RME1102
Fundamentals of Mechanical Engineering

Lecture 3

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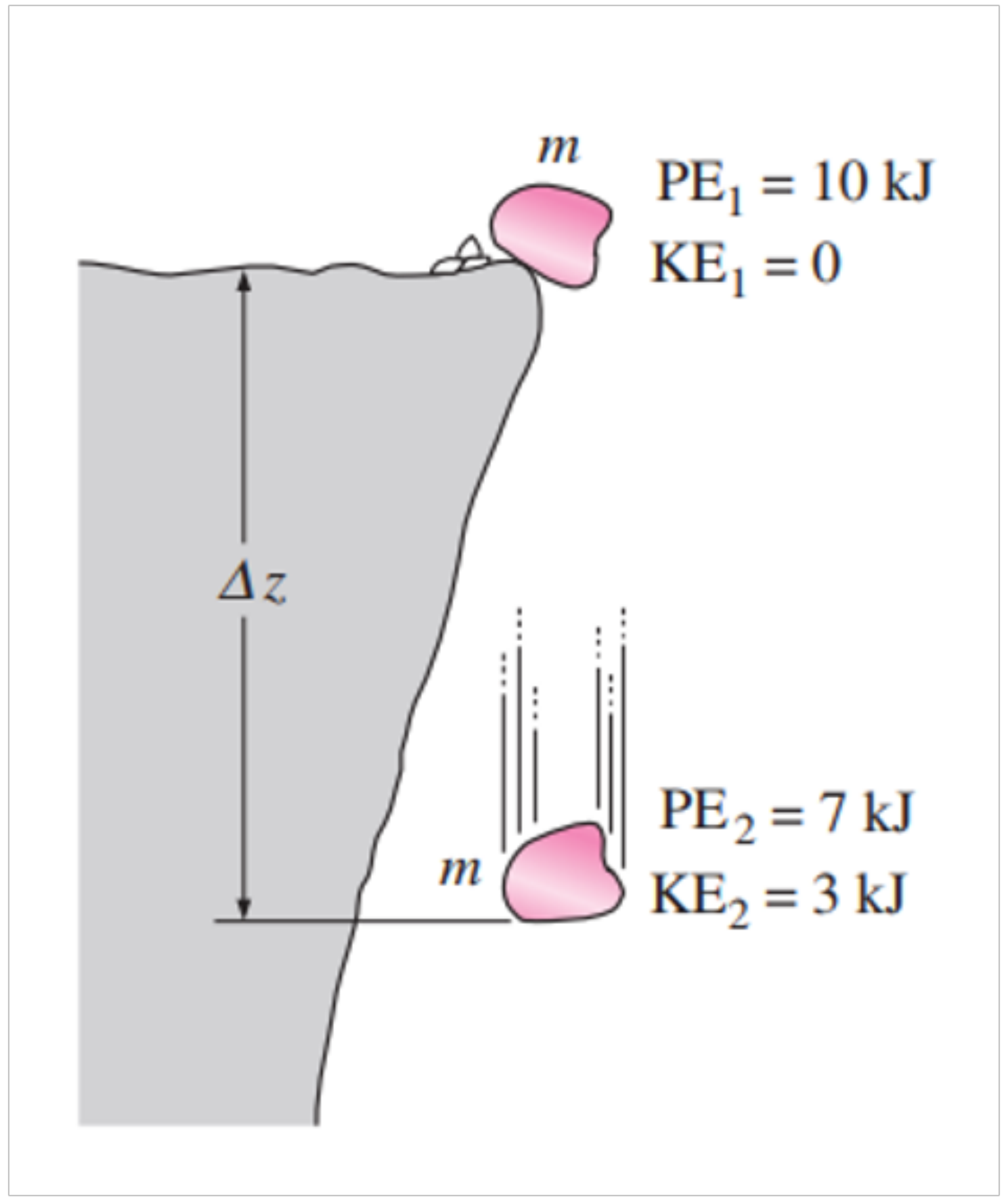
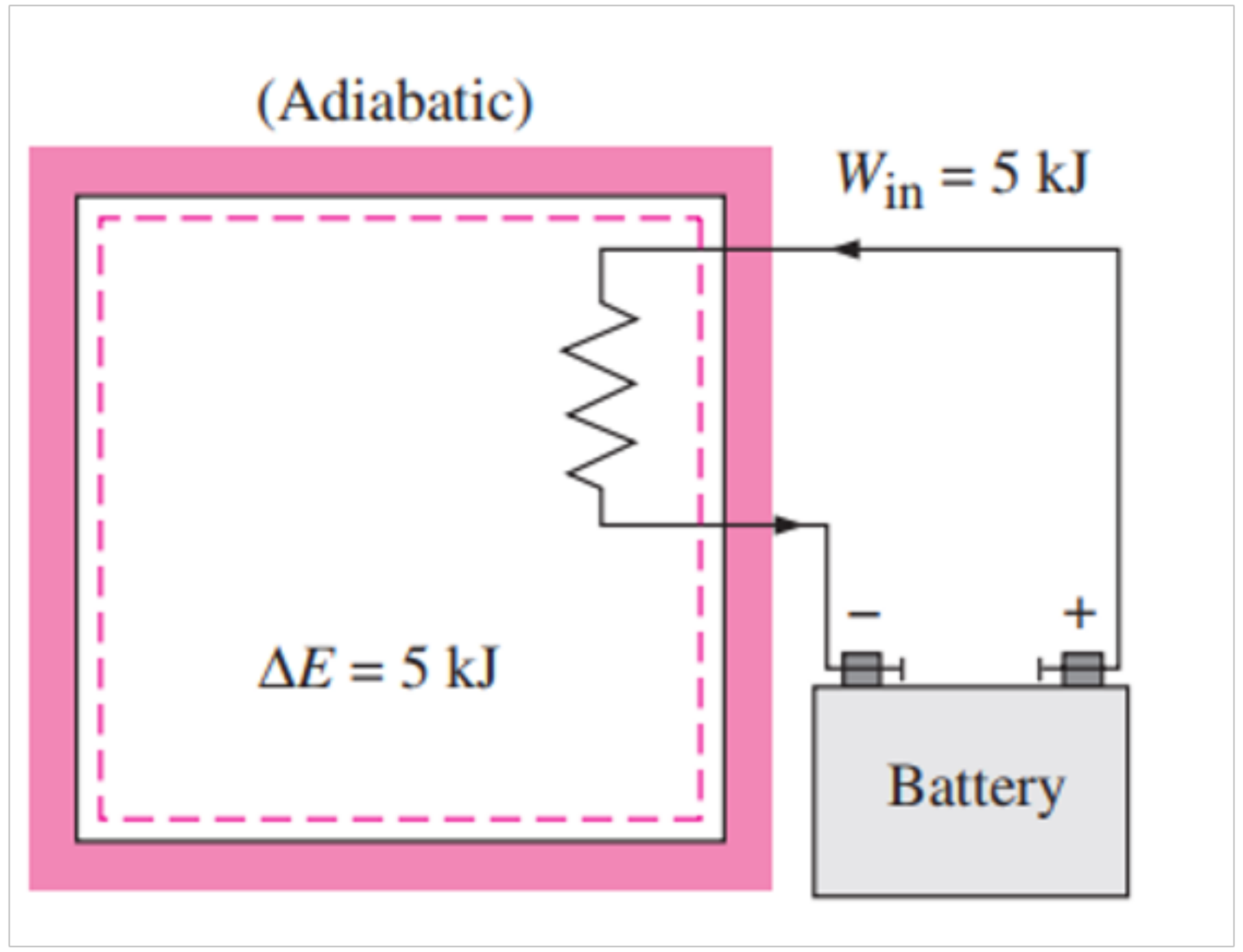
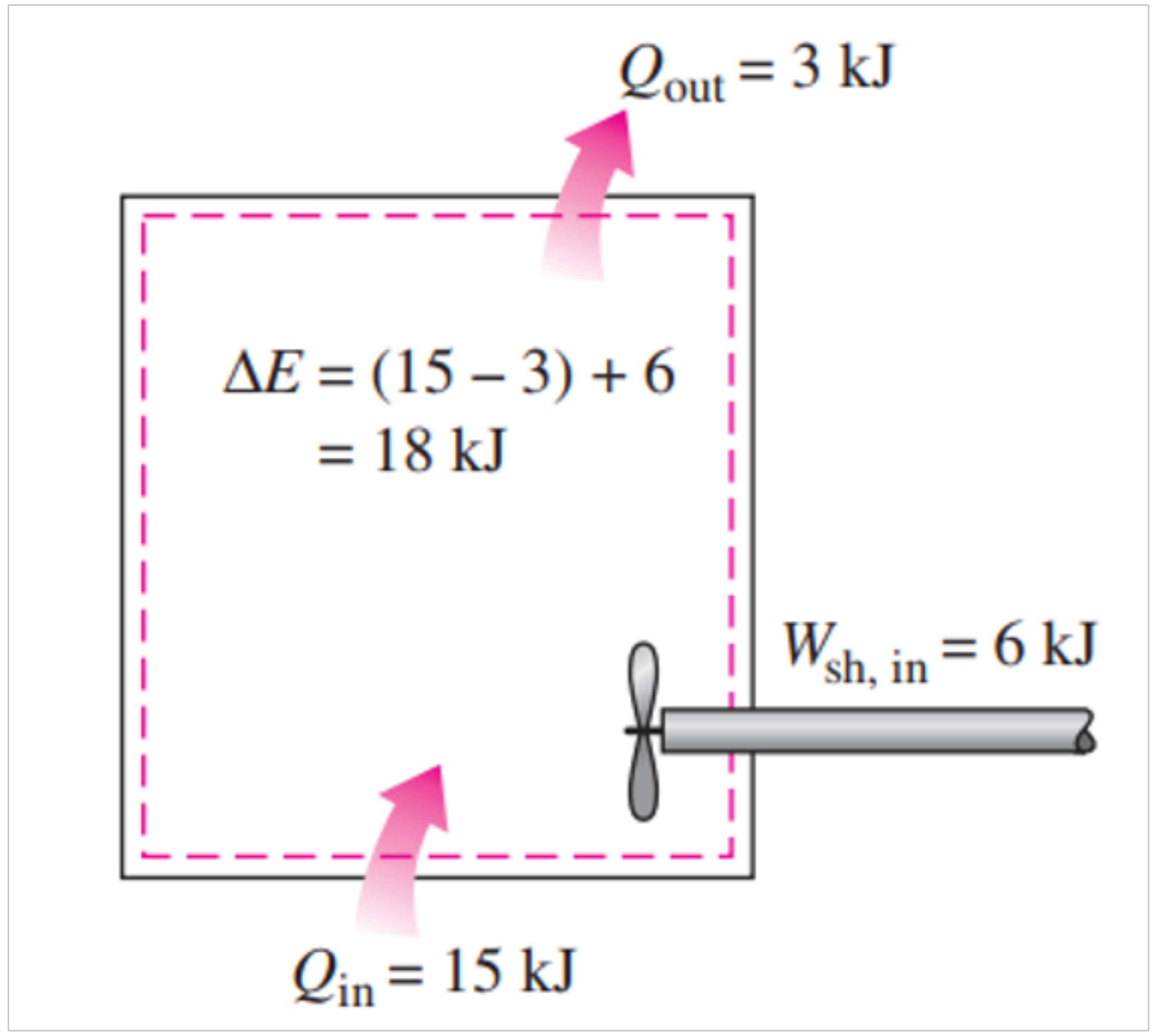
Conservation of energy for a CM system

