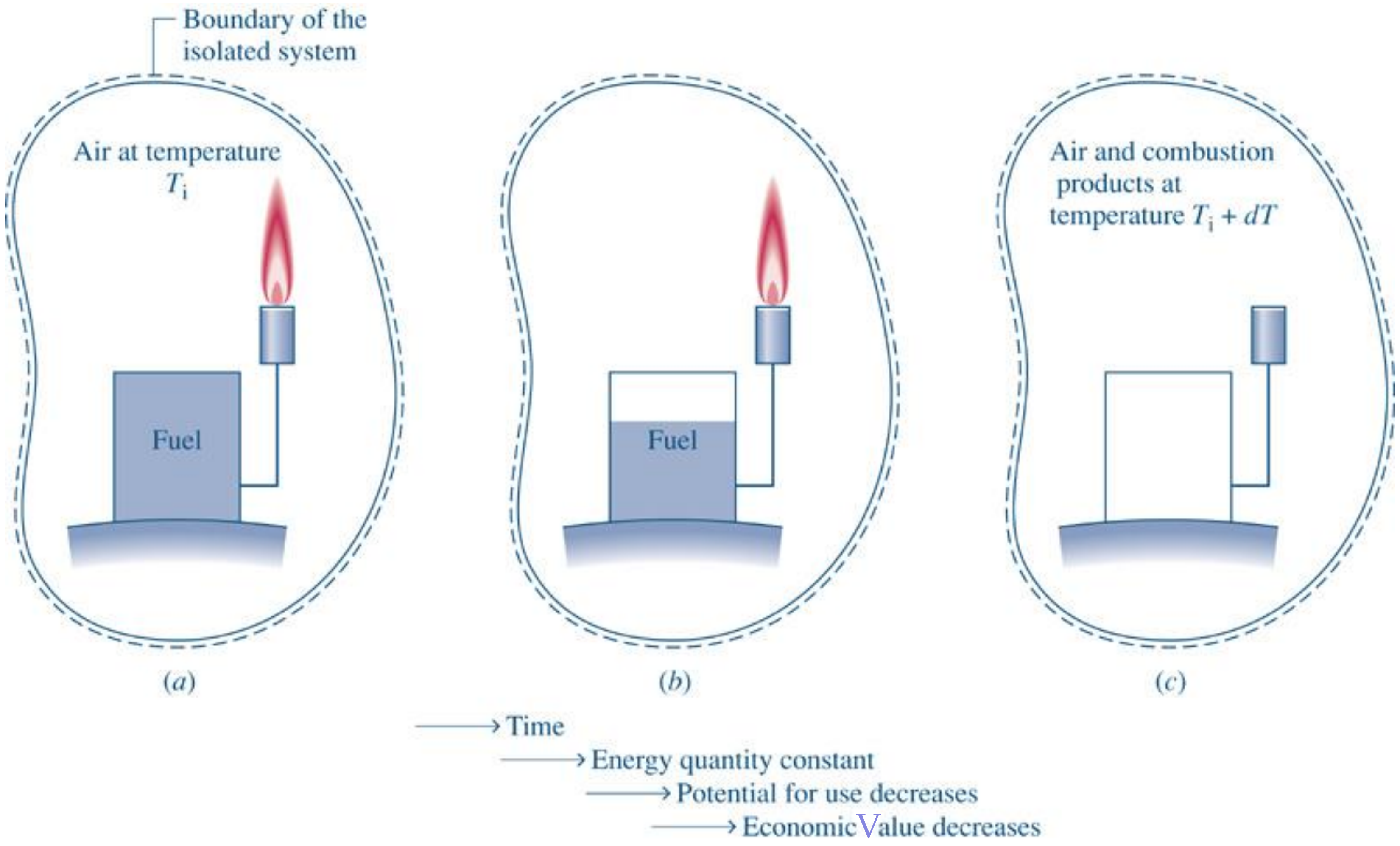
Cap. 7: Análise Exergética

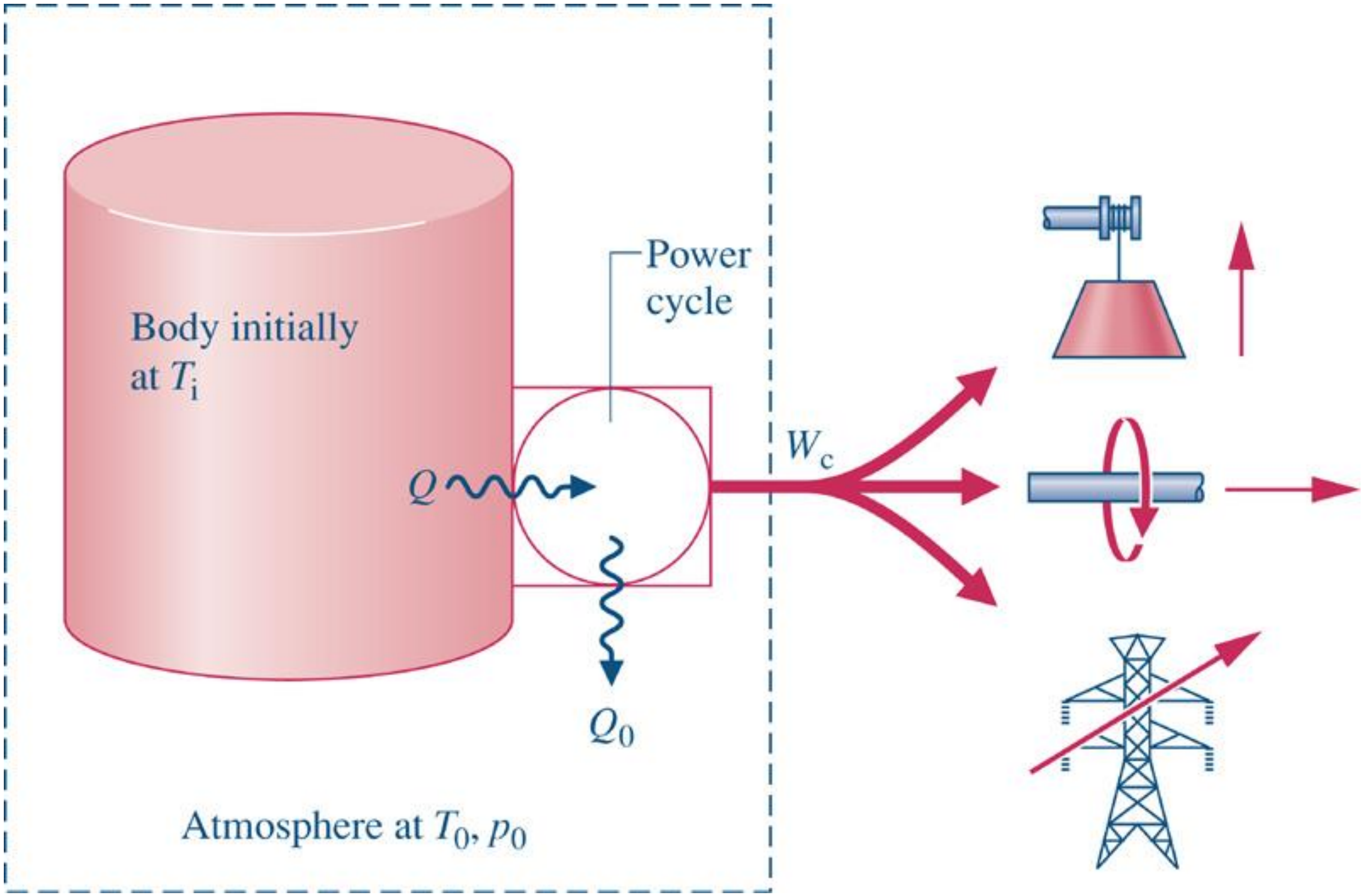


Cap. 7: Análise Exergética

- *Exergia* é a propriedade que quantifica o potencial de uso. Em um processo, ao contrário da Energia, a *Exergia* não é conservada e sim destruída por meio de irreversibilidades.

  - Existe um potencial para o desenvolvimento de trabalho sempre que dois sistemas em diferentes estados são postos em contato;
  - Pode-se desenvolver trabalho quando se permite que dois sistemas atinjam o equilíbrio.

Cap. 7: Análise Exergética



Cap. 7: Análise Exergética

- AMBIENTE e ESTADO MORTO

- Ambiente: Sistema compressível simples que é grande em extensão e uniforme em Temperatura, T_o e pressão, p_o.

  Normalmente o ambiente está T_o = 25ºC, p_o =1 atm

- Se o sistema está na mesma condição que o ambiente (T_o = 25ºC, p_o =1 atm) ele está no ESTADO MORTO.

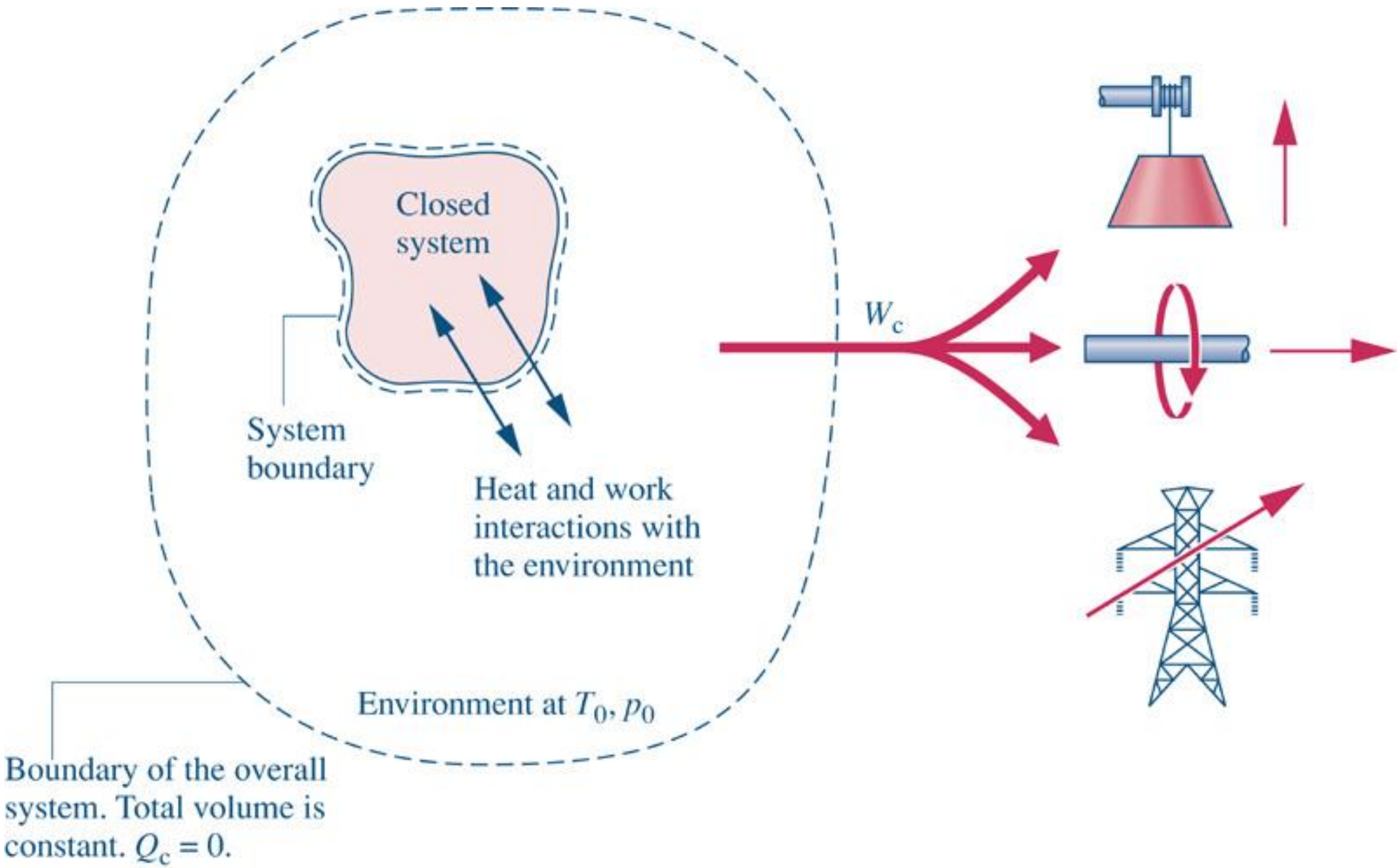
Definição de Exergia

- *Exergia (E) é o máximo trabalho teórico possível de ser obtido a partir de um sistema global, composto por um sistema e o ambiente, conforme este entra em equilíbrio com o ambiente (atinge o estado morto).*

$$E = (U - U_o) + p_o(V - V_o) - T_o(S - S_o) + EC + EP\ [\,\mathrm{J}\,]$$

$$\mathrm{e} = (u - u_o) + p_o(v - v_o) - T_o(s - s_o) + {V^2}/{2} + gz\ [\,\mathrm{J/kg}\,]$$

Cap. 7: Análise Exergética



Cap. 7: Análise Exergética

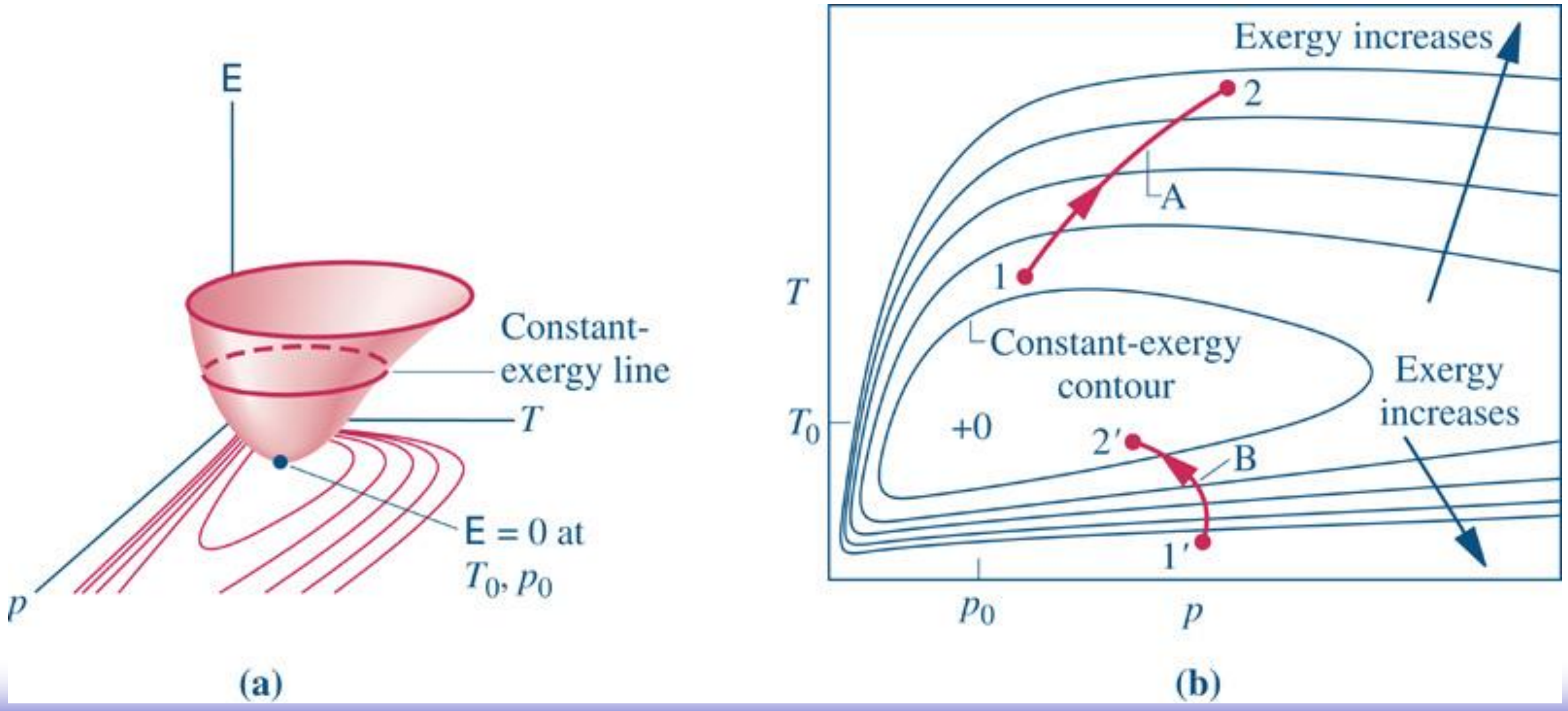
- 1. Exergia é a medida do desvio do estado de um sistema quando comparado com o ambiente.
- 2. O valor da Exergia não pode ser negativo. O sistema deverá mudar sua condição espontaneamente na direção do estado morto.
- 3. A Exergia não é conservada mas pode ser destruída pelas irreversibilidades.
- 4. A Exergia pode ser vista como o máximo trabalho teórico de se obter de um sistema.

