Chapter 4

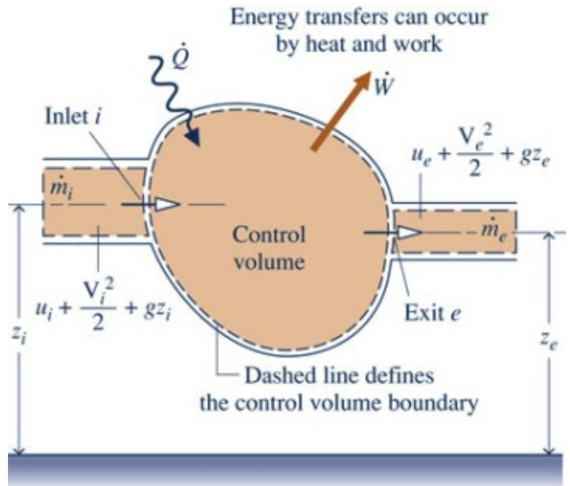
Control Volume Analysis Using Energy

(continued)

Learning Outcomes

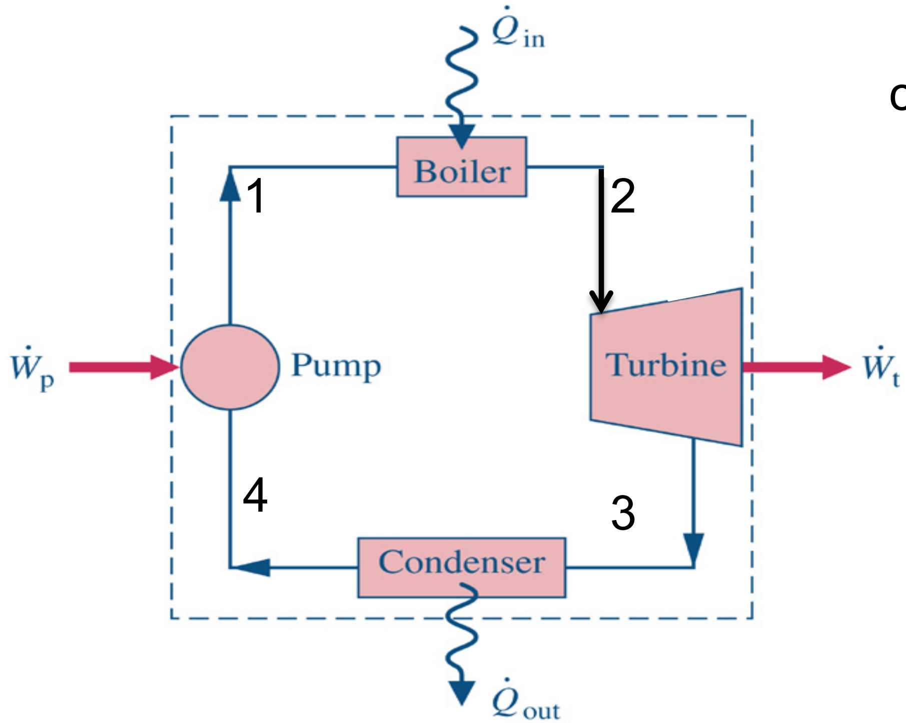
- ►Distinguish between steady-state and transient analysis,
- ►Distinguishing between mass flow rate and volumetric flow rate.
- ►Apply mass and energy balances to control volumes.
- ►Develop appropriate engineering models to analyze nozzles, turbines, compressors, heat exchangers, throttling devices.
- ►Use property data in control volume analysis appropriately.

Energy Rate Balance



[time ***rate of change*** of the energy contained within the control volume ***at time t***] = [***net rate*** at which energy is being transferred in by heat transfer ***at time t***] − [***net rate*** at which energy is being transferred out by work ***at time t***] + [***net rate*** of energy transfer ***into*** the control volume accompanying mass flow]

$$\frac{dE_{\text{cv}}}{dt} = \dot{Q}_{\text{cv}} - \dot{W}_{\text{cv}} + \dot{m}_i\left(h_i + \frac{V_i^2}{2} + gz_i\right) - \dot{m}_e\left(h_e + \frac{V_e^2}{2} + gz_e\right)$$



Consider a system similar to what the components that we've just analyzed in class.

Assume ideal conditions initially

Look up state 2 properties

	P (bar)	T (deg. C)	v m^3/kg	u kJ/kg	h kJ/kg	x
1		150				
2	40	500				
3	.6					.92
4						

TABLE A-3

Pressure Conversions:
1 bar = 0.1 MPa
= 10^2 kPa

Properties of Saturated Water (Liquid–Vapor): Pressure Table

		Specific Volume m^3/kg		Internal Energy kJ/kg		Enthalpy kJ/kg			Entropy kJ/kg · K		
Press. bar	Temp. °C	Sat. Liquid $v_f \times 10^3$	Sat. Vapor v_g	Sat. Liquid u_f	Sat. Vapor u_g	Sat. Liquid h_f	Evap. h_{fg}	Sat. Vapor h_g	Sat. Liquid s_f	Sat. Vapor s_g	Press. bar
0.04	28.96	1.0040	34.800	121.45	2415.2	121.46	2432.9	2554.4	0.4226	8.4746	0.04
0.06	36.16	1.0064	23.739	151.53	2425.0	151.53	2415.9	2567.4	0.5210	8.3304	0.06
0.08	41.51	1.0084	18.103	173.87	2432.2	173.88	2403.1	2577.0	0.5926	8.2287	0.08
0.10	45.81	1.0102	14.674	191.82	2437.9	191.83	2392.8	2584.7	0.6493	8.1502	0.10
0.20	60.06	1.0172	7.649	251.38	2456.7	251.40	2358.3	2609.7	0.8320	7.9085	0.20
0.30	69.10	1.0223	5.229	289.20	2468.4	289.23	2336.1	2625.3	0.9439	7.7686	0.30
0.40	75.87	1.0265	3.993	317.53	2477.0	317.58	2319.2	2636.8	1.0259	7.6700	0.40
0.50	81.33	1.0300	3.240	340.44	2483.9	340.49	2305.4	2645.9	1.0910	7.5939	0.50
0.60	85.94	1.0331	2.732	359.79	2489.6	359.86	2293.6	2653.5	1.1453	7.5320	0.60
0.70	89.95	1.0360	2.365	376.63	2494.5	376.70	2283.3	2660.0	1.1919	7.4797	0.70