- **First law of thermodynamics:** When a system undergoes a cyclic change, the net heat to/from the system is equal to the net work from/to the system.

$$J\oint \delta Q = \oint \delta W$$







Energy balance

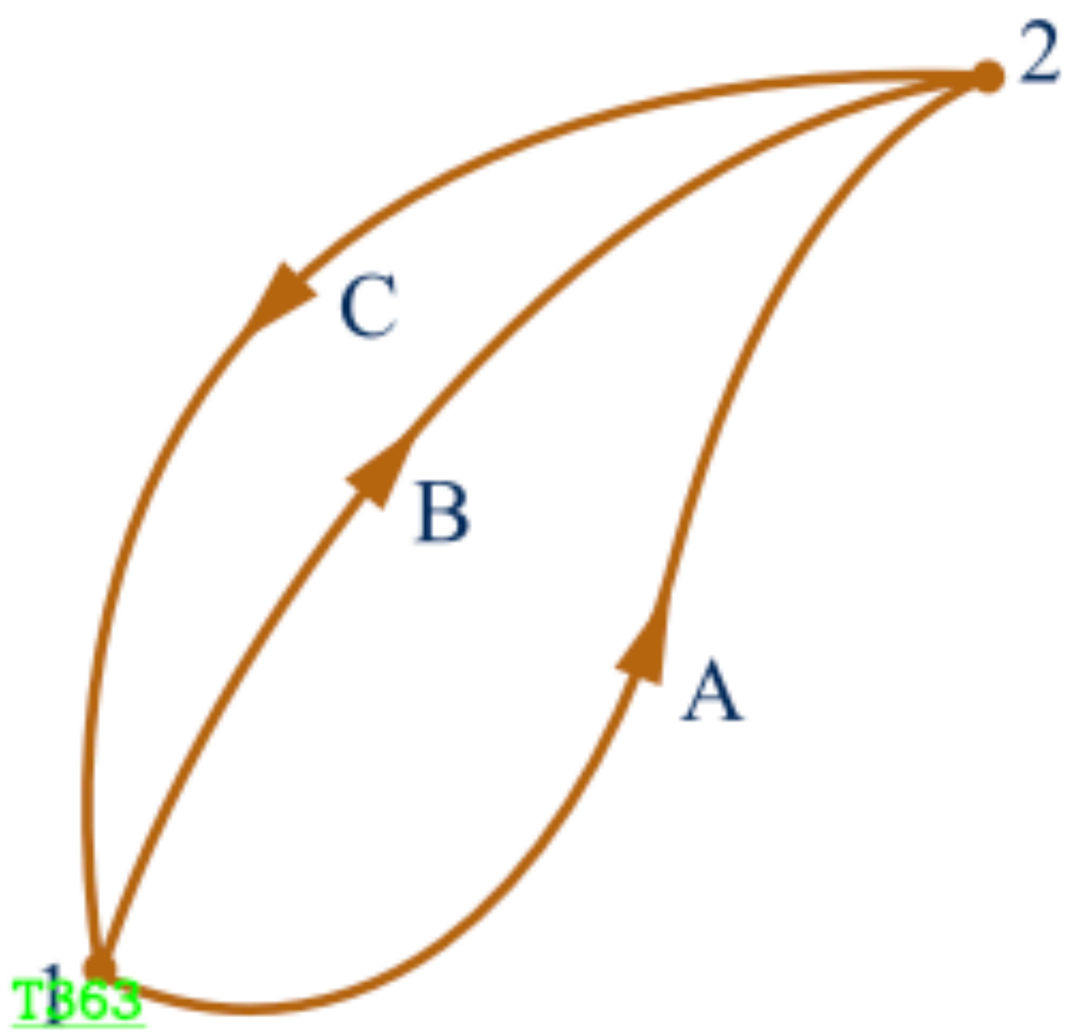
$$\begin{pmatrix}\text{Total energy}\\ \text{entering the system}\end{pmatrix} - \begin{pmatrix}\text{Total energy}\\ \text{leaving the system}\end{pmatrix} = \begin{pmatrix}\text{Change in the total}\\ \text{energy of the system}\end{pmatrix}$$

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

$$\text{Energy change} = \text{Energy at final state} - \text{Energy at initial state}$$

$$\Delta E_{system} = E_{final} - E_{initial} = E_2 - E_1$$

First law of thermodynamics for a change in state



$\Rightarrow \oint \delta W = J \oint \delta Q$

$\Rightarrow \oint \delta Q = \oint \delta W \qquad [J = 1.0 \text{ in SI unit}]$

$\Rightarrow \int_1^2 \delta Q_A + \int_2^1 \delta Q_C = \int_1^2 \delta W_A + \int_2^1 \delta W_C \quad \textcircled{1}$

$\Rightarrow \int_1^2 \delta Q_B + \int_2^1 \delta Q_C = \int_1^2 \delta W_B + \int_2^1 \delta W_C \quad \textcircled{2}$

- $\textcircled{1} - \textcircled{2} : \int_1^2 \delta Q_A - \int_1^2 \delta Q_B = \int_1^2 \delta W_A - \int_1^2 \delta W_B$

$\Rightarrow \int_1^2 \delta Q_A - \int_1^2 \delta W_A = \int_1^2 \delta Q_B - \int_1^2 \delta W_B$

$$\int_1^2 (\delta Q - \delta W)_A = \int_1^2 (\delta Q - \delta W)_B = \cdots$$

$\int_1^2 (\delta Q - \delta W)$ is independent of path and dependent only on the initial and final states; hence, it has the characteristics of a property and this property is denoted by energy, E.

$$\delta Q - \delta W = dE \qquad \Rightarrow \qquad Q_{12} - W_{12} = \Delta E$$

First law of thermodynamics for CM system

- $$E = U + KE + PE + \cdots$$

$\Rightarrow \delta Q - \delta W = dE = dU + d(KE) + d(PE) + \cdots$

$\Rightarrow \frac{\delta Q}{dt} - \frac{\delta W}{dt} = \frac{dE_{CM}}{dt} = \frac{dU}{dt} + \frac{d(KE)}{dt} + \frac{d(PE)}{dt} + \cdots$

- $$\frac{dE_{CM}}{dt} = \frac{dQ}{dt} - \frac{dW}{dt} = \dot{Q} - \dot{W}$$

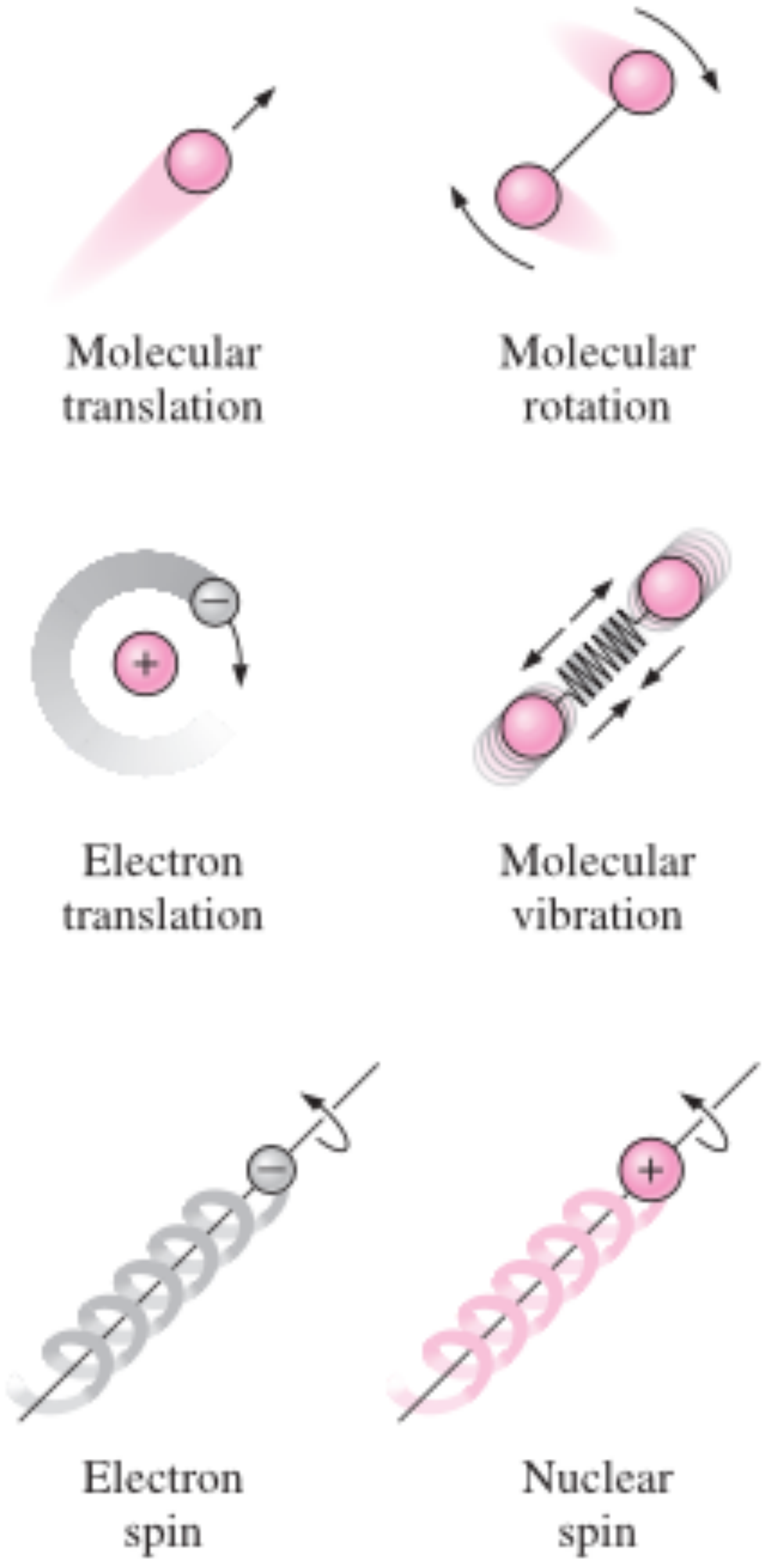
$\Rightarrow dU \Rightarrow \int_1^2 dU = U_2 - U_1 = m(u_2 - u_1)$