Variação da Exergia

$$E_1 = (U_1 - U_o) + p_o(V_1 - V_o) - T_o(S_1 - S_o) + EC_1 + EP_1$$

$$E_2 = (U_2 - U_o) + p_o(V_2 - V_o) - T_o(S_2 - S_o) + EC_2 + EP_2$$

$$\mathbf{E_2 - E_1 = (U_2 - U_1) + p_o(V_2 - V_1) - T_o(S_2 - S_1) + (EC_2 - EC_1) + (EP_2 - EP_1)}$$



Balanço de Exergia em Sistemas Fechado

$$E_2 - E_1 = E_q - E_w - E_d$$

Transferência de Exergia associado ao calor (E_q)

Transferência de Exergia associado ao trabalho (E_w)

Destruição de Exergia (E_d)

$$E_2 - E_1 = \int_1^2 \left(1 - \frac{T_o}{T_b}\right)\delta Q - [W - p_o(V_2 - V_1)] - T_o\sigma$$

Variação de Exergia ($E_2 - E_1$)

Transferência de Exergia ($\int_1^2 \left(1 - \frac{T_o}{T_b}\right)\delta Q - [W - p_o(V_2 - V_1)]$)

Destruição de Exergia ($T_o\sigma$)

Balanço de Exergia em Sistemas Fechado

$$E_d \begin{cases} > 0 & irreversibilidades\ presentes\ no\ sistema \\ = 0 & ausência\ de\ irreversibilidades\ no\ sistema \end{cases}$$

$$E_2 - E_1 \begin{cases} > 0 \\ = 0 \\ < 0 \end{cases}$$

$$\Delta E|_{isol} = -E_d|_{isol}$$

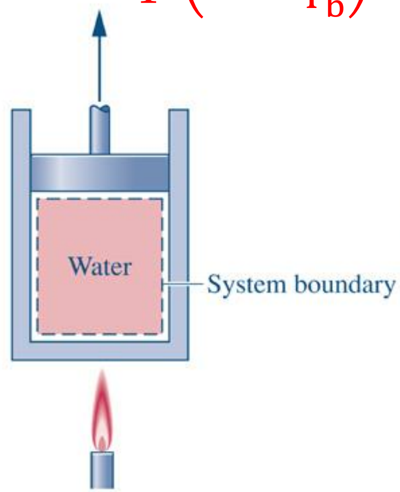
$$\text{e2} - \text{e1} = (u2 - u_1) + p_o(v2 - v_1) - T_o(s2 - s_1) + \Delta \, {}^{V^2}\!/_2 + \Delta gz$$

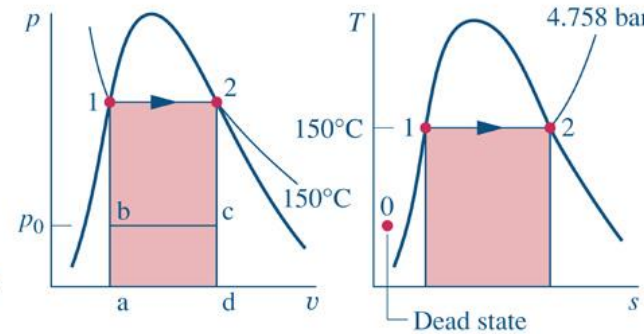
Ex. 7.2:

- Um conjunto cilindro-pistão contém água inicialmente a 150ºC. A água é aquecida até o estado de vapor saturado correspondente eu um processo internamente reversível a temperatura e pressão constantes. Para To=20ºC, po= 1 bar e ignorando os efeitos de movimento de gravidade, determine:
- A) A variação de Exergia
- B) A transferência de Exergia associada ao calor
- C) A transferência de Exergia associada ao trabalho
- D) A destruição de exergia

$$e2 - e1 = (u2 - u_1) + p_o(v2 - v_1) - T_o(s2 - s_1)$$

$$E_2 - E_1 = \int_1^2 \left(1 - \frac{T_o}{T_b}\right)\delta Q - [W - p_o(V_2 - V_1)] - T_o\sigma$$





Data from Example 6.1:

W/m = 186.38 kJ/kg, Q/m = 2114.1 kJ/kg

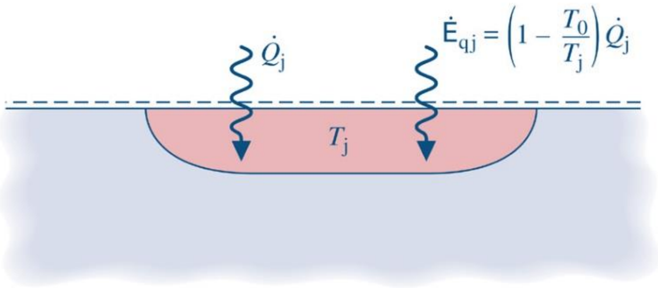
State	v (m^3/kg)	u (kJ/kg)	s (kJ/kg·K)
1	1.0905×10^{-3}	631.68	1.8418
2	0.3928	2559.5	6.8379

Balanço de Taxa Exergia em Sistemas Fechado

$$\frac{dE}{dt} = \sum_j \left(1 - \frac{T_o}{T_j}\right)\dot{Q}_j - \left[\dot{W} - p_o\frac{dV}{dt}\right] - \dot{E}_d$$

$$RP: \;\; 0 = \sum_i \left(1 - \frac{T_o}{T_j}\right)\dot{Q}_j - \dot{W} - \dot{E}_d$$

Fazendo $\dot{E}_{q.j} = \left(1 - \frac{T_o}{T_j}\right)\dot{Q}_j$



$$RP: \;\; 0 = \dot{E}_{q,j} - \dot{W} - \dot{E}_d$$

Balanço de Taxa Exergia para Volume de Controle em Regime Permanente

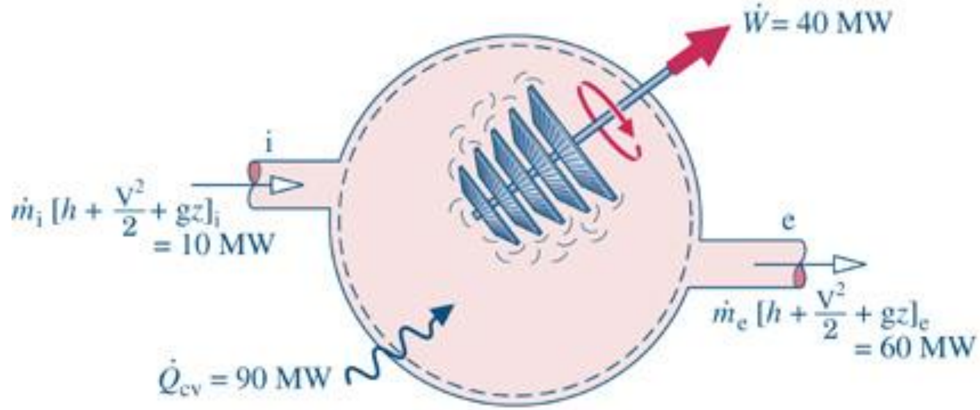
$$\left.\frac{dE}{dt}\right|_{VC} = \sum_j \left(1 - \frac{\mathrm{T_o}}{\mathrm{T_j}}\right)\dot{Q}_j - \left[\dot{W}_{VC} - \mathrm{p_o}\frac{dV_{VC}}{dt}\right]$$

$$+\sum_e \dot{m}\mathrm{e}_{fe} - \sum_s \dot{m}\mathrm{e}_{fs} - \dot{E}_d$$

RP: $0 = \sum_j \left(1 - \frac{\mathrm{T_o}}{\mathrm{T_j}}\right)\dot{Q}_j - \dot{W}_{VC} + \sum_e \dot{m}_e\mathrm{e}_{fe} - \sum_s \dot{m}_s\mathrm{e}_{fs} - \dot{E}_d$

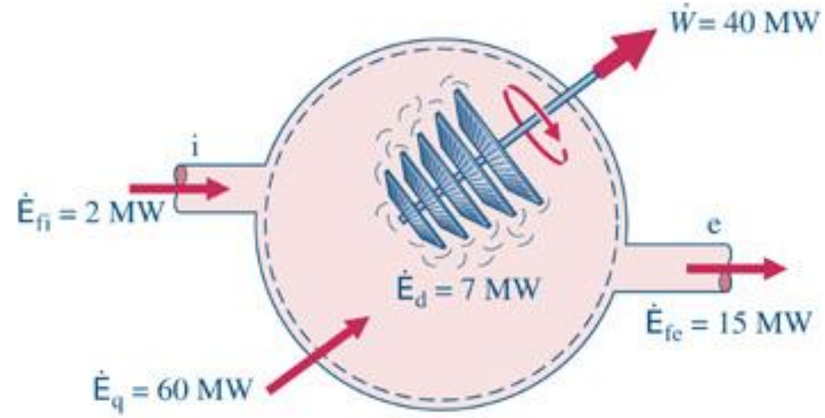
$$\mathrm{e_f} = h - h_o - T_o(s - s_o) + \frac{V^2}{2} + gz$$

$$\mathrm{e_{f1}} - \mathrm{e_{f2}} = (h_1 - h_2) - T_o(s_1 - s_2) + \frac{(V_1^2 - V_2^2)}{2} + g(z_1 - z_2)$$



Energy In	**Energy Out**
90 MW (heat transfer)	40 MW (power)
10 MW (at inlet i)	60 MW (at exit e)
100 MW	100 MW

(a)

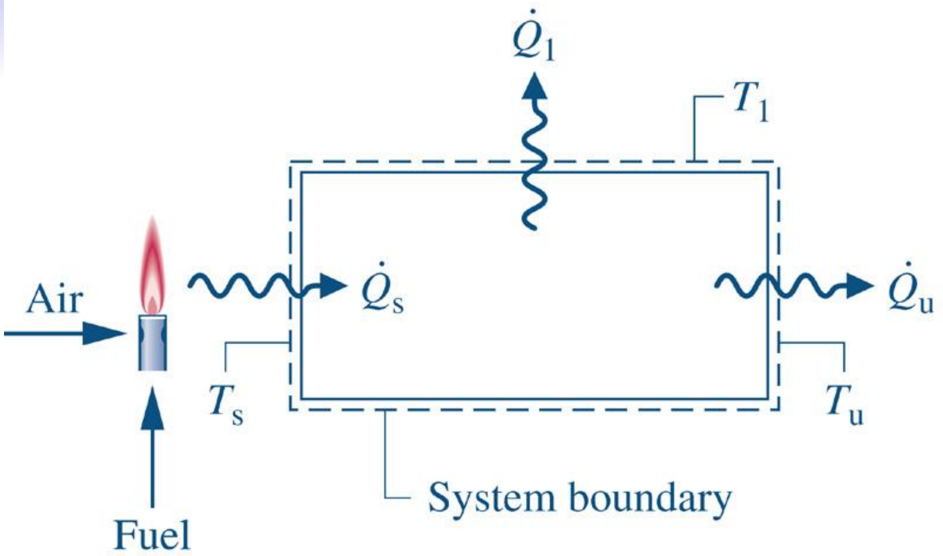


Exergy In	**Exergy Out**
60 MW (heat transfer)	40 MW (power)
2 MW (at inlet i)	15 MW (at exit e)
62 MW	55 MW

Exergy Destroyed = 62 MW – 55 MW = 7 MW

(b)

Eficiência Exergética: Eficiência da Segunda Lei



1ª LEI: $$\left.\frac{dE}{dt}\right|_{VC} = \left(\dot{Q}_s - \dot{Q}_u - \dot{Q}_1\right) - \dot{W}$$

Exergia: $$\left.\frac{dE}{dt}\right|_{VC} = \left(1 - \frac{T_o}{T_s}\right)\dot{Q}_s - \left(1 - \frac{T_o}{T_u}\right)\dot{Q}_u - \left(1 - \frac{T_o}{T_1}\right)\dot{Q}_1 - \left[\dot{W}_{VC} - p_o\frac{dV_{VC}}{dt}\right] - \dot{E}_d$$

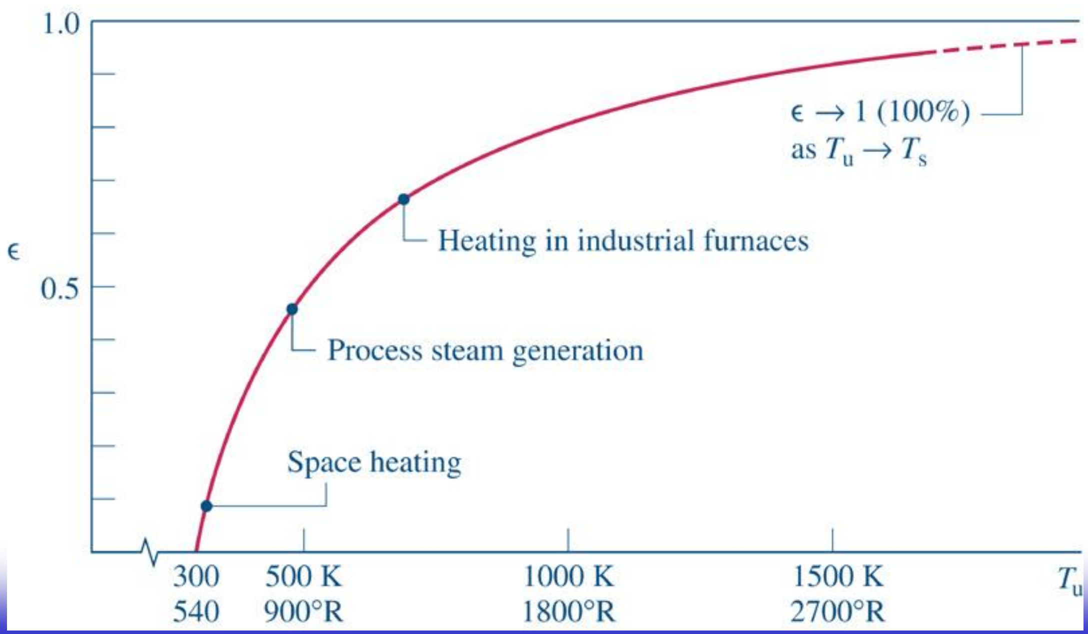
$$\dot{Q}_s = \dot{Q}_u + \dot{Q}_1$$

$$\left(1 - \frac{T_o}{T_s}\right)\dot{Q}_s = \left(1 - \frac{T_o}{T_u}\right)\dot{Q}_u + \left(1 - \frac{T_o}{T_1}\right)\dot{Q}_1 + \dot{E}_d$$

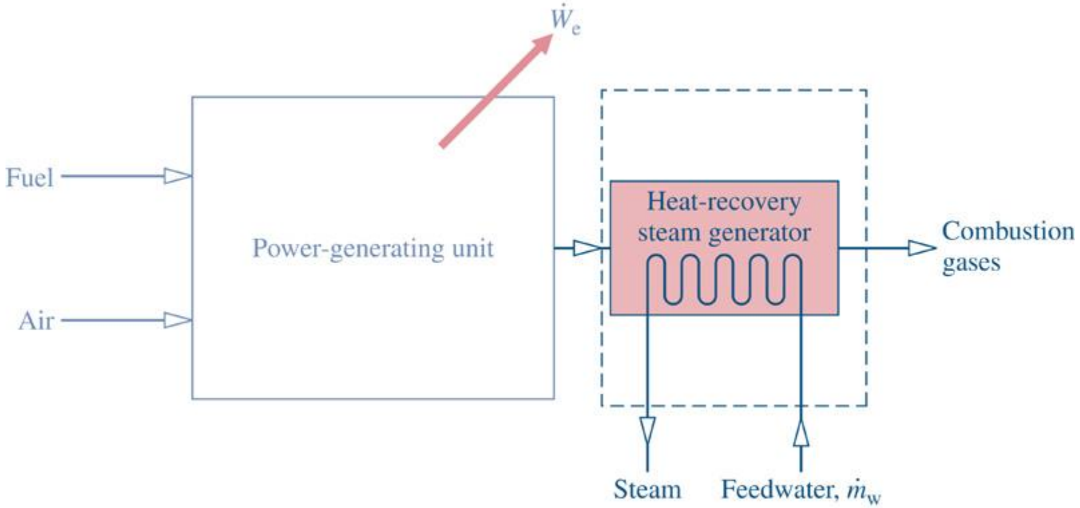
Eficiência Exergética

$$\eta = \frac{\dot{Q}_u}{\dot{Q}_s}$$

$$\varepsilon = \frac{\left(1 - \frac{T_o}{T_u}\right) \dot{Q}_u}{\left(1 - \frac{T_o}{T_s}\right) \dot{Q}_s} = \eta \frac{\left(1 - \frac{T_o}{T_u}\right)}{\left(1 - \frac{T_o}{T_s}\right)}$$