TABLE A-4

(Continued)

T °C	v m^3/kg	u kJ/kg	h kJ/kg	s kJ/kg · K
	p = 20.0 bar = 2.0 MPa (T_{sat} = 212.42°C)			
Sat.	0.0996	2600.3	2799.5	6.3409
240	0.1085	2659.6	2876.5	6.4952
280	0.1200	2736.4	2976.4	6.6828
320	0.1308	2807.9	3069.5	6.8452
360	0.1411	2877.0	3159.3	6.9917
400	0.1512	2945.2	3247.6	7.1271
440	0.1611	3013.4	3335.5	7.2540
500	0.1757	3116.2	3467.6	7.4317
540	0.1853	3185.6	3556.1	7.5434
600	0.1996	3290.9	3690.1	7.7024
640	0.2091	3362.2	3780.4	7.8035
700	0.2232	3470.9	3917.4	7.9487
	p = 40 bar = 4.0 MPa (T_{sat} = 250.4°C)			
Sat.	0.04978	2602.3	2801.4	6.0701
280	0.05546	2680.0	2901.8	6.2568
320	0.06199	2767.4	3015.4	6.4553
360	0.06788	2845.7	3117.2	6.6215
400	0.07341	2919.9	3213.6	6.7690
440	0.07872	2992.2	3307.1	6.9041
500	0.08643	3099.5	3445.3	7.0901
540	0.09145	3171.1	3536.9	7.2056
600	0.09885	3279.1	3674.4	7.3688
640	0.1037	3351.8	3766.6	7.4720
700	0.1110	3462.1	3905.9	7.6198
740	0.1157	3536.6	3999.6	7.7141

TABLE A-4

(Continued)

T °C	v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K
		p = 40 bar = 4.0 MPa (T_{sat} = 250.4°C)		
Sat.	0.04978	2602.3	2801.4	6.0701
280	0.05546	2680.0	2901.8	6.2568
320	0.06199	2767.4	3015.4	6.4553
360	0.06788	2845.7	3117.2	6.6215
400	0.07341	2919.9	3213.6	6.7690
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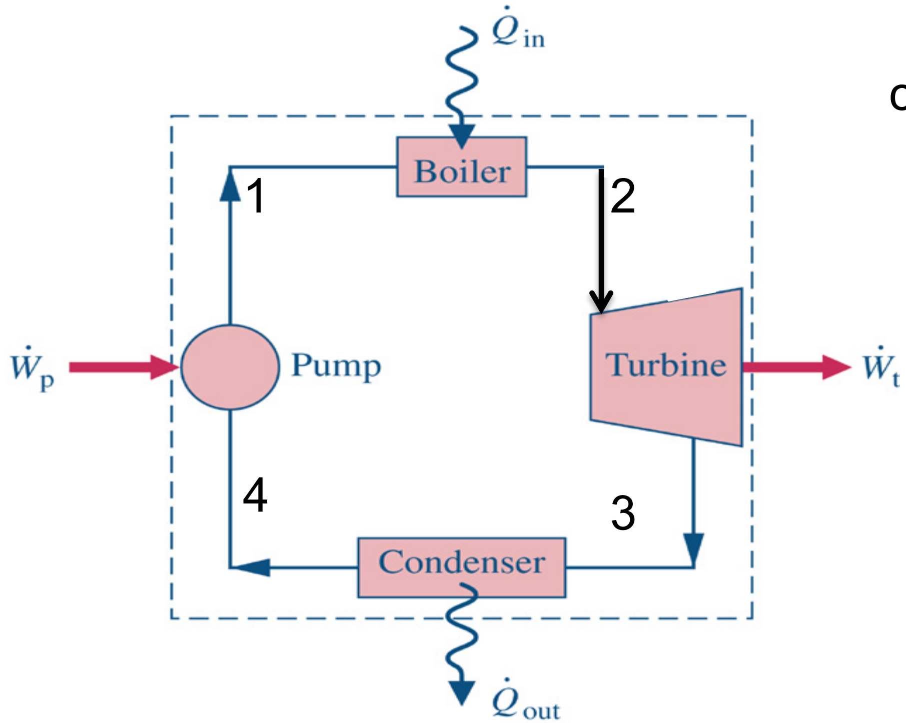


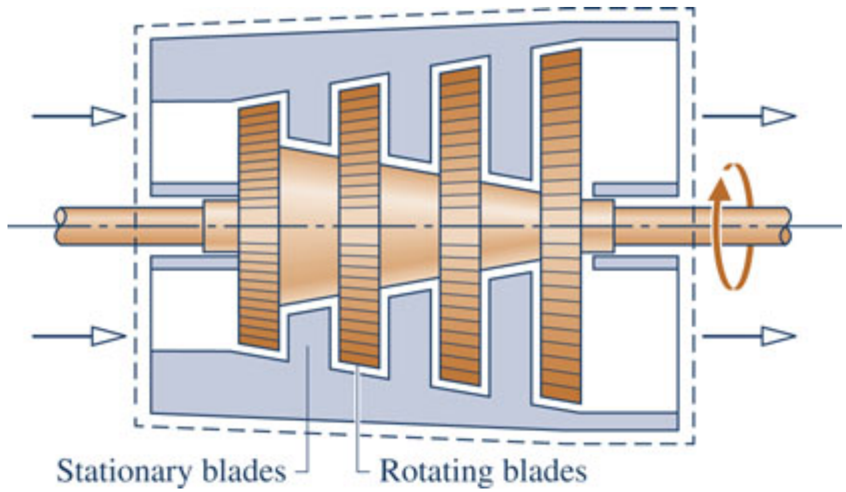
Consider a system similar to what the components that we've just analyzed in class.