$\Rightarrow d(KE) = m\mathbb{V}d\mathbb{V} \Rightarrow \int_1^2 d(KE) = \frac{1}{2}m(\mathbb{V}_2^2 - \mathbb{V}_1^2)$

$\Rightarrow d(PE) = mgdZ \Rightarrow \int_1^2 d(PE) = mg(Z_2 - Z_1) = mgh$

$$Q_{12} - W_{12} = \left[(U_2 - U_1) + \frac{1}{2}m(\mathbb{V}_2^2 - \mathbb{V}_1^2) + mg(Z_2 - Z_1) + \cdots\right] \simeq (U_2 - U_1)$$

$$q_{12} - w_{12} = \left[(u_2 - u_1) + \frac{1}{2}(\mathbb{V}_2^2 - \mathbb{V}_1^2) + g(Z_2 - Z_1) + \cdots\right] \simeq (u_2 - u_1)$$



First law of thermodynamics for CM system, cont'd

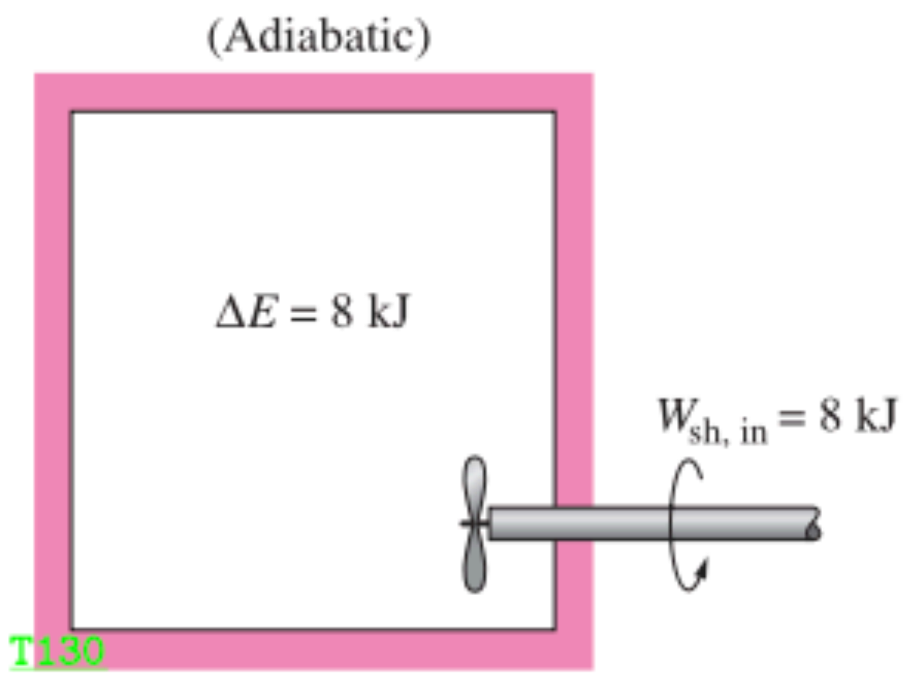
Stationary Systems

$z_1 = z_2 \rightarrow \Delta PE = 0$

$V_1 = V_2 \rightarrow \Delta KE = 0$

$\Delta E = \Delta U$

T129



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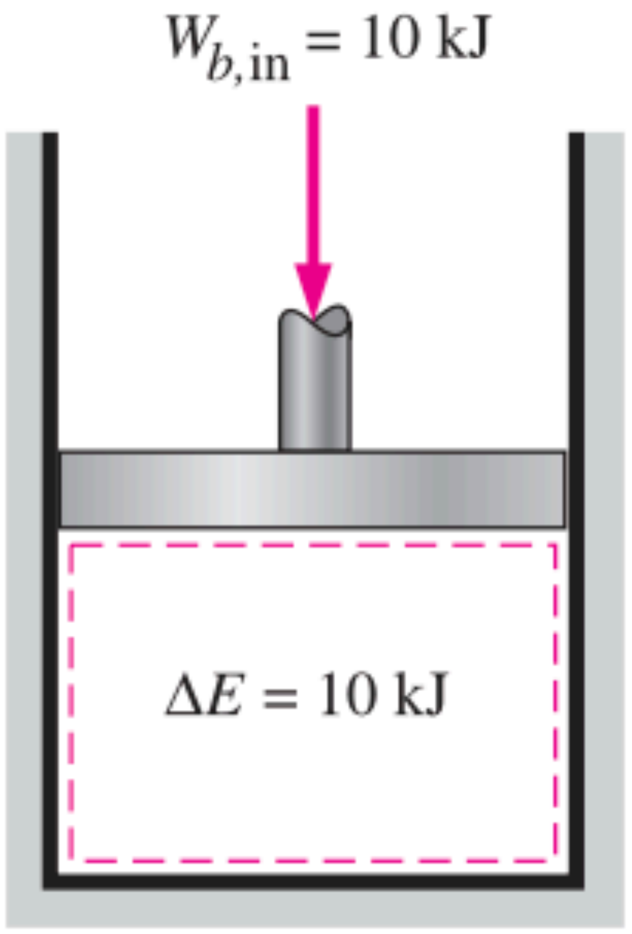

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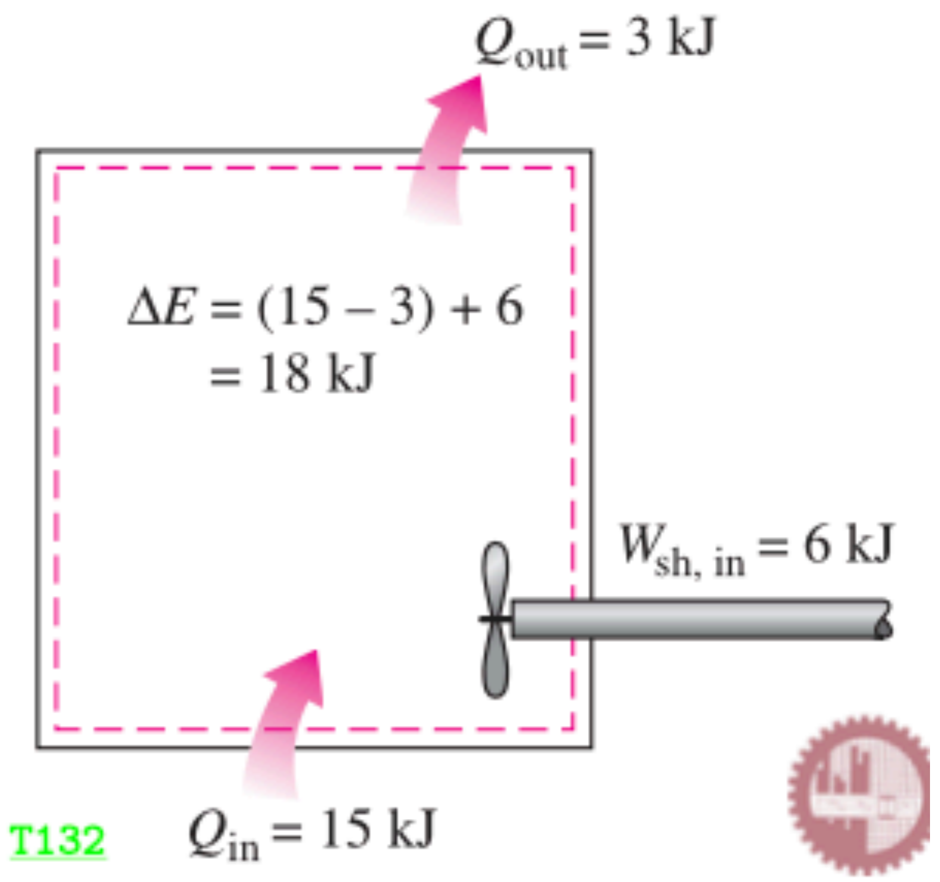

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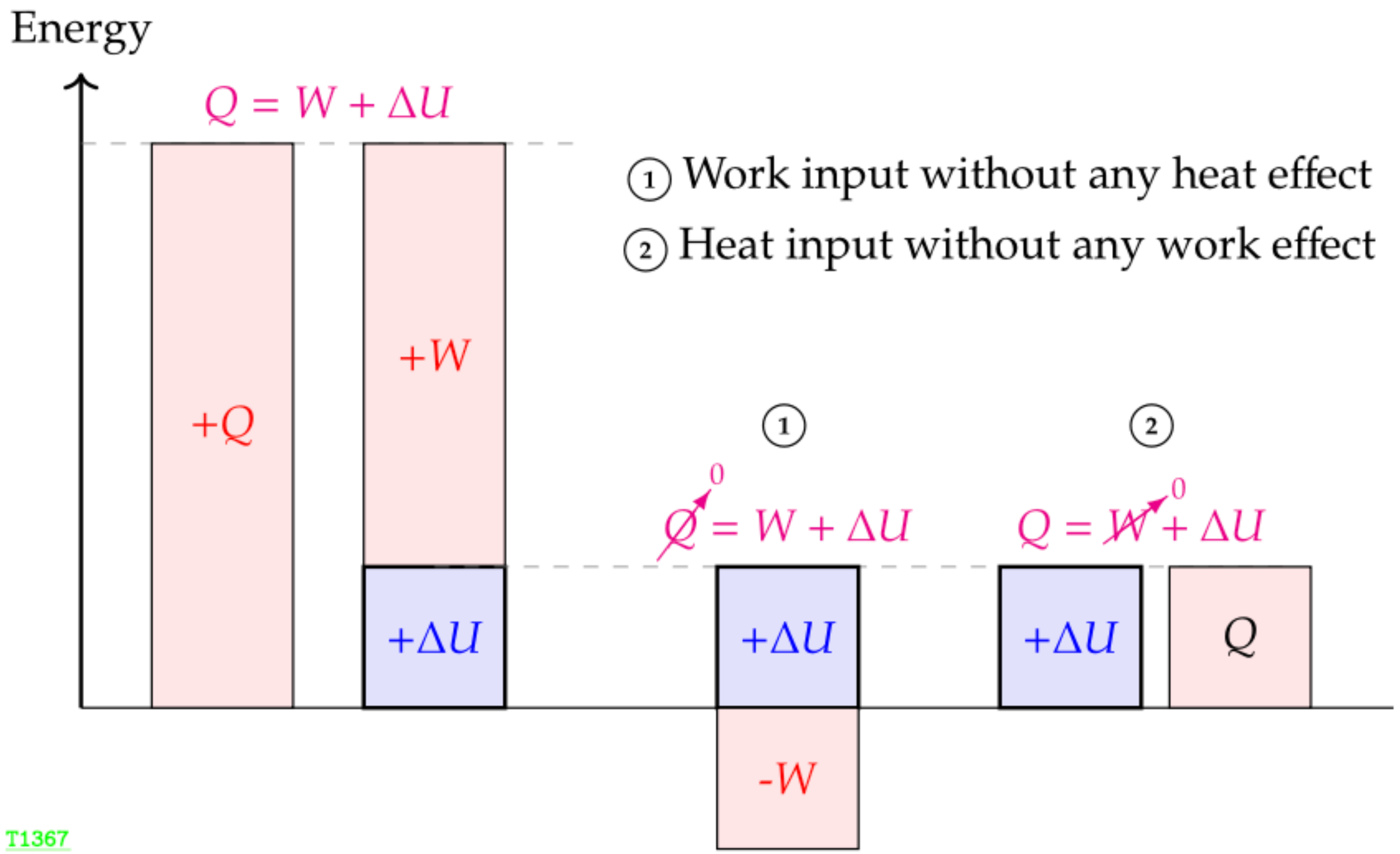