Termoeconômia



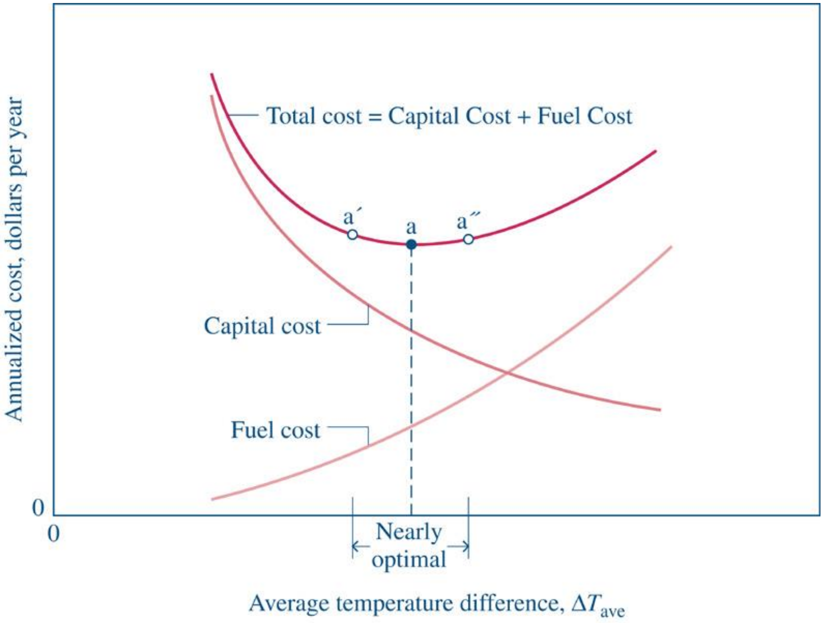


Fig07_02

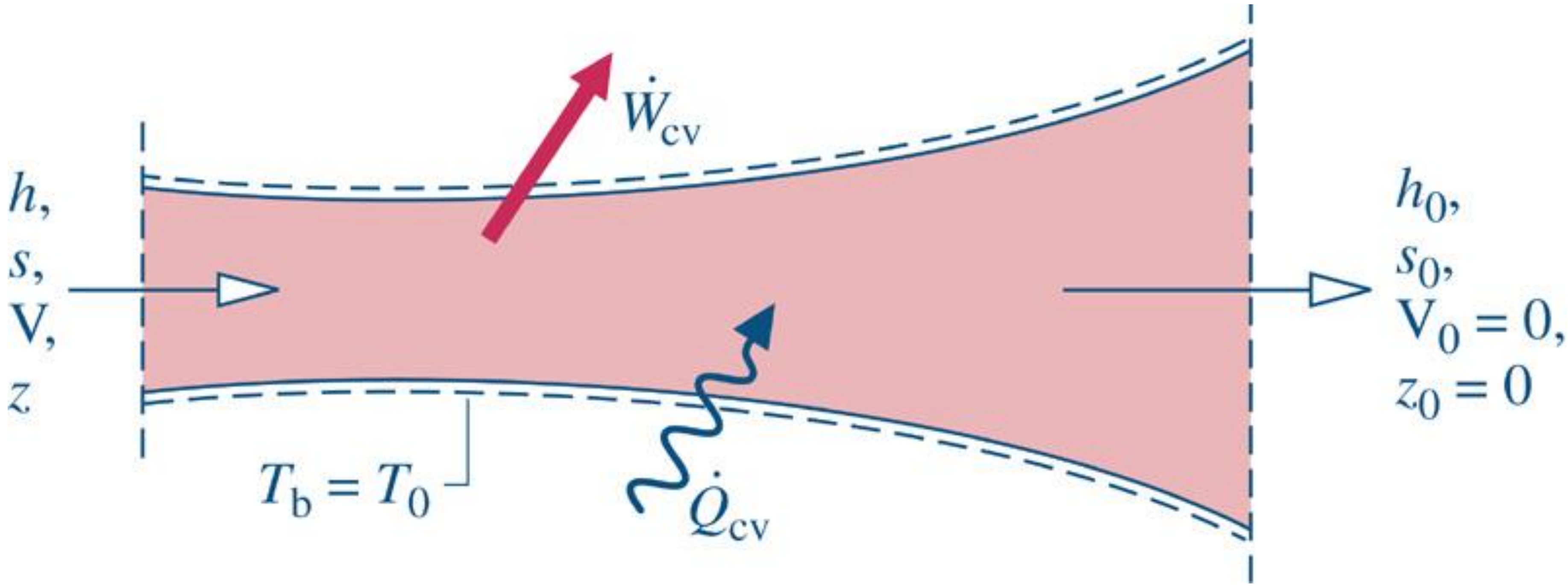


Fig07_05

Fig07_08

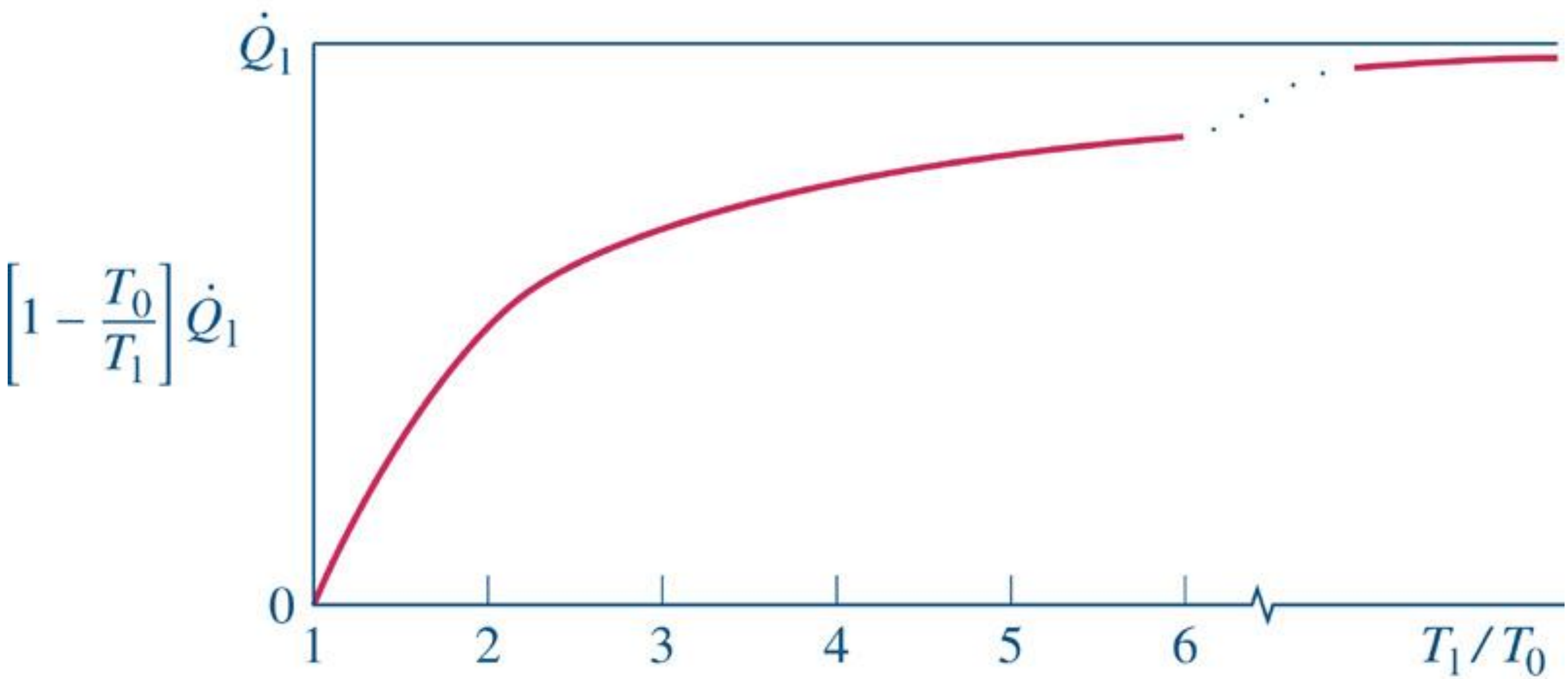


Fig07_09

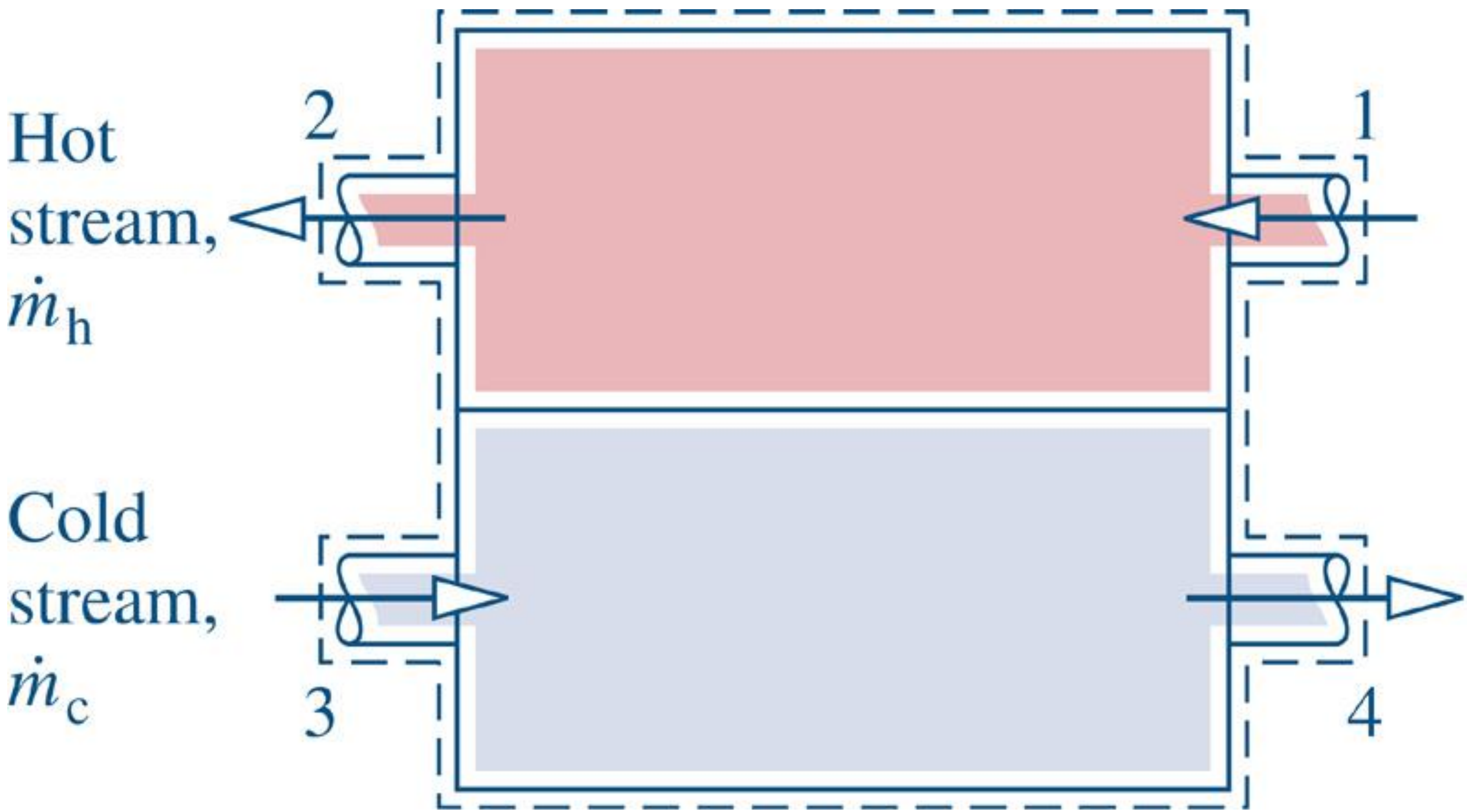


Fig07_10

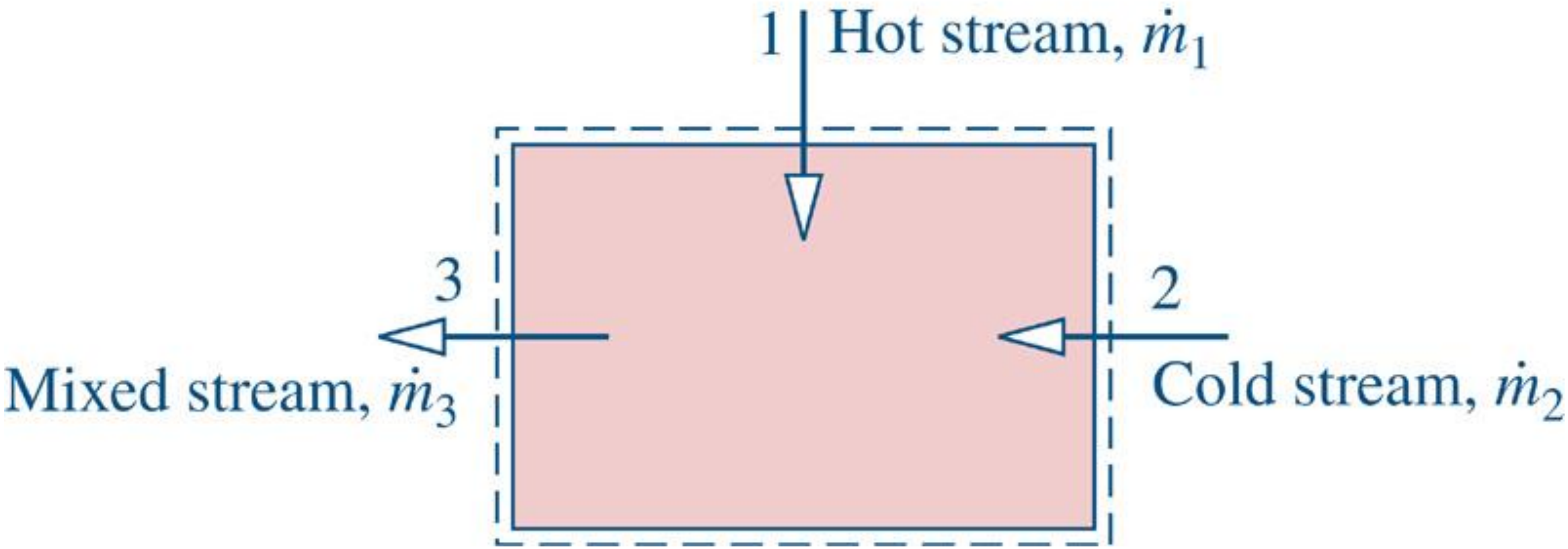
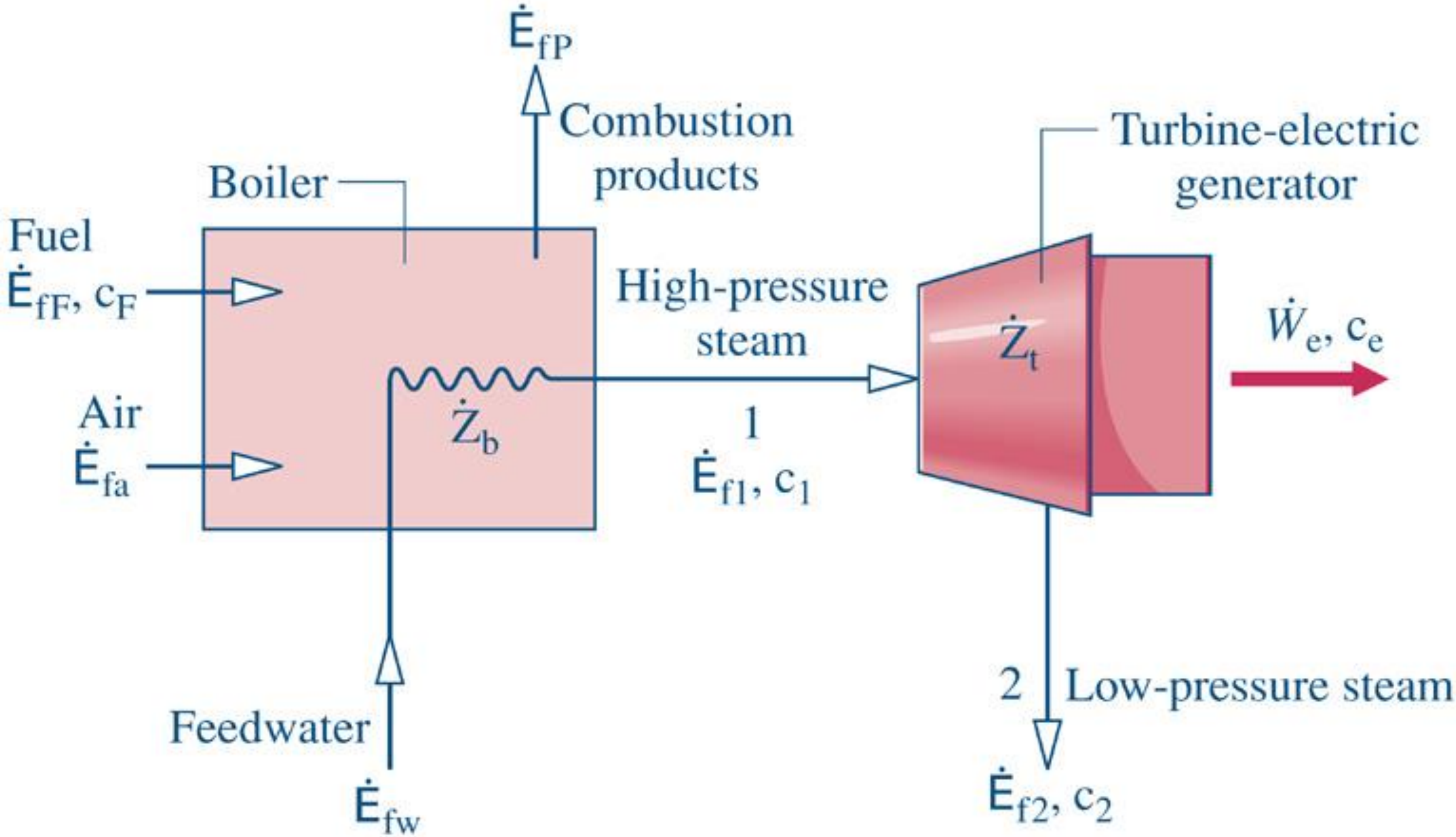


Fig07_11

Fig07_12

Fig07_13



$\dot{E}_{fP}$
Combustion
products
Boiler
Fuel
$\dot{E}_{fF}$, c_F
Air
$\dot{E}_{fa}$
$\dot{Z}_b$
Feedwater
$\dot{E}_{fw}$
High-pressure
steam
1
$\dot{E}_{f1}$, c_1
Turbine-electric
generator
$\dot{Z}_t$
$\dot{W}_e$, c_e
2
Low-pressure steam
$\dot{E}_{f2}$, c_2

Fig07_14

Fig07_E7

Fig07_E7

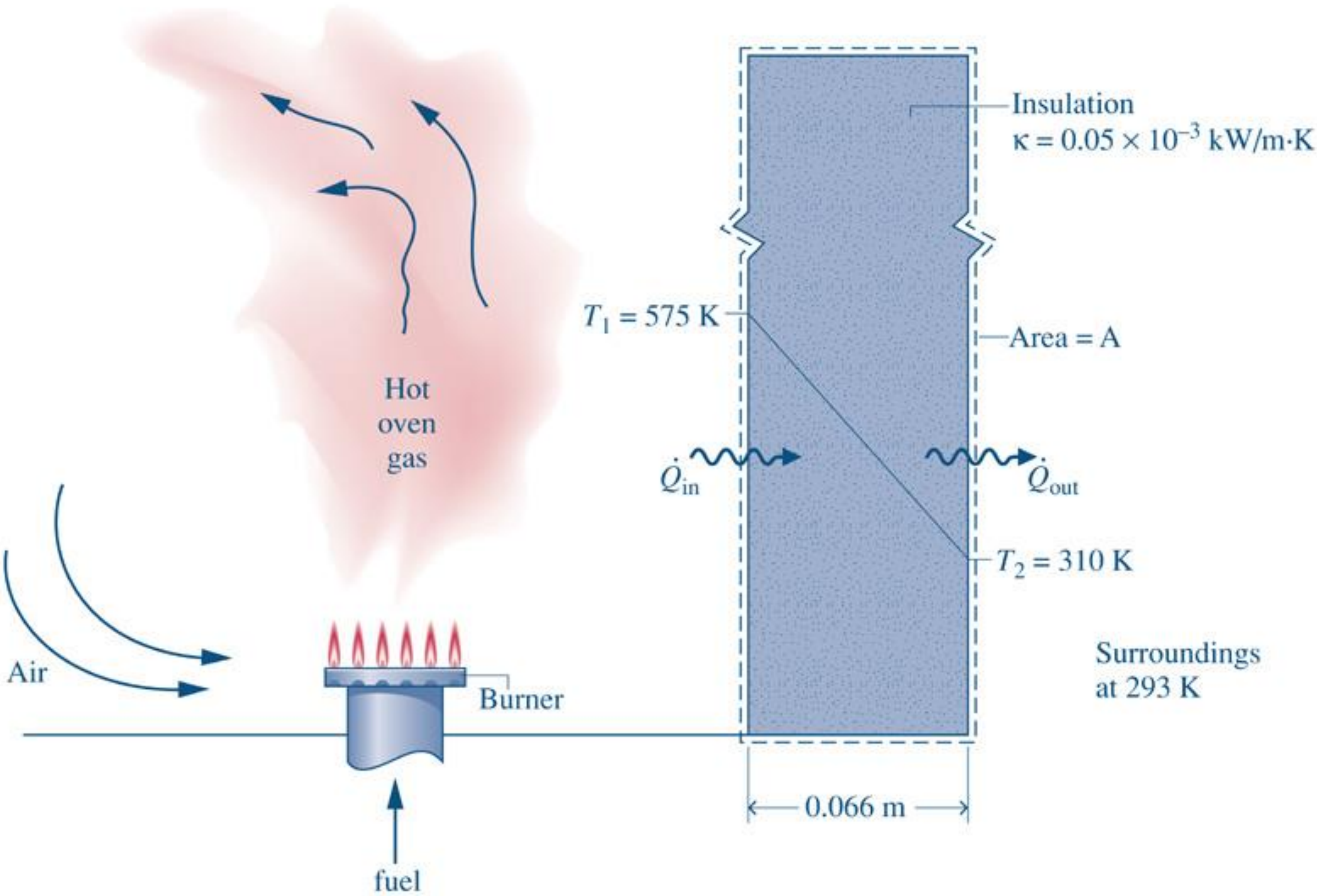
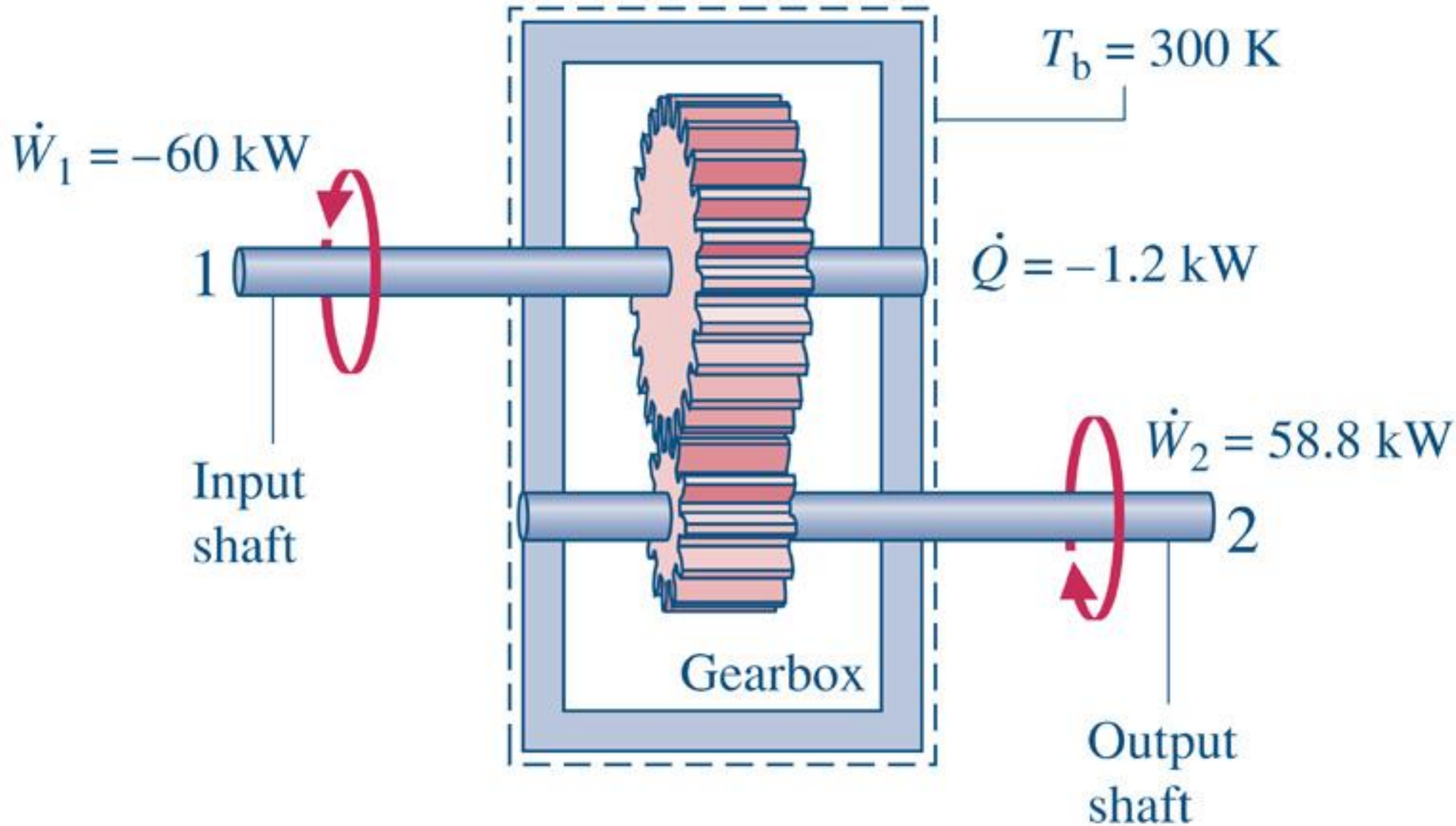

