CAE 208 / MMAE 320: Thermodynamics

Fall 2023

October 19, 2023

Mass & energy analysis of control volumes (3)

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ANNOUNCEMENTS

Announcements

- Assignment 5 solutions is posted

- Assignment 6 is due this Thursday

Announcements

- Midterm Exam 2 is moved to November 9 to accommodate the Physics exam

Announcements

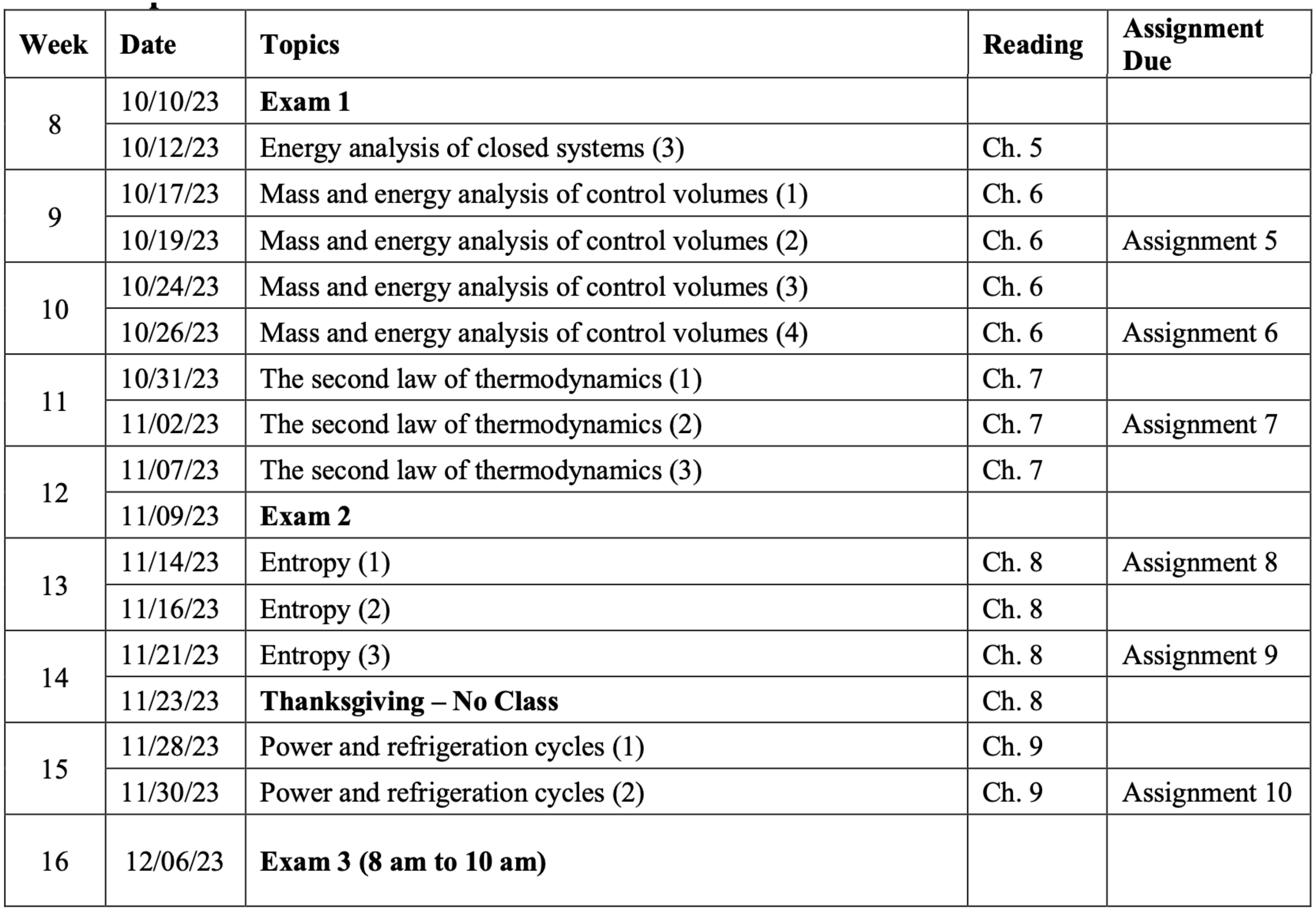
- Final exam date is posted:
  - ❑ Date: December 6
  - ❑ Time: 8 am to 10 am
  - ❑ Room: WH 116

Announcements

- Do not forget about the TA's office hours
  - ❑ Mondays 13-14:30
  - ❑ Fridays 11:30-13
  - ❑ Or schedule an appointment

Announcements

- The updated course syllabus:



Week	Date	Topics	Reading	Assignment Due
8	10/10/23	**Exam 1**		
	10/12/23	Energy analysis of closed systems (3)	Ch. 5	
9	10/17/23	Mass and energy analysis of control volumes (1)	Ch. 6	
	10/19/23	Mass and energy analysis of control volumes (2)	Ch. 6	Assignment 5
10	10/24/23	Mass and energy analysis of control volumes (3)	Ch. 6	
	10/26/23	Mass and energy analysis of control volumes (4)	Ch. 6	Assignment 6
11	10/31/23	The second law of thermodynamics (1)	Ch. 7	
	11/02/23	The second law of thermodynamics (2)	Ch. 7	Assignment 7
12	11/07/23	The second law of thermodynamics (3)	Ch. 7	
	11/09/23	**Exam 2**		
13	11/14/23	Entropy (1)	Ch. 8	Assignment 8
	11/16/23	Entropy (2)	Ch. 8	
14	11/21/23	Entropy (3)	Ch. 8	Assignment 9
	11/23/23	**Thanksgiving – No Class**	Ch. 8	
15	11/28/23	Power and refrigeration cycles (1)	Ch. 9	
	11/30/23	Power and refrigeration cycles (2)	Ch. 9	Assignment 10
16	12/06/23	**Exam 3 (8 am to 10 am)**		

RECAP

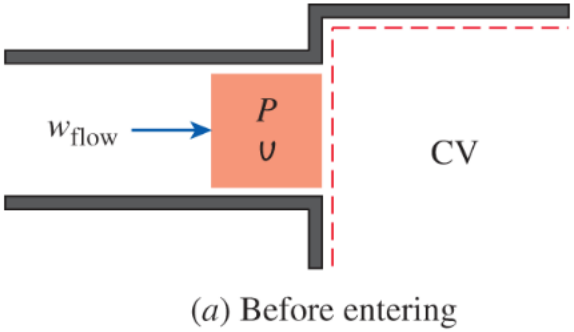
Recap

- To push the entire fluid element into the control volume, this force must act through a distance L

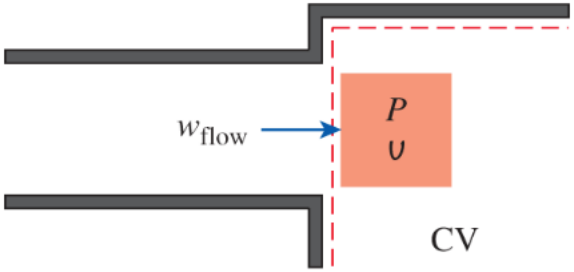
$$F = PA$$

$$W_{flow} = FL = PAL = P\forall$$

$$w_{flow} = Pv$$



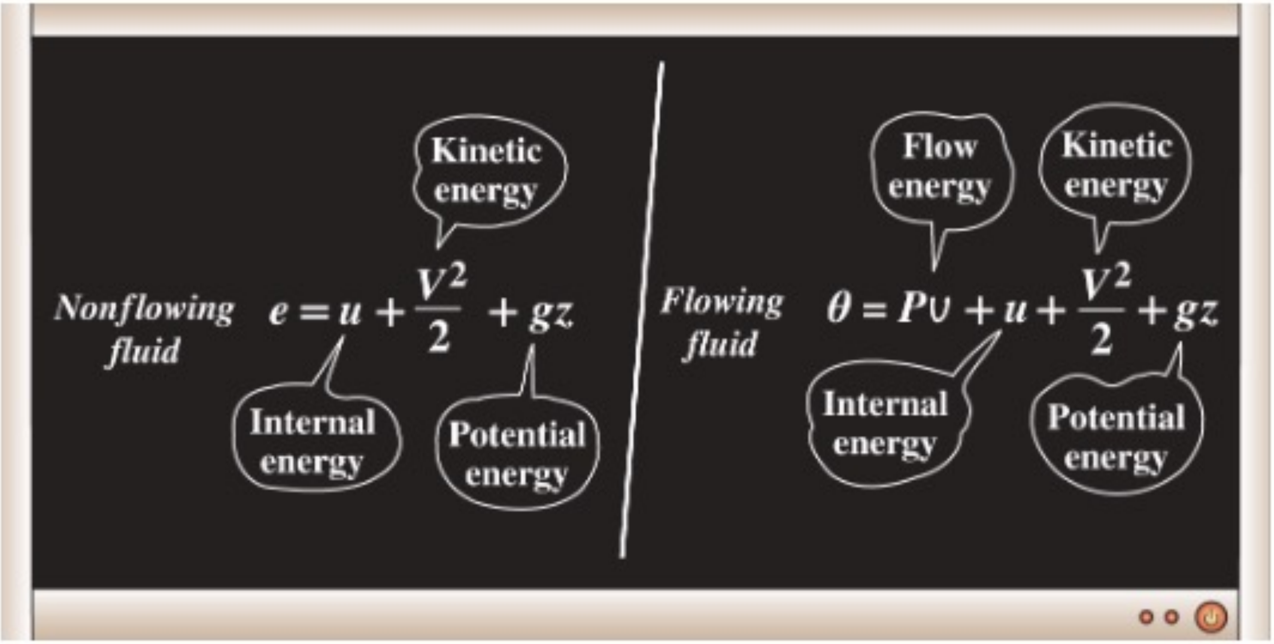
(*a*) Before entering



(*b*) After entering

Recap

- Total energy of a flowing fluid is:



$$\theta = Pv + e = Pv + (u + ke + pe) = (u + Pv) + ke + pe$$

QUIZ

Quiz

Quiz

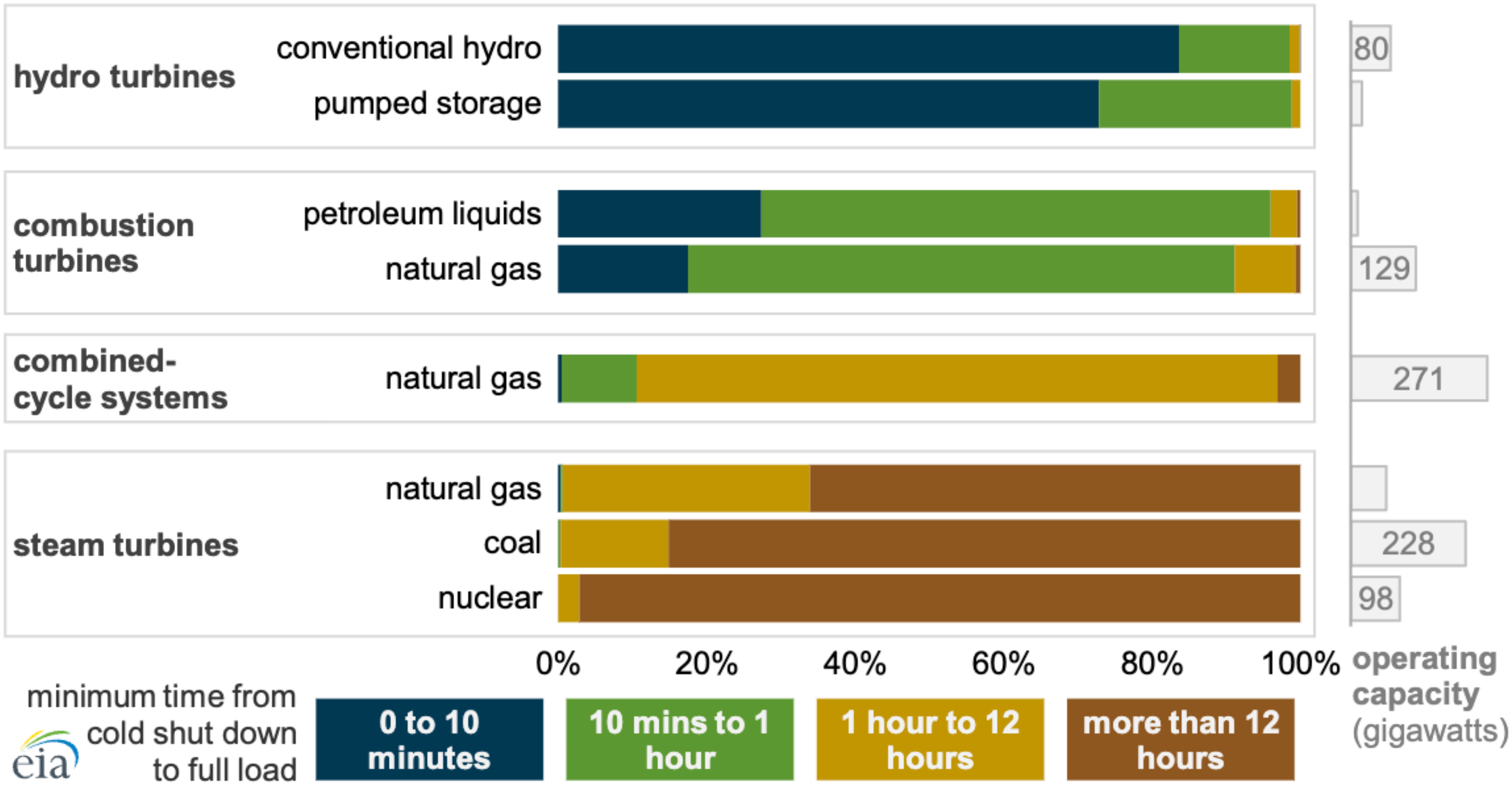
ENERGY ANALYSIS OF STEADY-FLOW SYSTEMS

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 conditions once the transient start-up period is completed and steady operation is established, and they are classified as *steady-flow devices*.

Energy Analysis of Steady-Flow Systems

- For example, power plants:



U.S. electric generating capacity by minimum time from cold shut down to full load (2019)

Source: U.S. Energy Information Administration, *Annual Electric Generator Inventory*
Note: Only technology/fuel combinations with at least 10 gigawatts of operating capacity are shown.