Assume ideal conditions initially

Look up state 2 properties

	P (bar)	T (deg. C)	v m^3/kg	u kJ/kg	h kJ/kg	x
1		150				
2	40	500	.08643	3099.5	3445.3	NA
3	.6					.92
4						

Turbines



► **Turbine**: a device in which power is developed as a result of a gas or liquid passing through a set of blades attached to a shaft free to rotate.

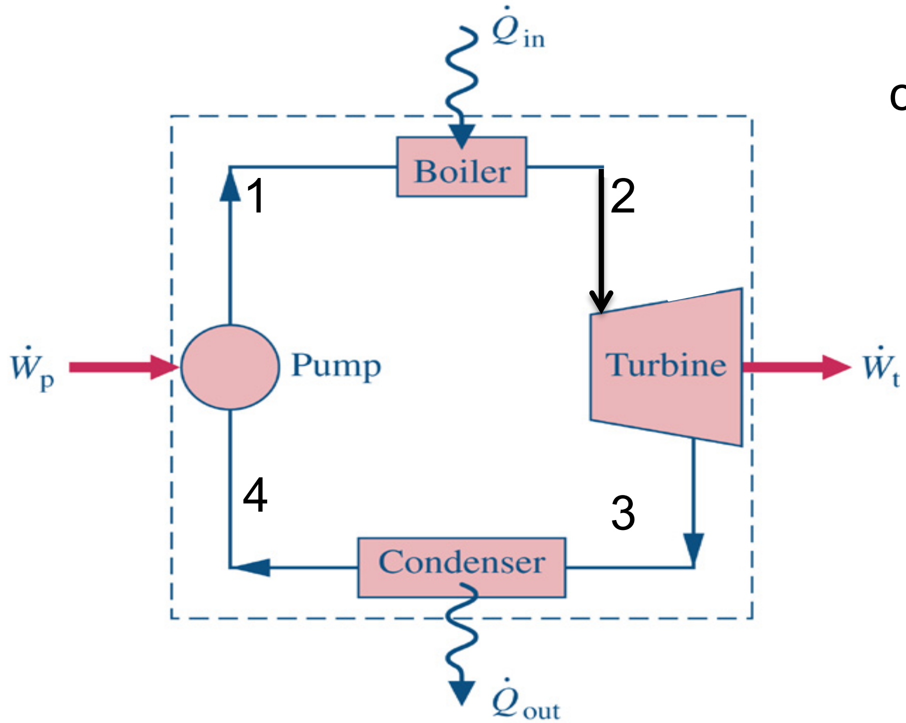
Turbine Modeling

$$0 = \dot{Q}_{cv} - \dot{W}_{cv} + \dot{m}\left[(h_1 - h_2) + \frac{(V_1^2 - V_2^2)}{2} + g(z_1 - z_2)\right]$$

Eq. 4.20a

- ►If the change in kinetic energy of flowing matter is negligible, $\frac{1}{2}(V_1^2 - V_2^2)$ drops out.
- ►If the change in potential energy of flowing matter is negligible, $g(z_1 - z_2)$ drops out.
- ►If the heat transfer with surroundings is negligible, $\dot{Q}_{cv}$ drops out.

$$\dot{W}_{cv} = \dot{m}(h_1 - h_2)$$



Consider a system similar to what the components that we've just analyzed in class.

Assume ideal conditions initially

Look up state 2 properties

Look up state 3 properties
in order to determine W of Turbine

	P (bar)	T (deg. C)	v m^3/kg	u kJ/kg	h kJ/kg	x
1		150				
2	40	500	.08643	3099.5	3445.3	NA
3	.6					.92
4						