Insulation
κ = 0.05 × 10⁻³ kW/m·K
T₁ = 575 K
Area = A
Hot
oven
gas
Q̇in
Q̇out
T₂ = 310 K
Surroundings
at 293 K
Air
Burner
0.066 m
fuel

Fig07_E7



$\dot{W}_1 = -60$ kW
1
Input shaft
Gearbox
$T_b = 300$ K
$\dot{Q} = -1.2$ kW
$\dot{W}_2 = 58.8$ kW
2
Output shaft

Fig07_E7

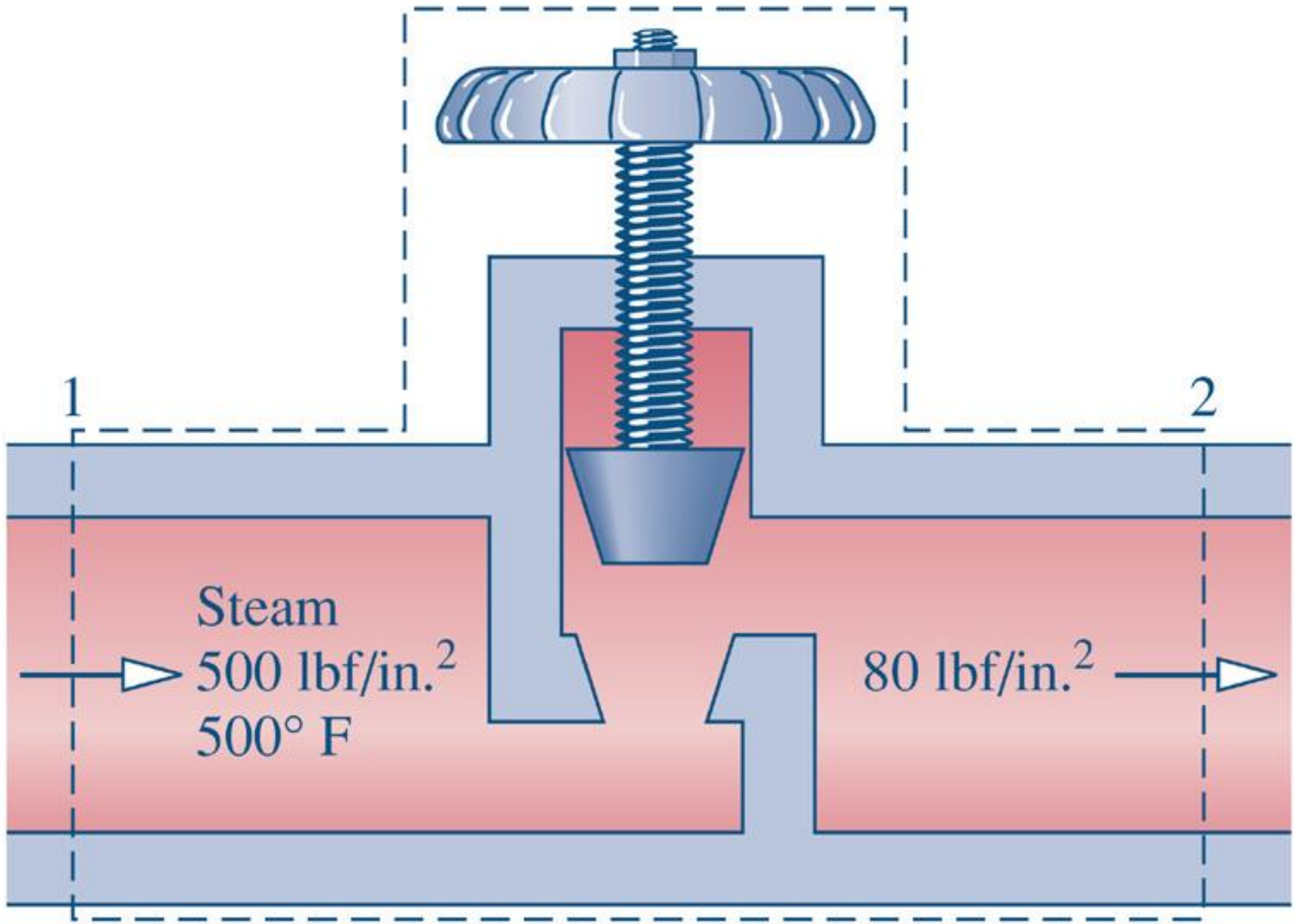
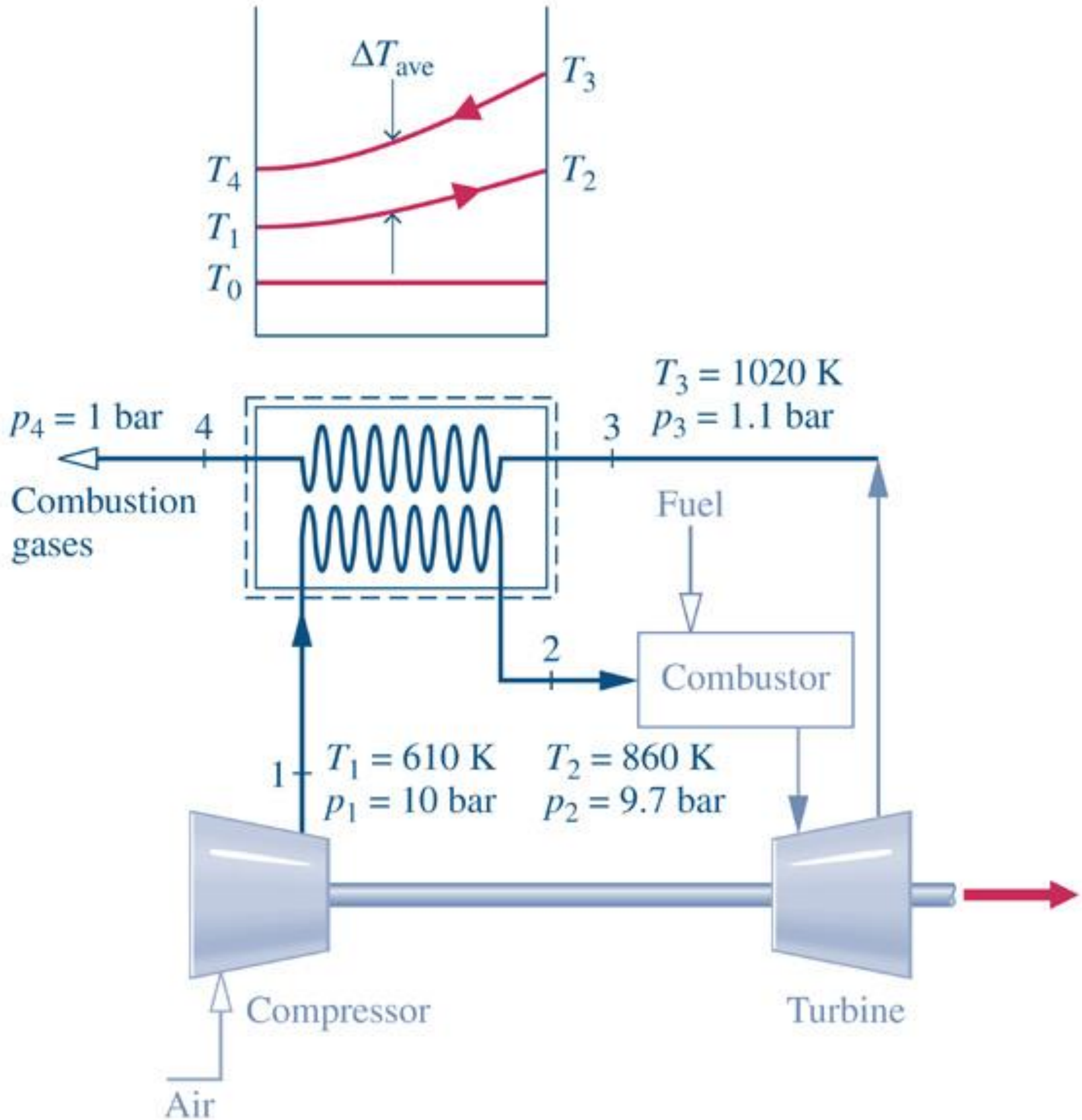
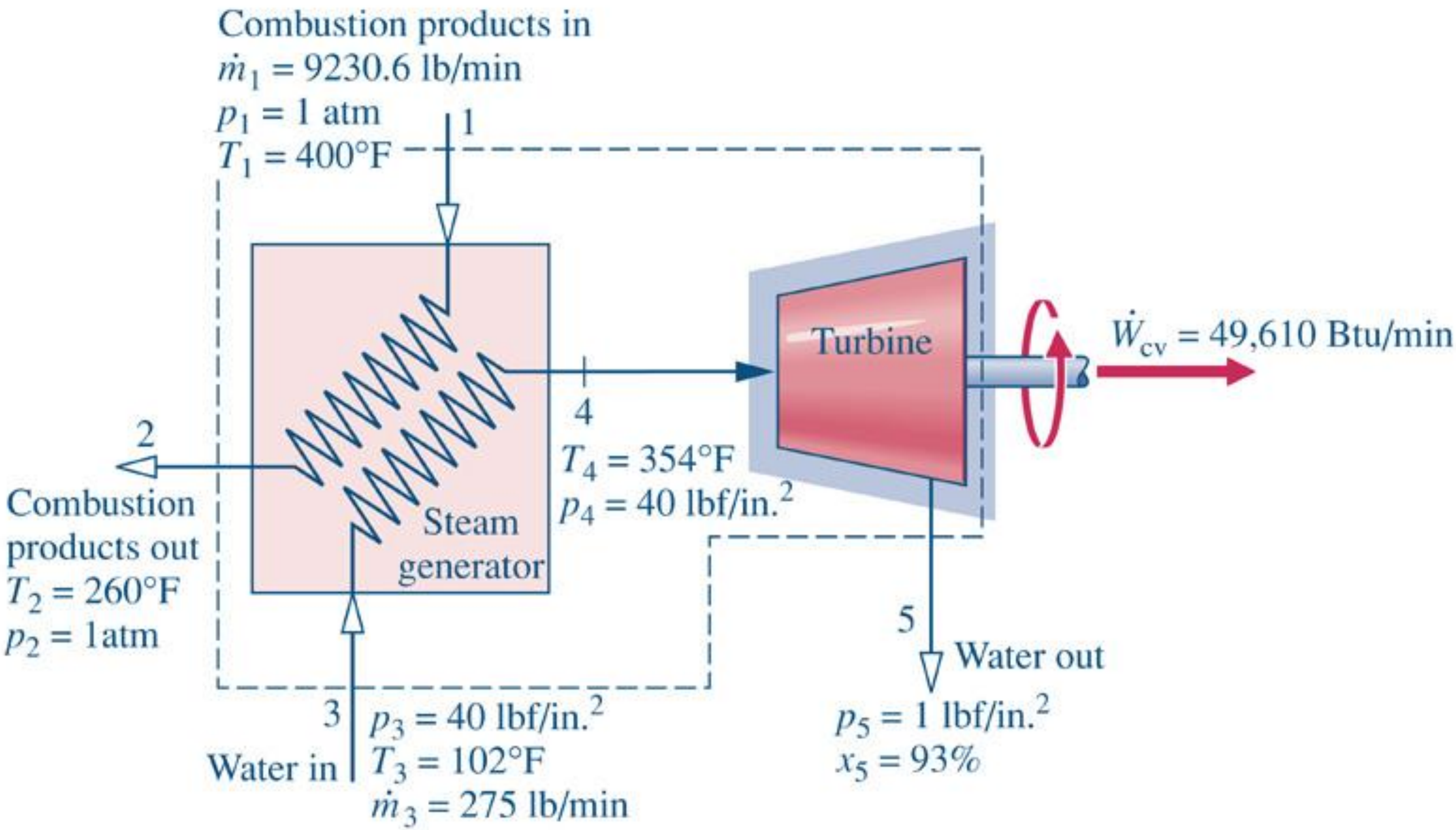


Fig07_E7



ΔT_{ave}
T_3
T_4
T_2
T_1
T_0
$T_3 = 1020$ K
$p_3 = 1.1$ bar
$p_4 = 1$ bar
4
3
Combustion gases
Fuel
2
Combustor
1
$T_1 = 610$ K
$p_1 = 10$ bar
$T_2 = 860$ K
$p_2 = 9.7$ bar
Compressor
Turbine
Air

Fig07_E7



Combustion products in
ṁ1 = 9230.6 lb/min
p1 = 1 atm
T1 = 400°F
1
Turbine
Ẇcv = 49,610 Btu/min
2
4
T4 = 354°F
p4 = 40 lbf/in.2
Combustion
products out
T2 = 260°F
p2 = 1atm
Steam
generator
5
Water out
3
p3 = 40 lbf/in.2
Water in
T3 = 102°F
ṁ3 = 275 lb/min
p5 = 1 lbf/in.2
x5 = 93%