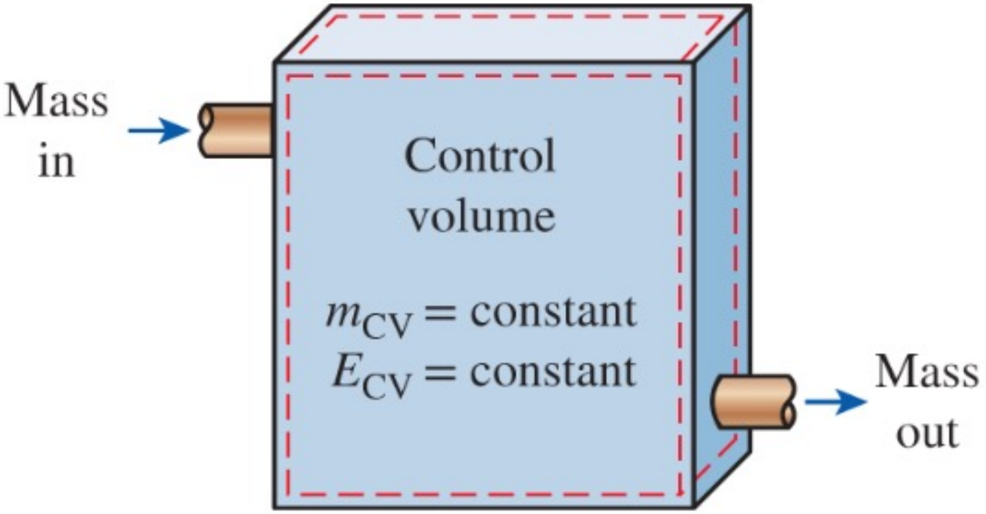
Energy Analysis of Steady-Flow Systems

- Process involving such devices can be represented reasonably well by a somewhat idealized process, called steady-flow process which was defined as a process during which a fluid flows through a control volume steadily

What do you think about a spatial and temporal change in a tank with a steady-flow?

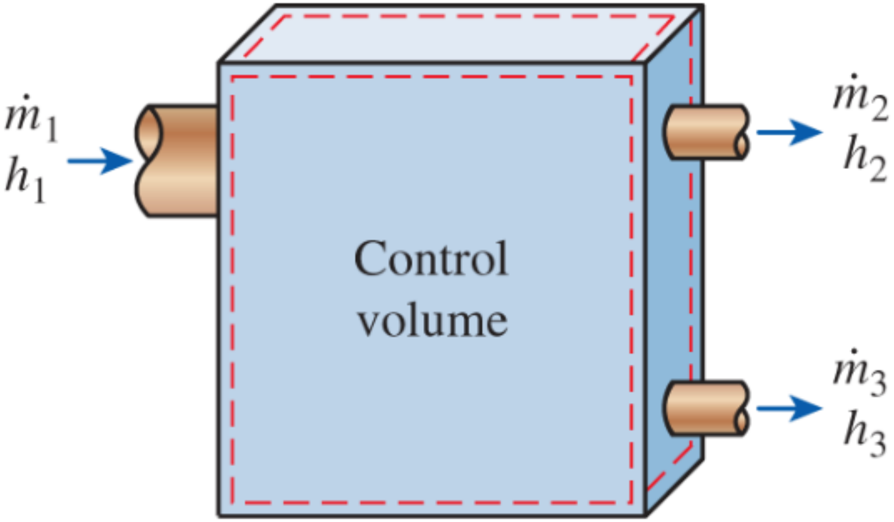
Energy Analysis of Steady-Flow Systems

- Steady-flow process:
  - ❑ No intensive or extensive properties within the control volume change with time
  - ❑ Boundary work is zero
  - ❑ $\Delta E_{CV} = 0$



Energy Analysis of Steady-Flow Systems

- Steady-flow process:
  - ☐ Power remain constant



Energy Analysis of Steady-Flow Systems

- Steady-flow process:

$$\sum_{in} \dot{m} = \sum_{out} \dot{m}$$

$$\dot{m}_1 = \dot{m}_2 \;\rightarrow\; \rho_1 A_1 V_1 = \rho_2 A_2 V_2$$

Energy Analysis of Steady-Flow Systems

- Steady-flow process:

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

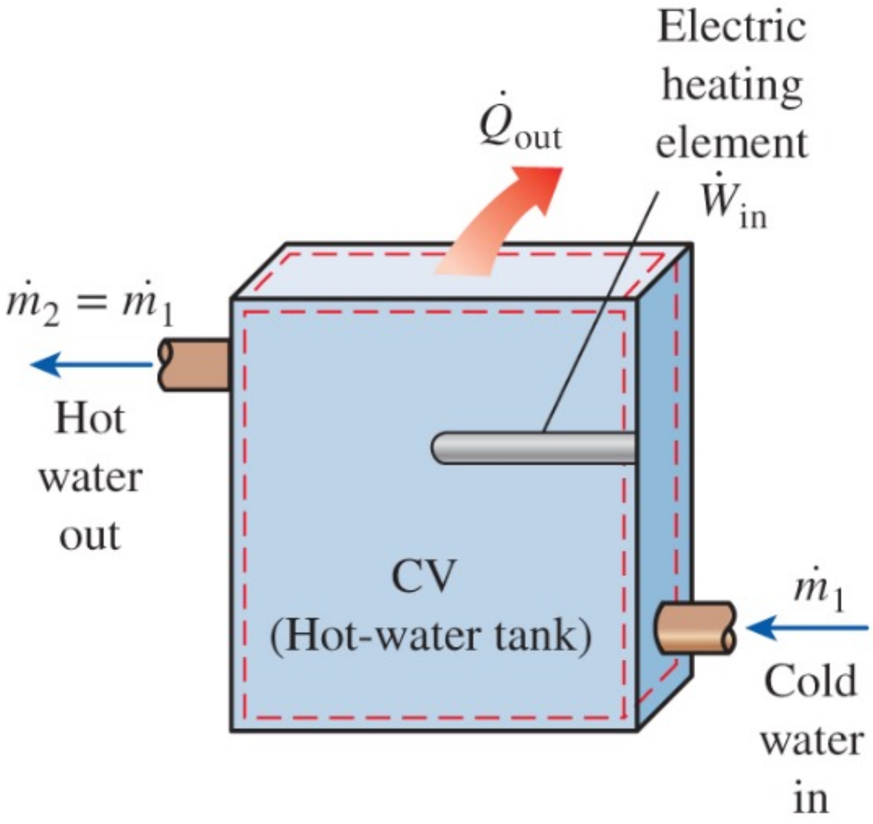
$$\dot{E}_{in} = \dot{E}_{out}$$

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

$$\dot{Q}_{in} + W_{in} + \sum_{in} \dot{m}(h + \frac{V^2}{2} + gz) = \dot{Q}_{out} + W_{out} + \sum_{out} \dot{m}(h + \frac{V^2}{2} + gz)$$

Energy Analysis of Steady-Flow Systems

- Consider an electric hot water heater under steady condition



Energy Analysis of Steady-Flow Systems

- Consider an electric hot water heater under steady condition

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

$$\dot{Q} - \dot{W} = \dot{m}\left(h_2 - h_1 + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)\right)$$

$$q - w = h_2 - h_1 + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)$$

$$q - w = h_2 - h_1$$

Energy Analysis of Steady-Flow Systems

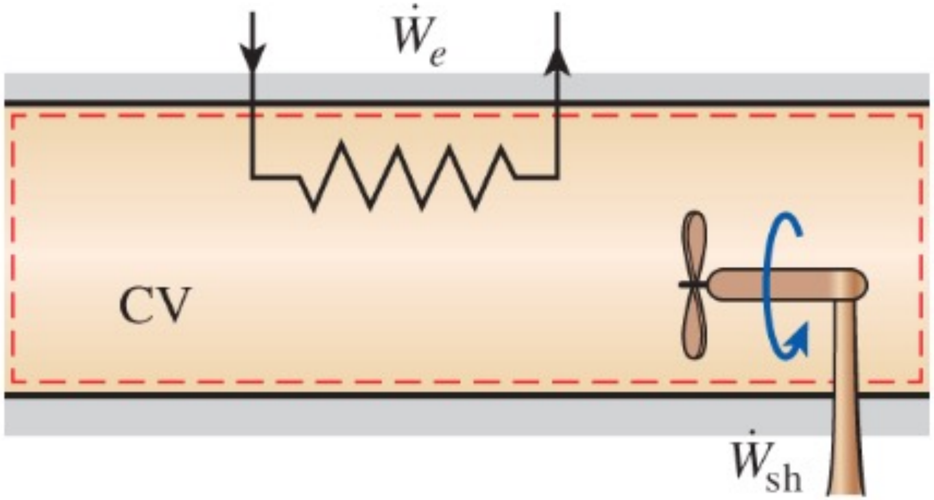
- Let’s look at $\dot{Q}$
  - ☐ Adiabatic
  - ☐ Heat transfer

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

Energy Analysis of Steady-Flow Systems

- Let’s look at $\dot{W}$:
  - ❑ Shaft work
  - ❑ Electrical work

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



Energy Analysis of Steady-Flow Systems

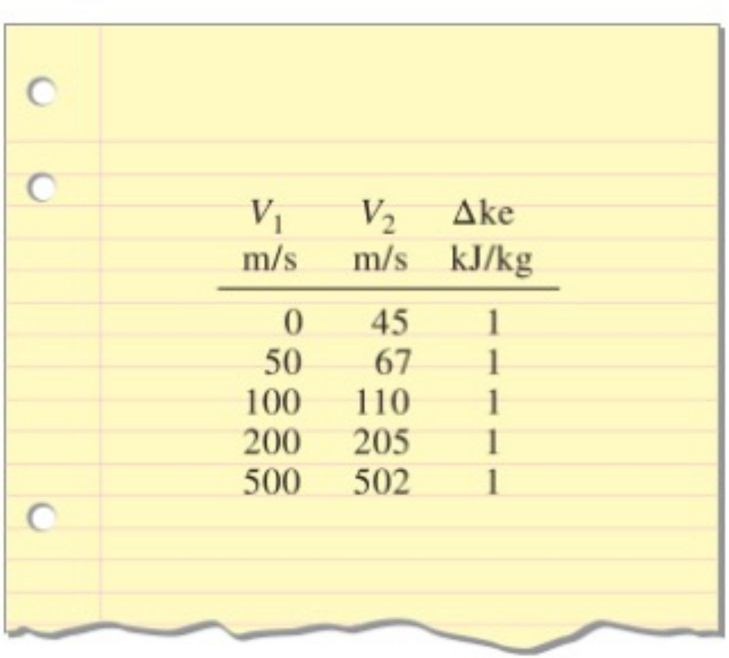
- Let’s look at $\Delta h = h_2 - h_1 = c_{p,avg}(T_2 - T_1)$

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

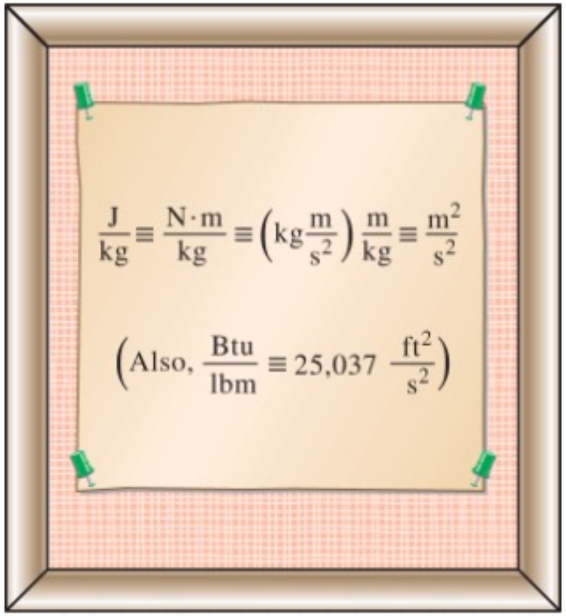
Energy Analysis of Steady-Flow Systems

- Let’s look at Δke

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



V_1 m/s	V_2 m/s	Δke kJ/kg
0	45	1
50	67	1
100	110	1
200	205	1
500	502	1



$$\frac{\text{J}}{\text{kg}} \equiv \frac{\text{N}\cdot\text{m}}{\text{kg}} \equiv \left(\text{kg}\frac{\text{m}}{\text{s}^2}\right)\frac{\text{m}}{\text{kg}} \equiv \frac{\text{m}^2}{\text{s}^2}$$

$$\left(\text{Also, } \frac{\text{Btu}}{\text{lbm}} \equiv 25{,}037 \ \frac{\text{ft}^2}{\text{s}^2}\right)$$

Energy Analysis of Steady-Flow Systems

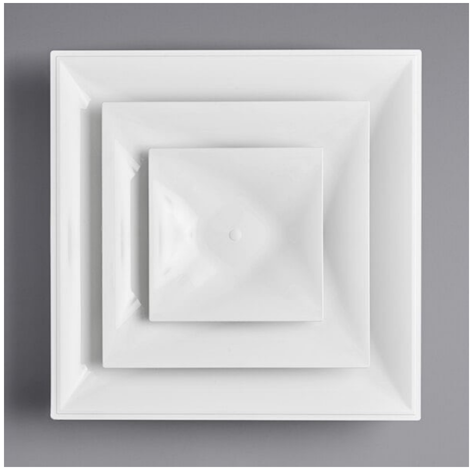
- Let’s look at Δpe

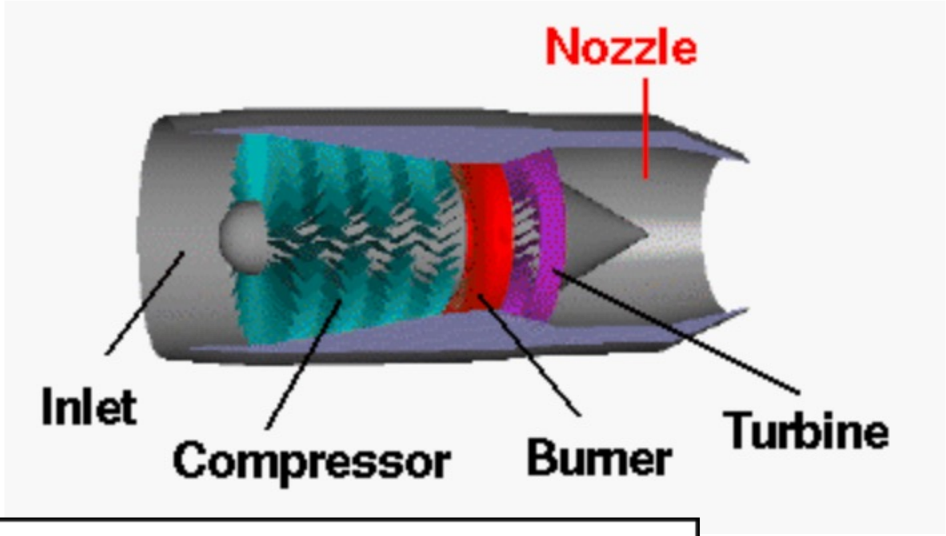
$$\dot{Q} - \dot{W} = \sum_{out} \dot{m}\left(h + \frac{V^2}{2} + gz\right) - \sum_{in} \dot{m}(h + \frac{V^2}{2} + gz)$$