T1367

Conservation of Energy for CV system

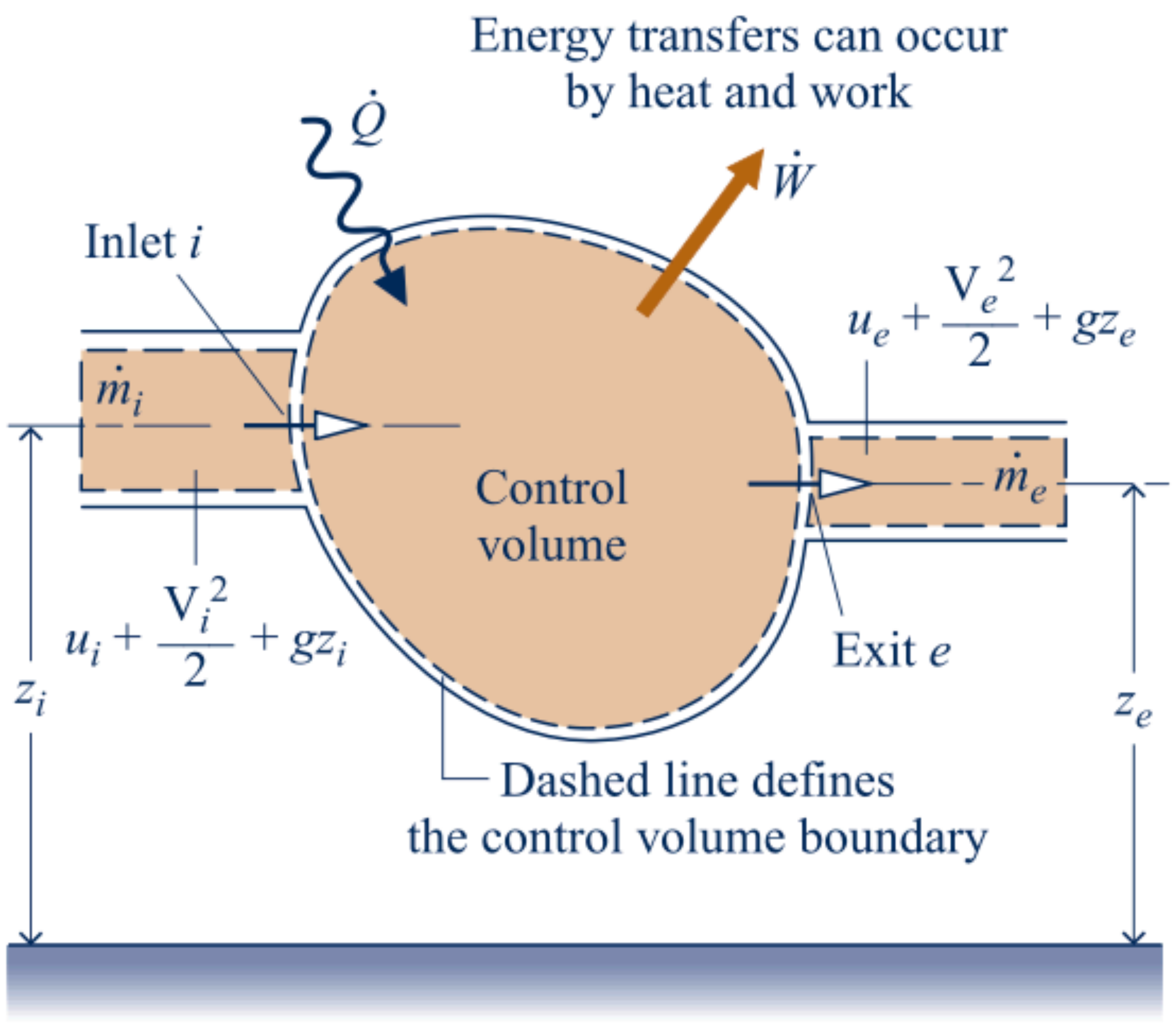
$$\begin{bmatrix}\text{time } \textit{rate of change} \\ \text{of the energy} \\ \text{contained within} \\ \text{the control volume} \\ \textit{at time t}\end{bmatrix} = \begin{bmatrix}\text{net } \textit{rate} \text{ at which} \\ \text{energy is being} \\ \text{transferred in} \\ \text{by heat transfer} \\ \textit{at time t}\end{bmatrix} - \begin{bmatrix}\textit{net} \text{ rate at which} \\ \text{energy is being} \\ \text{transferred out} \\ \text{by work } \textit{at} \\ \textit{time t}\end{bmatrix} + \begin{bmatrix}\textit{net} \text{ rate of energy} \\ \text{transfer } \textit{into} \text{ the} \\ \text{control volume} \\ \text{accompanying} \\ \text{mass flow}\end{bmatrix}$$

$$\frac{dE_{cv}}{dt} = \dot{Q} - \dot{W} + \dot{m}_i e_i - \dot{m}_e e_e$$

$$= \dot{Q} - \dot{W} + \dot{m}_i \left(u_i + \frac{\mathbb{V}_i^2}{2} + gz_i \right) - \dot{m}_e \left(u_e + \frac{\mathbb{V}_e^2}{2} + gz_e \right)$$

$$= \dot{Q} - \dot{W}_{cv} + \dot{m}_i \left(h_i + \frac{\mathbb{V}_i^2}{2} + gz_i \right) - \dot{m}_e \left(h_e + \frac{\mathbb{V}_e^2}{2} + gz_e \right)$$

- $\dot{W} = \dot{W}_s + \dot{W}_b + \dot{W}_f = \dot{W}_{cv} + \dot{W}_f$
- $\dot{W}_f = -P(\dot{V}_i - \dot{V}_e) = -P(\dot{m}_i v_i - \dot{m}_e v_e)$
- $h \equiv u + Pv$



First law of thermodynamics for CV system

$$\frac{dE_{CV}}{dt} = \dot{Q} - \dot{W}_{cv} + \sum_i \dot{m}_i \left(h_i + \frac{\mathbb{V}_i^2}{2} + gz_i \right) - \sum_e \dot{m}_e \left(h_e + \frac{\mathbb{V}_e^2}{2} + gz_e \right)$$

- Closed System: $\mapsto \dot{m}_i = \dot{m}_e = 0.$

$$\frac{dE_{CM}}{dt} = \dot{Q} - \dot{W}_{net}$$

- Closed & Adiabatic (Isolated) System: $\mapsto \dot{m}_i = \dot{m}_e = 0, \quad \dot{Q} = 0.$

$$\frac{dE_{CM}}{dt} = -\dot{W}_{net} \Rightarrow \Delta E_{CM} = -W_{ad}$$

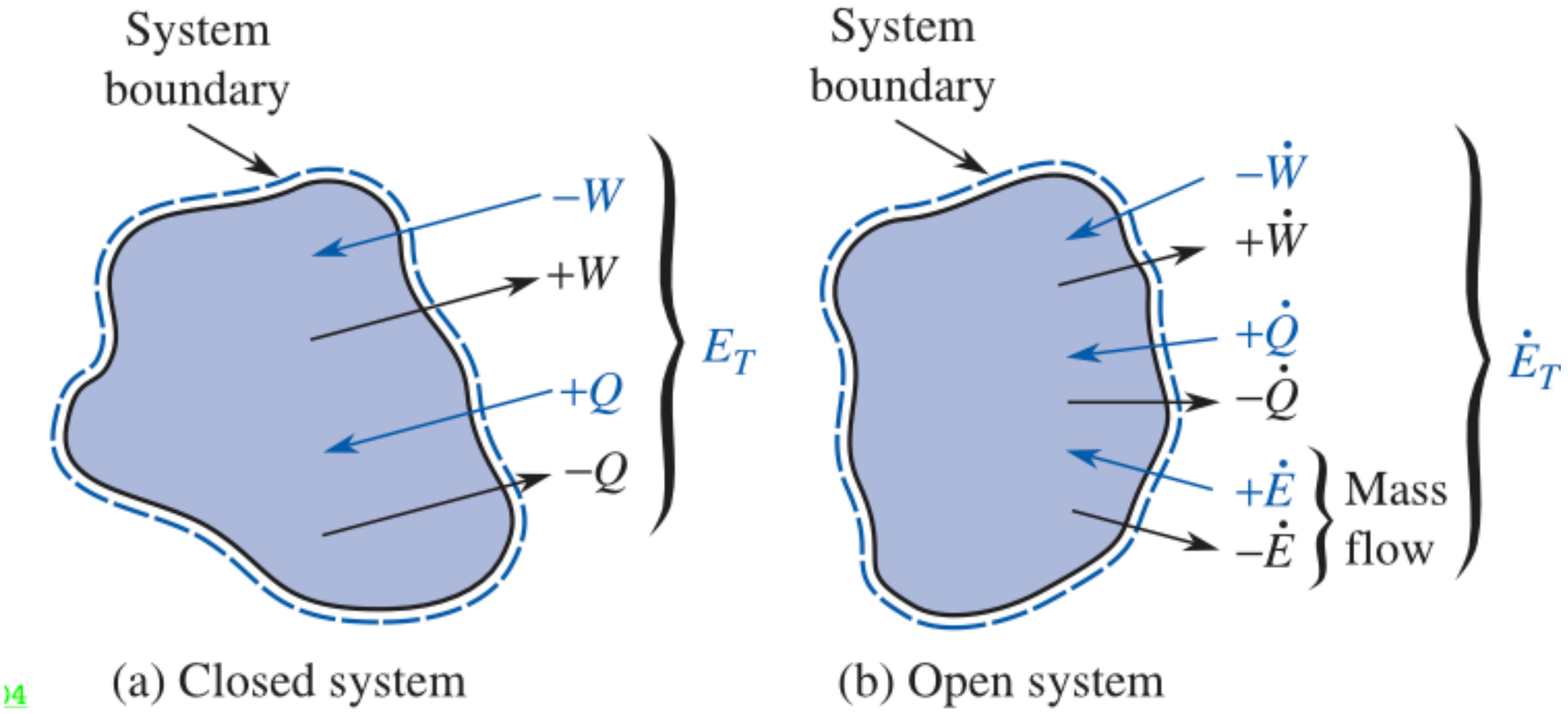
- Steady-State-Steady Flow (SSSF) System:

$$\frac{dm_{CV}}{dt} = 0 \Rightarrow \sum_i \dot{m}_i = \sum_e \dot{m}_e \quad : \quad \frac{dE_{cv}}{dt} = 0$$

