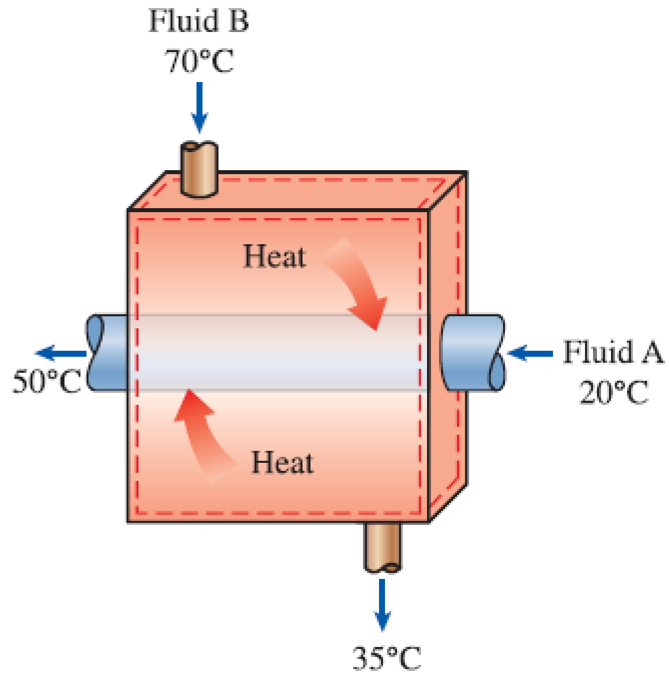
ESO201A : THERMODYNAMICS
2021-22 Ist semester
IIT Kanpur

Instructor : P.A.Apte

Lecture 12

Heat exchangers :



As the name implies, **heat exchangers** are devices where two moving fluid streams exchange heat without mixing. Heat exchangers are widely used in various industries, and they come in various designs.

The simplest form of a heat exchanger is a *double-tube* (also called *tube-and-shell*) *heat exchanger,* shown in Fig. It is composed of two concentric pipes of different diameters. One fluid flows in the inner pipe, and the other in the annular space between the two pipes. Heat is transferred from the hot fluid to the cold one through the wall separating them. Sometimes the inner tube makes a couple of turns inside the shell to increase the heat transfer area, and thus the rate of heat transfer. The mixing chambers discussed earlier are sometimes classified as *direct-contact* heat exchangers.

Ref. Cengel and Boles, 8th Edition (2015)

Heat exchangers :

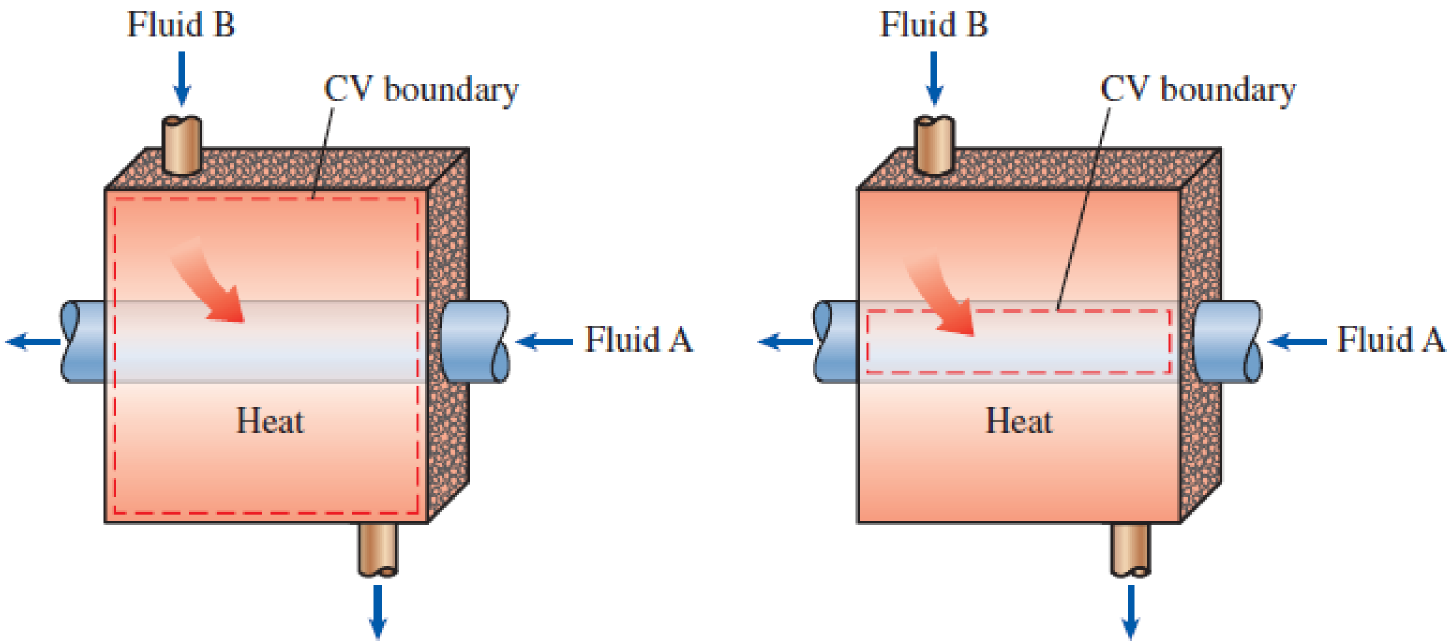
The conservation of mass principle for a heat exchanger in steady operation requires that the sum of the inbound mass flow rates equal the sum of the outbound mass flow rates. This principle can also be expressed as follows: *Under steady operation, the mass flow rate of each fluid stream flowing through a heat exchanger remains constant.*