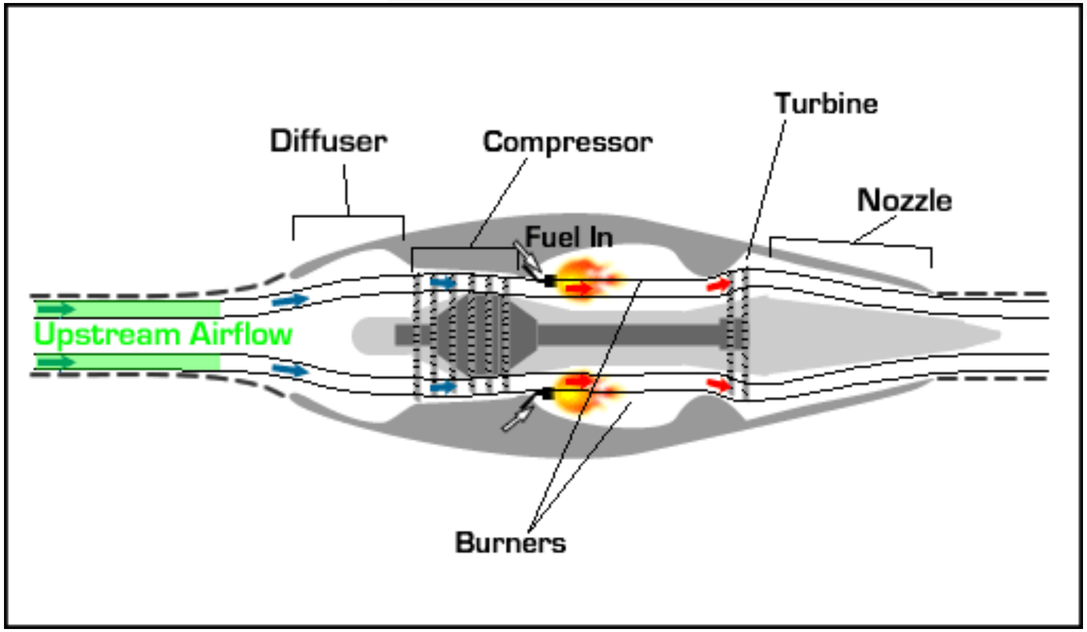
SOME STEADY-FLOW ENGINEERING DEVICES

Some Steady-Flow Energy Devices

- **Nozzles and Diffusers**



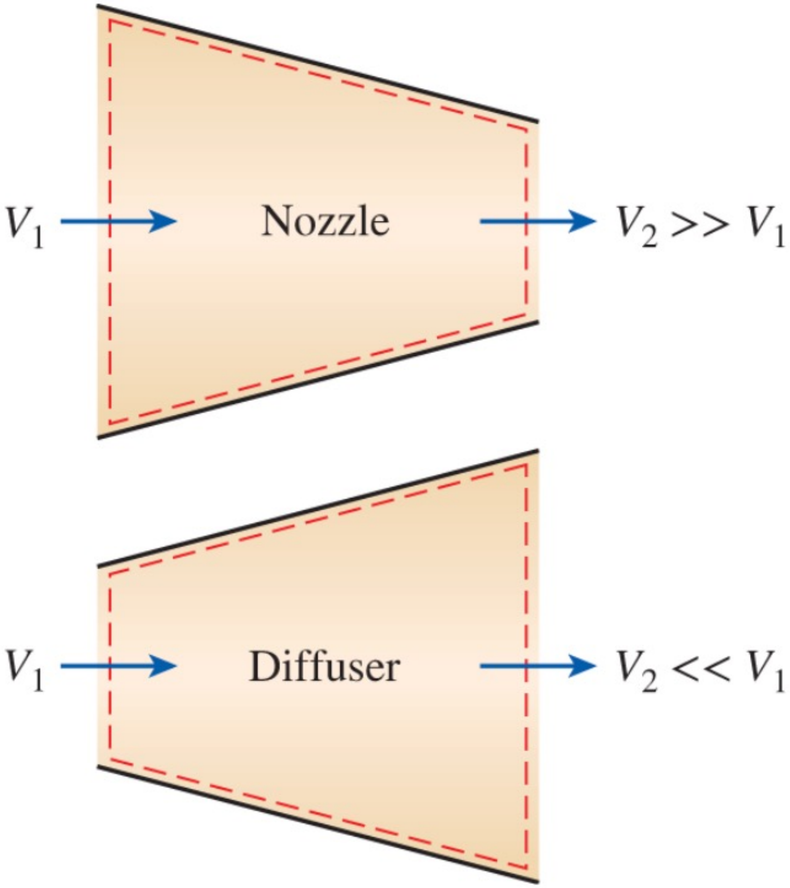




https://s2.smu.edu/ *& NASA*

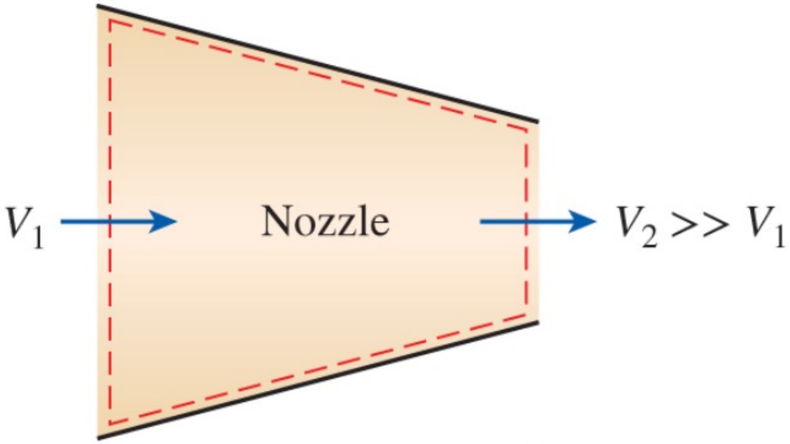
Some Steady-Flow Energy Devices

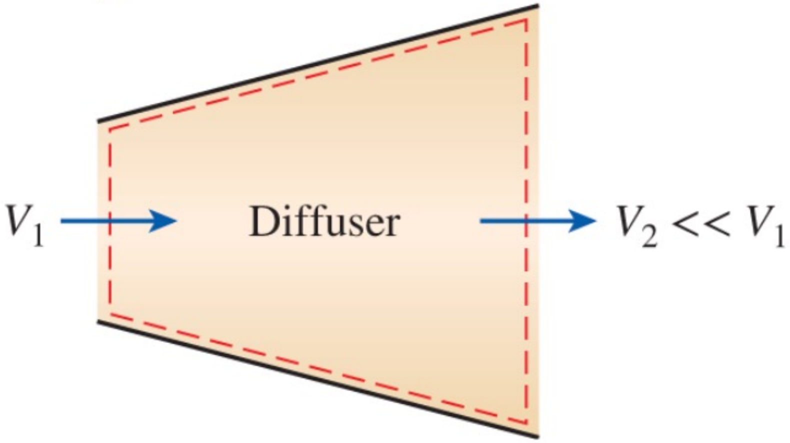
- **Nozzles and Diffusers**



Some Steady-Flow Energy Devices

- **Nozzles and Diffusers**





$$\dot{Q} \cong 0$$

$$\dot{W} = 0 \; (most\ times)$$

$$\Delta pe \cong 0$$

$$\Delta ke \neq 0$$

CLASS ACTIVITY

Class Activity

- 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
  b) The temperature of the air leaving the diffuser

Class Activity

- Solution (assumptions):
  1. This is a steady-flow process ($\Delta m_{CV} = 0$ 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 potential energy balance change is zero
  4. $\Delta pe = 0$
  5. Heat transfer is negligible
  6. Kinetic energy at the diffuser exit is negligible
  7. There are no work interactions

Class Activity

- Solution (a):

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

$$v_1 = \frac{RT_1}{P_1} = \frac{\left(0.287\ kPa - \frac{m^3}{kg-K}\right)(283\ K)}{80\ kPa} = 1.015\,\frac{m^3}{kg}$$

$$\dot{m}_1 = \rho_1 A_1 V_1 = \left(\frac{1}{v_1}\right) A_1 V_1 = \left(\frac{1}{0.15\,\frac{m^3}{kg}}\right)(0.4\ m^2)\left(200\,\frac{m}{s}\right) = 78.8\,\frac{kg}{s}$$

Class Activity

- Solution (b):

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

$$\dot{E}_{in} = \dot{E}_{out}$$

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

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

$(V_2^2 \ll V_1^2)$

Class Activity

- Solution (b):

$$Using\ Table\ A-21 \rightarrow\ h_1 = h_{@\,283\,K} = 283.14\frac{kJ}{kg}$$

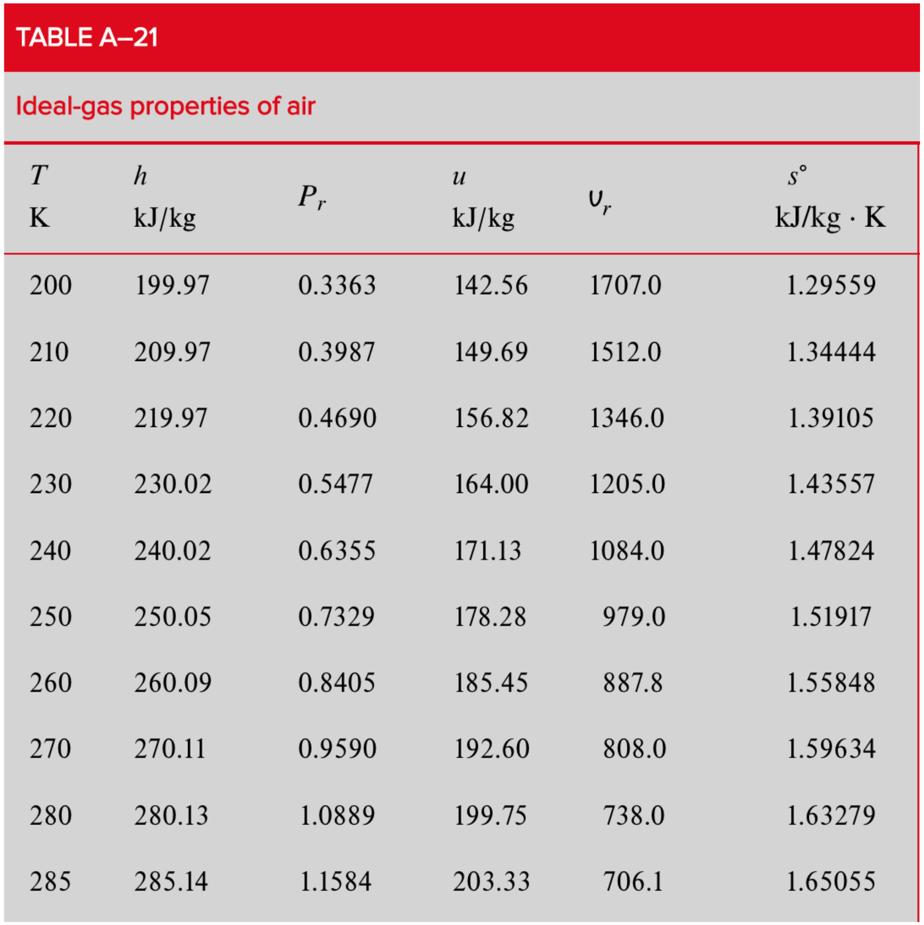


TABLE A–21

Ideal-gas properties of air

T K	h kJ/kg	P_r	u kJ/kg	v_r	$s°$ kJ/kg · K
200	199.97	0.3363	142.56	1707.0	1.29559
210	209.97	0.3987	149.69	1512.0	1.34444
220	219.97	0.4690	156.82	1346.0	1.39105
230	230.02	0.5477	164.00	1205.0	1.43557
240	240.02	0.6355	171.13	1084.0	1.47824
250	250.05	0.7329	178.28	979.0	1.51917
260	260.09	0.8405	185.45	887.8	1.55848
270	270.11	0.9590	192.60	808.0	1.59634
280	280.13	1.0889	199.75	738.0	1.63279
285	285.14	1.1584	203.33	706.1	1.65055

Class Activity

- Solution (b):

$$Using\ Table\ A-21\ \rightarrow\ h_1 = h_{@\ 283\ K} = 283.14\,\frac{kJ}{kg}$$

$$h_2 = 283.14\,\frac{kJ}{kg} - \frac{0-\left(200\,\frac{m}{s}\right)^2}{2}\left(\frac{1\,\frac{kJ}{kg}}{1000\,\frac{m^2}{s^2}}\right) = 303.14\,\frac{kJ}{kg}$$

Class Activity

- Solution (b):