Fig07_E7

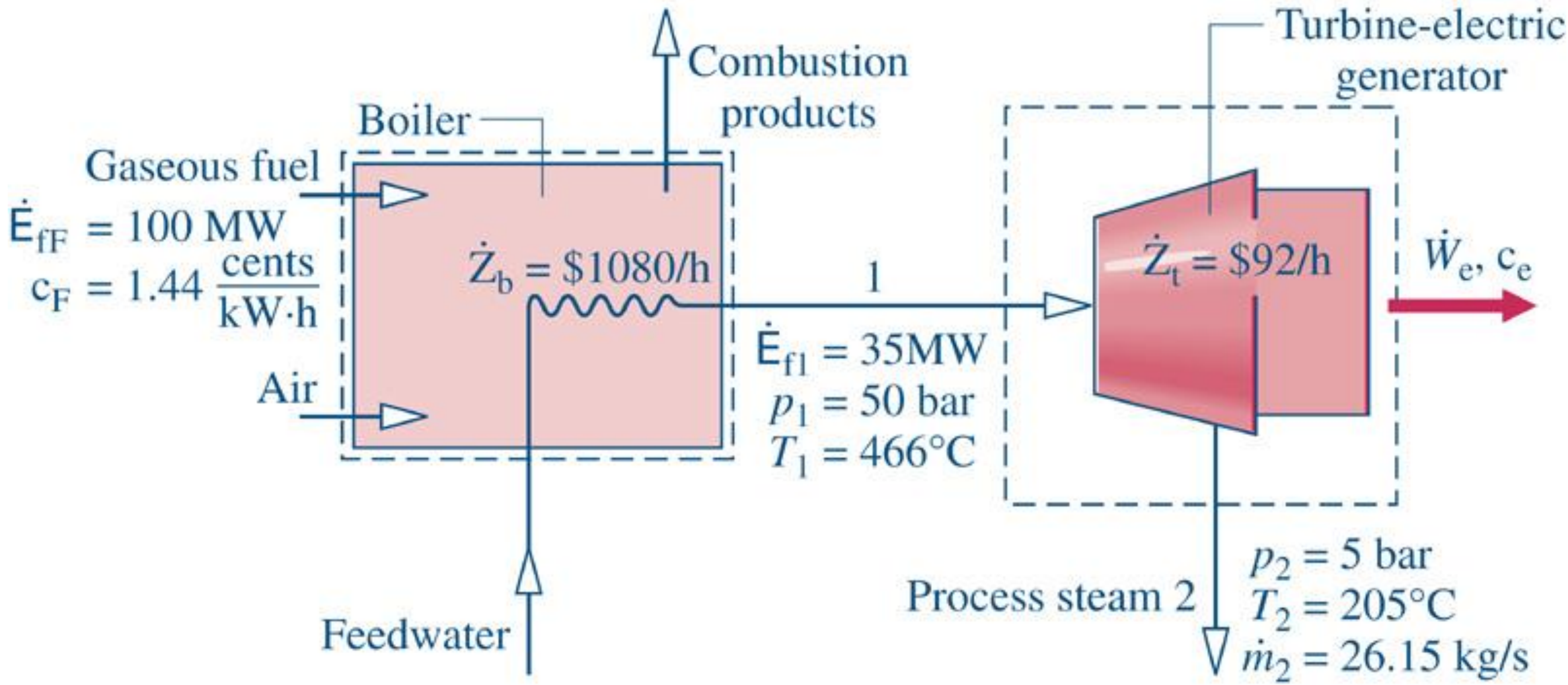
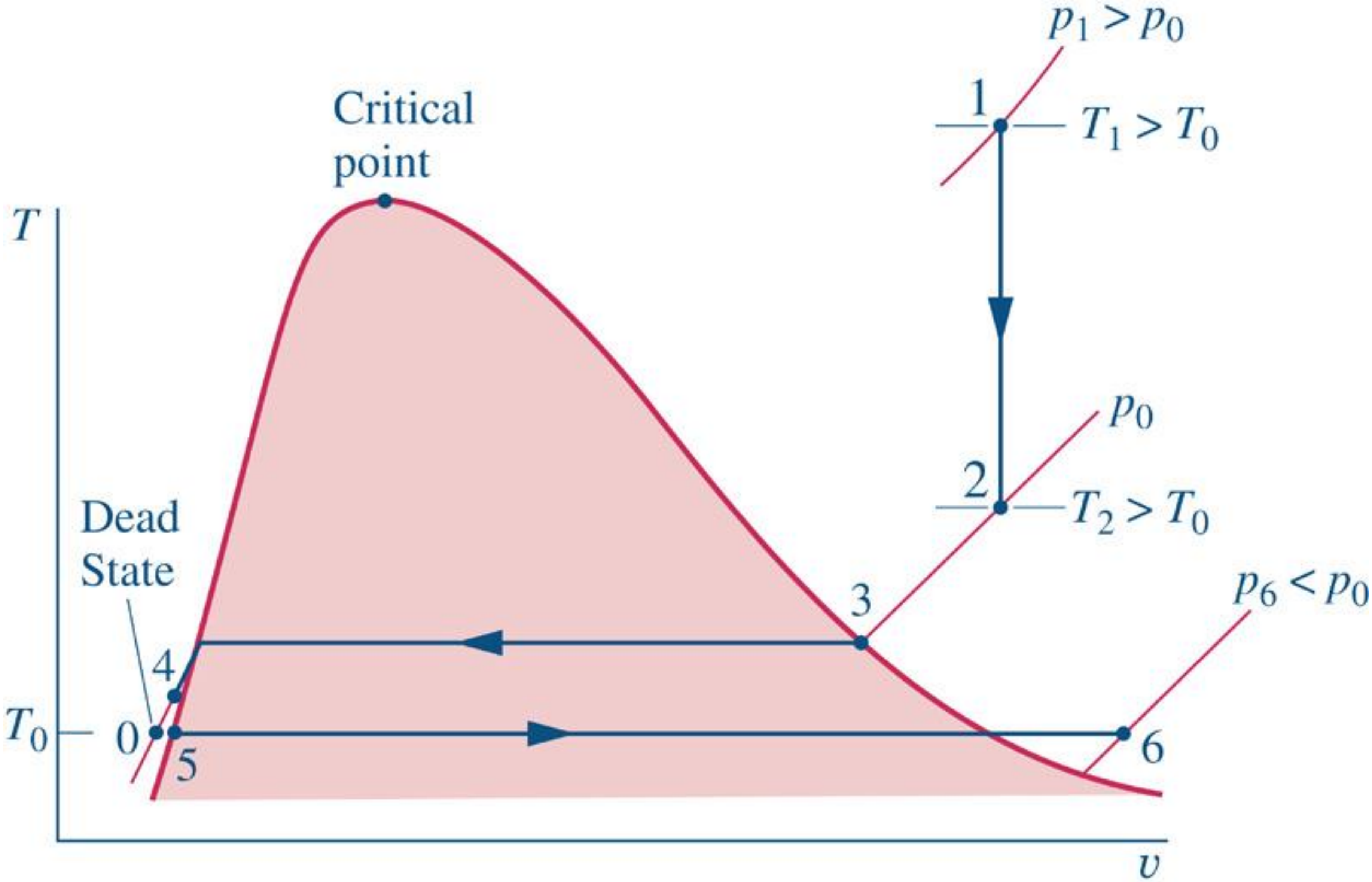

Combustion products
Turbine-electric generator
Boiler
Gaseous fuel
$\dot{E}_{fF}$ = 100 MW
$c_F = 1.44 \frac{\text{cents}}{\text{kW·h}}$
$\dot{Z}_b$ = $1080/h
1
$\dot{Z}_t$ = $92/h
$\dot{W}_e$, c_e
$\dot{E}_{f1}$ = 35MW
p_1 = 50 bar
T_1 = 466°C
Air
Feedwater
Process steam 2
p_2 = 5 bar
T_2 = 205°C
$\dot{m}_2$ = 26.15 kg/s

Fig07_E7



p1 > p0
1
T1 > T0
Critical
point
T
p0
2
T2 > T0
Dead
State
3
p6 < p0
4
T0
0
5
6
v

Fig07_P7

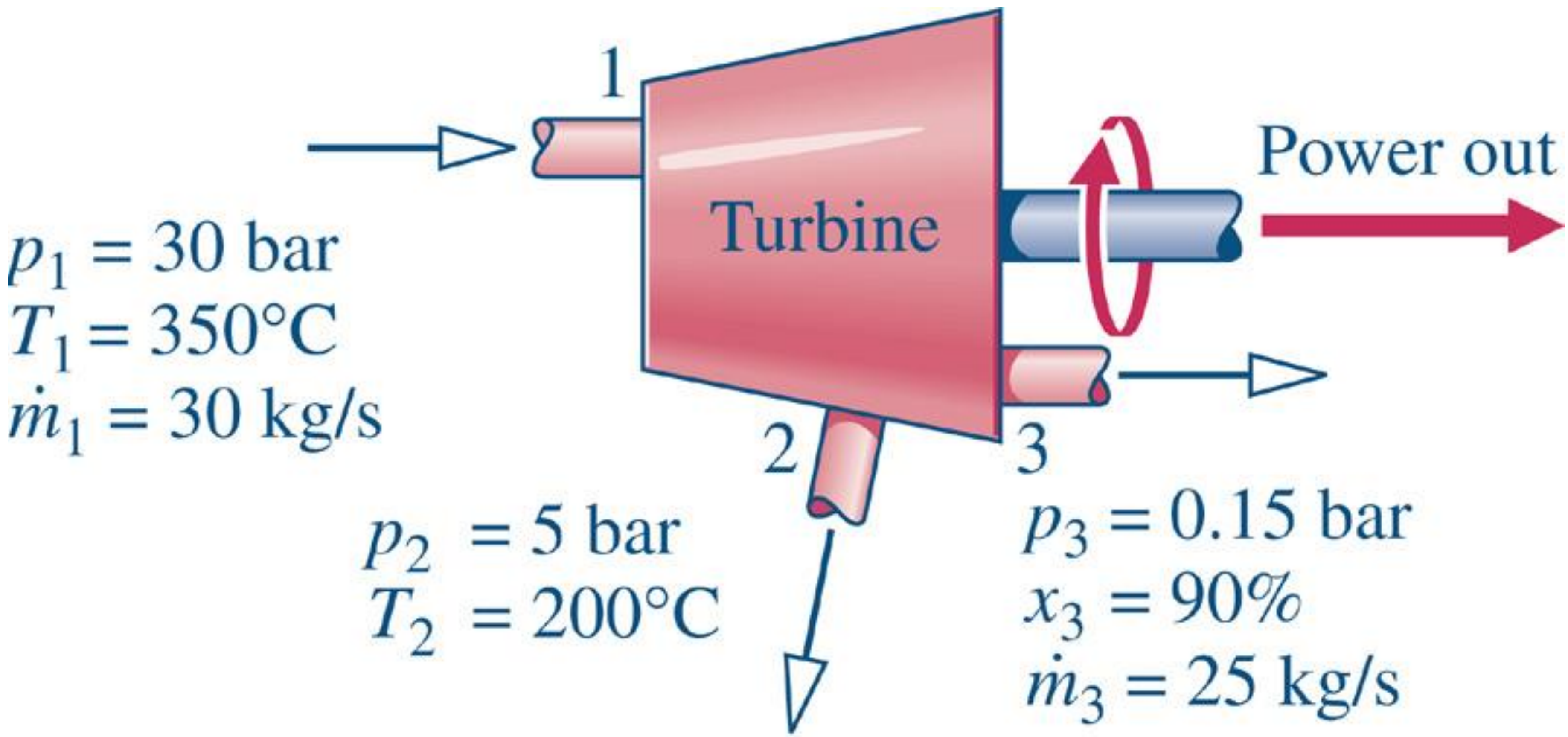

1
Turbine
Power out
$p_1 = 30$ bar
$T_1 = 350°C$
$\dot{m}_1 = 30$ kg/s
2
$p_2 = 5$ bar
$T_2 = 200°C$
3
$p_3 = 0.15$ bar
$x_3 = 90\%$
$\dot{m}_3 = 25$ kg/s

Fig07_P7

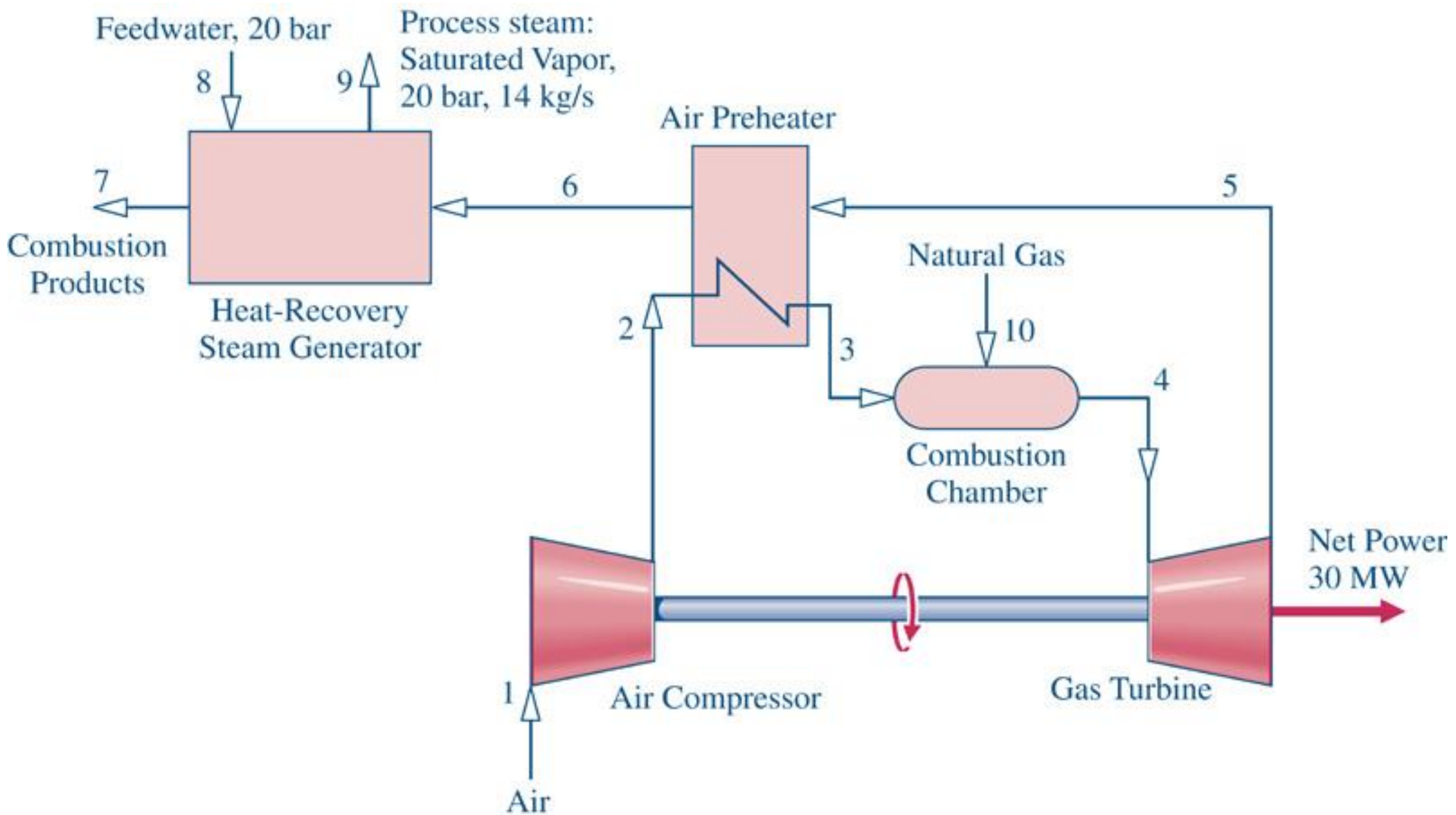
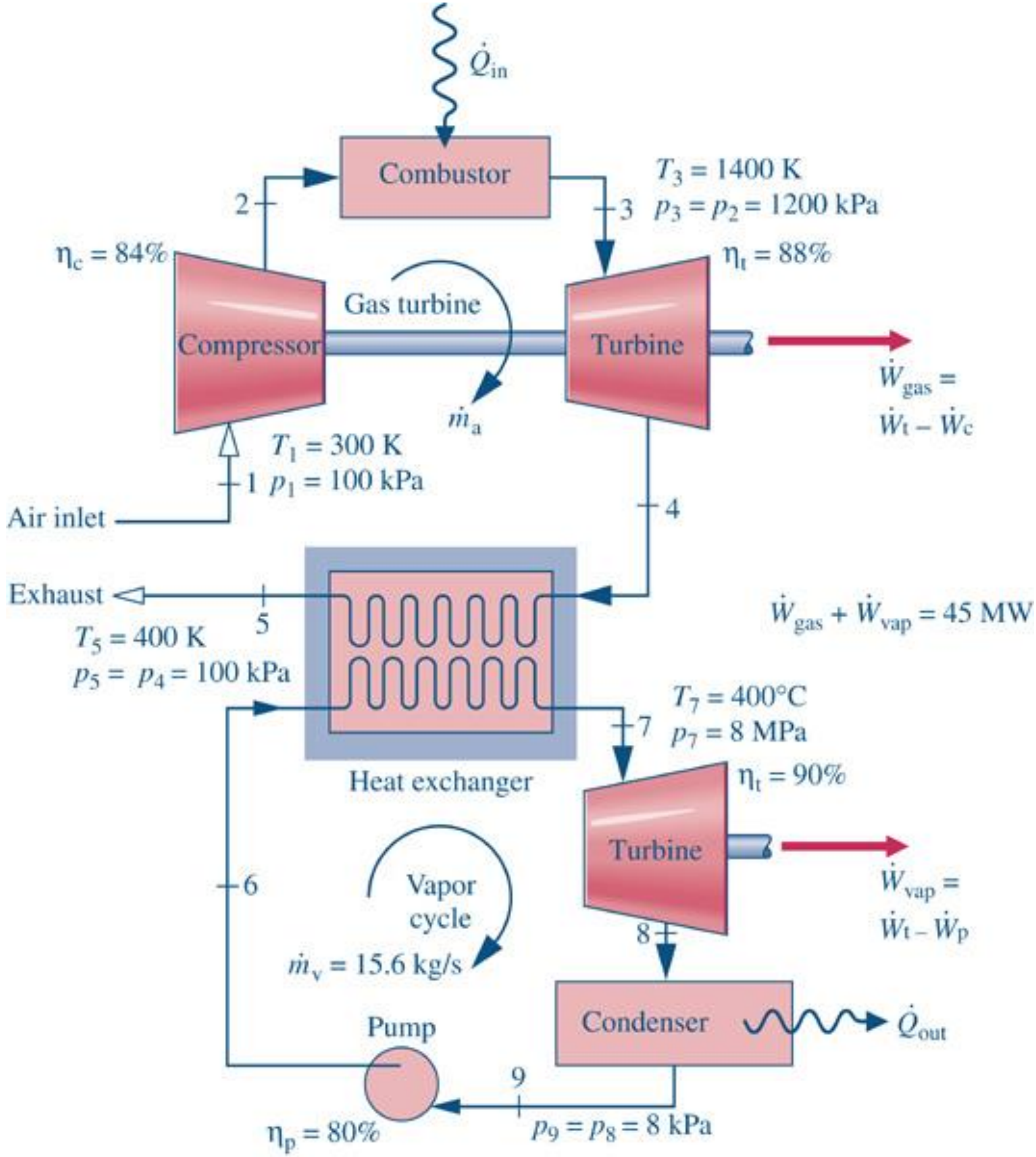

Feedwater, 20 bar
8
9
Process steam:
Saturated Vapor,
20 bar, 14 kg/s
Air Preheater
7
6
5
Combustion
Products
Heat-Recovery
Steam Generator
Natural Gas
10
2
3
4
Combustion
Chamber
Net Power
30 MW
1
Air Compressor
Gas Turbine
Air

Fig07_P7



$\dot{Q}_{in}$
Combustor
2
3
$T_3 = 1400$ K
$p_3 = p_2 = 1200$ kPa
$\eta_c = 84\%$
$\eta_t = 88\%$
Gas turbine
Compressor
Turbine
$\dot{m}_a$
$\dot{W}_{gas} = \dot{W}_t - \dot{W}_c$
$T_1 = 300$ K
1 $p_1 = 100$ kPa
Air inlet
4
Exhaust
5
$T_5 = 400$ K
$p_5 = p_4 = 100$ kPa
$\dot{W}_{gas} + \dot{W}_{vap} = 45$ MW
$T_7 = 400°C$
7 $p_7 = 8$ MPa
Heat exchanger
$\eta_t = 90\%$
Turbine
$\dot{W}_{vap} = \dot{W}_t - \dot{W}_p$
6
Vapor cycle
$\dot{m}_v = 15.6$ kg/s
8
Pump
Condenser
$\dot{Q}_{out}$
9
$\eta_p = 80\%$
$p_9 = p_8 = 8$ kPa