- One-inlet, One-exit & Steady-state: $\mapsto \dot{m}_i = \dot{m}_e = \dot{m}.$

$$0 = \dot{Q} - \dot{W}_{CV} + \dot{m} \left[(h_1 - h_2) + \left(\frac{\mathbb{V}_1^2 - \mathbb{V}_2^2}{2} \right) + g(z_1 - z_2) \right]$$

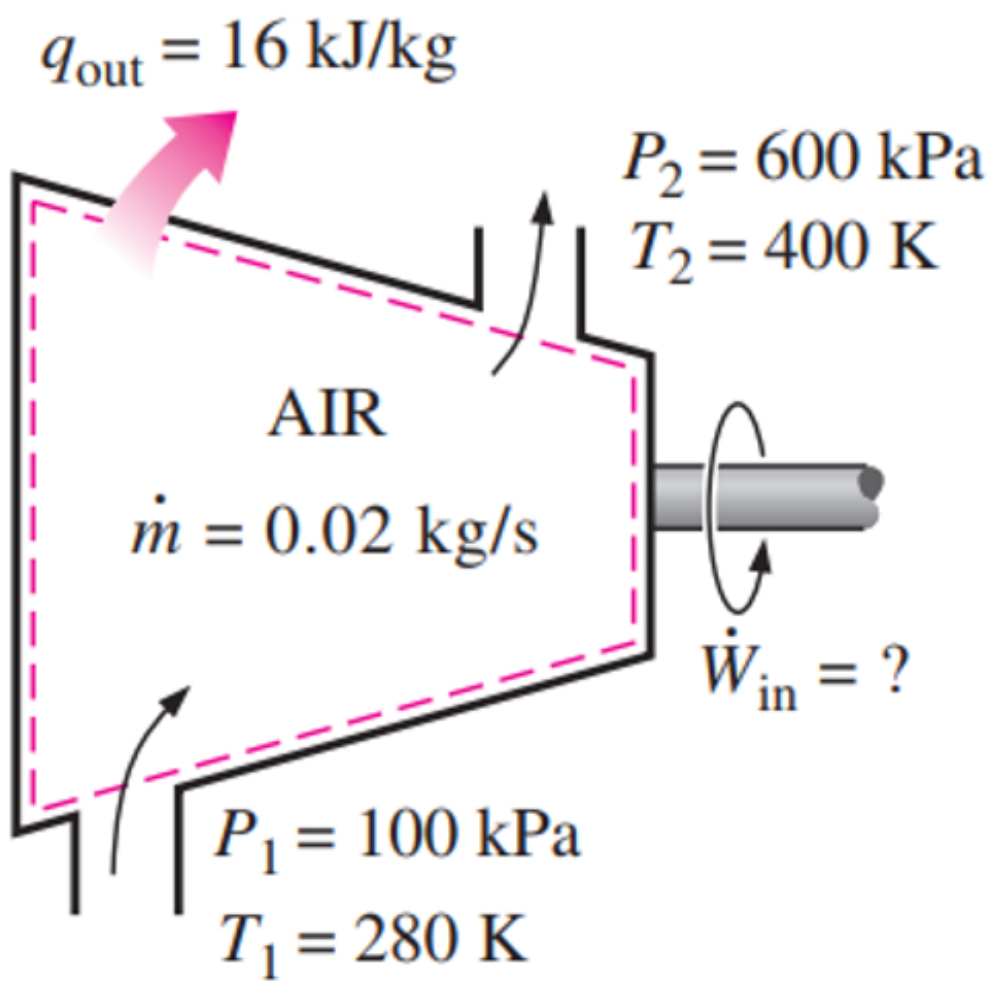
Sign convention



Problem 1

EXAMPLE 5–6 Compressing Air by a Compressor

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.



Under stated assumptions and observations, the energy balance for this steady-flow system can be expressed in the rate form as

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\text{Rate of net energy transfer by heat, work, and mass}} = \underbrace{dE_{system}/dt}_{\text{Rate of change in internal, kinetic, potential, etc., energies}}\overset{\nearrow 0 \text{ (steady)}}{} = 0$$

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

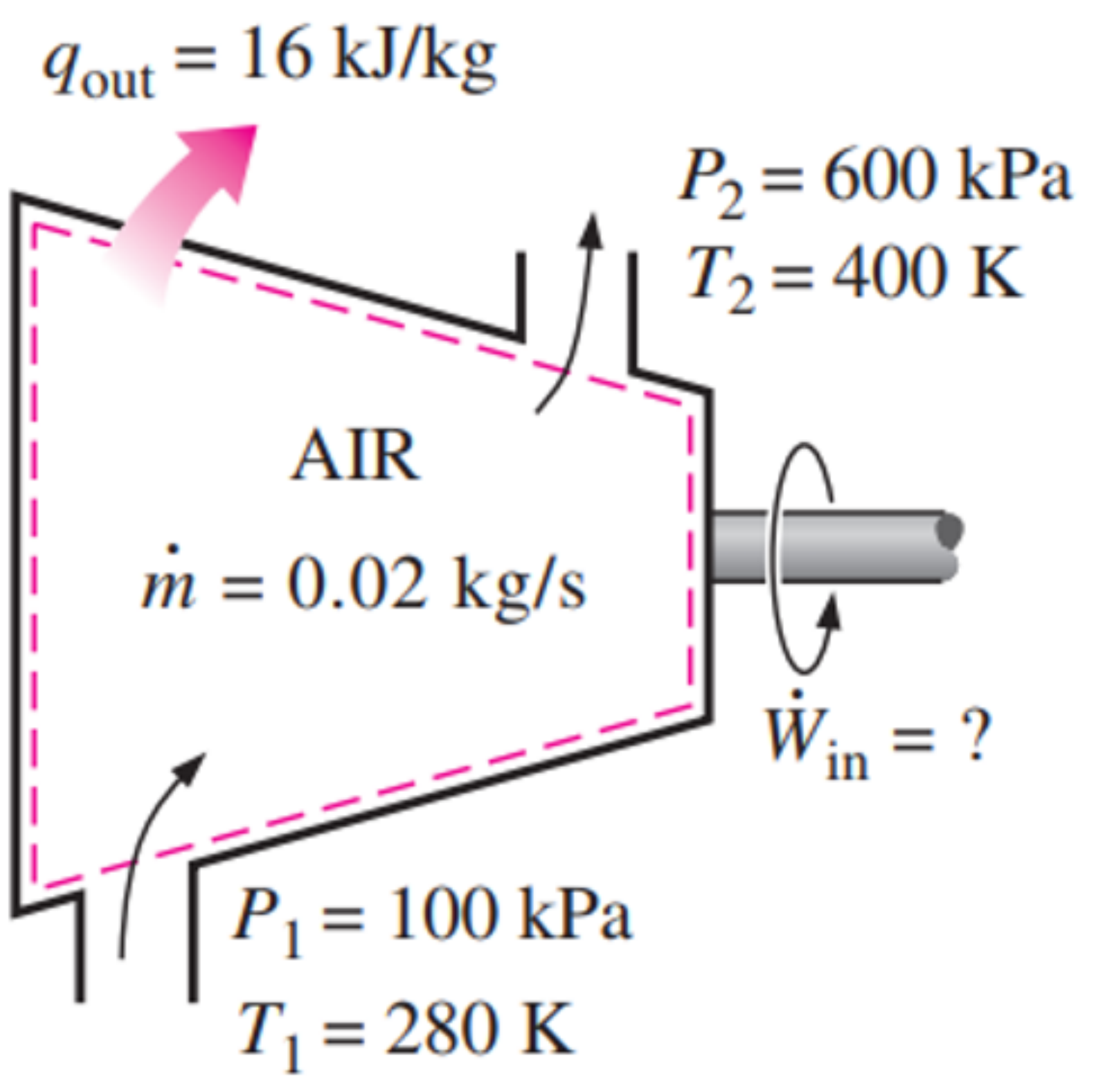
$$\dot{W}_{in} + \dot{m}h_1 = \dot{Q}_{out} + \dot{m}h_2 \qquad (\text{since } \Delta ke = \Delta pe \cong 0)$$

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

Problem 1, cont'd

EXAMPLE 5–6 Compressing Air by a Compressor

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.