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

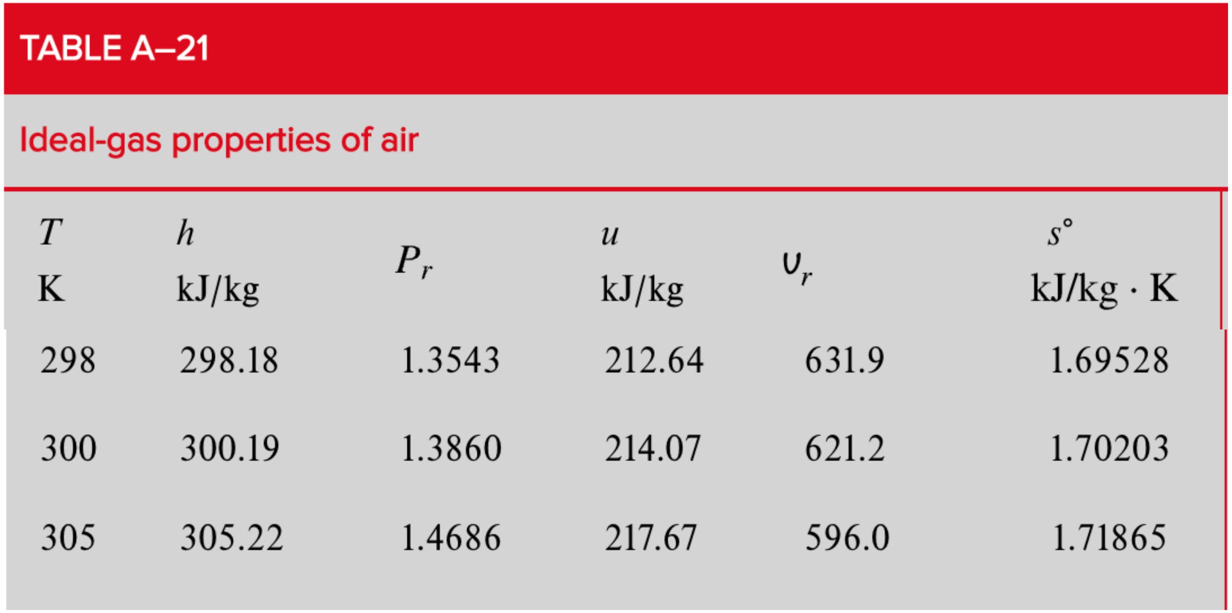


TABLE A–21

Ideal-gas properties of air

T K	h kJ/kg	P_r	u kJ/kg	v_r	$s°$ kJ/kg · K
298	298.18	1.3543	212.64	631.9	1.69528
300	300.19	1.3860	214.07	621.2	1.70203
305	305.22	1.4686	217.67	596.0	1.71865

$$From\ Table\ A - 21\ \rightarrow T_2 = 303\ K$$

Some Steady-Flow Energy Devices

- **Turbines, Compressors, fans, and Pumps**
  - ☐ Turbine produce power output whereas compressors, pumps, and fans require power input
  - ☐ Heat Transfer is usually negligible ($\dot{Q} \cong 0$)
  - ☐ Potential energy is negligible ($pe \cong 0$)
  - ☐ Kinetic energy is negligible ($ke \cong 0$) - except for fans and turbines but the change in enthalpy is significant compared to the velocity change

CLASS ACTIVITY

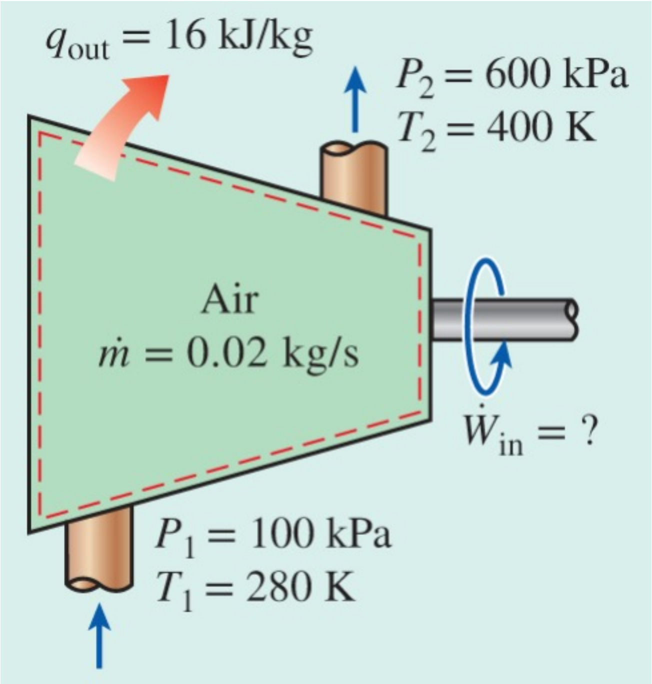
Class Activity

- 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.

Class Activity

- Solution (assumptions):
  1. Steady-flow ($\Delta m_{CV} = 0$ and $\Delta \mathrm{E}_{\mathrm{CV}} = 0$)
  2. Air is an ideal gas since it is at a high temperature and low pressure relative to its critical-point value
  3. The kinetic and potential energy changes are zero ($\Delta \mathrm{ke} = \Delta pe = 0$)

$$\dot{m}_1 = \dot{m}_2 = \dot{m} = 0.02\,\frac{kg}{s}$$



Class Activity

- Solution:

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

$$\dot{W}_{in} + \dot{m}h_1 = \dot{Q}_{out} + \dot{m}h_2$$

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

Class Activity

- Solution (From Table A-21):

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

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

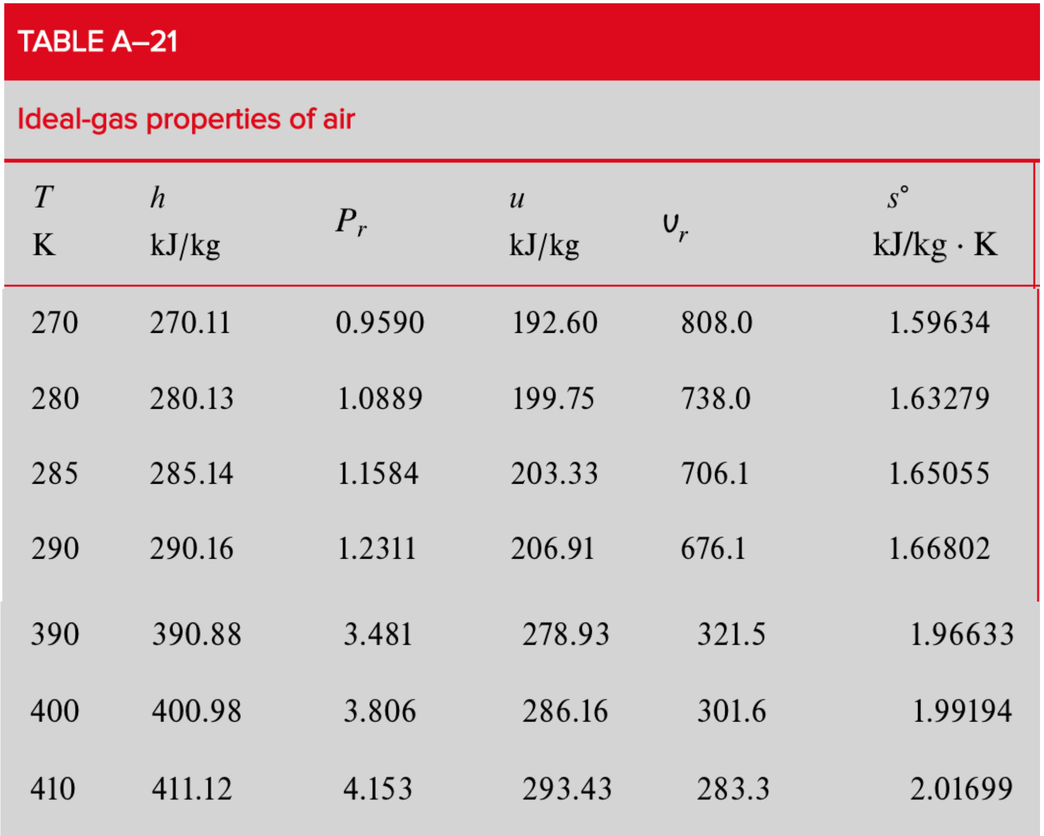


TABLE A–21

Ideal-gas properties of air

T K	h kJ/kg	P_r	u kJ/kg	v_r	$s°$ kJ/kg · K
270	270.11	0.9590	192.60	808.0	1.59634
280	280.13	1.0889	199.75	738.0	1.63279
285	285.14	1.1584	203.33	706.1	1.65055
290	290.16	1.2311	206.91	676.1	1.66802
390	390.88	3.481	278.93	321.5	1.96633
400	400.98	3.806	286.16	301.6	1.99194
410	411.12	4.153	293.43	283.3	2.01699

Class Activity

- Solution:

$$\dot{W}_{in} = \left(0.02\,\frac{kg}{s}\right)\left(16\,\frac{kJ}{kg}\right) + \left(0.02\,\frac{kg}{s}\right)\left(400.98 - 280.13\,\frac{kJ}{kg}\right) = 2.74\ kW$$

Some Steady-Flow Energy Devices

- **Throttling valves**
  - Throttling valves are any kind of flow-restricting devices that cause a significant pressure drop in the fluid (e.g., valves, capillary tubes, porous plugs)
  - 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

(*a*) An adjustable valve

(*b*) A porous plug

(*c*) A capillary tube

Some Steady-Flow Energy Devices

- **Throttling valves**

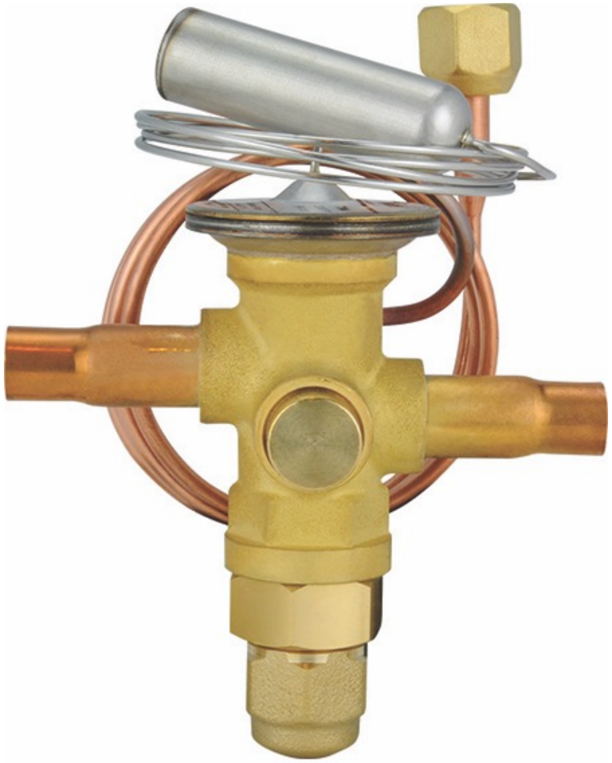
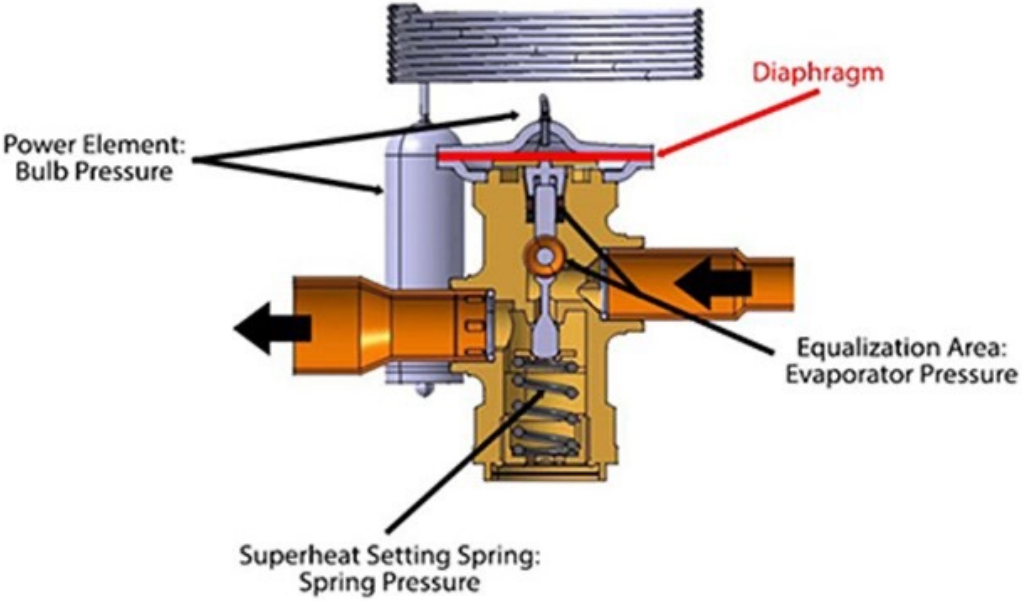


Figure 1



TXV Parts

Credit: Danfoss

Some Steady-Flow Energy Devices

- **Throttling valves**
  - ☐ They are usually small, the process can be adiabatic ($q \cong 0$)
  - ☐ No work is done ($w \cong 0$)
  - ☐ $\Delta pe \cong 0$
  - ☐ $\Delta ke \cong 0$

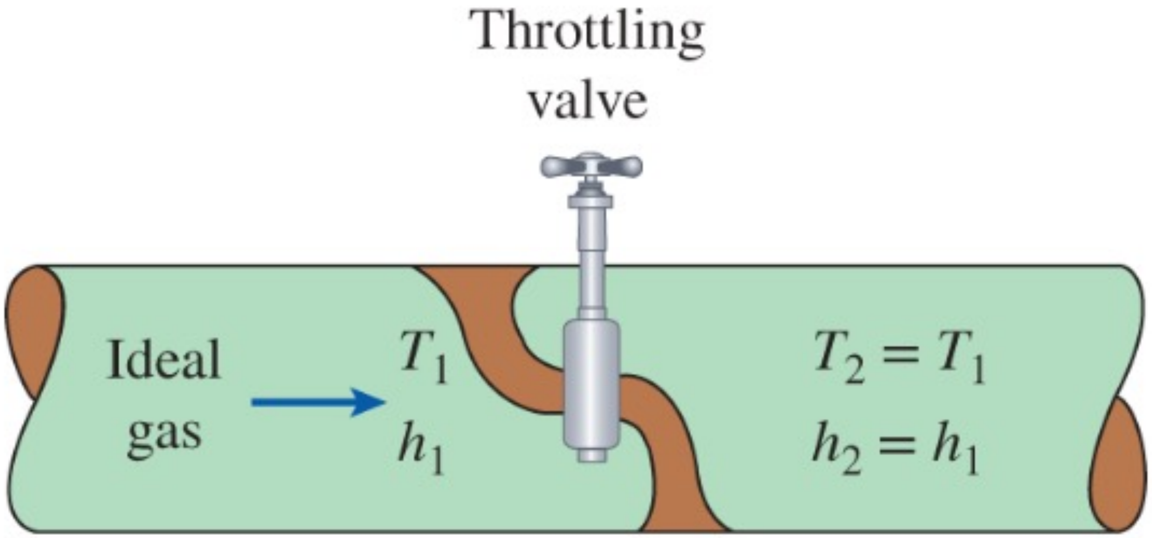
$$h_2 \cong h_1$$ *(Isenthalpic device)*

$$u_1 + P_1 v_1 = u_2 + P_2 v_2$$

$$Internal\ energy + Flow\ energy = Constant$$

Some Steady-Flow Energy Devices

- **Throttling valves**
  - ☐ In case of an ideal gas, $h = h(T)$, and thus the temperature has to remain constant during a throttling process:



