \frac{V_2^2 - V_1^2}{2} =?$$

$$\Delta pe = g(z_2 - z_1) =?$$

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

$$\dot{E}_{in} - \dot{E}_{out} = dE_{system}/dt = 0\ (since\ it\ it\ a\ steady\ system)$$

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

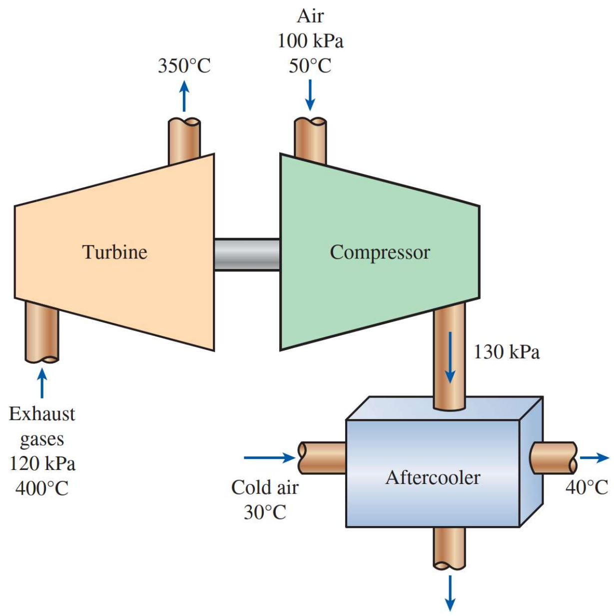
Dividing by the mass flow rate $\dot{m}$ and substituting, the work done by the turbine per unit mass of the steam is determined to be

$$w_{out}=?$$

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

$$\dot{m}=\frac{\dot{W}_{out}}{w_{out}}=?\,kg/s$$

6. The turbocharger of an internal combustion engine consists of a turbine and a compressor. Hot exhaust gases flow through the turbine to produce work, and the work output from the turbine is used as the work input to the compressor. The pressure of ambient air is increased as it flows through the compressor before it enters the engine cylinders. Thus, the purpose of a turbocharger is to increase the pressure of air so that more air gets into the cylinder. Consequently, more fuel can be burned, and more power can be produced by the engine. In a turbocharger, exhaust gases enter the turbine at 400°C and 120 kPa at a rate of 0.02 kg/s and leave at 350°C. Air enters. the compressor at 50°C and 100 kPa and leaves at 130 kPa at a rate of 0.018 kg/s. The compressor increases the air pressure with a side effect: It also increases the air temperature, which increases the possibility that a gasoline engine will experience an engine knock. To avoid this, an aftercooler is placed after the compressor to cool the warm air with cold ambient air before it enters the engine cylinders. It is estimated that the aftercooler must decrease the air temperature below 80°C if knock is to be avoided. The cold ambient air enters the aftercooler at 30°C and leaves at 40°C. Disregarding any frictional losses in the turbine and the compressor and treating the exhaust gases as air, determine (a) the temperature of the air at the compressor outlet and (b) the minimum volume flow rate of ambient air required to avoid knock. **(30 Points)**



The turbocharger of an internal combustion engine consisting of a turbine, a compressor, and an aftercooler is considered. The temperature of the air at the compressor outlet and the minimum flow rate of ambient air are to be determined.

Assumptions:

1 All processes are steady since there is no change with time.
2 Kinetic and potential energy changes are negligible.
3 Air properties are used for exhaust gases.
4 Air is an ideal gas with constant specific heats.
5 The mechanical efficiency between the turbine and the compressor is 100%.
6 All devices are adiabatic.
7 The local atmospheric pressure is 100 kPa.

Properties:

The constant pressure specific heats of exhaust gases, warm air, and cold ambient air are taken to be cp = 1.063, 1.008, and 1.005 kJ/kg·K, respectively (Table A-2b).

Analysis:

(a) An energy balance on turbine gives

$$\dot{W}_T = \dot{m}_{exh} c_{p,exh}\left(T_{exh,1} - T_{exh,2}\right) = ?$$

This is also the power input to the compressor since the mechanical efficiency between the turbine and the compressor is assumed to be 100%. An energy balance on the compressor gives the air temperature at the compressor outlet

$$\dot{W}_T = \dot{W}_C = \dot{m}_a c_{p,a}\left(T_{a,2} - T_{a,1}\right) = ?$$

(b) An energy balance on the aftercooler gives the mass flow rate of cold ambient air

$$\dot{m}_a c_{p,a}\left(T_{a,2} - T_{a,3}\right) = \dot{m}_{ca} c_{p,ca}\left(T_{ca,2} - T_{ca,1}\right)$$

$$\dot{m}_{ca} = ?$$

The volume flow rate may be determined if we first calculate specific volume of cold ambient air at the inlet of aftercooler. That is,

$$v_{ca} = \frac{RT}{P}$$

$$\dot{V}_{ca} = \dot{m} v_{ca} = ?$$