TABLE A-3

Pressure Conversions:
1 bar = 0.1 MPa
= 10^2 kPa

Properties of Saturated Water (Liquid–Vapor): Pressure Table

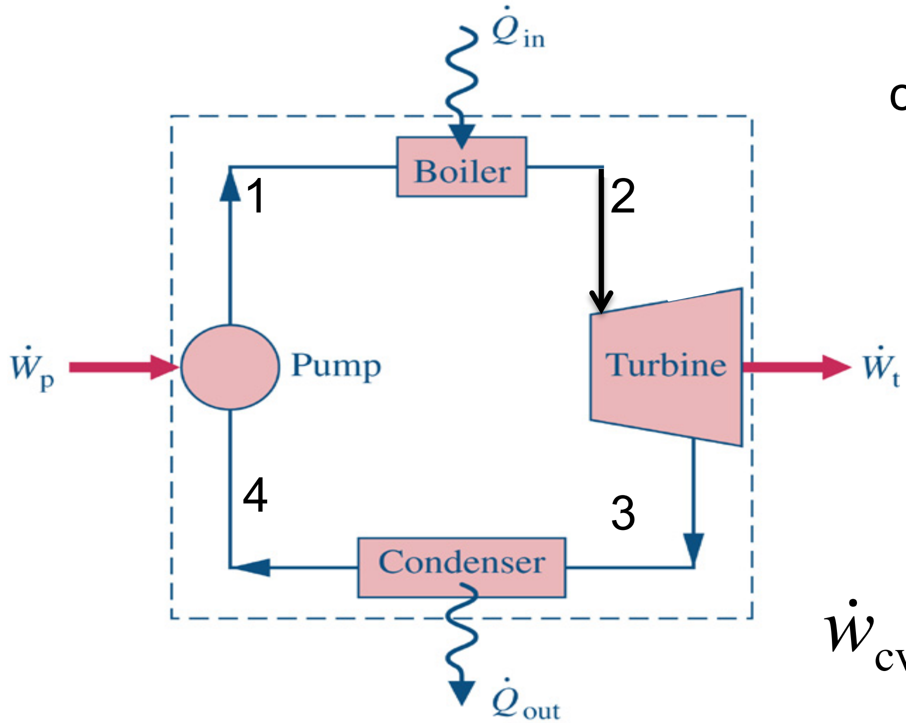
		Specific Volume m^3/kg		Internal Energy kJ/kg		Enthalpy kJ/kg		
Press. bar	Temp. °C	Sat. Liquid $v_f \times 10^3$	Sat. Vapor v_g	Sat. Liquid u_f	Sat. Vapor u_g	Sat. Liquid h_f	Evap. h_{fg}	Sat. Vapor h_g
0.04	28.96	1.0040	34.800	121.45	2415.2	121.46	2432.9	2554.4
0.06	36.16	1.0064	23.739	151.53	2425.0	151.53	2415.9	2567.4
0.08	41.51	1.0084	18.103	173.87	2432.2	173.88	2403.1	2577.0
0.10	45.81	1.0102	14.674	191.82	2437.9	191.83	2392.8	2584.7
0.20	60.06	1.0172	7.649	251.38	2456.7	251.40	2358.3	2609.7
0.30	69.10	1.0223	5.229	289.20	2468.4	289.23	2336.1	2625.3
0.40	75.87	1.0265	3.993	317.53	2477.0	317.58	2319.2	2636.8
0.50	81.33	1.0300	3.240	340.44	2483.9	340.49	2305.4	2645.9
0.60	85.94	1.0331	2.732	359.79	2489.6	359.86	2293.6	2653.5
0.70	89.95	1.0360	2.365	376.63	2494.5	376.70	2283.3	2660.0

$$v_3 = v_f + x(v_g - v_f)$$

$$v_3 = .0010331 + .92(2.732 - .0010331) = 2.514$$

$$h_3 = h_f + x(h_{fg}) = 359.9 + .92(2293.6) = 2470$$

$$u_3 = 359.8 + .92(2489.6 - 359.8) = 2319.2$$



Consider a system similar to what the components that we've just analyzed in class.

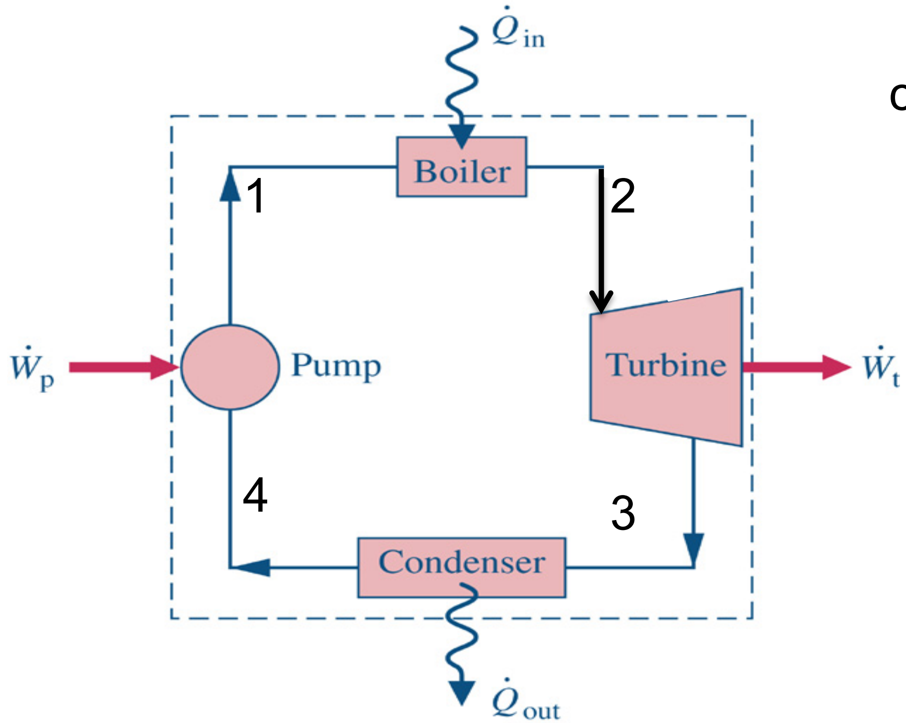
Assume ideal conditions initially

Look up state 2 properties

Look up state 3 properties
in order to determine W of Turbine

$$\dot{w}_{cv} = \frac{\dot{W}_{cv}}{\dot{m}} = (h_2 - h_3) = 975.3\frac{kJ}{kg}$$

	P (bar)	T (deg. C)	v m^3/kg	u kJ/kg	h kJ/kg	x
1		150				
2	40	500	.08643	3099.5	3445.3	NA
3	.6	85.94	2.514	2319.2	2470	.92
4						



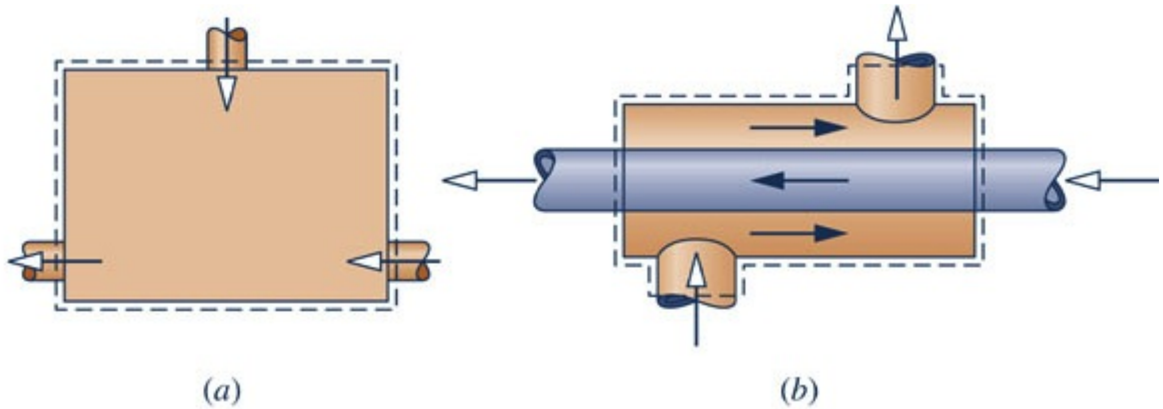
Consider a system similar to what the components that we've just analyzed in class.