Heat exchangers typically involve no work interactions ($w = 0$) and negligible kinetic and potential energy changes ($\Delta ke \cong 0$, $\Delta pe \cong 0$) for each fluid stream. The heat transfer rate associated with heat exchangers depends on how the control volume is selected. Heat exchangers are intended for heat transfer between two fluids *within* the device, and the outer shell is usually well insulated to prevent any heat loss to the surrounding medium.

Ref. Cengel and Boles, 8th Edition (2015)

Heat exchangers :

Choice of control volume for a heat exchanger :



(*a*) System: Entire heat exchanger ($Q_{CV} = 0$)

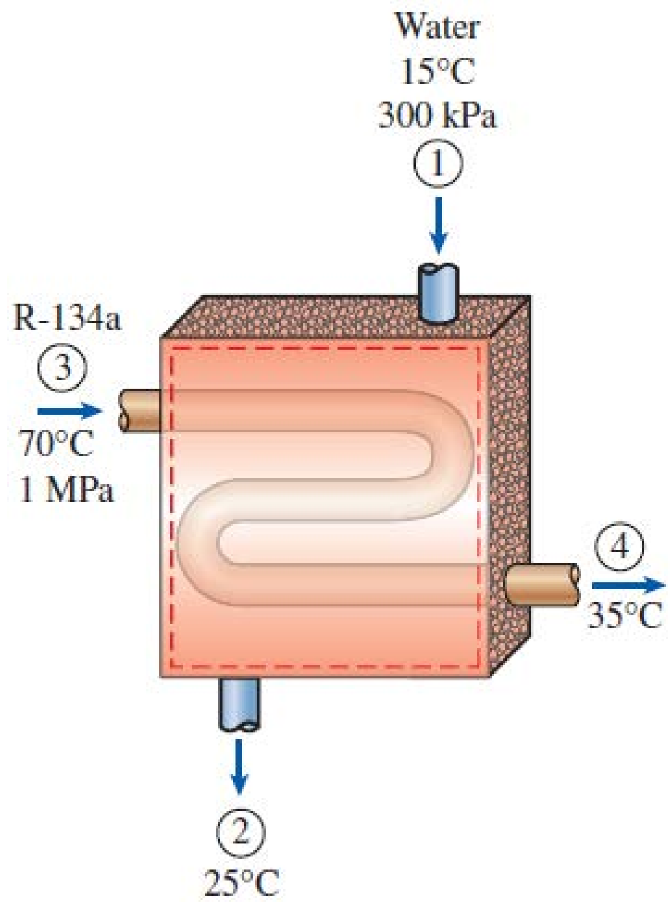
(*b*) System: Fluid A ($Q_{CV} \neq 0$)

When the entire heat exchanger is selected as the control volume, $\dot{Q}$ becomes zero, since the boundary for this case lies just beneath the insulation and little or no heat crosses the boundary (Fig. 5–39). If, however, only one of the fluids is selected as the control volume, then heat will cross this boundary as it flows from one fluid to the other and $\dot{Q}$ will not be zero. In fact, $\dot{Q}$ in this case will be the rate of heat transfer between the two fluids.