CLASS ACTIVITY

Class Activity

- Refrigerant-134a enters the capillary tube of a refrigerator as saturated liquid at 0.8 MPa and is throttled to a pressure of 0.12 MPa. Determine the quality of the refrigerant at the final state and the temperature drop during this process

Class Activity

- Solution:

At inlet:

$$\left.\begin{array}{c} P_1 = 0.8\ MPa \\ sat.\ liquid \end{array}\right\} \rightarrow \begin{array}{c} T_1 = T_{sat\ @\ 0.8\ MPa = 31.31\ °C} \\ h_1 = h_{f\ @\ 0.8\ MPa = 95.48\ kJ/kg} \end{array}$$

(Table A-12)

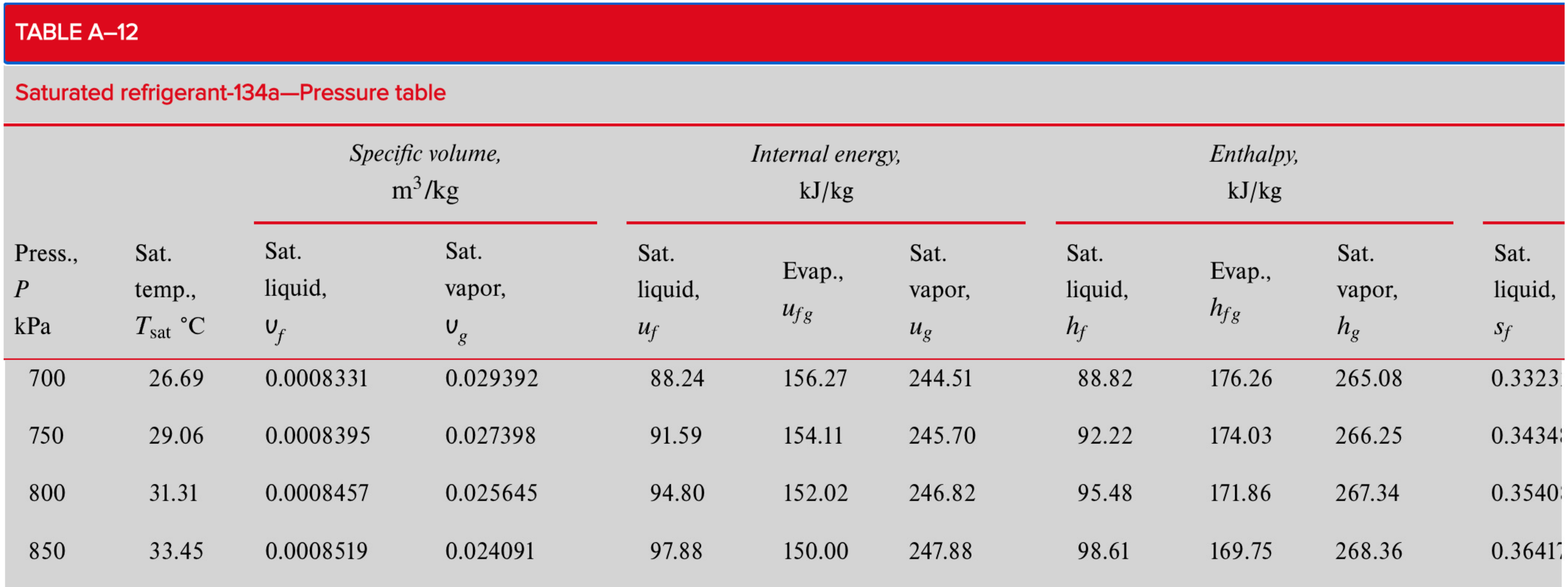


TABLE A–12

Saturated refrigerant-134a—Pressure table

		Specific volume, m^3/kg		*Internal energy,* kJ/kg			*Enthalpy,* kJ/kg			
Press., P kPa	Sat. temp., T_{sat} °C	Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, s_f
700	26.69	0.0008331	0.029392	88.24	156.27	244.51	88.82	176.26	265.08	0.3323
750	29.06	0.0008395	0.027398	91.59	154.11	245.70	92.22	174.03	266.25	0.3434
800	31.31	0.0008457	0.025645	94.80	152.02	246.82	95.48	171.86	267.34	0.3540
850	33.45	0.0008519	0.024091	97.88	150.00	247.88	98.61	169.75	268.36	0.3641

Class Activity

- Solution:

At exit

$$\left.\begin{matrix} P_2 = 0.12\ MPa \\ h_1 = h_2 \end{matrix}\right\} \rightarrow \begin{matrix} h_f = 22.47\ kJ/kg \\ h_g = 236.99\ kJ/kg \end{matrix} \rightarrow T_{sat} = -22.32\,°C$$

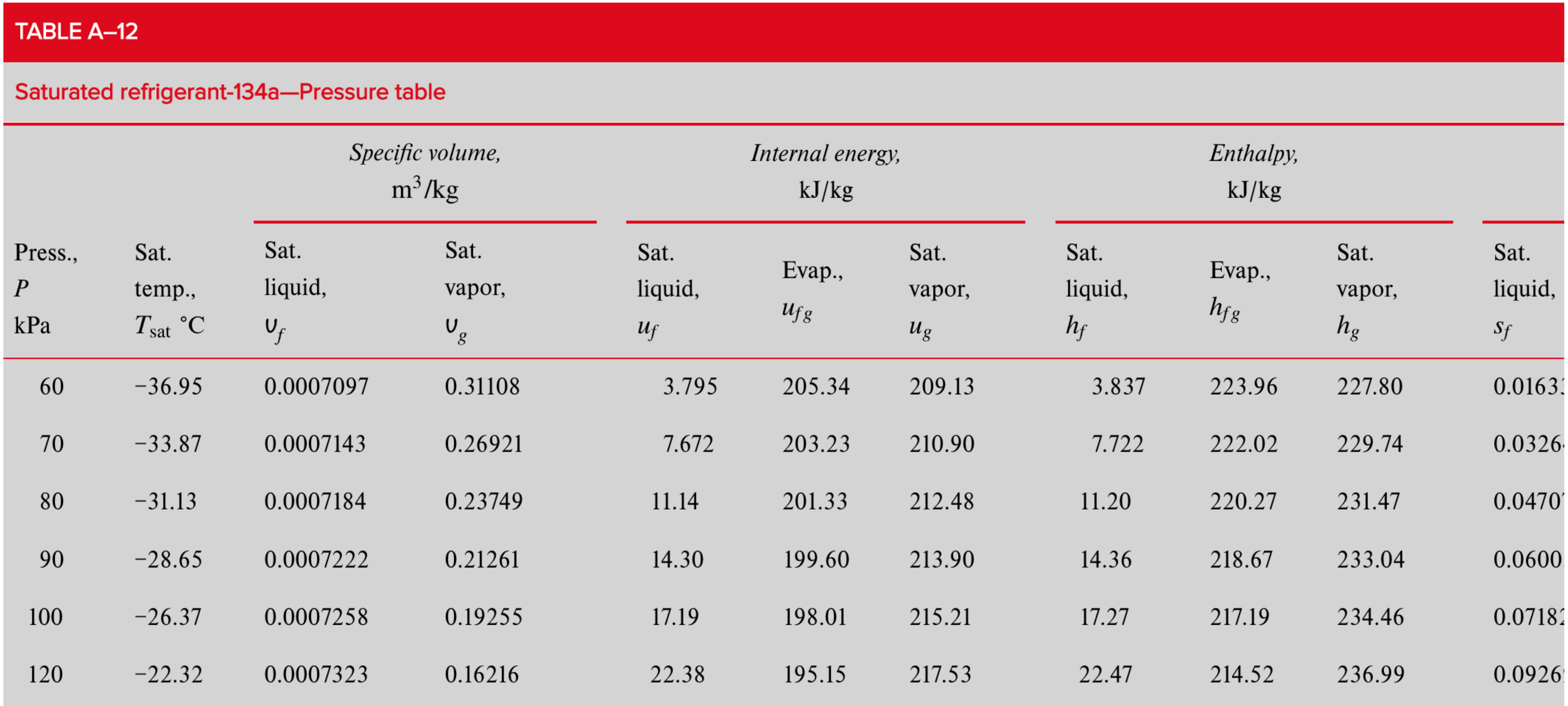


TABLE A–12

Saturated refrigerant-134a—Pressure table

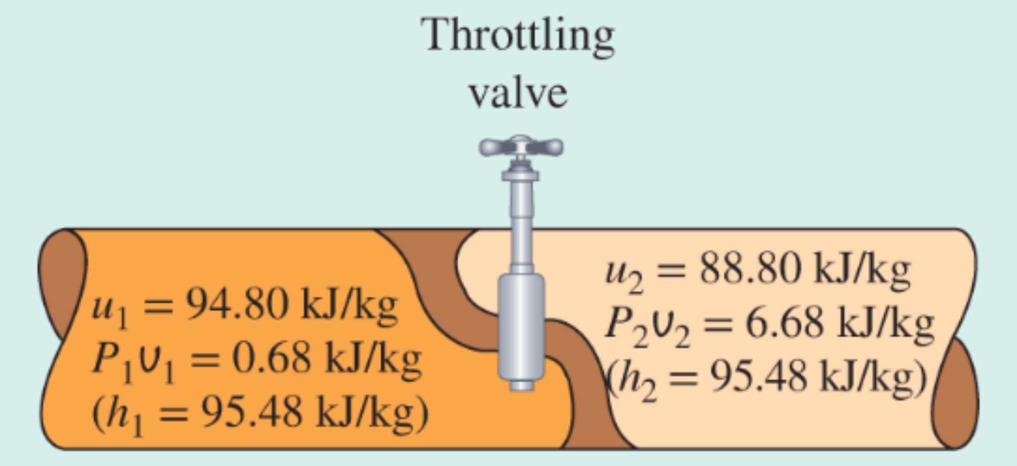
		Specific volume, m^3/kg		Internal energy, kJ/kg			Enthalpy, kJ/kg			
Press., P kPa	Sat. temp., T_{sat} °C	Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, s_f
60	−36.95	0.0007097	0.31108	3.795	205.34	209.13	3.837	223.96	227.80	0.0163
70	−33.87	0.0007143	0.26921	7.672	203.23	210.90	7.722	222.02	229.74	0.0326
80	−31.13	0.0007184	0.23749	11.14	201.33	212.48	11.20	220.27	231.47	0.0470
90	−28.65	0.0007222	0.21261	14.30	199.60	213.90	14.36	218.67	233.04	0.0600
100	−26.37	0.0007258	0.19255	17.19	198.01	215.21	17.27	217.19	234.46	0.0718
120	−22.32	0.0007323	0.16216	22.38	195.15	217.53	22.47	214.52	236.99	0.0926

Class Activity

- Solution:

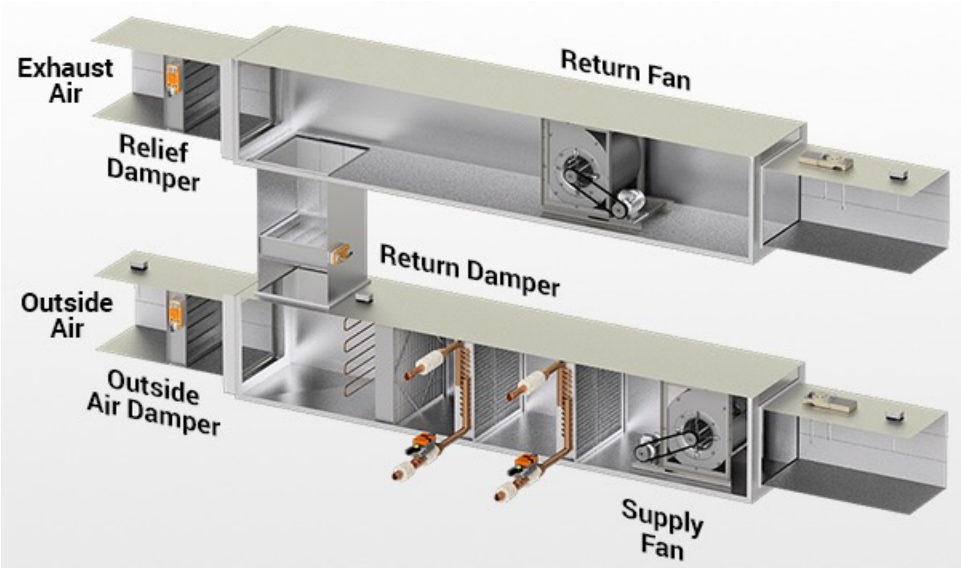
$$h_f < h_2 < h_g$$

$$x_2 = \frac{h_2 - h_f}{h_{fg}} = \frac{95.48 - 22.47}{236.99 - 22.47} = 0.340$$



Some Steady-Flow Energy Devices

- **Mixing chambers**
  - ☐ In engineering applications, mixing two streams of fluids is not a rate occurrence
  - ☐ They are usually well-insulated ($q \cong 0$)
  - ☐ Do not involve any kind of work ($w \cong 0$)
  - ☐ Kinetic and potential energies negligible ($ke \cong 0$ & $pe \cong 0$)



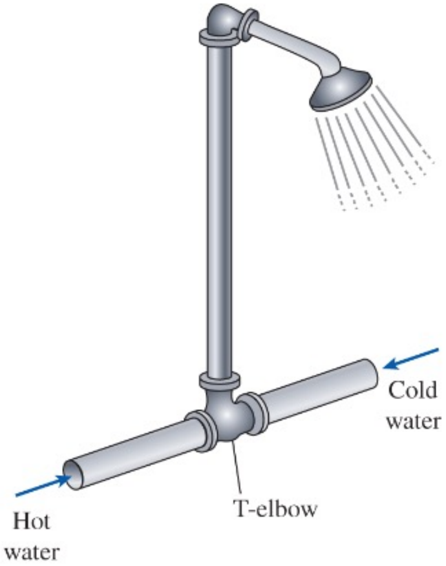


Photo credit: Belimo

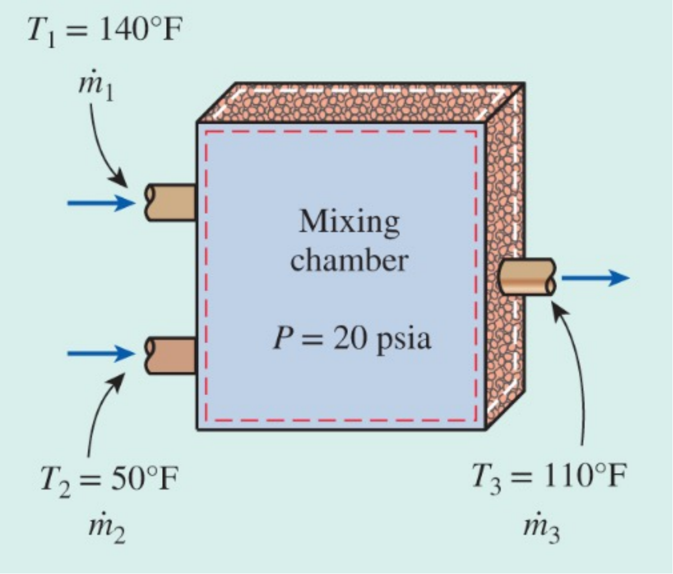
CLASS ACTIVITY

Class Activity

- 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 steam 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.