Assume ideal conditions initially

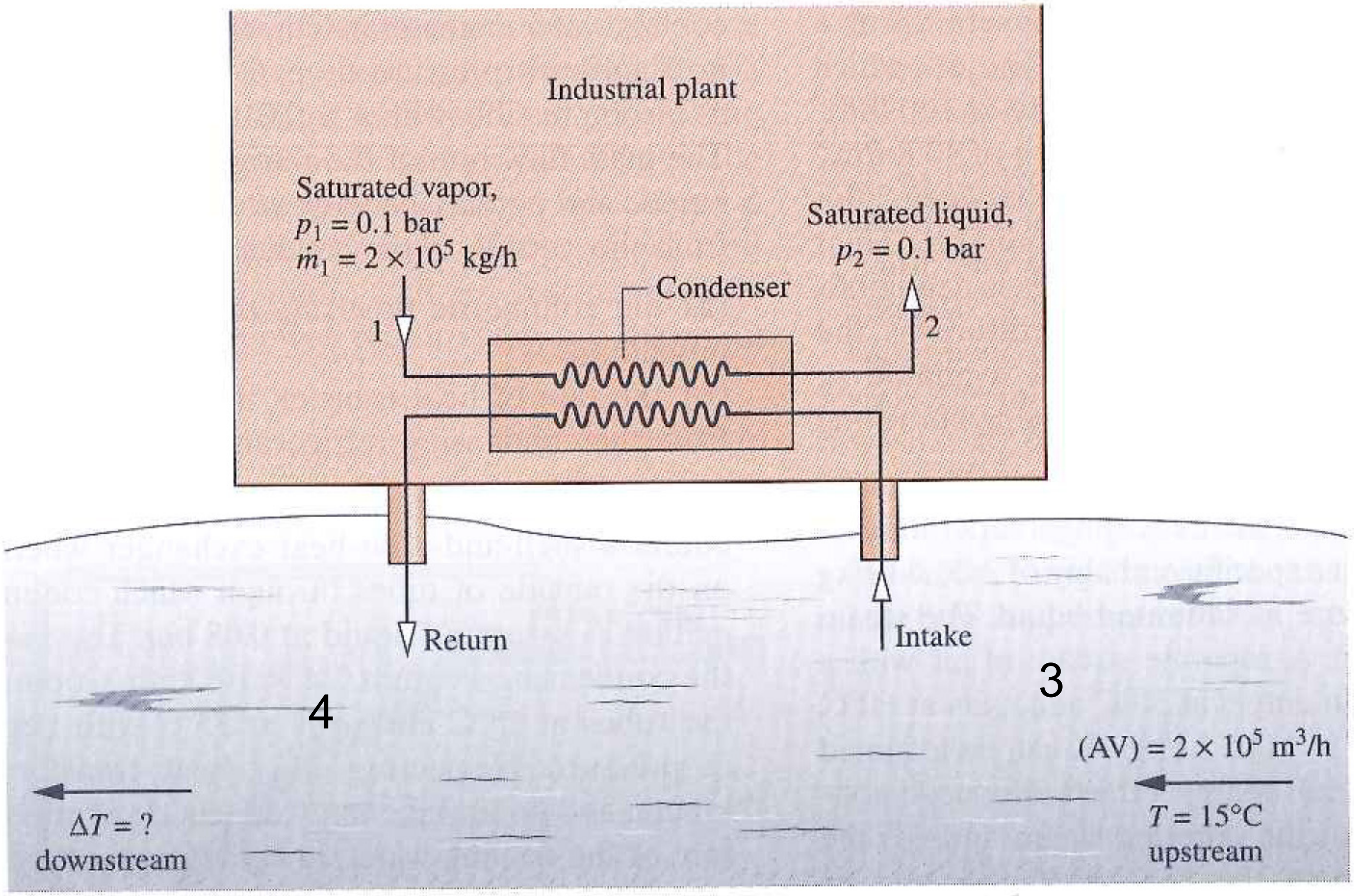
Look up state 4 properties

	P (bar)	T (deg. C)	v m^3/kg	u kJ/kg	h kJ/kg	x
1		150				
2	40	500	.08643	3099.5	3445.3	NA
3	.6	85.94	2.514	2319.2	2470	.92
4						