Ref. Cengel and Boles, 8th Edition (2015)

Example : heat exchanger

Refrigerant-134a is to be cooled by water in a condenser. The refrigerant enters the condenser with a mass flow rate of 6 kg/min at 1 MPa and 70°C and leaves at 35°C. The cooling water enters at 300 kPa and 15°C and leaves at 25°C. Neglecting any pressure drops, determine (*a*) the mass flow rate of the cooling water required and (*b*) the heat transfer rate from the refrigerant to water.



Ref. Cengel and Boles, 8th Edition (2015)

Example : heat exchanger

SOLUTION Refrigerant-134a is cooled by water in a condenser. The mass flow rate of the cooling water and the rate of heat transfer from the refrigerant to the water are 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, ke $\cong$ pe $\cong$ 0. **3** Heat losses from the system are negligible and thus $\dot{Q} \cong 0$. **4** There is no work interaction.

Analysis We take the *entire heat exchanger* as the system This is a *control volume* since mass crosses the system boundary during the process. In general, there are several possibilities for selecting the control volume for multiple-stream steady-flow devices, and the proper choice depends on the situation at hand. We observe that there are two fluid streams (and thus two inlets and two exits) but no mixing.

Mass balance: $$\dot{m}_{in} = \dot{m}_{out}$$

for each fluid stream since there is no mixing. Thus,

$$\dot{m}_1 = \dot{m}_2 = \dot{m}_w$$

$$\dot{m}_3 = \dot{m}_4 = \dot{m}_R$$

Ref. Cengel and Boles, 8th Edition (2015)

Example : heat exchanger

Energy balance:

$$\dot{m}_1 h_1 + \dot{m}_3 h_3 = \dot{m}_2 h_2 + \dot{m}_4 h_4 \quad (\text{since } \dot{Q} \cong 0,\ \dot{W} = 0,\ \text{ke} \cong \text{pe} \cong 0)$$

Combining the mass and energy balances and rearranging give

$$\dot{m}_w(h_1 - h_2) = \dot{m}_R(h_4 - h_3)$$

Now we need to determine the enthalpies at all four states. Water exists as a compressed liquid at both the inlet and the exit since the temperatures at both locations are below the saturation temperature of water at 300 kPa (133.52°C). Approximating the compressed liquid as a saturated liquid at the given temperatures, we have

$$h_1 \cong h_{f @ 15^\circ C} = 62.982 \text{ kJ/kg}$$

(Table A–4)

$$h_2 \cong h_{f @ 25^\circ C} = 104.83 \text{ kJ/kg}$$

Ref. Cengel and Boles, 8th Edition (2015)

Example : heat exchanger

Energy balance:

The refrigerant enters the condenser as a superheated vapor and leaves as a compressed liquid at 35°C. From refrigerant-134a tables,

$$\left.\begin{array}{l} P_3 = 1 \text{ MPa} \\ T_3 = 70^\circ\text{C} \end{array}\right\} \quad h_3 = 303.87 \text{ kJ/kg} \qquad \text{(Table A–13)}$$

$$\left.\begin{array}{l} P_4 = 1 \text{ MPa} \\ T_4 = 35^\circ\text{C} \end{array}\right\} \quad h_4 \cong h_{f\,@\,35^\circ\text{C}} = 100.88 \text{ kJ/kg} \qquad \text{(Table A–11)}$$

Substituting, we find

$$\dot{m}_w(62.982 - 104.83) \text{ kJ/kg} = (6 \text{ kg/min})[(100.88 - 303.87) \text{ kJ/kg}]$$

$$\dot{m}_w = \mathbf{29.1 \text{ kg/min}}$$

Ref. Cengel and Boles, 8th Edition (2015)

Example : heat exchanger

Energy balance:

(*b*) To determine the heat transfer from the refrigerant to the water, we have to choose a control volume whose boundary lies on the path of heat transfer. We can choose the volume occupied by either fluid as our control volume. For no particular reason, we choose the volume occupied by the water. All the assumptions stated earlier apply, except that the heat transfer is no longer zero. Then assuming heat to be transferred to water, the energy balance for this single-stream steady-flow system reduces to

$$\dot{Q}_{w,\,in} + \dot{m}_w h_1 = \dot{m}_w h_2$$

Rearranging and substituting,

$$\dot{Q}_{w,in} = \dot{m}_w(h_2 - h_1) = (29.1 \text{ kg/min})[(104.83 - 62.982) \text{ kJ/kg}]$$
$$= \mathbf{1218 \text{ kJ/min}}$$