Class Activity

- Solution (assumptions):
  1. Steady-flow ($\Delta m_{CV} = 0$ and $\Delta \mathrm{E_{CV}} = 0$)
  2. The kinetic and potential energy changes are zero ($\Delta \mathrm{ke} = \Delta pe = 0$)
  3. Heat losses from the system are negligible ($\dot{Q} \cong 0$)
  4. There is no work interaction involved



Class Activity

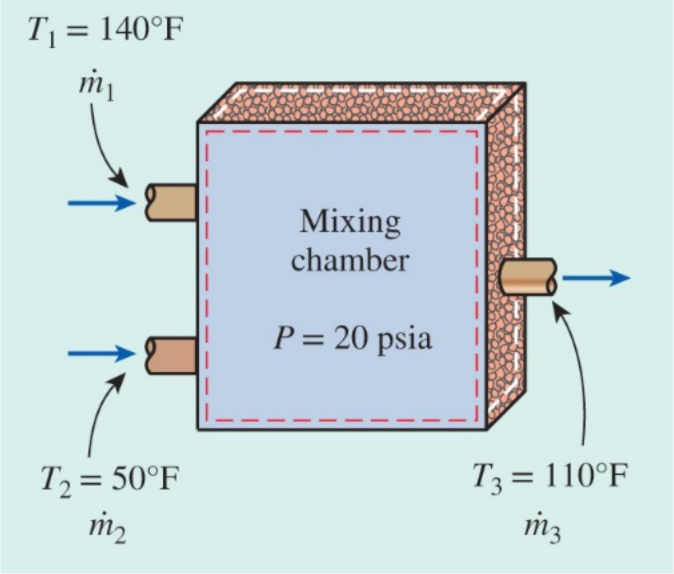
- Solution:

$$\dot{m}_{in} - \dot{m}_{out} = \frac{dm_{system}}{dt} = 0$$

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

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

$$\dot{m}_1 h_1 + \dot{m}_2 h_2 = \dot{m}_3 h_3$$



Class Activity

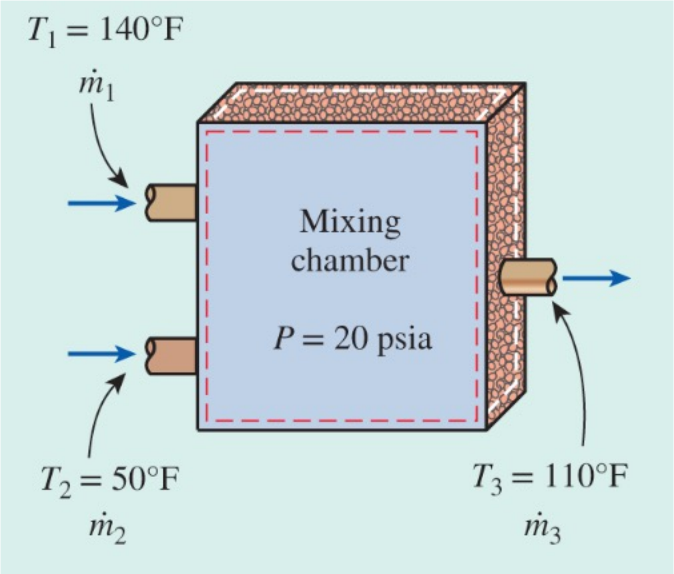
- Solution:

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

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

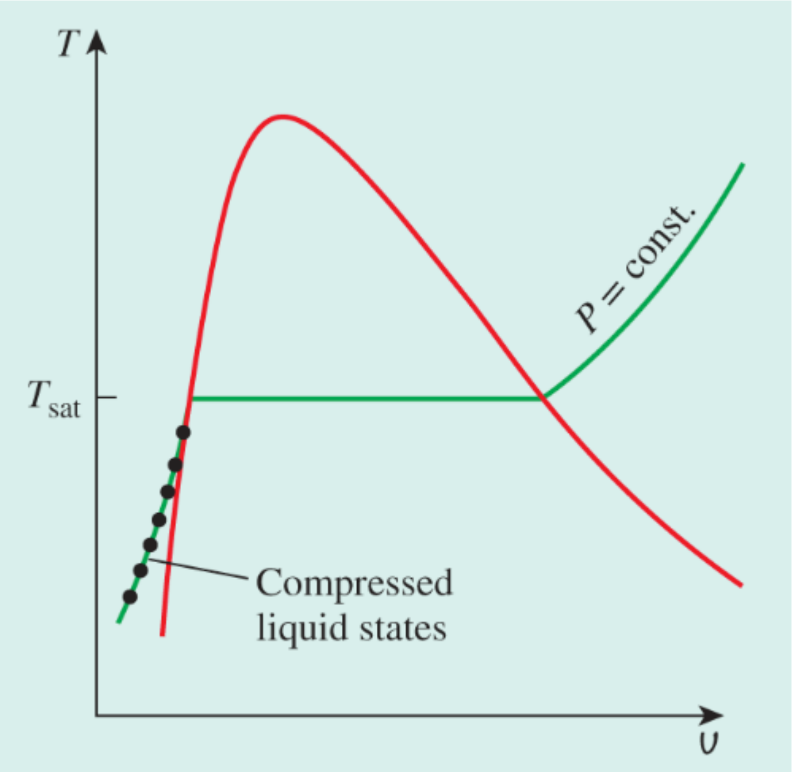
$$y = \frac{\dot{m}_1}{\dot{m}_2}$$

$$y h_1 + h_2 = (y + 1) h_3$$



Class Activity

- Solution:
  - ❑ The saturation temperature of water at 20 psia is 227.92 °F. Since the temperature of all three steams are below this value ($T<T_{sat}$), the water in all three streams exists as a compressed liquid



Class Activity

- Solution:

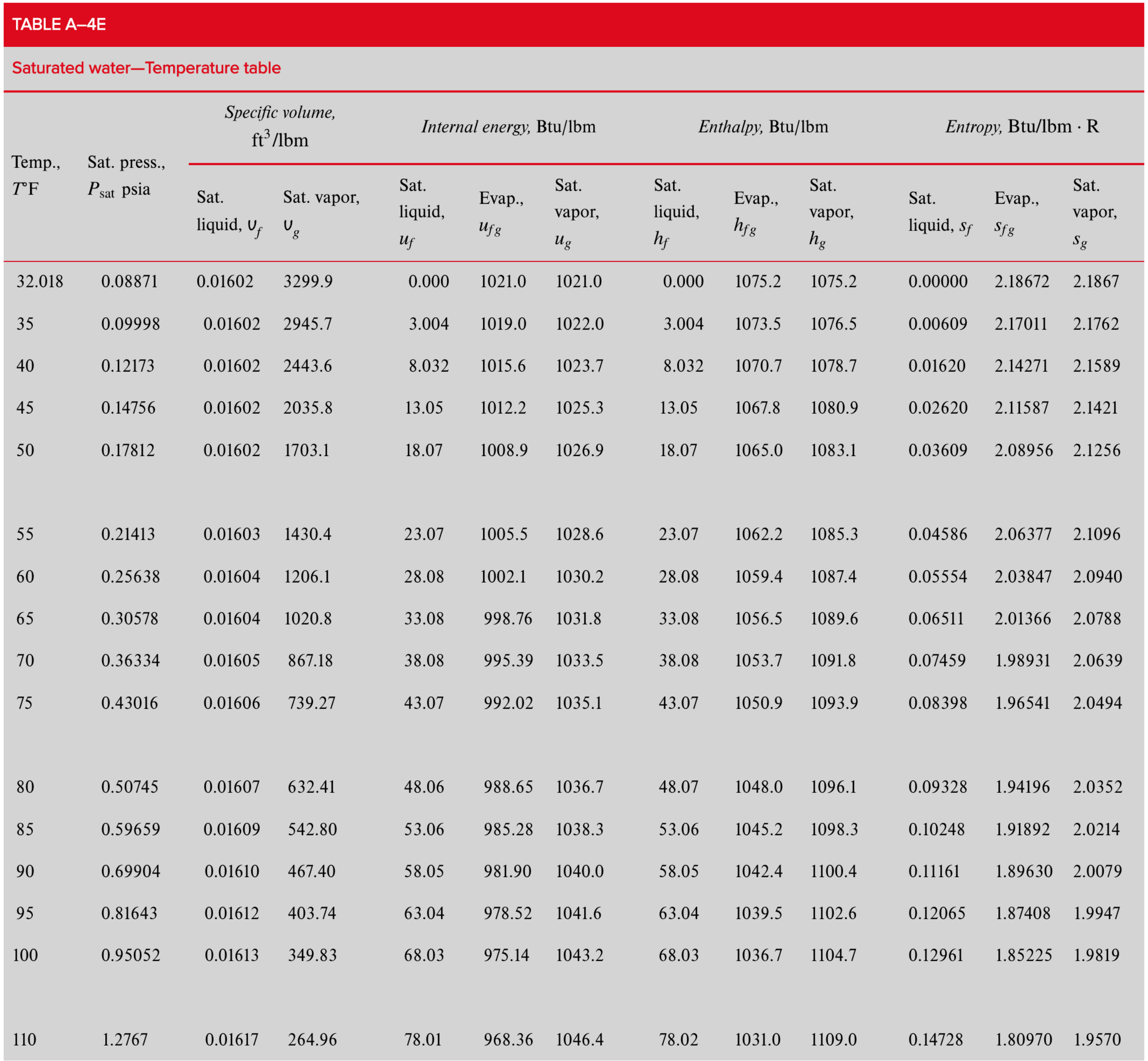


TABLE A–4E

Saturated water—Temperature table

Temp., T°F	Sat. press., P_{sat} psia	*Specific volume,* ft^3/lbm		*Internal energy,* Btu/lbm			*Enthalpy,* Btu/lbm			*Entropy,* Btu/lbm · R		
		Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g	Sat. liquid, s_f	Evap., s_{fg}	Sat. vapor, s_g
32.018	0.08871	0.01602	3299.9	0.000	1021.0	1021.0	0.000	1075.2	1075.2	0.00000	2.18672	2.1867
35	0.09998	0.01602	2945.7	3.004	1019.0	1022.0	3.004	1073.5	1076.5	0.00609	2.17011	2.1762
40	0.12173	0.01602	2443.6	8.032	1015.6	1023.7	8.032	1070.7	1078.7	0.01620	2.14271	2.1589
45	0.14756	0.01602	2035.8	13.05	1012.2	1025.3	13.05	1067.8	1080.9	0.02620	2.11587	2.1421
50	0.17812	0.01602	1703.1	18.07	1008.9	1026.9	18.07	1065.0	1083.1	0.03609	2.08956	2.1256
55	0.21413	0.01603	1430.4	23.07	1005.5	1028.6	23.07	1062.2	1085.3	0.04586	2.06377	2.1096
60	0.25638	0.01604	1206.1	28.08	1002.1	1030.2	28.08	1059.4	1087.4	0.05554	2.03847	2.0940
65	0.30578	0.01604	1020.8	33.08	998.76	1031.8	33.08	1056.5	1089.6	0.06511	2.01366	2.0788
70	0.36334	0.01605	867.18	38.08	995.39	1033.5	38.08	1053.7	1091.8	0.07459	1.98931	2.0639
75	0.43016	0.01606	739.27	43.07	992.02	1035.1	43.07	1050.9	1093.9	0.08398	1.96541	2.0494
80	0.50745	0.01607	632.41	48.06	988.65	1036.7	48.07	1048.0	1096.1	0.09328	1.94196	2.0352
85	0.59659	0.01609	542.80	53.06	985.28	1038.3	53.06	1045.2	1098.3	0.10248	1.91892	2.0214
90	0.69904	0.01610	467.40	58.05	981.90	1040.0	58.05	1042.4	1100.4	0.11161	1.89630	2.0079
95	0.81643	0.01612	403.74	63.04	978.52	1041.6	63.04	1039.5	1102.6	0.12065	1.87408	1.9947
100	0.95052	0.01613	349.83	68.03	975.14	1043.2	68.03	1036.7	1104.7	0.12961	1.85225	1.9819
110	1.2767	0.01617	264.96	78.01	968.36	1046.4	78.02	1031.0	1109.0	0.14728	1.80970	1.9570