Fig07_P7

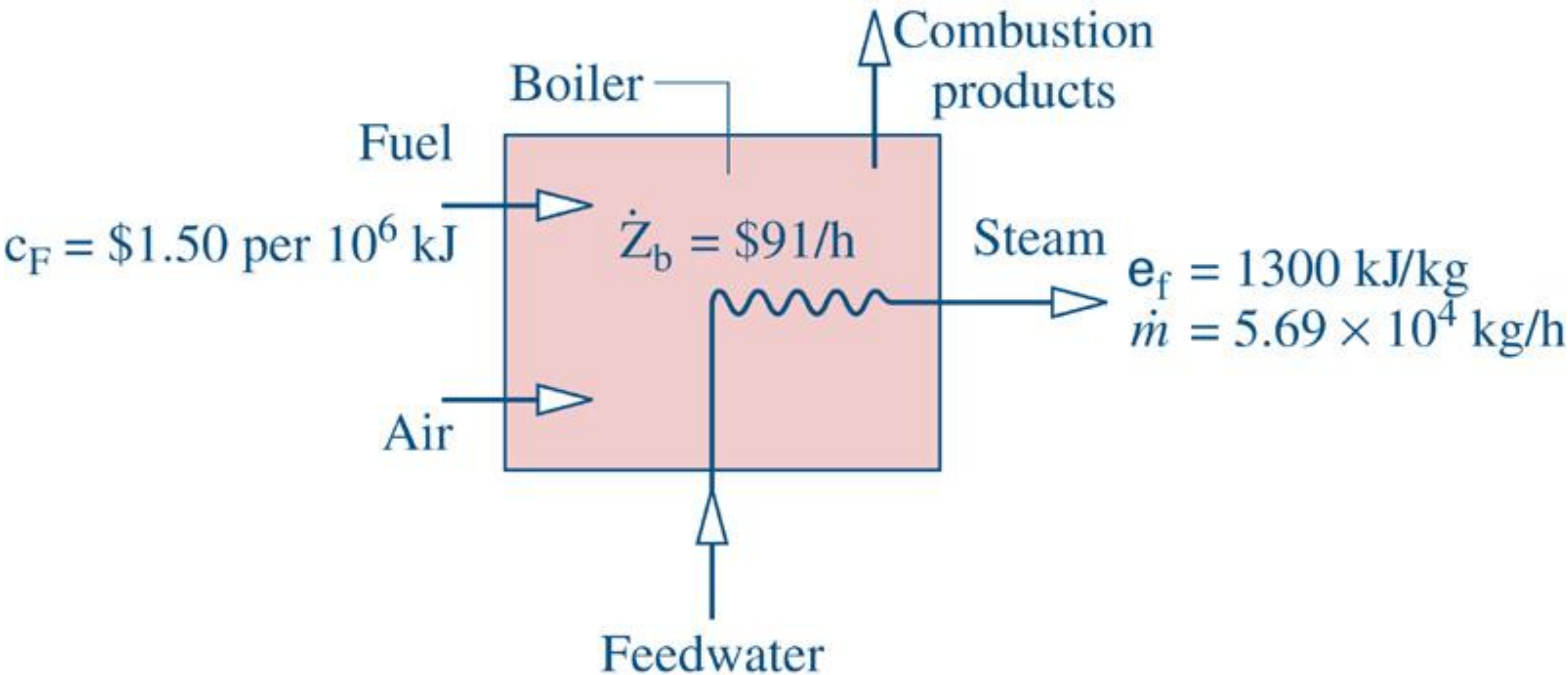
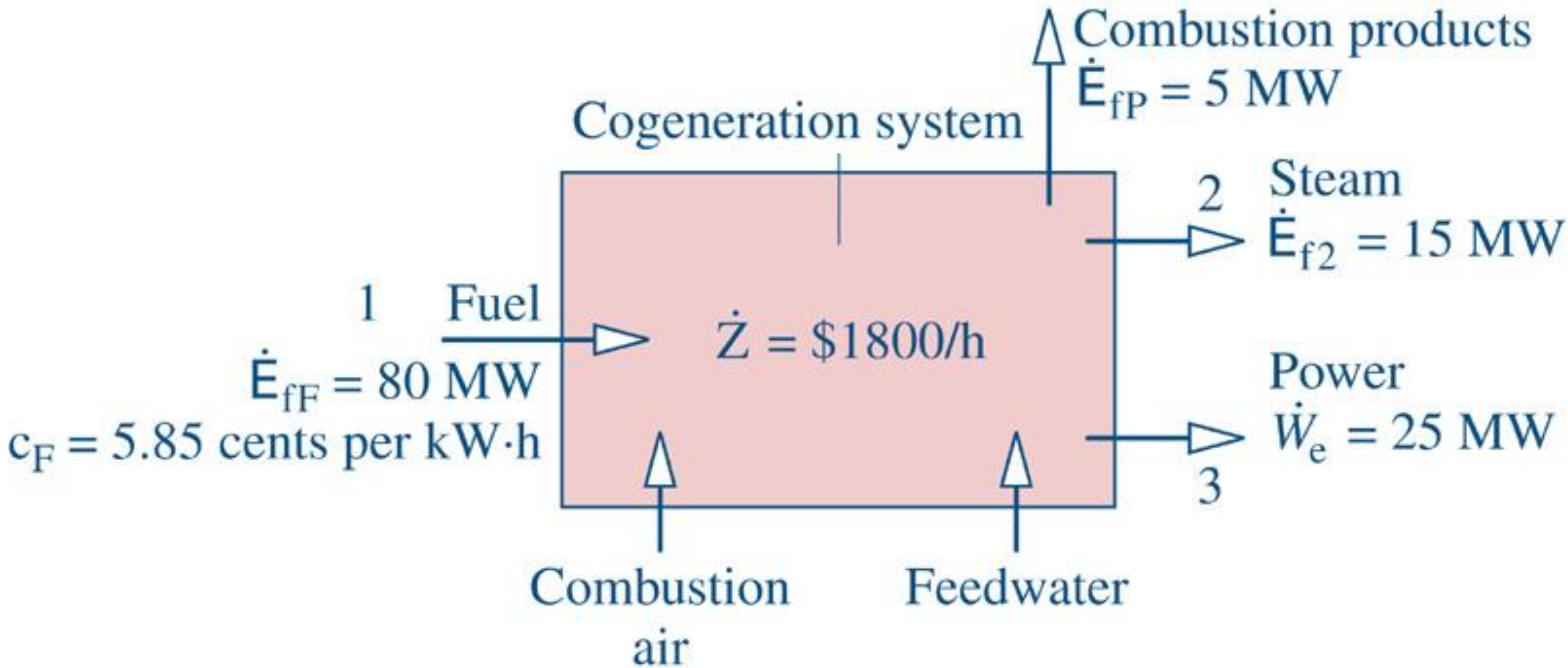
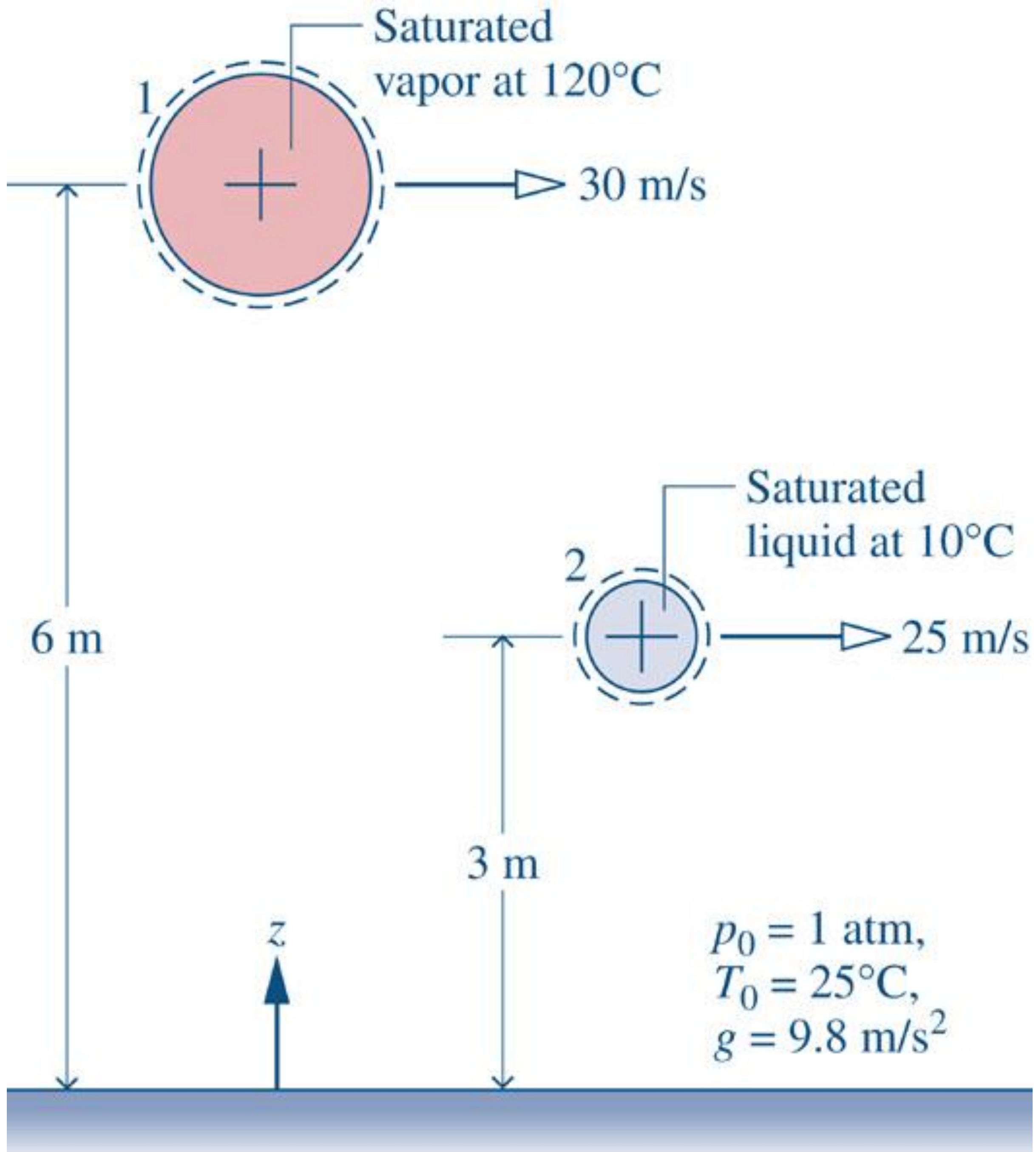

Combustion products
Boiler
Fuel
cF = $1.50 per 10^6 kJ
Ż_b = $91/h
Steam
e_f = 1300 kJ/kg
ṁ = 5.69 × 10^4 kg/h
Air
Feedwater

Fig07_P7



Combustion products
Ė_fP = 5 MW
Cogeneration system
2
Steam
Ė_f2 = 15 MW
1
Fuel
Ė_fF = 80 MW
c_F = 5.85 cents per kW·h
Ż = $1800/h
Power
Ẇ_e = 25 MW
3
Combustion
air
Feedwater

Fig07_P7


Saturated
vapor at 120°C
1
30 m/s
Saturated
liquid at 10°C
2
25 m/s
6 m
3 m
z
p_0 = 1 atm,
T_0 = 25°C,
g = 9.8 m/s²
Fig07_P7

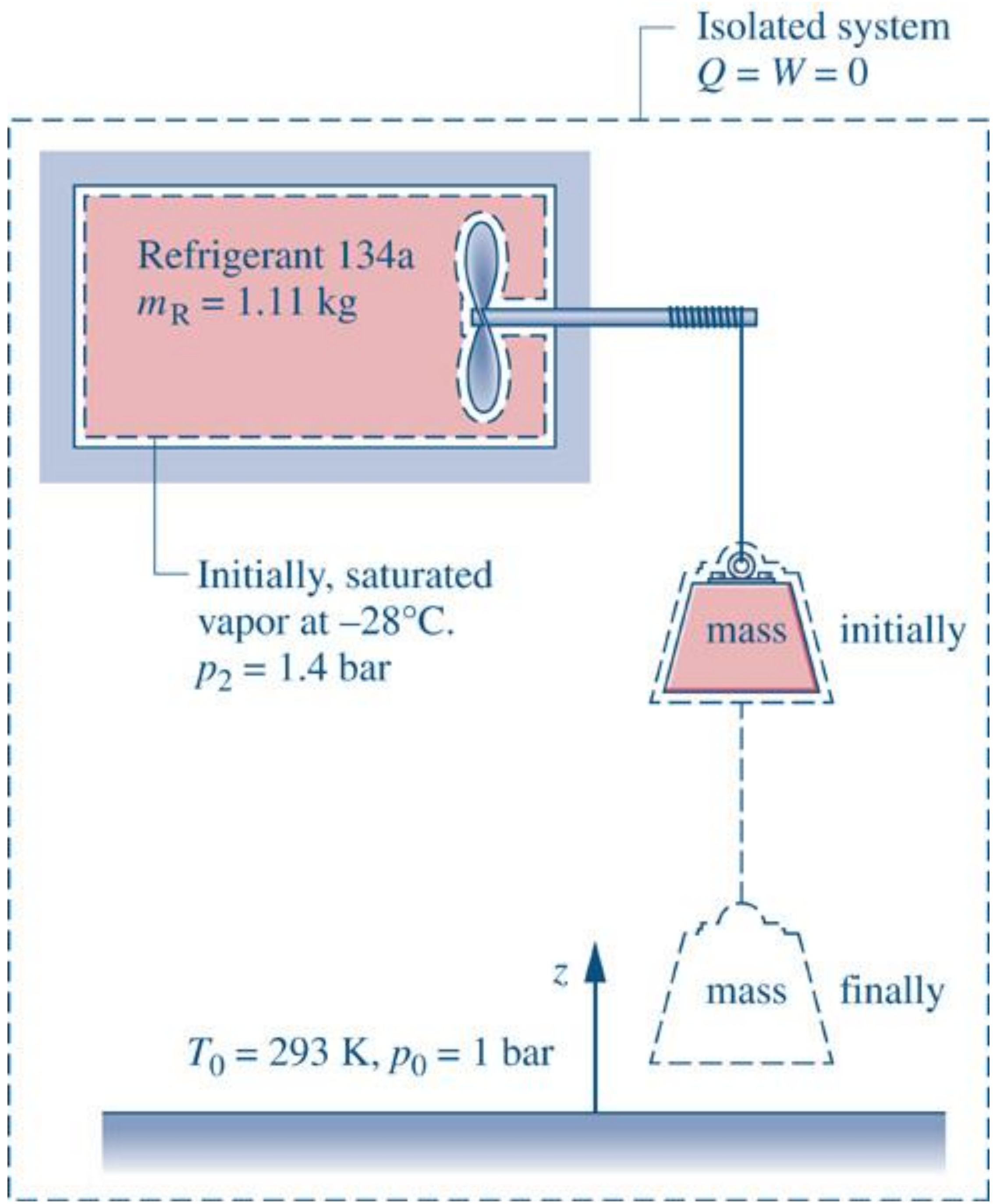

Isolated system
$Q = W = 0$
Refrigerant 134a
$m_R = 1.11$ kg
Initially, saturated
vapor at –28°C.
$p_2 = 1.4$ bar
mass
initially
mass
finally
z
$T_0 = 293$ K, $p_0 = 1$ bar