Heat Exchangers

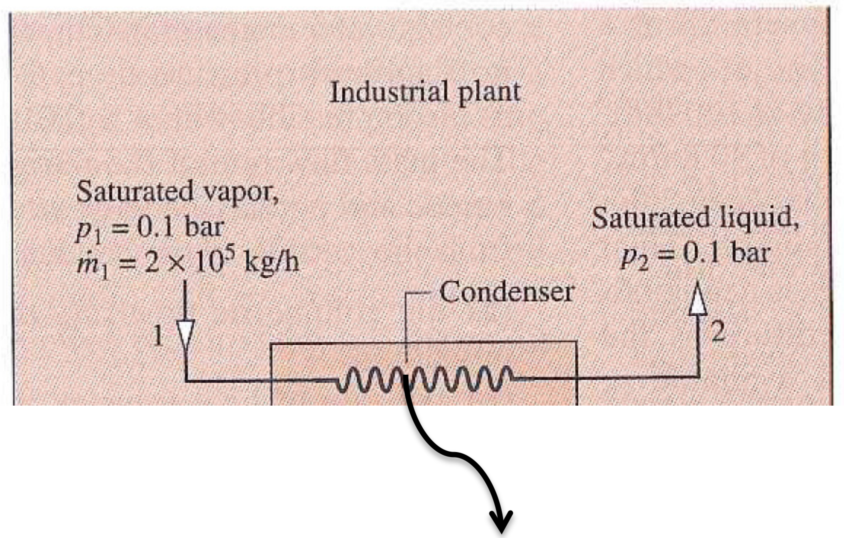


- **Direct contact**: A mixing chamber in which hot and cold streams are mixed directly.
- **Tube-within-a-tube counterflow**: A gas or liquid stream is *separated* from another gas or liquid by a wall through which energy is conducted. Heat transfer occurs from the hot stream to the cold stream as the streams flow in opposite directions.



$$0 = \dot{Q}_{cv} - \dot{W}_{cv} + \sum_i \dot{m}\left(h_i + \frac{V_i^2}{2} + gz_i\right) - \sum_e \dot{m}\left(h_e + \frac{V_e^2}{2} + gz_e\right)$$

$$\dot{m}_3(h_4 - h_3) = \dot{m}_1(h_1 - h_2) \qquad h_4 = h_3 + \frac{\dot{m}_1}{\dot{m}_3}(h_1 - h_2)$$



Q rejected

$$0 = \dot{Q}_{cv} - \dot{W}_{cv} + \dot{m}\left(h_i + \frac{V_i^2}{2} + gz_i\right) - \dot{m}\left(h_e + \frac{V_e^2}{2} + gz_e\right)$$

$$\dot{q}_{cv} = \frac{\dot{Q}_{cv}}{\dot{m}} = (h_4 - h_3)$$

TABLE A-3

Properties of Saturated Water (Liquid–Vapor): Pressure Table

Pressure Conversions:
1 bar = 0.1 MPa
= 10^2 kPa

Press. bar	Temp. °C	Specific Volume m³/kg: Sat. Liquid $v_f \times 10^3$	Sat. Vapor v_g	Internal Energy kJ/kg: Sat. Liquid u_f	Sat. Vapor u_g	Enthalpy kJ/kg: Sat. Liquid h_f	Evap. h_{fg}	Sat. Vapor h_g
0.04	28.96	1.0040	34.800	121.45	2415.2	121.46	2432.9	2554.4
0.06	36.16	1.0064	23.739	151.53	2425.0	151.53	2415.9	2567.4
0.08	41.51	1.0084	18.103	173.87	2432.2	173.88	2403.1	2577.0
0.10	45.81	1.0102	14.674	191.82	2437.9	191.83	2392.8	2584.7
0.20	60.06	1.0172	7.649	251.38	2456.7	251.40	2358.3	2609.7
0.30	69.10	1.0223	5.229	289.20	2468.4	289.23	2336.1	2625.3
0.40	75.87	1.0265	3.993	317.53	2477.0	317.58	2319.2	2636.8
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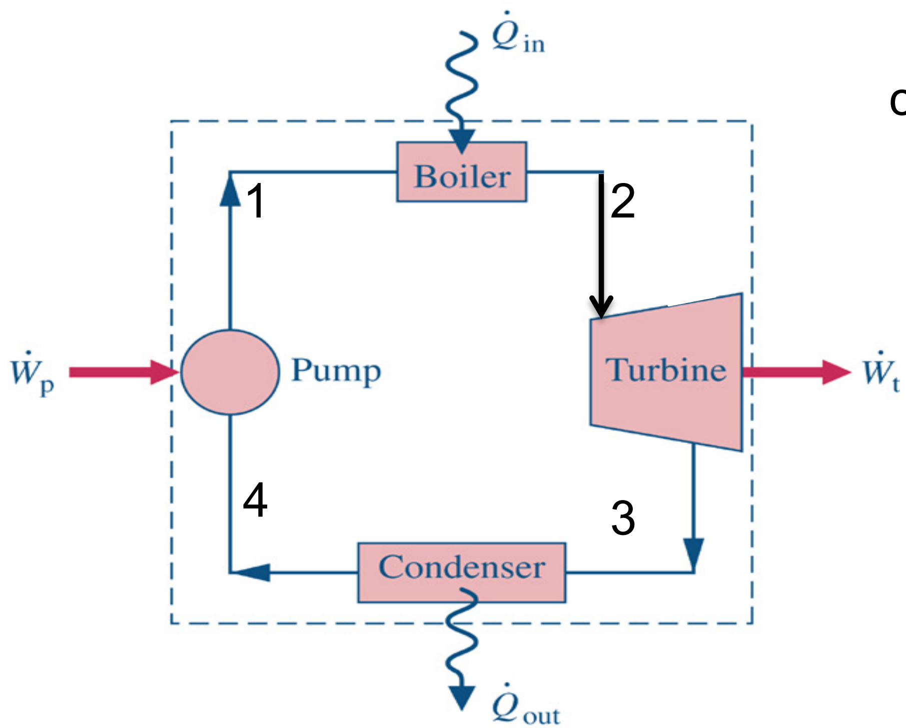
0.60	85.94	1.0331	2.732	359.79	2489.6	359.86	2293.6	2653.5
0.70	89.95	1.0360	2.365	376.63	2494.5	376.70	2283.3	2660.0

$$v_4 = v_f = .0010331$$

$$h_4 = h_f = 359.9 \qquad u_4 = u_f = 359.79$$



Consider a system similar to what the components that we've just analyzed in class.