Ref. Cengel and Boles, 8th Edition (2015)

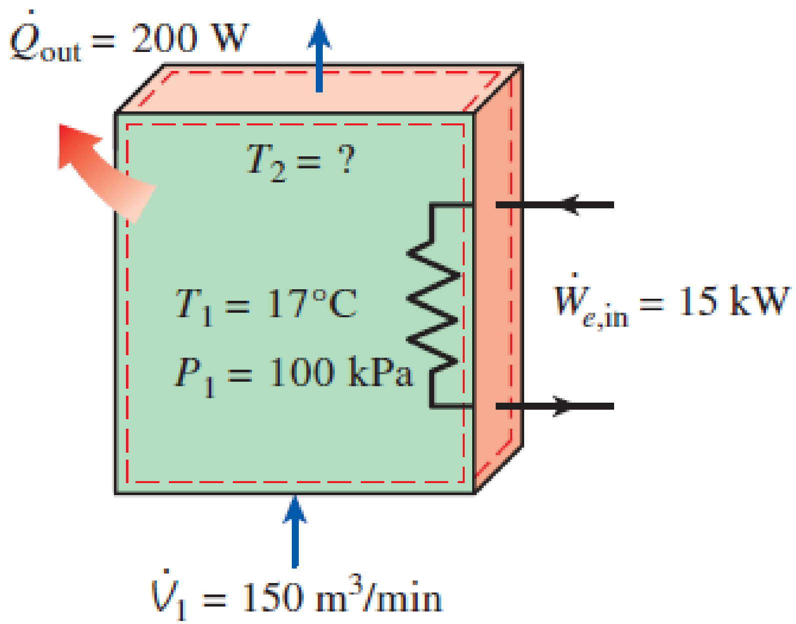
Problems on pipe and duct flow :

The transport of liquids or gases in pipes and ducts is of great importance in many engineering applications. Flow through a pipe or a duct usually satisfies the steady-flow conditions and thus can be analyzed as a steady-flow process. This, of course, excludes the transient start-up and shut-down periods. The control volume can be selected to coincide with the interior surfaces of the portion of the pipe or the duct that we are interested in analyzing.

Ref. Cengel and Boles, 8th Edition (2015)

Problems on pipe and duct flow :

The electric heating systems used in many houses consist of a simple duct with resistance heaters. 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°C with a volume flow rate of 150 m^3/min. If heat is lost from the air in the duct to the surroundings at a rate of 200 W, determine the exit temperature of air.

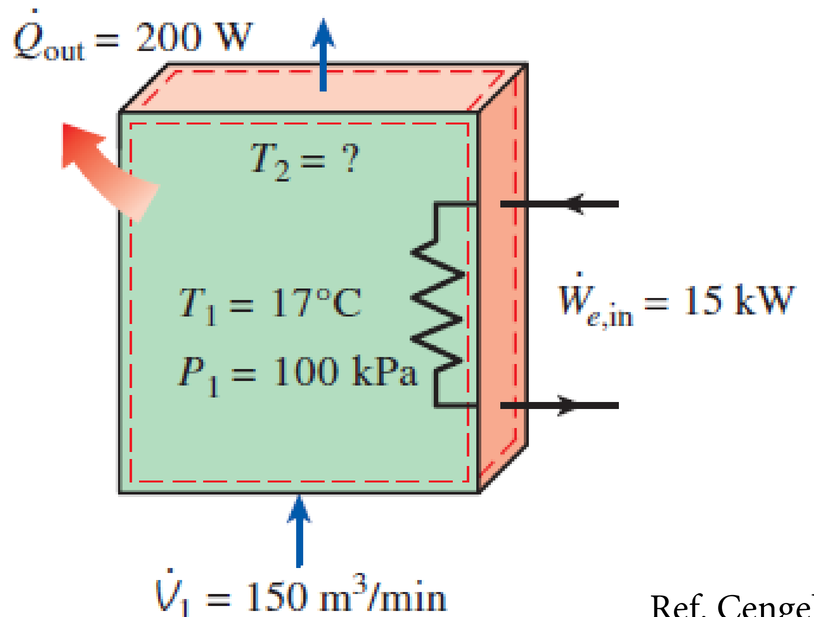


Ref. Cengel and Boles, 8th Edition (2015)

Problems on pipe and duct flow :

SOLUTION The electric heating system of a house is considered. For specified electric power consumption and air flow rate, the air exit temperature 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 negligible, $\Delta ke \cong \Delta pe \cong 0$. **4** Constant specific heats at room temperature can be used for air.