Class Activity

- Solution:

$$h_1 \cong h_{f\ @\ 140\ °F} = 107.99\,\frac{Btu}{lbm}$$

$$h_2 \cong h_{f\ @\ 50\ °F} = 18.07\,\frac{Btu}{lbm}$$

$$h_3 \cong h_{f\ @\ 110\ °F} = 78.02\,\frac{Btu}{lbm}$$

Class Activity

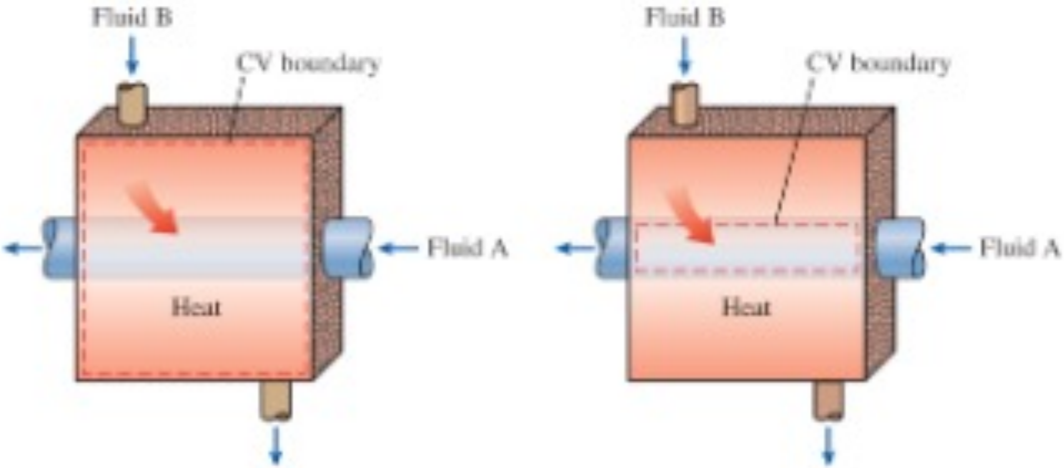
- Solution:
  - ❑ Solving for y and substituting yields:

$$y = \frac{h_3 - h_2}{h_1 - h_3} = \frac{78.02 - 18.07}{107.99 - 78.02} = 2.0$$

$$y = \frac{\dot{m}_1}{\dot{m}_2} = 2 \quad \rightarrow \quad \dot{m}_1 = 2 \times \dot{m}_2$$

Some Steady-Flow Energy Devices

- **Heat Exchangers**
  - ❑ Under stead operation, the mass flow rate of each fluid stream flowing through a heat exchanger remains constant
  - ❑ Do not involve any kind of work $(w \cong 0)$
  - ❑ Kinetic and potential energies negligible $(ke \cong 0 \;\&\; pe \cong 0)$
  - ❑ $\dot{Q}$ depends!

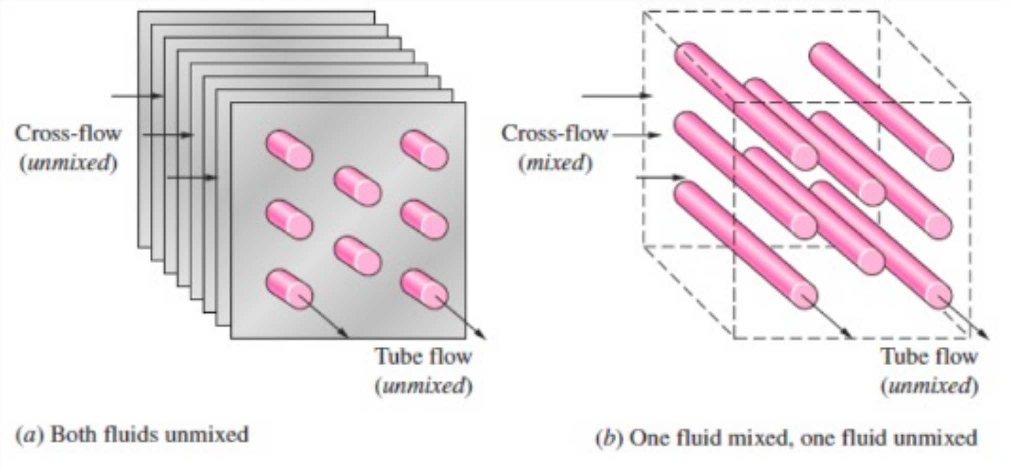


(*a*) System: Entire heat exchanger ($Q_{CV} = 0$)

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

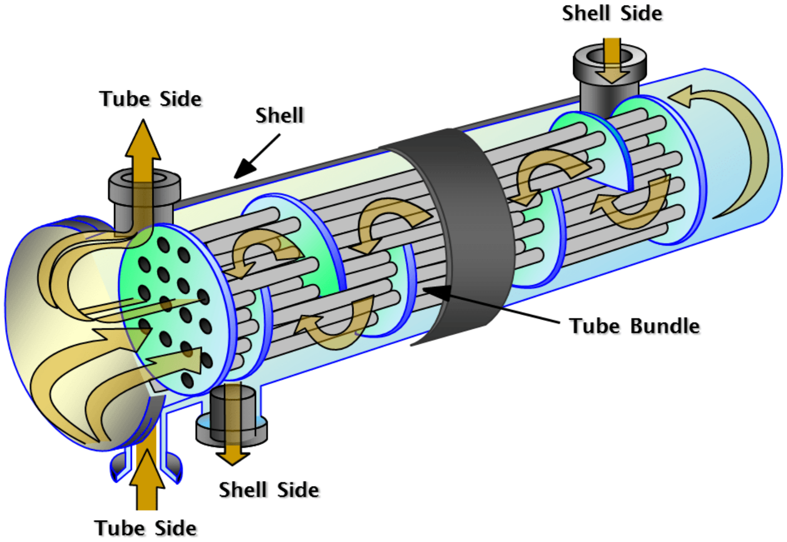
Some Steady-Flow Energy Devices

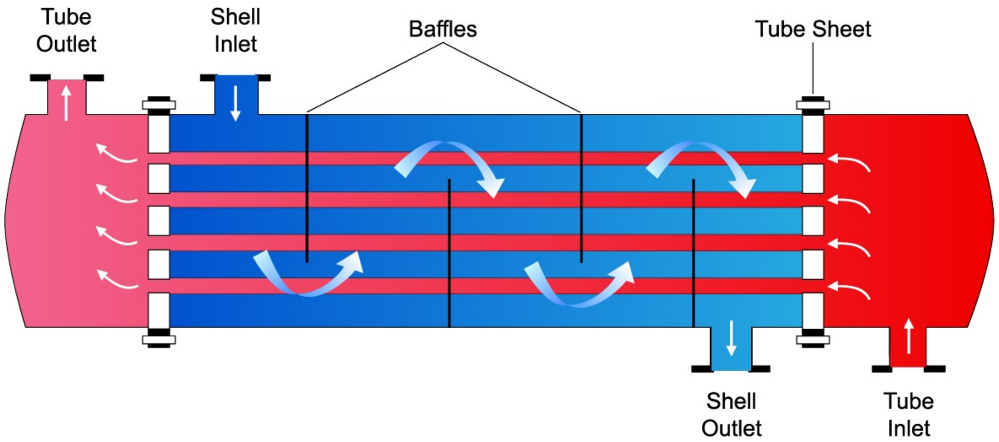
- **Heat Exchangers**



(a) Both fluids unmixed

(b) One fluid mixed, one fluid unmixed





Class Activity

- 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 (superheated) and leaves at 35 °C (compressed liquid). 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
  b) The heat transfer rate from the refrigerant to the water

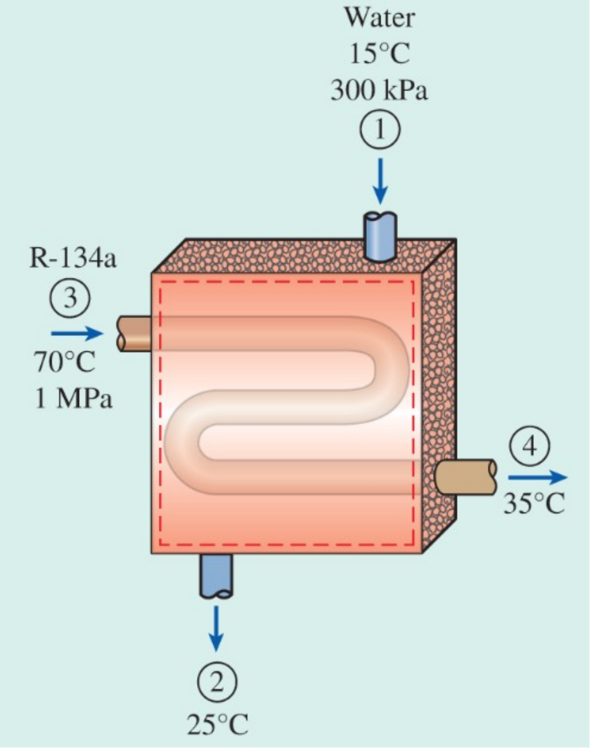
Class Activity

- Solution (assumptions):
  1. Steady-flow ($\Delta m_{CV} = 0$ and $\Delta \mathrm{E}_{\mathrm{CV}} = 0$)
  2. The kinetic and potential energy changes are zero ($\Delta \mathrm{ke} = \Delta pe = 0$)
  3. Heat losses from the system are negligible ($\dot{Q} \cong 0$)
  4. There is no work interaction involved

$$\dot{m}_{in} = \dot{m}_{out}$$

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

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



Class Activity

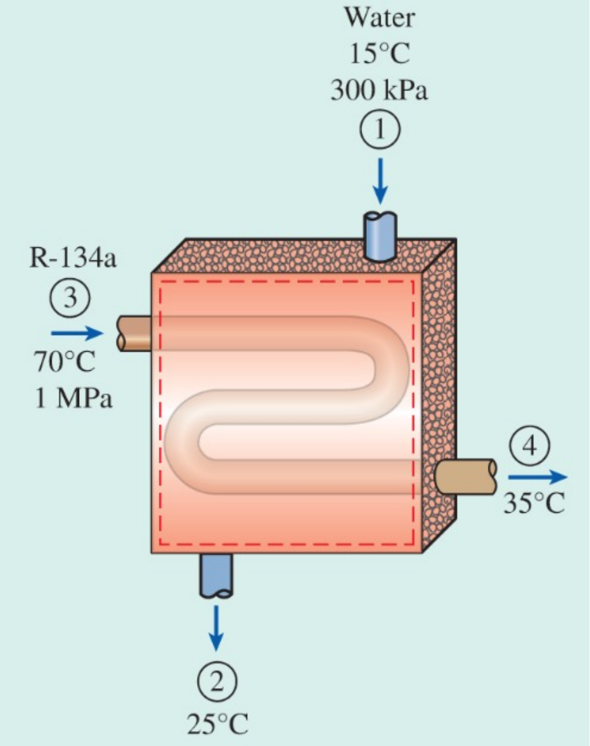
- Solution (a):

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

$$\dot{E}_{in} = \dot{E}_{out}$$

$$\dot{m}_1 h_1 + \dot{m}_3 h_3 = \dot{m}_2 h_2 + \dot{m}_4 h_4$$

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



Class Activity

- Solution (a):
  - ❑ Water exits as a compressed liquid at both the inlet and exit since temperatures at both locations are below the saturation temperature of water at 300 kPa (113.53 °C)

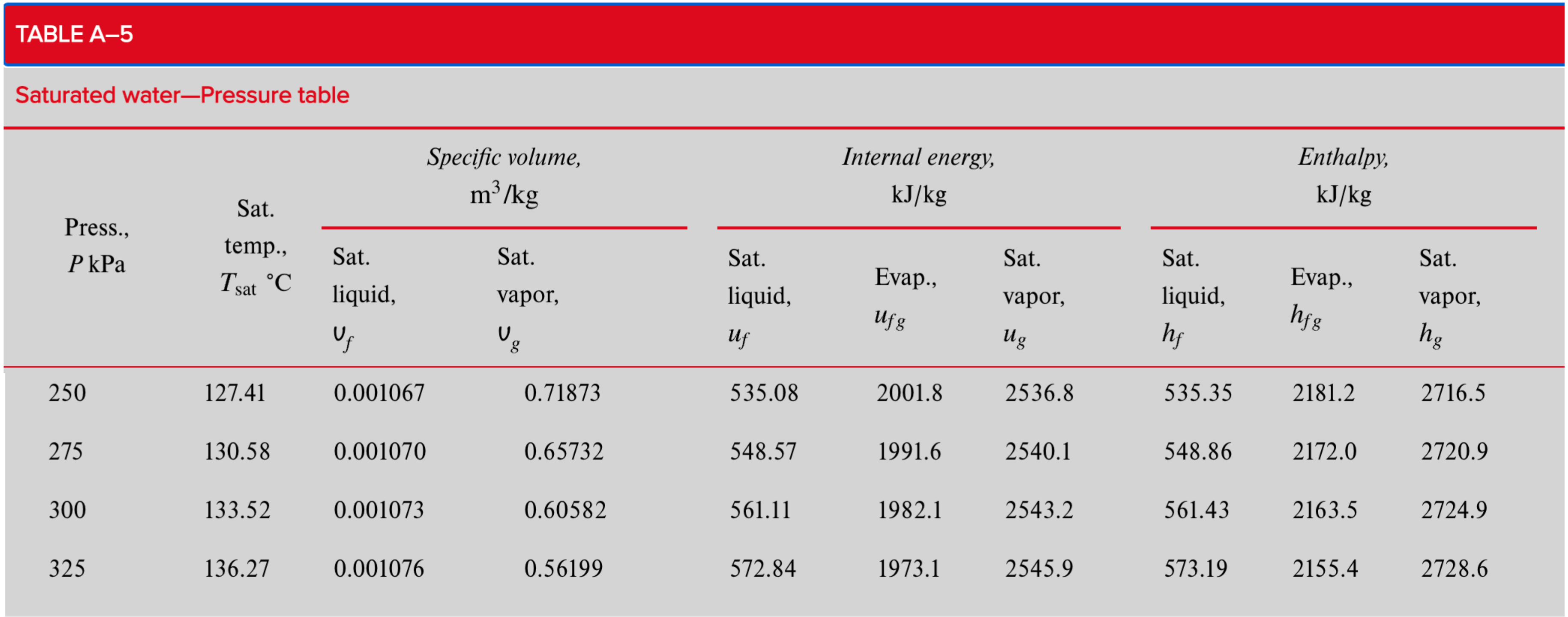


TABLE A–5

Saturated water—Pressure table

Press., P kPa	Sat. temp., T_{sat} °C	*Specific volume,* m^3/kg		*Internal energy,* kJ/kg			*Enthalpy,* kJ/kg		
		Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g
250	127.41	0.001067	0.71873	535.08	2001.8	2536.8	535.35	2181.2	2716.5
275	130.58	0.001070	0.65732	548.57	1991.6	2540.1	548.86	2172.0	2720.9
300	133.52	0.001073	0.60582	561.11	1982.1	2543.2	561.43	2163.5	2724.9
325	136.27	0.001076	0.56199	572.84	1973.1	2545.9	573.19	2155.4	2728.6