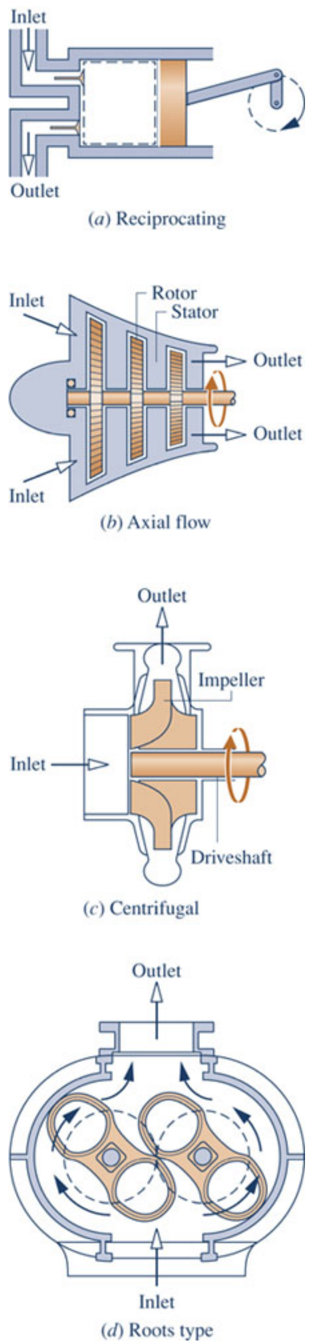
Assume ideal conditions initially

Look up state 4 properties

Now one can solve for Q rejected

$$\dot{q}_{cv} = \frac{\dot{Q}_{cv}}{\dot{m}} = (h_4 - h_3) = -2110\,\frac{kJ}{kg}$$

	P (bar)	T (deg. C)	v m^3/kg	u kJ/kg	h kJ/kg	x
1		150				
2	40	500	.08643	3099.5	3445.3	NA
3	.6	85.94	2.514	2319.2	2470	.92
4	.6	85.94	.0010331	359.79	359.86	0



<u>Compressors and Pumps</u>

- **Compressors and Pumps**: devices in which work is done on the substance flowing through them to change the state of the substance, typically to increase the pressure and/or elevation.
- *Compressor*: substance is gas
- *Pump*: substance is liquid

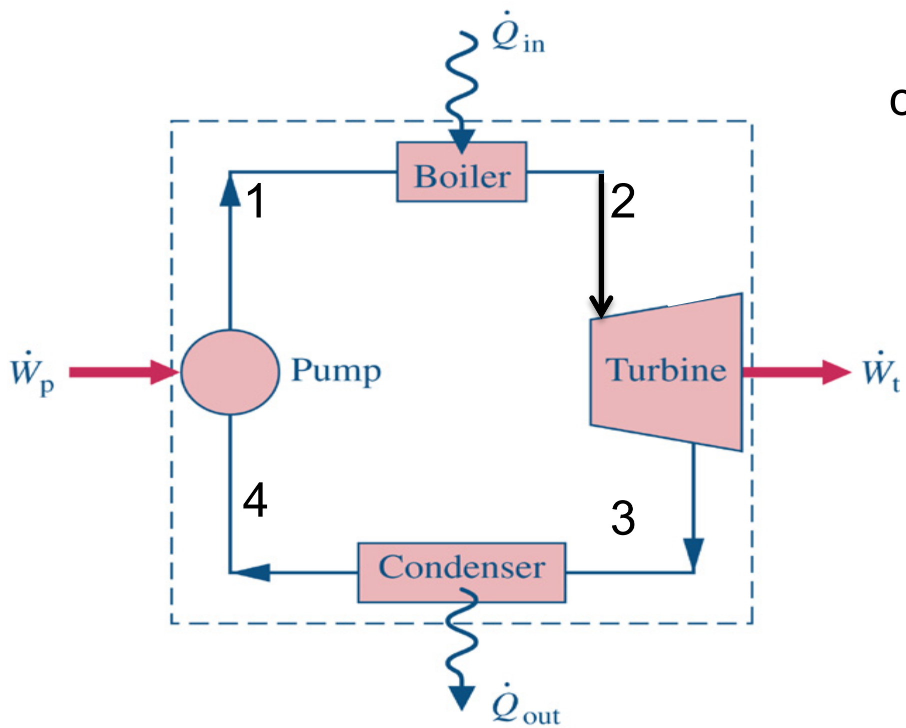
Compressor and Pump Modeling

$$0 = \dot{Q}_{cv} - \dot{W}_{cv} + \dot{m}\left[(h_1 - h_2) + \frac{(V_1^2 - V_2^2)}{2} + g(z_1 - z_2)\right]$$

Eq. 4.20a

- ►If the change in kinetic energy of flowing matter is negligible, $\frac{1}{2}(V_1^2 - V_2^2)$ drops out.
- ►If the change in potential energy of flowing matter is negligible, $g(z_1 - z_2)$ drops out.
- ►If the heat transfer with surroundings is negligible, $\dot{Q}_{cv}$ drops out.

$$\dot{W}_{cv} = \dot{m}(h_1 - h_2)$$



Consider a system similar to what the components that we've just analyzed in class.