Control volume is taken as denoted by dotted red line in the figure.

The conditions at the inlet and outlet are denoted by subscripts "1" and "2", respectively.

Ref. Cengel and Boles, 8th Edition (2015)

Problems on pipe and duct flow :

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

$$\dot{W}_{e,\text{in}} - \dot{Q}_{\text{out}} = \dot{m}c_p(T_2 - T_1)$$

From the ideal-gas relation, the specific volume of air at the inlet of the duct is

$$v_1 = \frac{RT_1}{P_1} = \frac{(0.287 \text{ kPa}\cdot\text{m}^3/\text{kg}\cdot\text{K})(290 \text{ K})}{100 \text{ kPa}} = 0.832 \text{ m}^3/\text{kg}$$

The mass flow rate of the air through the duct is determined from

$$\dot{m} = \frac{\dot{V}_1}{v_1} = \frac{150 \text{ m}^3/\text{min}}{0.832 \text{ m}^3/\text{kg}}\left(\frac{1 \text{ min}}{60 \text{ s}}\right) = 3.0 \text{ kg/s}$$

Substituting the known quantities, the exit temperature of the air is determined to be

$$(15 \text{ kJ/s}) - (0.2 \text{ kJ/s}) = (3 \text{ kg/s})(1.005 \text{ kJ/kg}\cdot{}^\circ\text{C})(T_2 - 17)^\circ\text{C}$$

$$T_2 = \mathbf{21.9^\circ C}$$

Discussion Note that heat loss from the duct reduces the exit temperature of air.

Ref. Cengel and Boles, 8th Edition (2015)

Unsteady flow problems :

The following are the equations we shall use for solving unsteady flow problems.

Mass balance :

$$\frac{dM_{CV}}{dt} = \sum_{in} \dot{m} - \sum_{out} \dot{m}$$

First law (or energy balance) :

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

Unsteady flow problems :

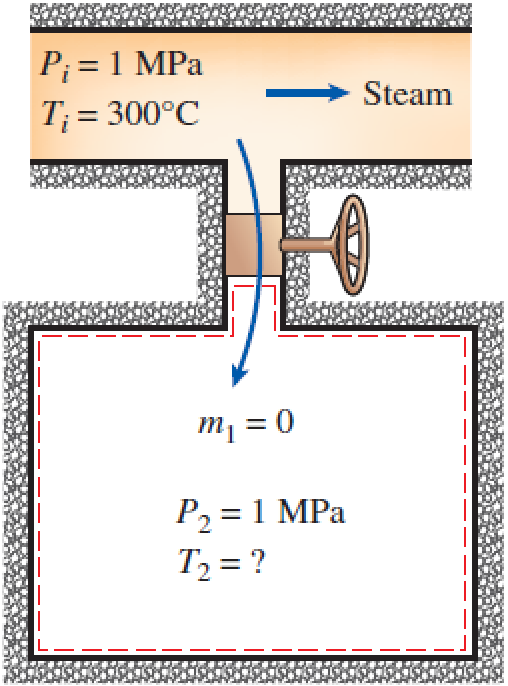
In order to simplify the unsteady-flow problems, we often make the following assumptions with respect to inlets and outlets. These assumptions are sometimes called as Uniform flow assumptions

(i) As in the case of steady flow problems, these properties are assumed to be constant over the cross sectional area of any inlet or outlet . This assumption is already taken into account in arriving at the equations on the last slide.

(ii) The fluid properties at any inlet or outlet do not change with time. In case properties at inlet or outlet change with time, the average values of these properties are considered and then this averages are treated as constants.