The enthalpy of an ideal gas depends on temperature only, and the enthalpies of the air at the specified temperatures are determined from the air table (Table A–17) to be

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

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

Substituting, the power input to the compressor is determined to be

$$\dot{W}_{in} = (0.02\text{ kg/s})(16\text{ kJ/kg}) + (0.02\text{ kg/s})(400.98 - 280.13)\text{ kJ/kg}$$
$$= \mathbf{2.74\ kW}$$

Problem 1, cont'd

TABLE A–17

Ideal-gas properties of air

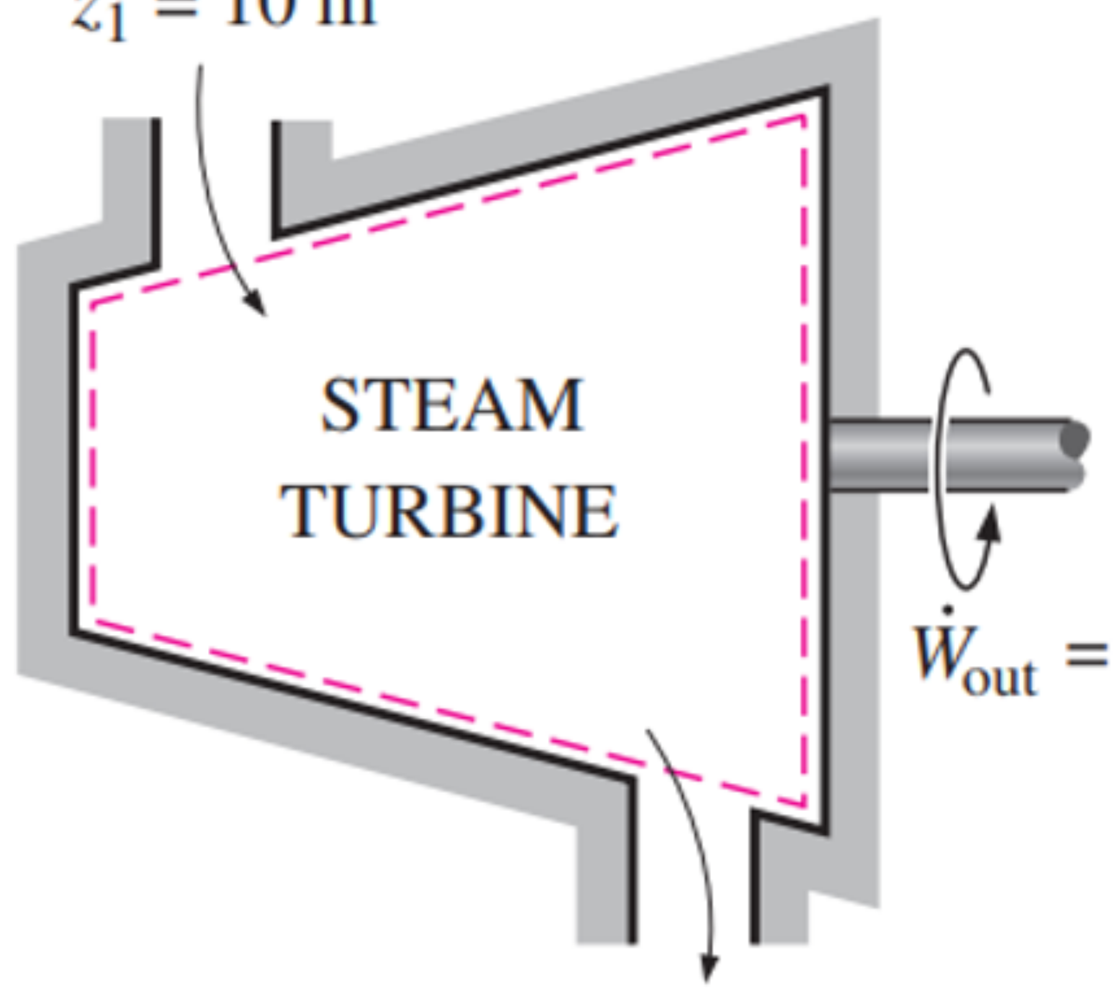
T K	h kJ/kg	P_r	u kJ/kg	v_r	s° kJ/kg·K	T K	h kJ/kg	P_r	u kJ/kg	v_r	s° kJ/kg·K
200	199.97	0.3363	142.56	1707.0	1.29559	580	586.04	14.38	419.55	115.7	2.37348
210	209.97	0.3987	149.69	1512.0	1.34444	590	596.52	15.31	427.15	110.6	2.39140
220	219.97	0.4690	156.82	1346.0	1.39105	600	607.02	16.28	434.78	105.8	2.40902
230	230.02	0.5477	164.00	1205.0	1.43557	610	617.53	17.30	442.42	101.2	2.42644
240	240.02	0.6355	171.13	1084.0	1.47824	620	628.07	18.36	450.09	96.92	2.44356
250	250.05	0.7329	178.28	979.0	1.51917	630	638.63	19.84	457.78	92.84	2.46048
260	260.09	0.8405	185.45	887.8	1.55848	640	649.22	20.64	465.50	88.99	2.47716
270	270.11	0.9590	192.60	808.0	1.59634	650	659.84	21.86	473.25	85.34	2.49364
280	280.13	1.0889	199.75	738.0	1.63279	660	670.47	23.13	481.01	81.89	2.50985
285	285.14	1.1584	203.33	706.1	1.65055	670	681.14	24.46	488.81	78.61	2.52589
290	290.16	1.2311	206.91	676.1	1.66802	680	691.82	25.85	496.62	75.50	2.54175
295	295.17	1.3068	210.49	647.9	1.68515	690	702.52	27.29	504.45	72.56	2.55731
298	298.18	1.3543	212.64	631.9	1.69528	700	713.27	28.80	512.33	69.76	2.57277
300	300.19	1.3860	214.07	621.2	1.70203	710	724.04	30.38	520.23	67.07	2.58810
305	305.22	1.4686	217.67	596.0	1.71865	720	734.82	32.02	528.14	64.53	2.60319
390	390.88	3.481	278.93	321.5	1.96633	900	932.93	75.29	674.58	34.31	2.84856
400	400.98	3.806	286.16	301.6	1.99194	920	955.38	82.05	691.28	32.18	2.87324
410	411.12	4.153	293.43	283.3	2.01699	940	977.92	89.28	708.08	30.22	2.89748

Problem 2

EXAMPLE 5–7 Power Generation by a Steam Turbine

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. 5–28.

(*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.



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

$$h_2 = h_f + x_2 h_{fg} = [225.94 + (0.9)(2372.3)] \text{ kJ/kg} = 2361.01 \text{ kJ/kg}$$

Then

$$\Delta h = h_2 - h_1 = (2361.01 - 3248.4) \text{ kJ/kg} = \mathbf{-887.39 \text{ kJ/kg}}$$

$$\Delta \text{ke} = \frac{V_2^2 - V_1^2}{2} = \frac{(180 \text{ m/s})^2 - (50 \text{ m/s})^2}{2}\left(\frac{1 \text{ kJ/kg}}{1000 \text{ m}^2/\text{s}^2}\right) = \mathbf{14.95 \text{ kJ/kg}}$$

$$\Delta \text{pe} = g(z_2 - z_1) = (9.81 \text{ m/s}^2)[(6 - 10) \text{ m}]\left(\frac{1 \text{ kJ/kg}}{1000 \text{ m}^2/\text{s}^2}\right) = \mathbf{-0.04 \text{ kJ/kg}}$$

Problem 2, cont'd

TABLE A–6

Superheated water (*Concluded*)

T °C	*v* m³/kg	*u* kJ/kg	*h* kJ/kg	*s* kJ/kg·K	*v* m³/kg	*u* kJ/kg	*h* kJ/kg	*s* kJ/kg·K	*v* m³/kg	*u* kJ/kg	*h* kJ/kg	*s* kJ/kg·K
	P = 1.00 MPa (179.88°C)				*P* = 1.20 MPa (187.96°C)				*P* = 1.40 MPa (195.04°C)			
Sat.	0.19437	2582.8	2777.1	6.5850	0.16326	2587.8	2783.8	6.5217	0.14078	2591.8	2788.9	6.4675
200	0.20602	2622.3	2828.3	6.6956	0.16934	2612.9	2816.1	6.5909	0.14303	2602.7	2803.0	6.4975
250	0.23275	2710.4	2943.1	6.9265	0.19241	2704.7	2935.6	6.8313	0.16356	2698.9	2927.9	6.7488
300	0.25799	2793.7	3051.6	7.1246	0.21386	2789.7	3046.3	7.0335	0.18233	2785.7	3040.9	6.9553
350	0.28250	2875.7	3158.2	7.3029	0.23455	2872.7	3154.2	7.2139	0.20029	2869.7	3150.1	7.1379
400	0.30661	2957.9	3264.5	7.4670	0.25482	2955.5	3261.3	7.3793	0.21782	2953.1	3258.1	7.3046
500	0.35411	3125.0	3479.1	7.7642	0.29464	3123.4	3477.0	7.6779	0.25216	3121.8	3474.8	7.6047
600	0.40111	3297.5	3698.6	8.0311	0.33395	3296.3	3697.0	7.9456	0.28597	3295.1	3695.5	7.8730
700	0.44783	3476.3	3924.1	8.2755	0.37297	3475.3	3922.9	8.1904	0.31951	3474.4	3921.7	8.1183
800	0.49438	3661.7	4156.1	8.5024	0.41184	3661.0	4155.2	8.4176	0.35288	3660.3	4154.3	8.3458
900	0.54083	3853.9	4394.8	8.7150	0.45059	3853.3	4394.0	8.6303	0.38614	3852.7	4393.3	8.5587
1000	0.58721	4052.7	4640.0	8.9155	0.48928	4052.2	4639.4	8.8310	0.41933	4051.7	4638.8	8.7595
1100	0.63354	4257.9	4891.4	9.1057	0.52792	4257.5	4891.0	9.0212	0.45247	4257.0	4890.5	8.9497
1200	0.67983	4469.0	5148.9	9.2866	0.56652	4468.7	5148.5	9.2022	0.48558	4468.3	5148.1	9.1308
1300	0.72610	4685.8	5411.9	9.4593	0.60509	4685.5	5411.6	9.3750	0.51866	4685.1	5411.3	9.3036
	P = 1.60 MPa (201.37°C)				*P* = 1.80 MPa (207.11°C)				*P* = 2.00 MPa (212.38°C)			
Sat.	0.12374	2594.8	2792.8	6.4200	0.11037	2597.3	2795.9	6.3775	0.09959	2599.1	2798.3	6.3390
225	0.13293	2645.1	2857.8	6.5537	0.11678	2637.0	2847.2	6.4825	0.10381	2628.5	2836.1	6.4160
250	0.14190	2692.9	2919.9	6.6753	0.12502	2686.7	2911.7	6.6088	0.11150	2680.3	2903.3	6.5475
300	0.15866	2781.6	3035.4	6.8864	0.14025	2777.4	3029.9	6.8246	0.12551	2773.2	3024.2	6.7684
350	0.17459	2866.6	3146.0	7.0713	0.15460	2863.6	3141.9	7.0120	0.13860	2860.5	3137.7	6.9583
400	0.19007	2950.8	3254.9	7.2394	0.16849	2948.3	3251.6	7.1814	0.15122	2945.9	3248.4	7.1292
500	0.22029	3120.1	3472.6	7.5410	0.19551	3118.5	3470.4	7.4845	0.17568	3116.9	3468.3	7.4337
600	0.24999	3293.9	3693.9	7.8101	0.22200	3292.7	3692.3	7.7543	0.19962	3291.5	3690.7	7.7043

Problem 2, cont'd

(*a*) Compare the magnitudes of Δh, Δke, and Δpe.
(*b*) Determine the work done per unit mass of the steam flowing through the turbine.