Class Activity

- Solution (a):

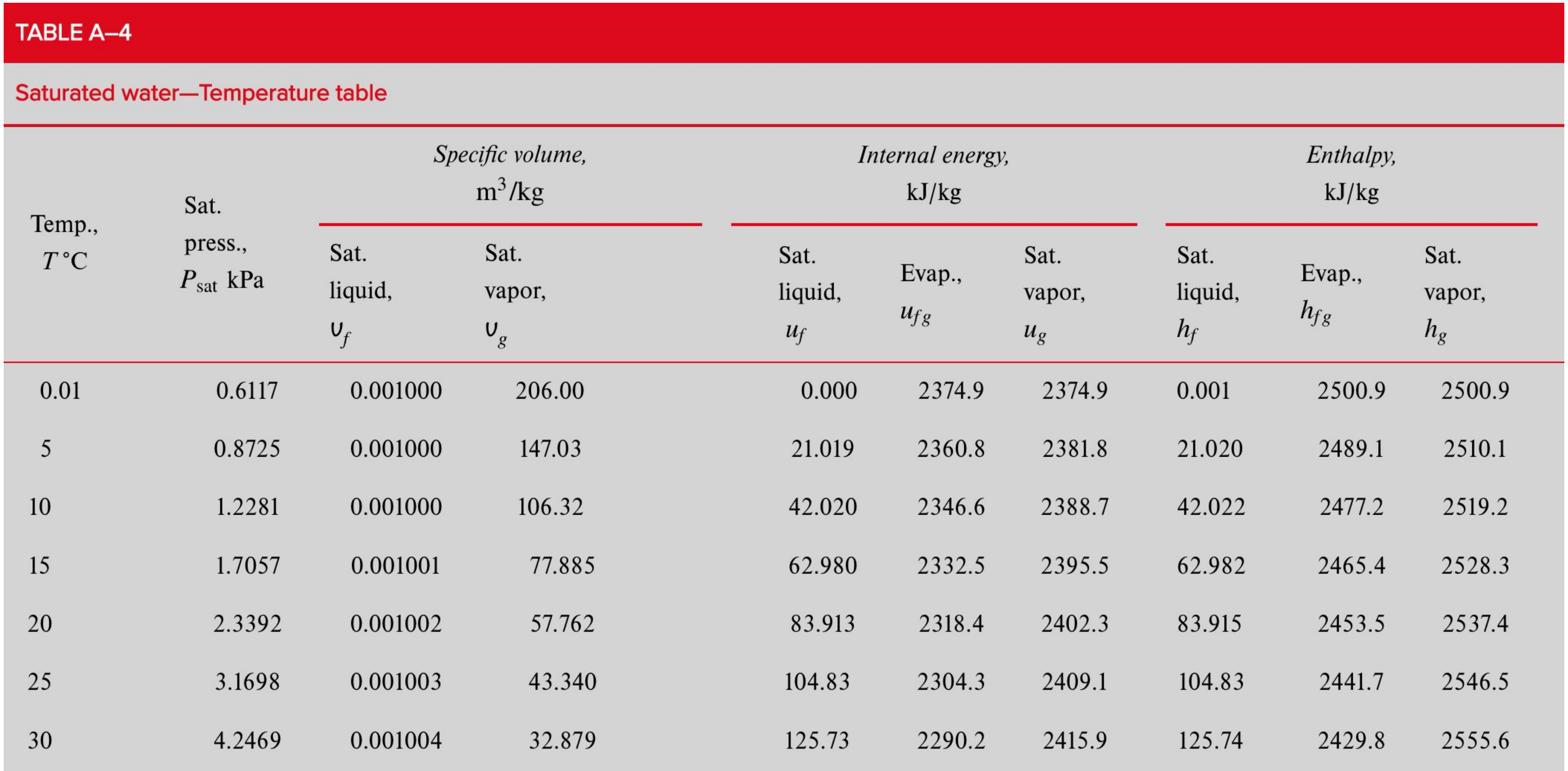


TABLE A–4

Saturated water—Temperature table

		Specific volume, m^3/kg		*Internal energy,* kJ/kg			*Enthalpy,* kJ/kg		
Temp., $T\,°C$	Sat. press., P_{sat} kPa	Sat. liquid, v_f	Sat. vapor, v_g	Sat. liquid, u_f	Evap., u_{fg}	Sat. vapor, u_g	Sat. liquid, h_f	Evap., h_{fg}	Sat. vapor, h_g
0.01	0.6117	0.001000	206.00	0.000	2374.9	2374.9	0.001	2500.9	2500.9
5	0.8725	0.001000	147.03	21.019	2360.8	2381.8	21.020	2489.1	2510.1
10	1.2281	0.001000	106.32	42.020	2346.6	2388.7	42.022	2477.2	2519.2
15	1.7057	0.001001	77.885	62.980	2332.5	2395.5	62.982	2465.4	2528.3
20	2.3392	0.001002	57.762	83.913	2318.4	2402.3	83.915	2453.5	2537.4
25	3.1698	0.001003	43.340	104.83	2304.3	2409.1	104.83	2441.7	2546.5
30	4.2469	0.001004	32.879	125.73	2290.2	2415.9	125.74	2429.8	2555.6

$$h_1 \cong h_{f\,@\,15\,°C} = 62.982\,\frac{kJ}{kg}$$

$$h_2 \cong h_{f\,@\,25\,°C} = 104.83\,\frac{kJ}{kg}$$

Class Activity

- Solution (a):

$$\left.\begin{array}{l} P_3 = 1\ MPa \\ T_3 = 70\ °C \end{array}\right\} (superheated) \rightarrow \ h_3 = 303.87\,\frac{kJ}{kg}$$

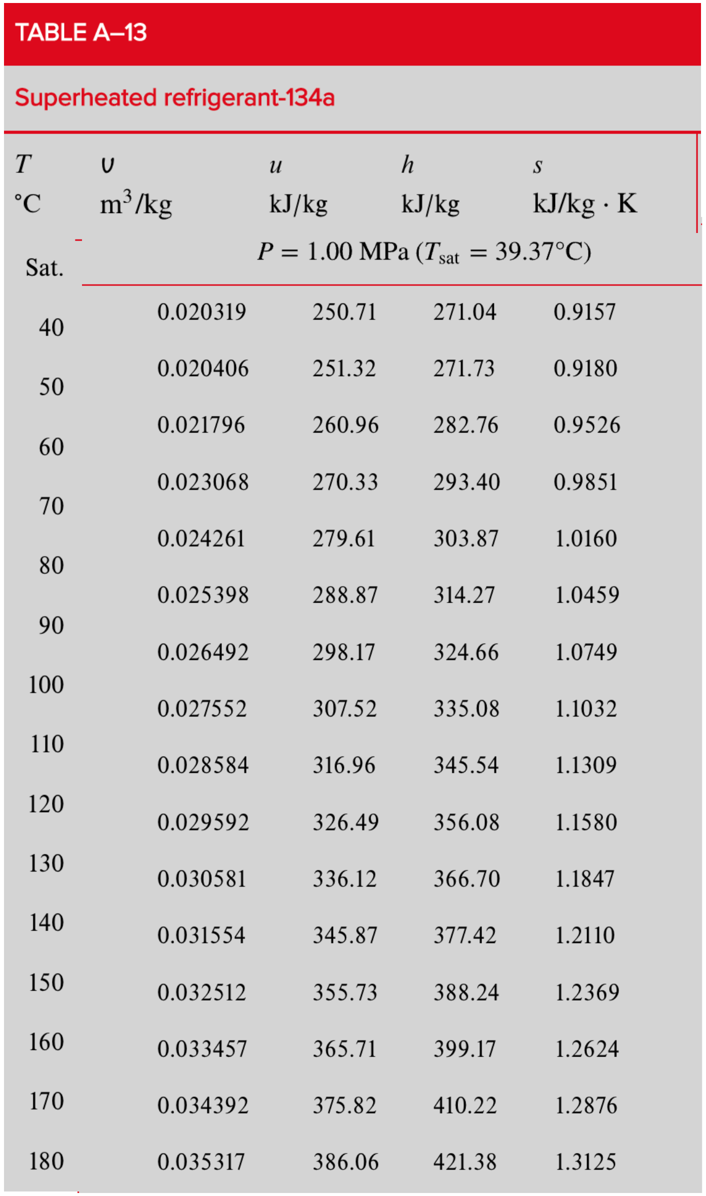


TABLE A–13

Superheated refrigerant-134a

T °C	*υ* m^3/kg	*u* kJ/kg	*h* kJ/kg	*s* kJ/kg · K
	P = 1.00 MPa (T_{sat} = 39.37°C)			
Sat.	0.020319	250.71	271.04	0.9157
40	0.020406	251.32	271.73	0.9180
50	0.021796	260.96	282.76	0.9526
60	0.023068	270.33	293.40	0.9851
70	0.024261	279.61	303.87	1.0160
80	0.025398	288.87	314.27	1.0459
90	0.026492	298.17	324.66	1.0749
100	0.027552	307.52	335.08	1.1032
110	0.028584	316.96	345.54	1.1309
120	0.029592	326.49	356.08	1.1580
130	0.030581	336.12	366.70	1.1847
140	0.031554	345.87	377.42	1.2110
150	0.032512	355.73	388.24	1.2369
160	0.033457	365.71	399.17	1.2624
170	0.034392	375.82	410.22	1.2876
180	0.035317	386.06	421.38	1.3125

Class Activity

- Solution (a):

$$\left.\begin{array}{r} P_3 = 1\ MPa \\ T_3 = 35\ °C \end{array}\right\} (compressed\ liquid) \rightarrow\ h_4 = h_{f\ @\ 35\ °C} = 100.88\frac{kJ}{kg}$$

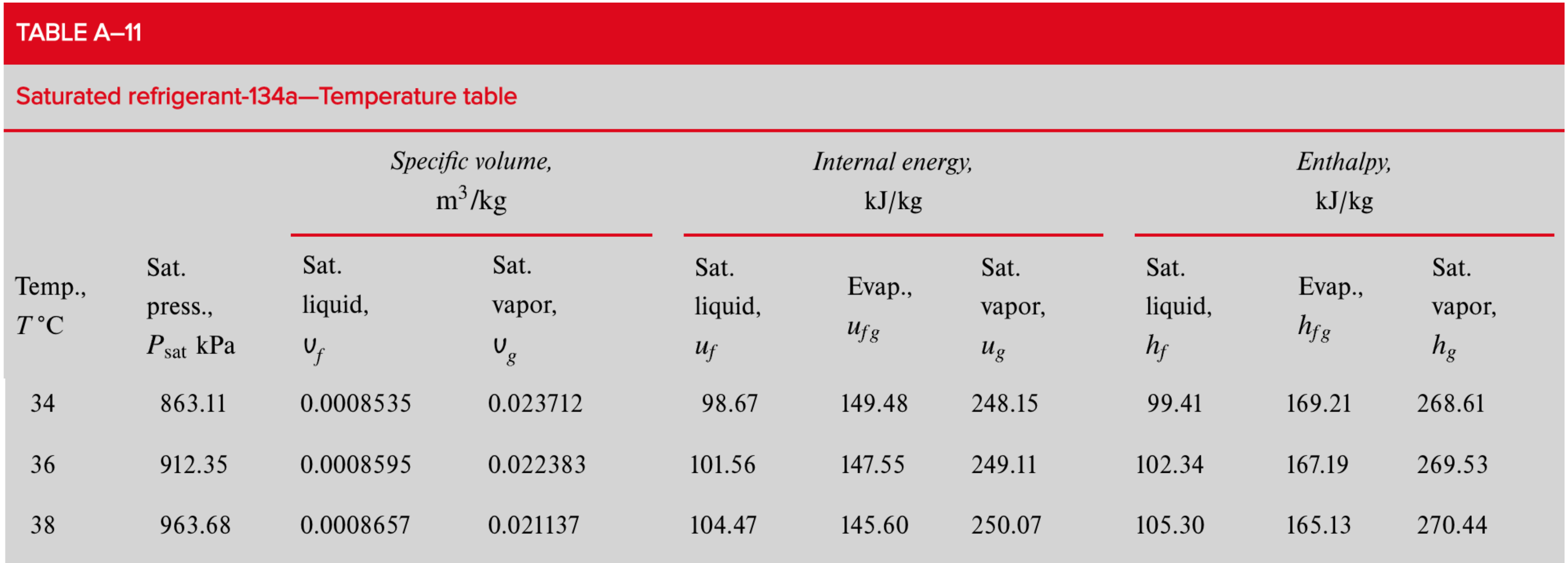


TABLE A–11

Saturated refrigerant-134a—Temperature table

Temp., T °C	Sat. press., P_{sat} kPa	Specific volume, m^3/kg Sat. liquid, v_f	 Sat. vapor, v_g	Internal energy, kJ/kg Sat. liquid, u_f	 Evap., u_{fg}	 Sat. vapor, u_g	Enthalpy, kJ/kg Sat. liquid, h_f	 Evap., h_{fg}	 Sat. vapor, h_g
34	863.11	0.0008535	0.023712	98.67	149.48	248.15	99.41	169.21	268.61
36	912.35	0.0008595	0.022383	101.56	147.55	249.11	102.34	167.19	269.53
38	963.68	0.0008657	0.021137	104.47	145.60	250.07	105.30	165.13	270.44

Class Activity

- Solution (a):

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

$$\dot{m}_w = 29.1\,\frac{kg}{min}$$

Class Activity

- Solution (b):
  - We need to choose a control volume for this part: either water or the refrigerant. Here we chose water for no specific reason

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

$$\dot{E}_{in} = \dot{E}_{out}$$

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

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