Unsteady flow problems :

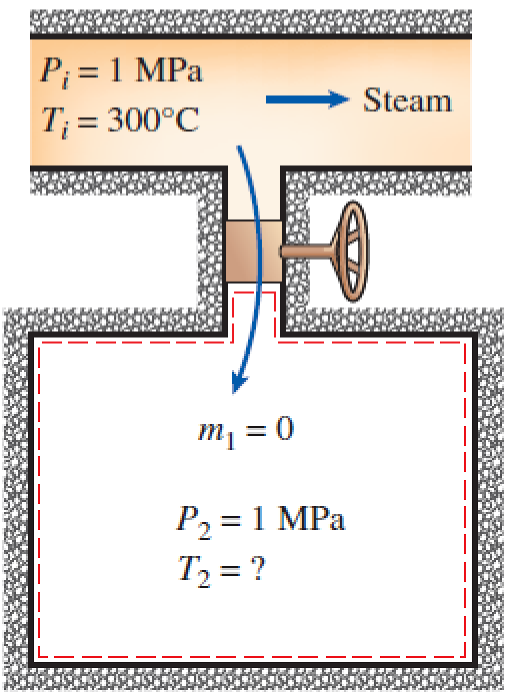
A rigid, insulated tank that is initially evacuated is connected through a valve to a supply line that carries steam at 1 MPa and 300°C. Now the valve is opened, and steam is allowed to flow slowly into the tank until the pressure reaches 1 MPa, at which point the valve is closed. Determine the final temperature of the steam in the tank.



Ref. Cengel and Boles, 8th Edition (2015)

Unsteady flow problems :

We consider tank as our control volume (denoted by dotted red line in the figure below). We make uniform flow assumption for the flow through the inlet to the tank. Further we neglect changes in potential and kinetic energies.



Ref. Cengel and Boles, 8th Edition (2015)

Since there is only a single inlet and no outlet, mass balance equation reduces to:

$$\frac{dM_{CV}}{dt} = \dot{m}_{in}$$

Integrating both sides with respect to time, we get

$$m_2 - m_1 = m_{in}$$

Since tank is empty initially, $m_1 = 0$

Therefore, mass balance equation yields

$$m_2 = m_{in}$$

Unsteady flow problems :

Since there is a single inlet and no outlet, neglecting kinetic and potential energies at inlet, energy balance yields

$$\frac{dE_{CV}}{dt} = (\dot{m}h)_{in}$$

Neglecting changes in kinetic and potential energies

of the mass of the fluid in the tank, we get

$$\frac{d(mu)_{CV}}{dt} = \dot{m}_{in}h_{in}$$

Integrating with respect to time while considering

h(inlet) to be constant, we get

$(mu)_2 - (mu)_1 = m_{in}h_{in}$

Since as per mass balance $m_1 = 0$ and $m_{in} = m_2$, we get

$m_2u_2 = m_2h_{in}$

Cancelling m_2 from both sides, we get

$u_2 = h_{in}$

Unsteady flow problems :

To find out the inlet enthalpy, the relevant portion of Table A-6 is reproduced below :

TABLE A–6

Superheated water (*Concluded*)

T °C	v m^3/kg	u kJ/kg	h kJ/kg	s kJ/kg·K
		P = 1.00 MPa (179.88°C)		
Sat.	0.19437	2582.8	2777.1	6.5850
200	0.20602	2622.3	2828.3	6.6956
250	0.23275	2710.4	2943.1	6.9265
300	0.25799	2793.7	3051.6	7.1246
350	0.28250	2875.7	3158.2	7.3029
400	0.30661	2957.9	3264.5	7.4670
500	0.35411	3125.0	3479.1	7.7642

From this table, h_{in} (1 MPa, 300 ^{0}C) = 3051.6 kJ/kg

Therefore as per energy balance, $u_2 = h_{in}$ = 3051.6 kJ/kg.

If we check the third column in the above table,

$$u\,(1\text{ MPa}, 500\,^0\text{C}) > u_2 > u\,(1\text{ MPa}, 400\,^0\text{C})$$

We therefore use **linear interpolation** to find T_2 as follows :

$$T_2=400+\left(\frac{500\text{-}400}{3125\text{-}2957.9}\right)(3051.6\text{-}2957.9)=456.1\ ^0\text{C}$$

Ref. Cengel and Boles, 8th Edition (2015)

Unsteady flow problems :

Discussion : Note that the temperature of the steam in the tank is higher than the temperature of the steam in the supply line. This is because flow work is being done in pushing the steam into the tank and as a result of this energy transfer the temperature of the steam in the tank increases.