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

$$\underbrace{\dot{E}_{in} - \dot{E}_{out}}_{\substack{\text{Rate of net energy transfer} \\ \text{by heat, work, and mass}}} = \underbrace{dE_{system}/dt}_{\substack{\text{Rate of change in internal, kinetic,} \\ \text{potential, etc., energies}}} \nearrow^{0\text{ (steady)}} = 0$$

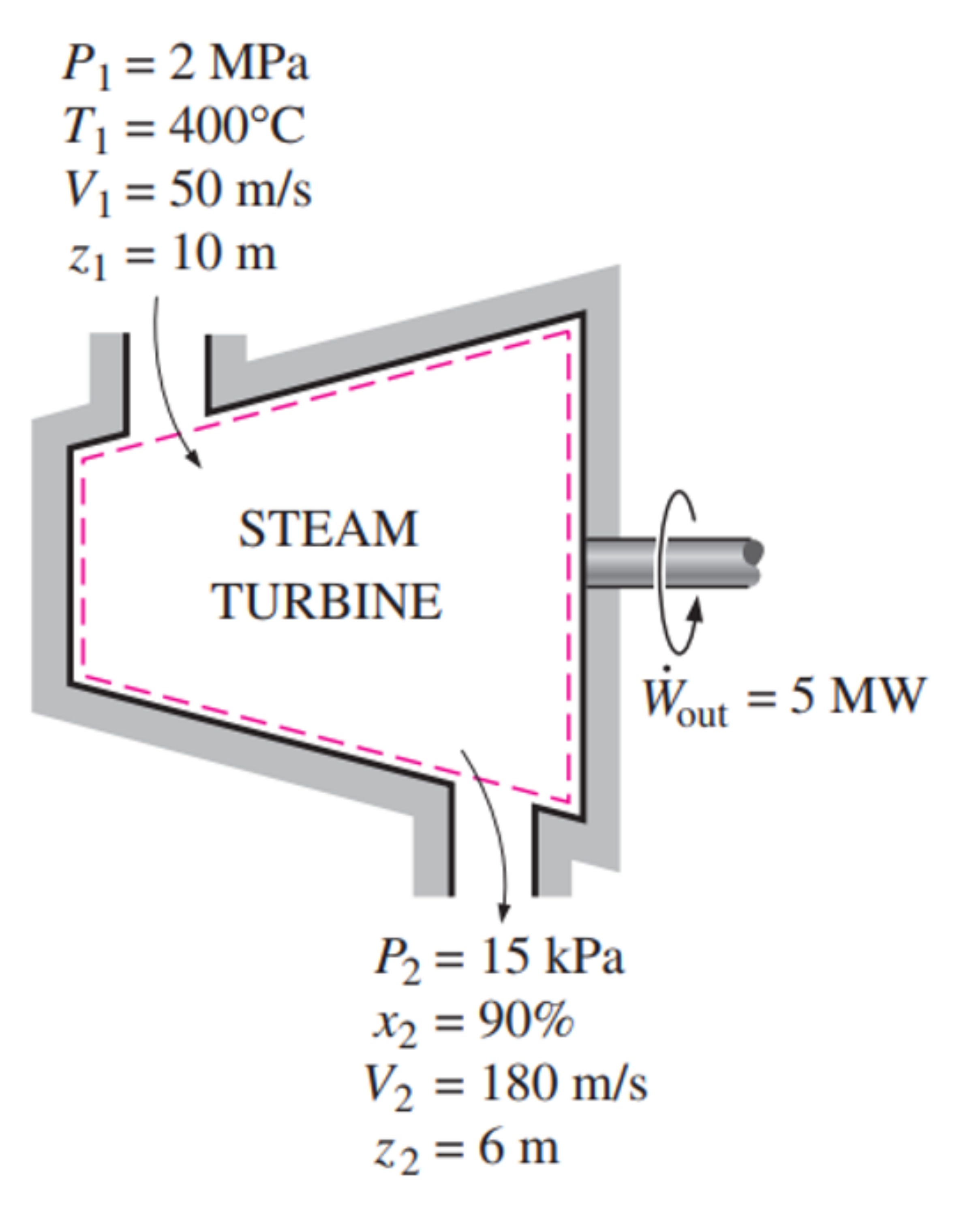
$$\dot{E}_{in} = \dot{E}_{out}$$

$$\dot{m}\left(h_1 + \frac{V_1^2}{2} + gz_1\right) = \dot{W}_{out} + \dot{m}\left(h_2 + \frac{V_2^2}{2} + gz_2\right) \qquad (\text{since } \dot{Q} = 0)$$

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

$$w_{out} = -\left[(h_2 - h_1) + \frac{V_2^2 - V_1^2}{2} + g(z_2 - z_1)\right] = -(\Delta h + \Delta ke + \Delta pe)$$

$$= -[-887.39 + 14.95 - 0.04] \text{ kJ/kg} = \mathbf{872.48 \text{ kJ/kg}}$$



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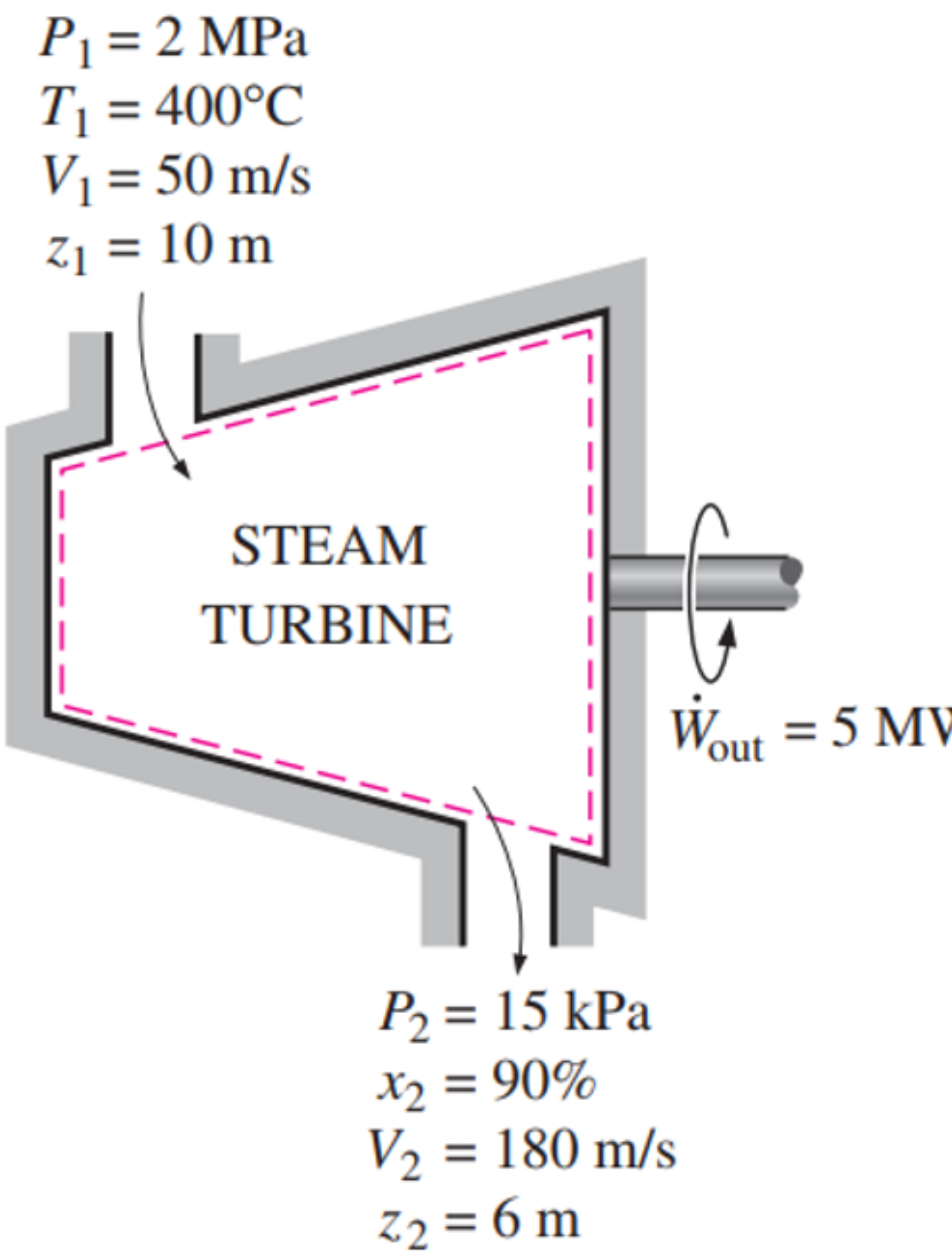