Fig07_P7

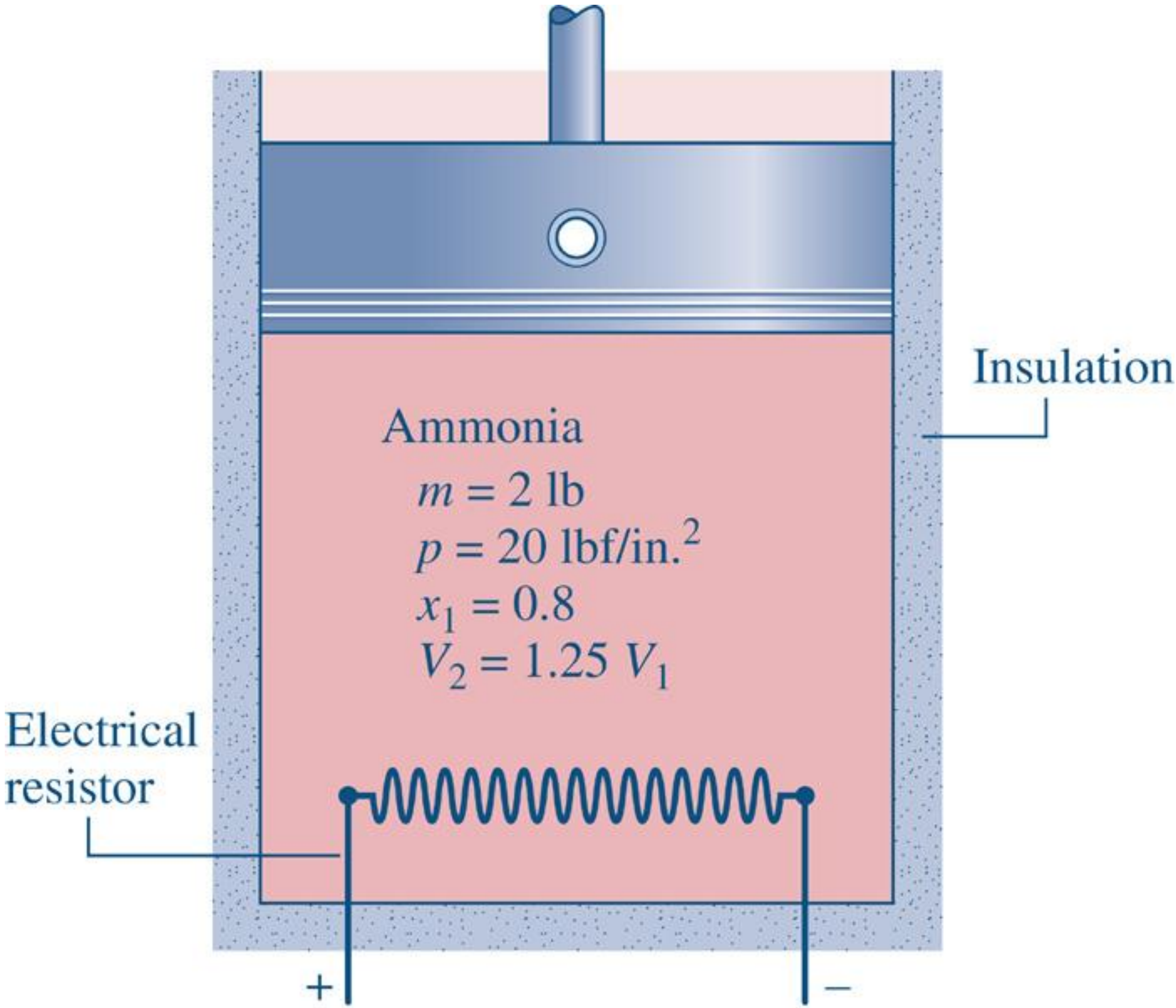
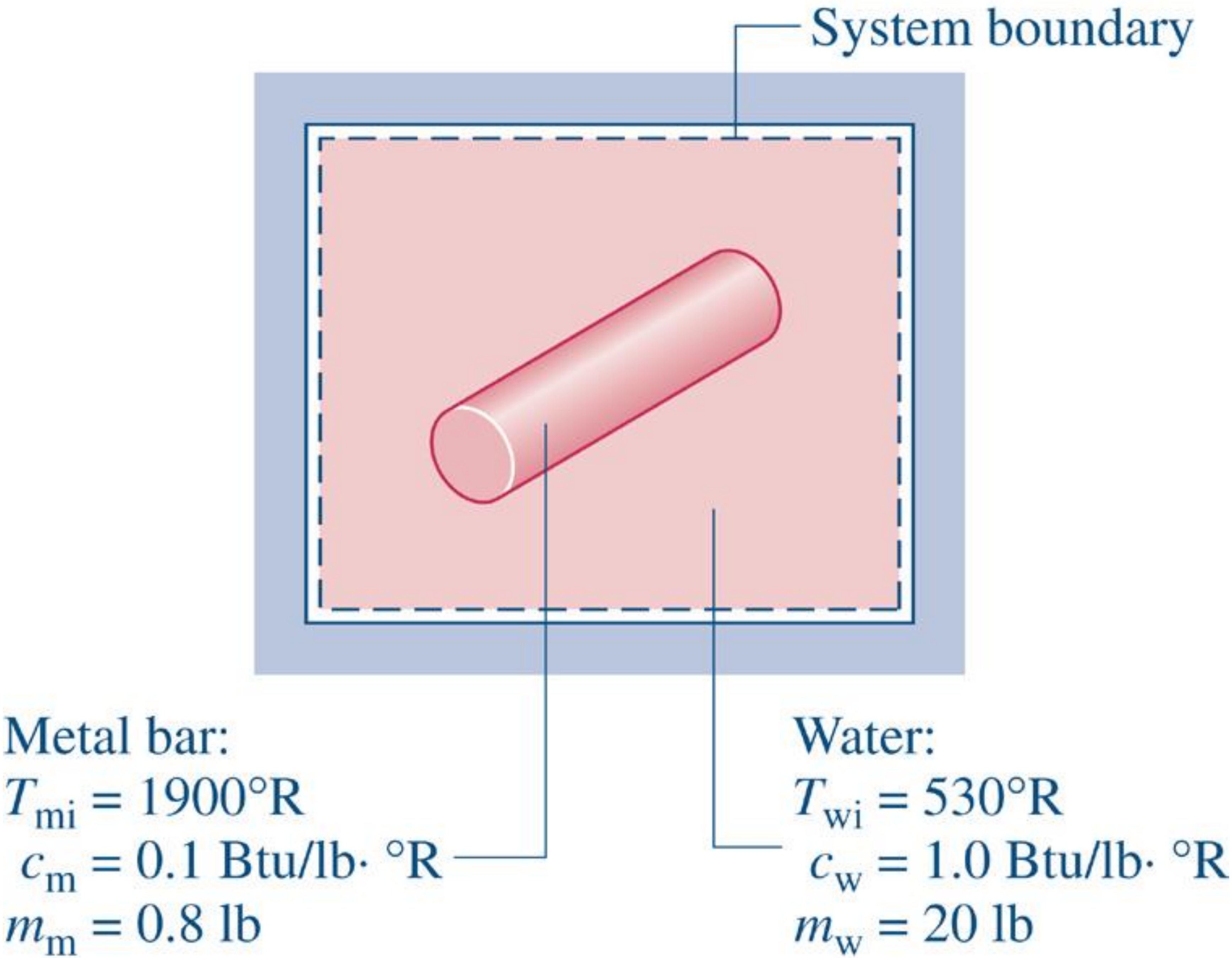

Insulation
Ammonia
$m = 2$ lb
$p = 20$ lbf/in.^{2}
$x_1 = 0.8$
$V_2 = 1.25\ V_1$
Electrical
resistor
+
−

Fig07_P7



System boundary
Metal bar:
$T_{mi} = 1900°R$
$c_m = 0.1$ Btu/lb· °R
$m_m = 0.8$ lb
Water:
$T_{wi} = 530°R$
$c_w = 1.0$ Btu/lb· °R
$m_w = 20$ lb

Fig07_P7

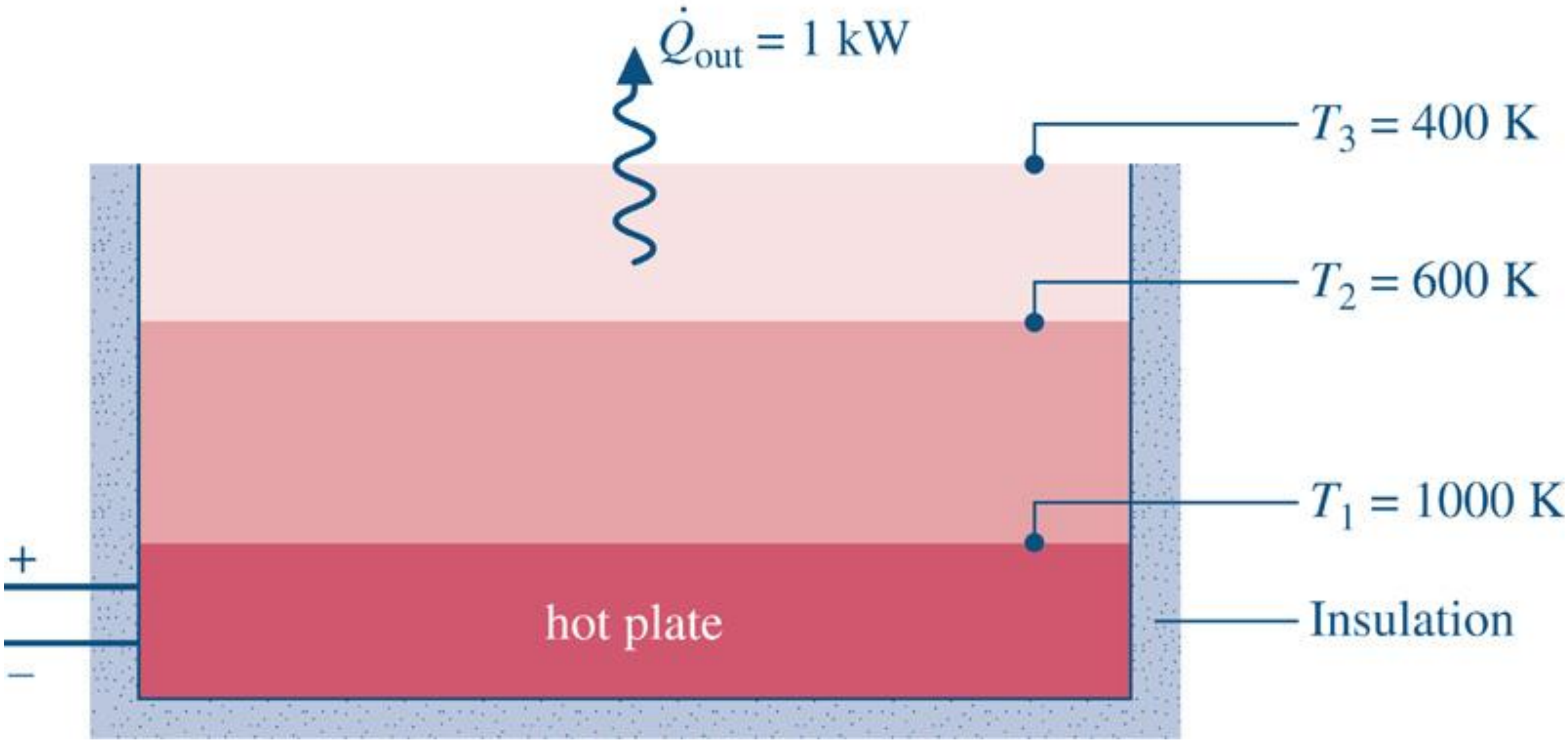


Fig07_P7

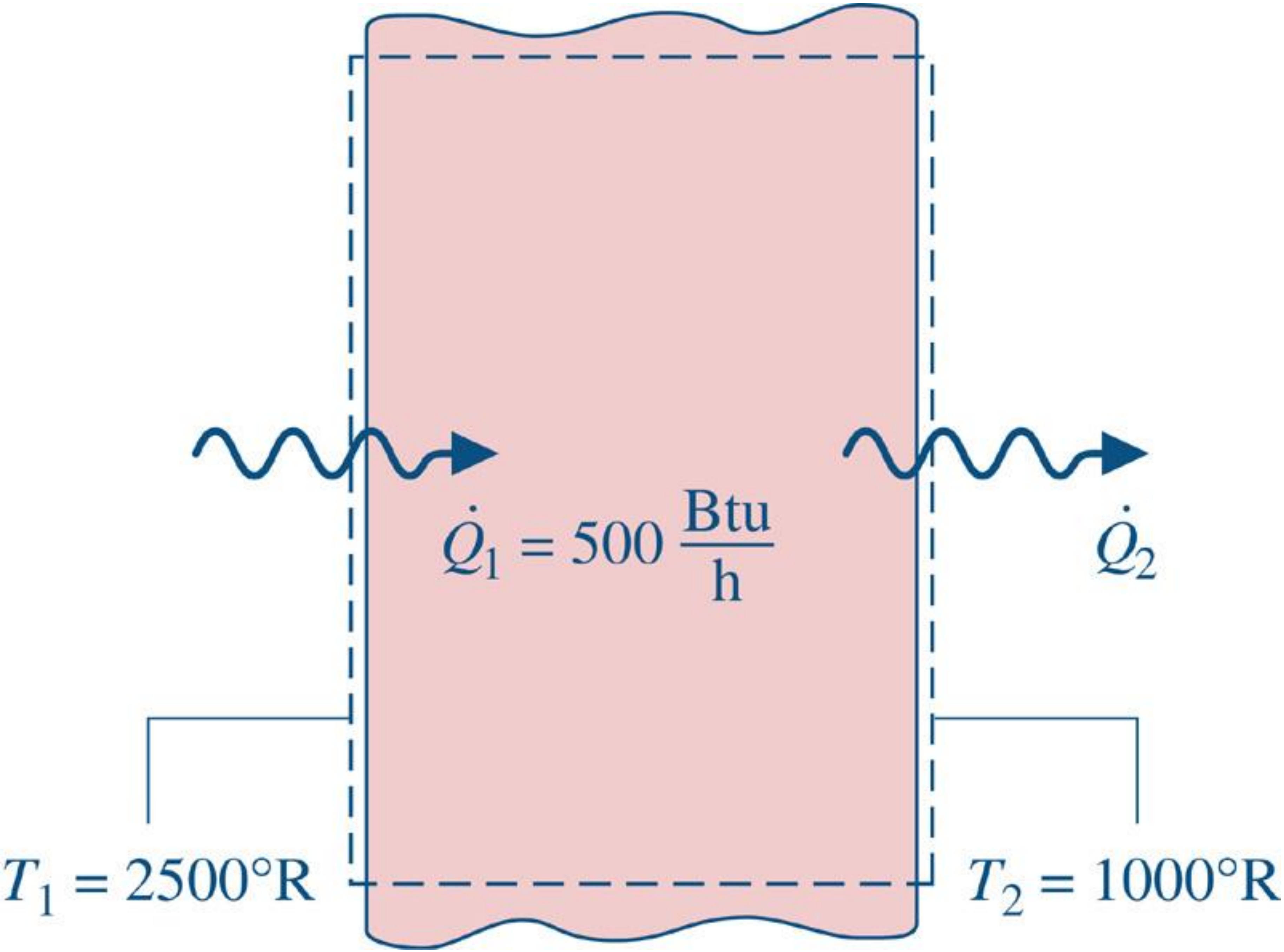


Fig07_P7

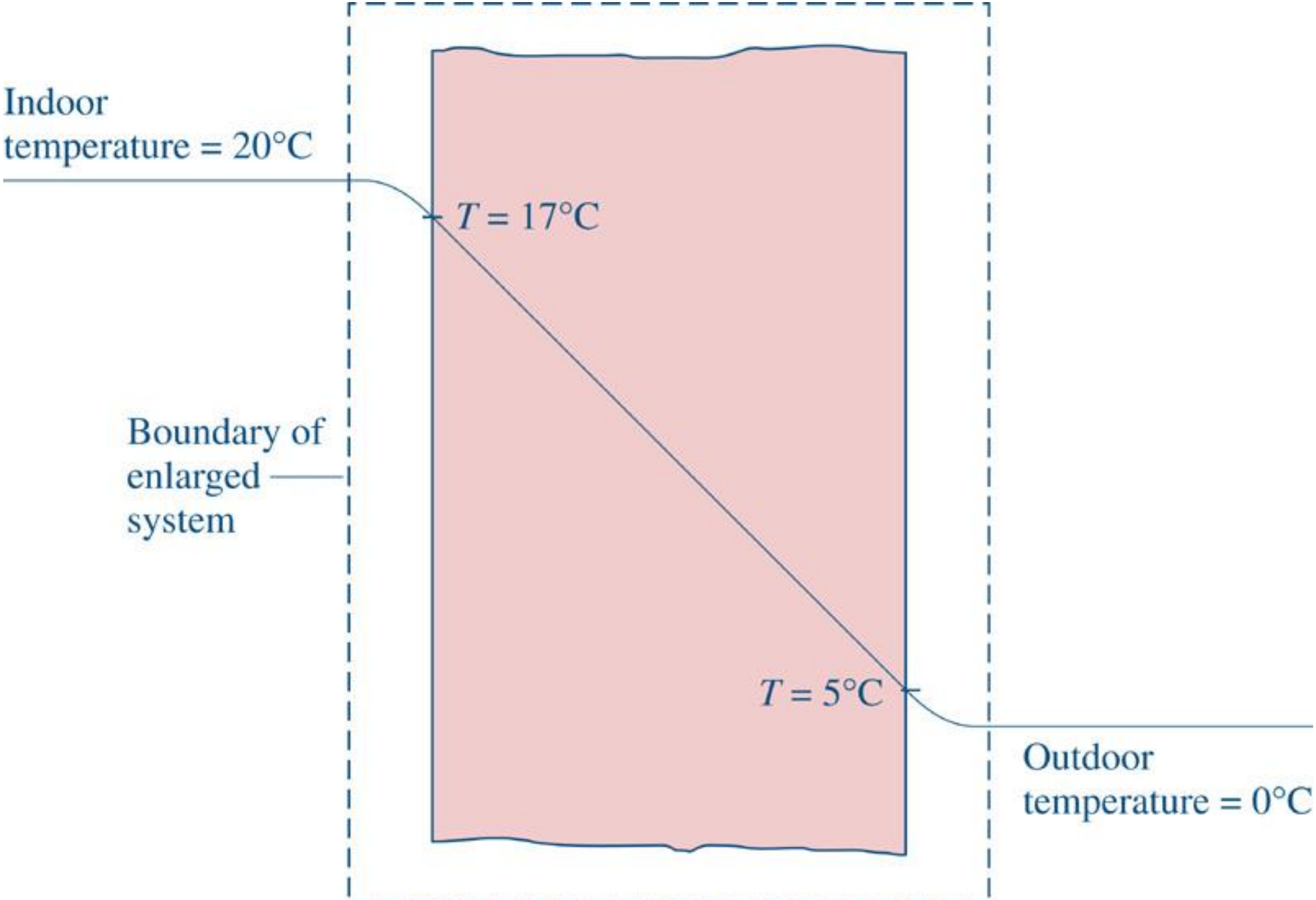

Indoor
temperature = 20°C
T = 17°C
Boundary of
enlarged
system
T = 5°C
Outdoor
temperature = 0°C