Assume ideal conditions initially

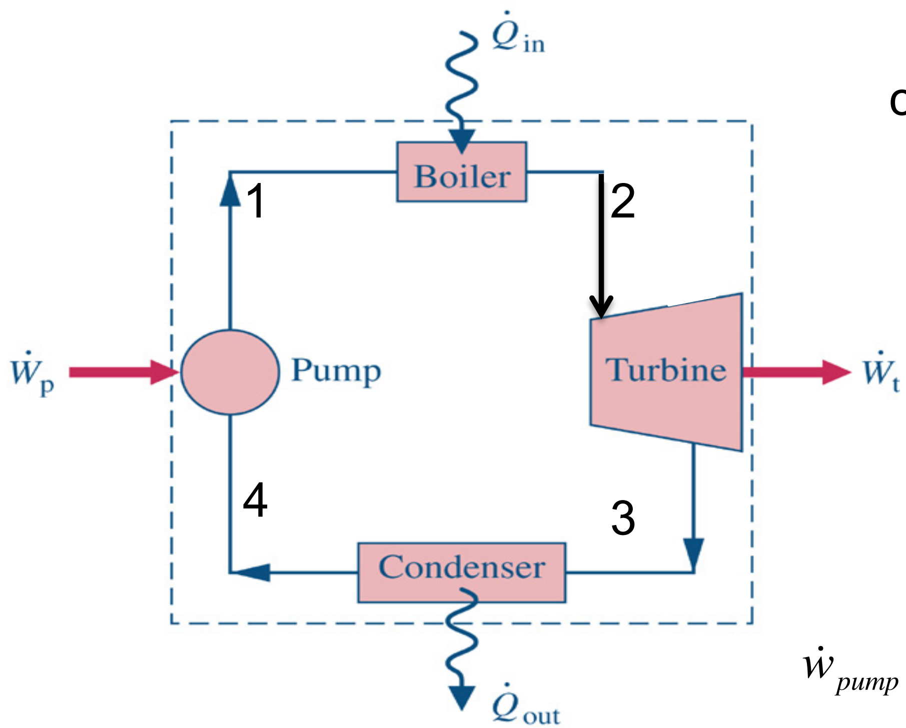
Look up state 1 properties

	P (bar)	T (deg. C)	v m^3/kg	u kJ/kg	h kJ/kg	x
1	40	150				0
2	40	500	.08643	3099.5	3445.3	NA
3	.6	85.94	2.514	2319.2	2470	.92
4	.6	85.94	.0010331	359.79	359.86	0

TABLE A-2

(Continued)

		Specific Volume m³/kg		Internal Energy kJ/kg		Enthalpy kJ/kg		
Temp. °C	Press. bar	Sat. Liquid $v_f \times 10^3$	Sat. Vapor v_g	Sat. Liquid u_f	Sat. Vapor u_g	Sat. Liquid h_f	Evap. h_{fg}	Sat. Vapor h_g
100	1.014	1.0435	1.673	418.94	2506.5	419.04	2257.0	2676.1
110	1.433	1.0516	1.210	461.14	2518.1	461.30	2230.2	2691.5
120*	1.985	1.0603	0.8919	503.50	2529.3	503.71	2202.6	2706.3
130	2.701	1.0697	0.6685	546.02	2539.9	546.31	2174.2	2720.5
140	3.613	1.0797	0.5089	588.74	2550.0	589.13	2144.7	2733.9
150	4.758	1.0905	0.3928	631.68	2559.5	632.20	2114.3	2746.5
160	6.178	1.1020	0.3071	674.86	2568.4	675.55	2082.6	2758.1
170	7.917	1.1143	0.2428	718.33	2576.5	719.21	2049.5	2768.7



Consider a system similar to what the components that we've just analyzed in class.

Assume ideal conditions initially

Look up state 1 properties

Now one can solve for W pump

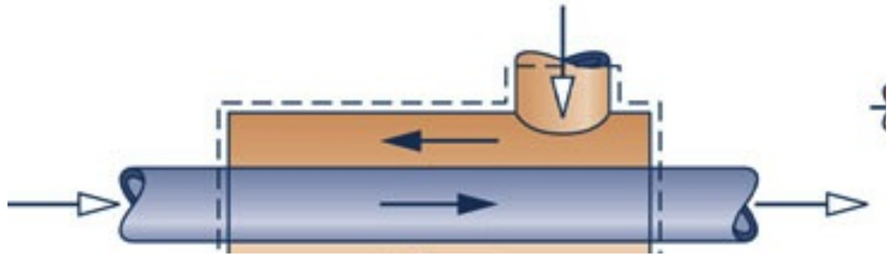
$$\dot{W}_{pump} = \dot{m}(h_4 - h_1)$$

$$\dot{w}_{pump} = \frac{\dot{W}_{pump}}{\dot{m}} = (h_4 - h_1) = 359.86 - 632.2 = -272.3$$

	P (bar)	T (deg. C)	v m^3/kg	u kJ/kg	h kJ/kg	x
1	40	150	.0010905	631.68	632.2	0
2	40	500	.08643	3099.5	3445.3	NA
3	.6	85.94	2.514	2319.2	2470	.92
4	.6	85.94	.0010331	359.79	359.86	0

Heat Exchangers – Boilers too

Pump State 1



To turbine, state 2

$$\dot{q}_{cv} = \frac{\dot{Q}_{cv}}{\dot{m}} = (h_2 - h_1) = 3445.3 - 632.2 = 2813.1 \frac{kJ}{kg}$$

Power Cycle

►Applying the closed system energy balance to each cycle of operation,

$$\Delta E_{\text{cycle}} = Q_{\text{cycle}} - W_{\text{cycle}} \qquad \textbf{(Eq. 2.39)}$$

►Since the system returns to its initial state after each cycle, there is no net change in its energy: $\mathbf{\Delta E_{cycle} = 0}$, and the energy balance reduces to give

$$W_{\text{cycle}} = Q_{\text{in}} - Q_{\text{out}} \qquad \textbf{(Eq. 2.41)}$$

►In words, the ***net*** energy transfer by work from the system equals the ***net*** energy transfer by heat to the system, each per cycle of operation.

Power Cycle

►The performance of a system undergoing a power cycle is evaluated on an energy basis in terms of the extent to which the energy added by heat, Q_{in}, is converted to a net work output, W_{cycle}. This is represented by the ratio

$$\eta = \frac{W_{\text{cycle}}}{Q_{\text{in}}} = \frac{W_{turbine} - W_{pump}}{Q_{boiler}} = \frac{975.3 - 272.3}{2813} = 25\%$$

called the thermal efficiency.

$$\eta = \frac{Q_{\text{in}} - Q_{\text{out}}}{Q_{\text{in}}} = 1 - \frac{Q_{condenser}}{Q_{boiler}} = 1 - \frac{2110}{2813} = 25\%$$