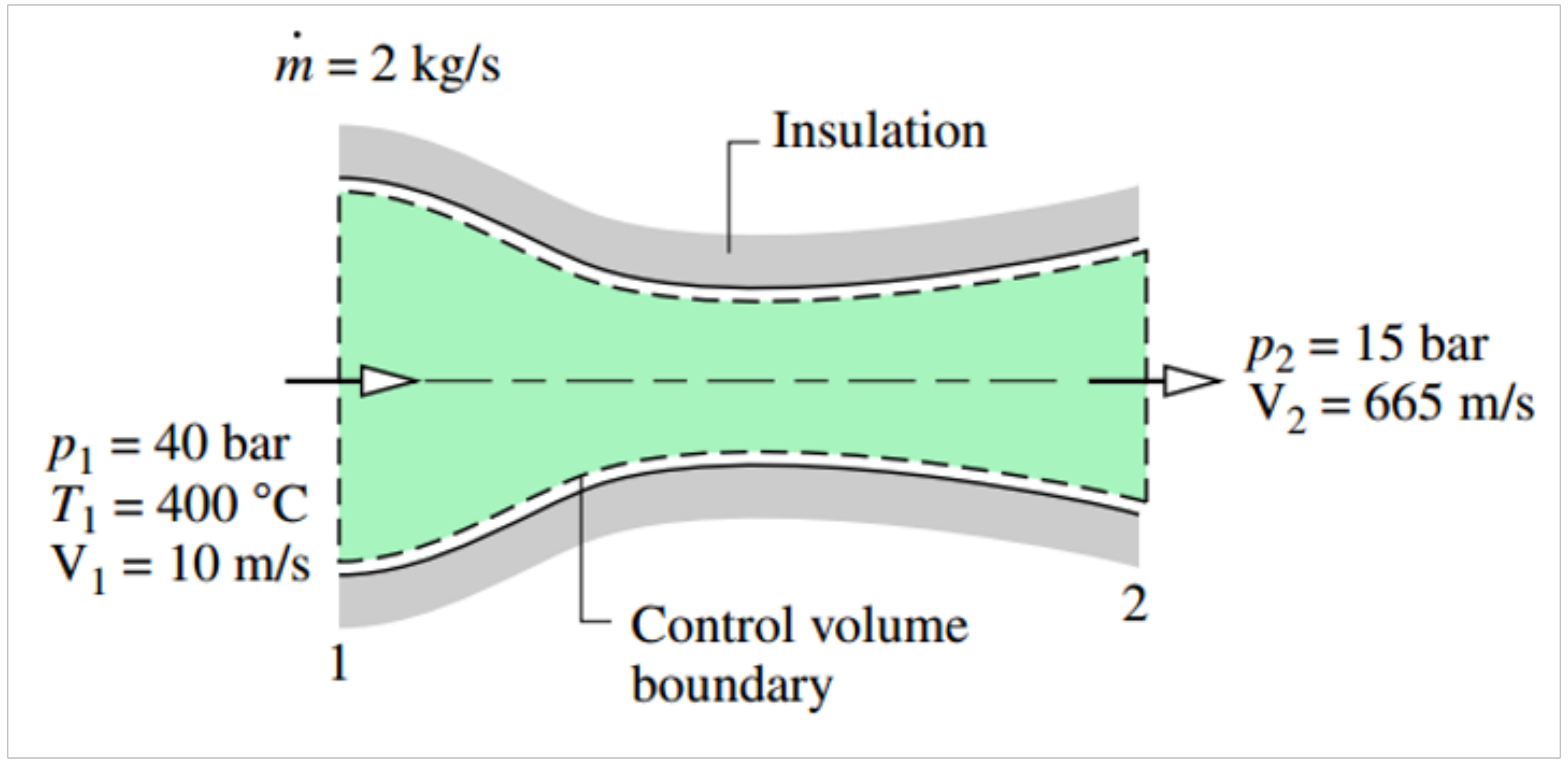
(*c*) The required mass flow rate for a 5-MW power output is

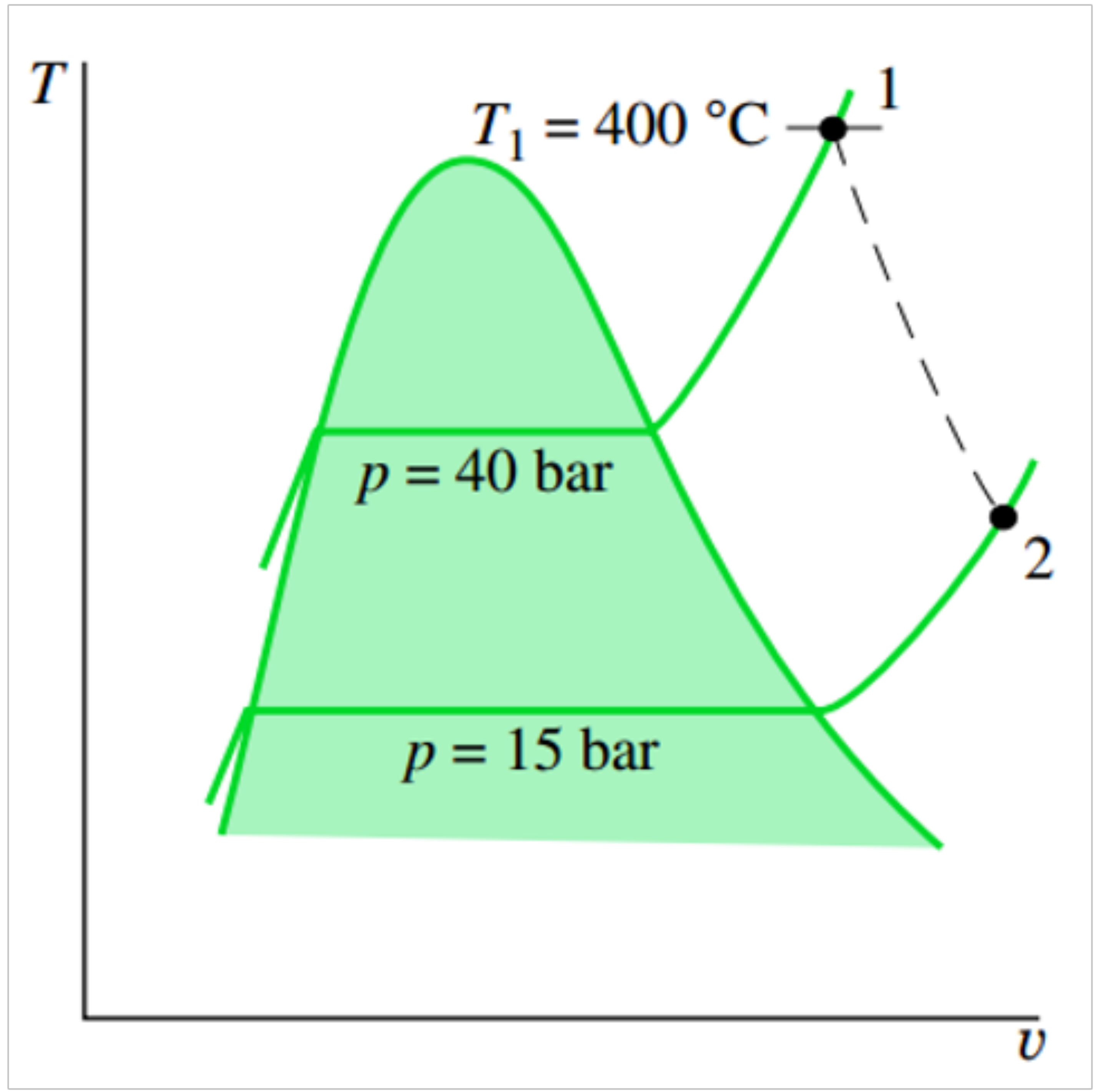
$$\dot{m} = \frac{\dot{W}_{out}}{w_{out}} = \frac{5000\ \text{kJ/s}}{872.48\ \text{kJ/kg}} = \mathbf{5.73\ kg/s}$$

Problem 3

Steam enters a converging-diverging nozzle operating at steady state with P_1 = 40 bar, T_1 = 400°C, and a velocity of 10 m/s. The steam flows through the nozzle with negligible heat transfer and no significant change in potential energy. At the exit, P_2 = 15 bar, and the velocity is 665 m/s. The mass flow rate is 2 kg/s. Determine the exit area of the nozzle.

Ans: 4.89E-4 m²





Problem 3, cont'd

Soln:

We have, since no external energy is involved and no change in potential energy,

$$h_1 + \frac{1}{2}v_1^2 = h_2 + \frac{1}{2}v_2^2$$

$$\Rightarrow h_2 = h_1 - \frac{1}{2}(v_2^2 - v_1^2) \;...(1)$$

P_1 = 40 bar = 4 MPa

T_1 = 400°C

V_1 = 0.07343 m³/kg

h_1 = 3214.5 KJ/kg

thus, from (1)

$h_2 = 3214.5 - 0.5*(665^2 - 10^2)/1000$

= 2993.4375 KJ/kg

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TABLE A–6

Superheated water (*Continued*)

T °C	*v* m³/kg	*u* kJ/kg	*h* kJ/kg	*s* kJ/kg · K
	P = 4.0 MPa (250.35°C)			
Sat.	0.04978	2601.7	2800.8	6.0696
275	0.05461	2668.9	2887.3	6.2312
300	0.05887	2726.2	2961.7	6.3639
350	0.06647	2827.4	3093.3	6.5843
400	0.07343	2920.8	3214.5	6.7714
450	0.08004	3011.0	3331.2	6.9386
500	0.08644	3100.3	3446.0	7.0922
600	0.09886	3279.4	3674.9	7.3706
700	0.11098	3462.4	3906.3	7.6214
800	0.12292	3650.6	4142.3	7.8523
900	0.13476	3844.8	4383.9	8.0675
1000	0.14653	4045.1	4631.2	8.2698
1100	0.15824	4251.4	4884.4	8.4612
1200	0.16992	4463.5	5143.2	8.6430

896 (14 / 50)

P_2 = 15 bar = 1.5 MPa

h_2 = 2993.4375 KJ/kg

v m³/kg	u kJ/kg	h kJ/kg	s kJ/kg · K
P = 1.40 MPa (195.04°C)			
0.14078	2591.8	2788.9	6.4675
0.14303	2602.7	2803.0	6.4975
0.16356	2698.9	2927.9	6.7488
0.18233	2785.7	3040.9	6.9553
0.20029	2869.7	3150.1	7.1379
0.21782	2953.1	3258.1	7.3046
0.25216	3121.8	3474.8	7.6047
0.28597	3295.1	3695.5	7.8730
0.31951	3474.4	3921.7	8.1183
0.35288	3660.3	4154.3	8.3458
0.38614	3852.7	4393.3	8.5587
0.41933	4051.7	4638.8	8.7595
0.45247	4257.0	4890.5	8.9497
0.48558	4468.3	5148.1	9.1308
0.51866	4685.1	5411.3	9.3036

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	P = 1.60 MPa (201.37°C)			
Sat.	0.12374	2594.8	2792.8	6.4200
225	0.13293	2645.1	2857.8	6.5537
250	0.14190	2692.9	2919.9	6.6753
300	0.15866	2781.6	3035.4	6.8864
350	0.17459	2866.6	3146.0	7.0713
400	0.19007	2950.8	3254.9	7.2394
500	0.22029	3120.1	3472.6	7.5410
600	0.24999	3293.9	3693.9	7.8101
700	0.27941	3473.5	3920.5	8.0558
800	0.30865	3659.5	4153.4	8.2834
900	0.33780	3852.1	4392.6	8.4965
1000	0.36687	4051.2	4638.2	8.6974
1100	0.39589	4256.6	4890.0	8.8878
1200	0.42488	4467.9	5147.7	9.0689
1300	0.45383	4684.8	5410.9	9.2418

For 1.4 MPa, interpolating for 2993.4375 in h column, we get, v = 0.17444 m³/kg

For 1.6 MPa, interpolating for 2993.4375 in h column, we get, v = 0.15257 m³/kg

For 1.5 MPa, we have, specific volume v = (0.15257+0.17444)/2 = 0.1635 m³/kg

Density of steam at the output condition, $D = v^{-1}$ = 6.116 kg/m³

Now, flow rate m = 2 kg/s

Velocity = 665 m/s

Density = 6.116 kg/m³

$$\text{Area} = \frac{flow\ rate}{velocity * density} = 4.917\times10^{-4}\ m^2$$