Fig07_P7

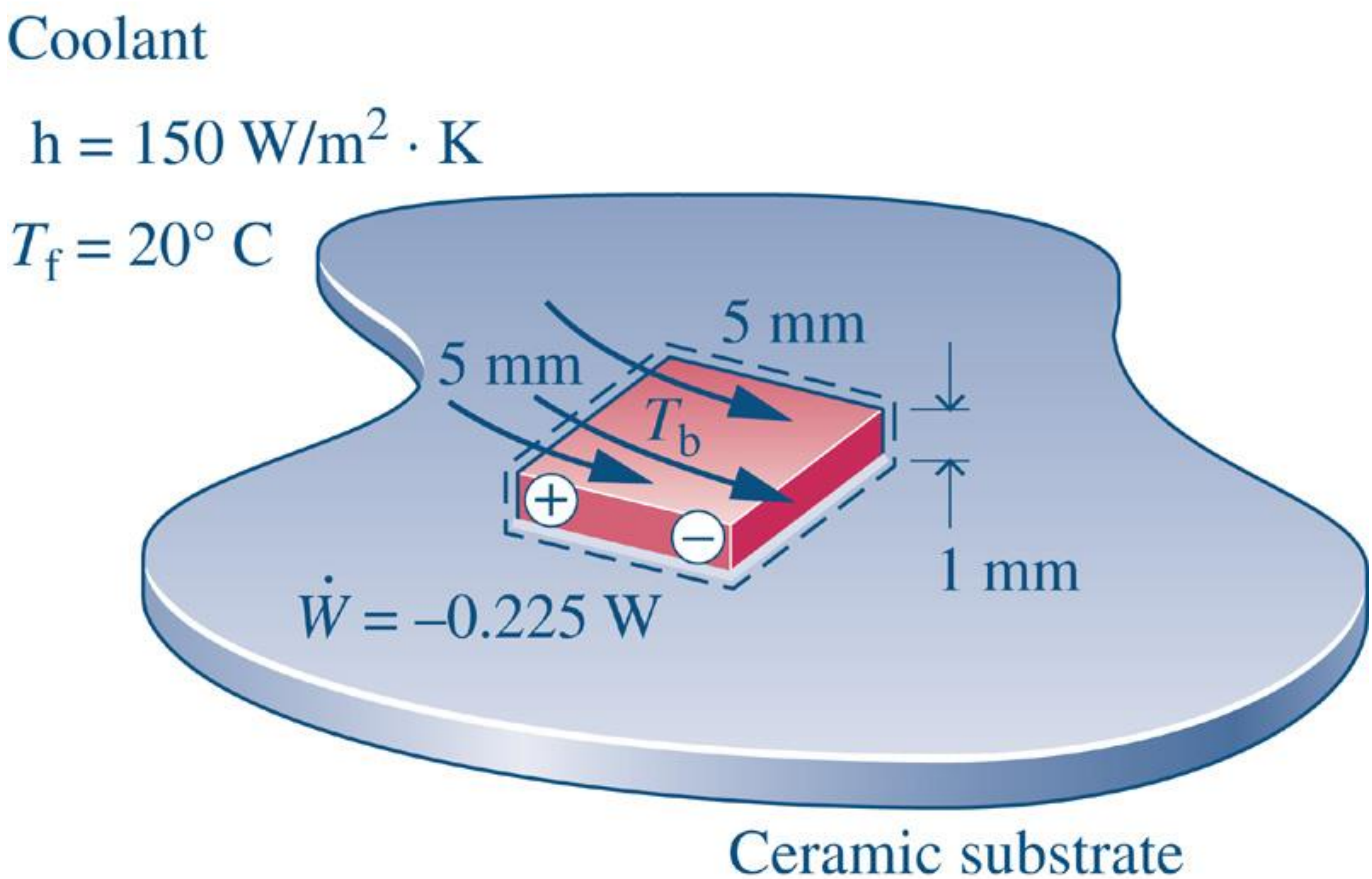
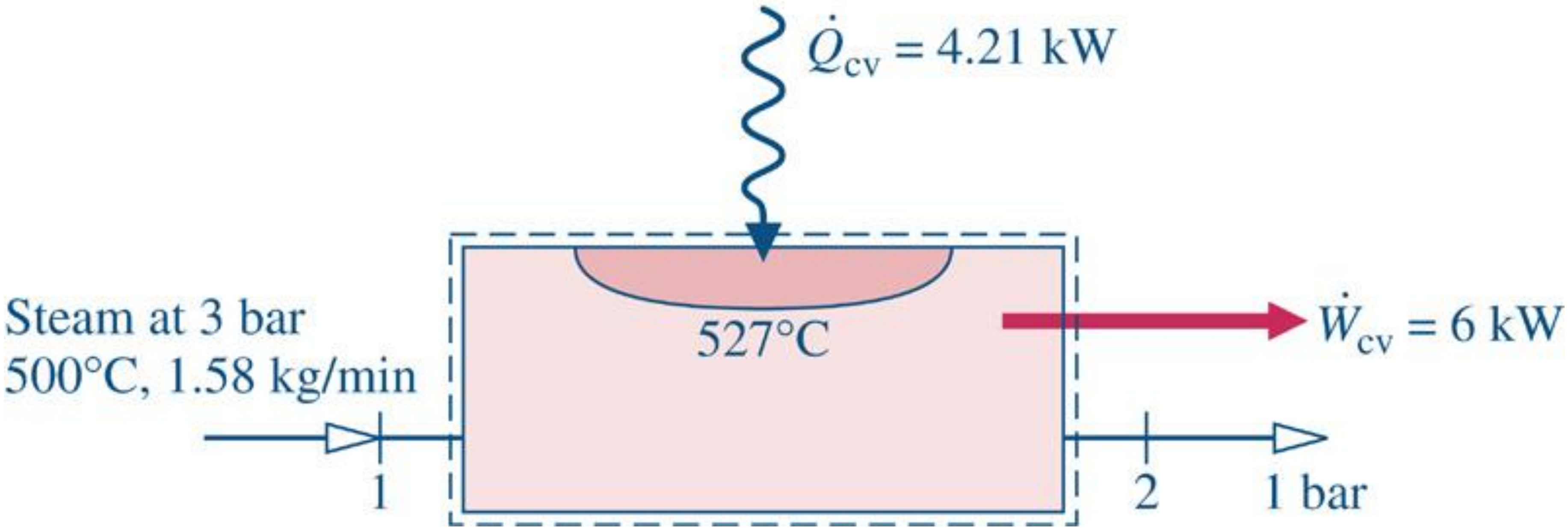

Coolant
h = 150 W/m² · K
T_f = 20° C
5 mm
5 mm
T_b
1 mm
$\dot{W}$ = –0.225 W
Ceramic substrate

Fig07_P7



$\dot{Q}_{cv}$ = 4.21 kW
Steam at 3 bar
500°C, 1.58 kg/min
527°C
$\dot{W}_{cv}$ = 6 kW
1
2
1 bar

Fig07_P7

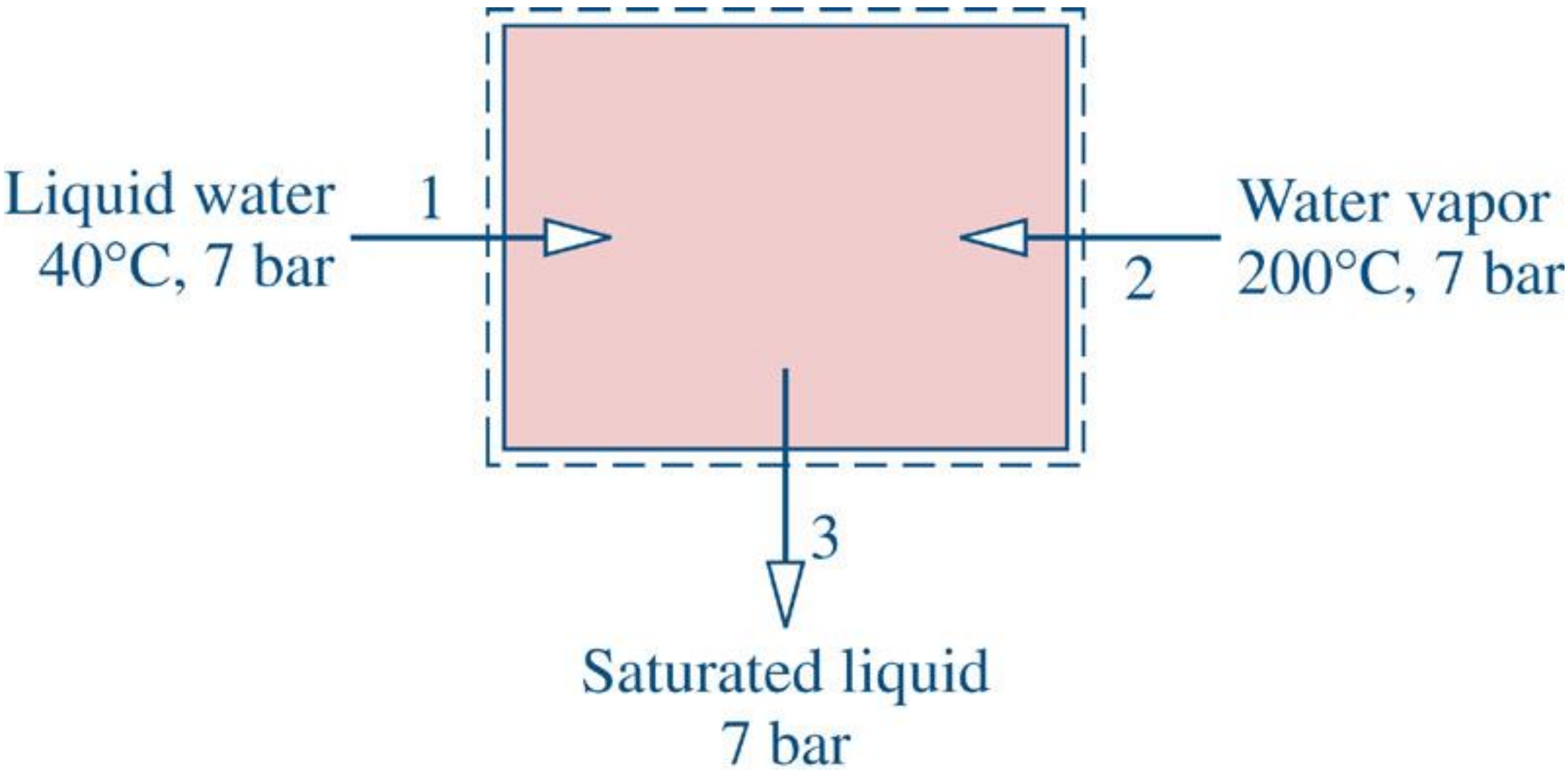

Liquid water
40°C, 7 bar
1
Water vapor
200°C, 7 bar
2
3
Saturated liquid
7 bar

Fig07_P7

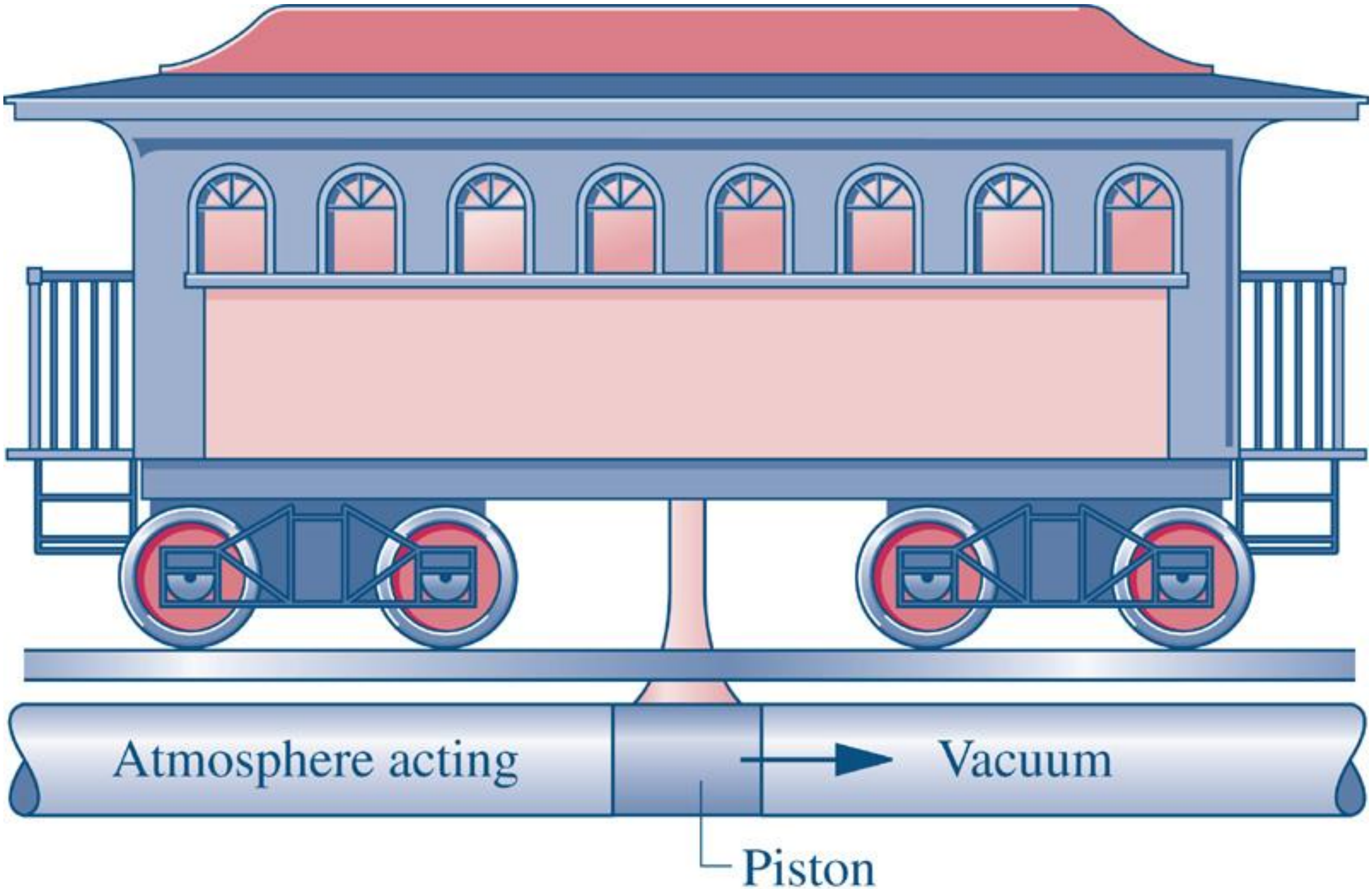


Fig07_P7

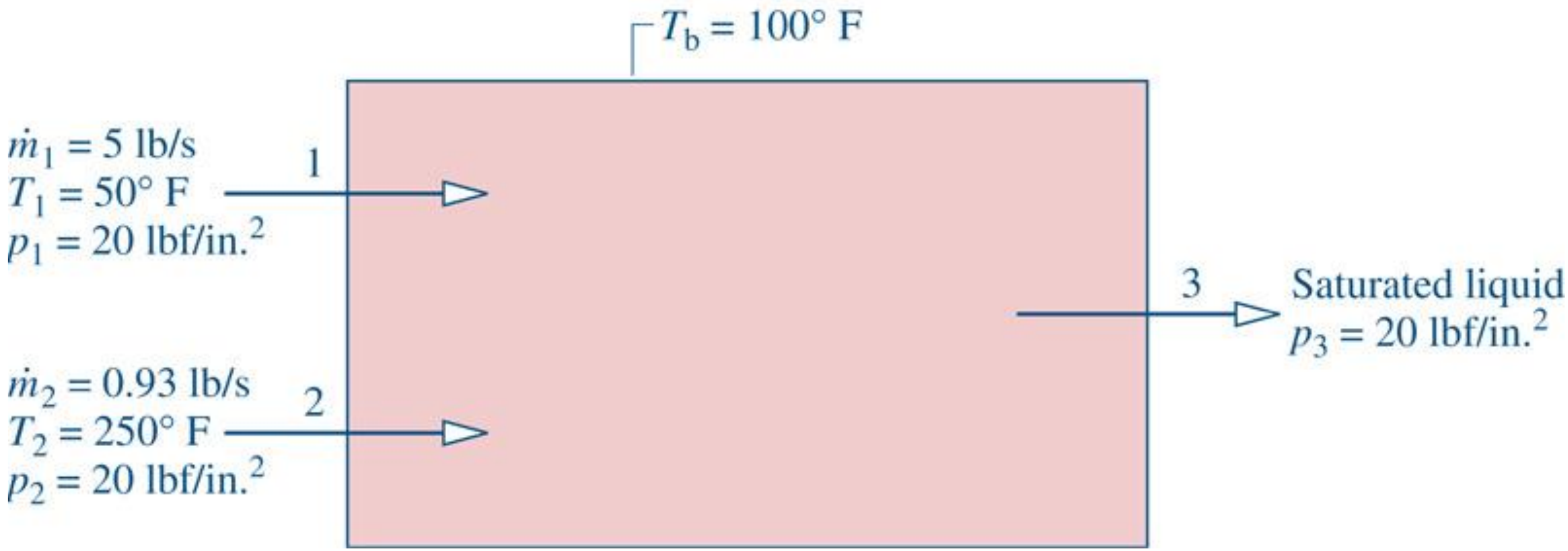

$T_b = 100° F$
$\dot{m}_1 = 5$ lb/s
$T_1 = 50° F$
$p_1 = 20$ lbf/in.^{2}
1
$\dot{m}_2 = 0.93$ lb/s
$T_2 = 250° F$
$p_2 = 20$ lbf/in.^{2}
2
3
Saturated liquid
$p_3 = 20$ lbf/in.^{2}

Fig07_P7

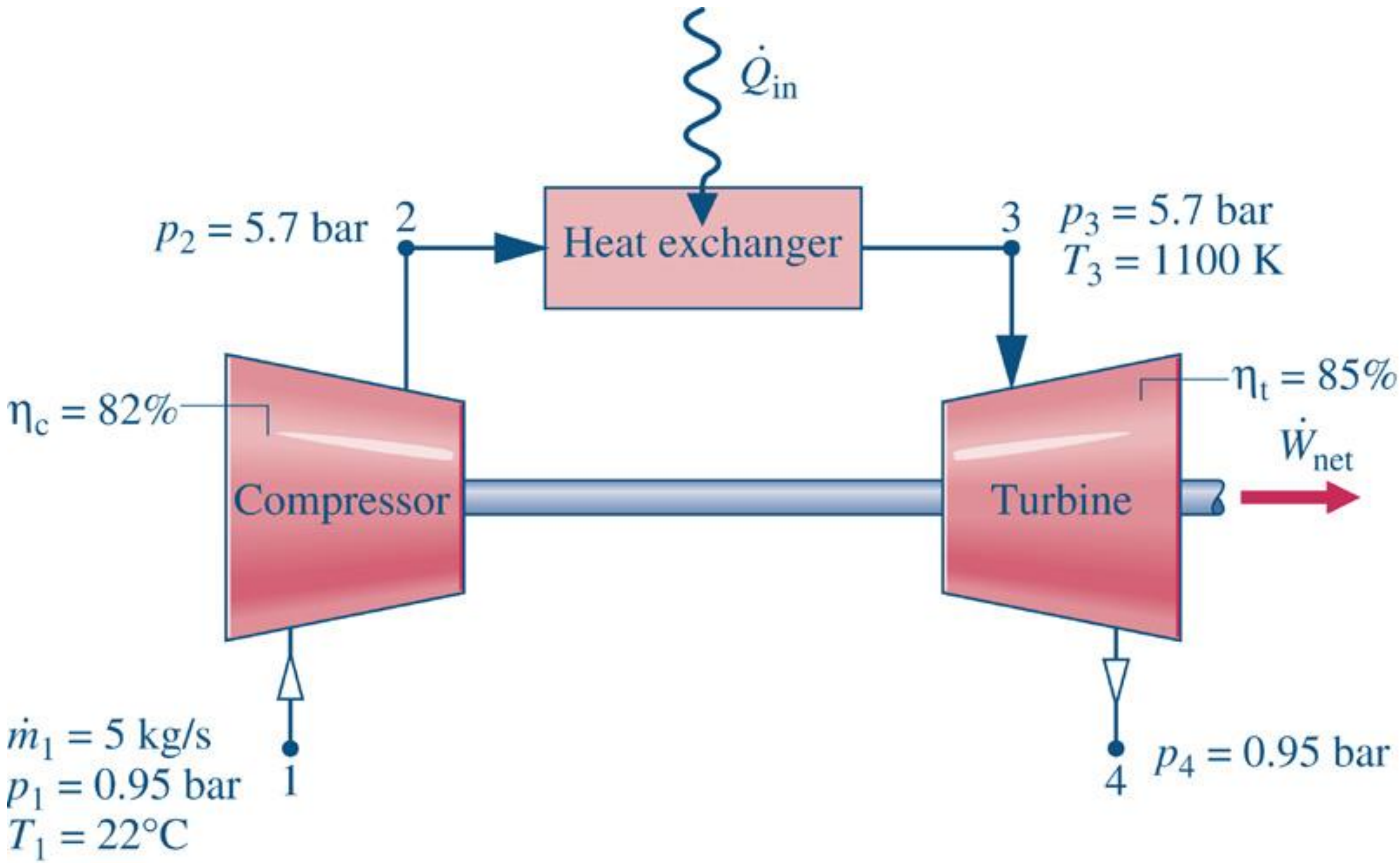
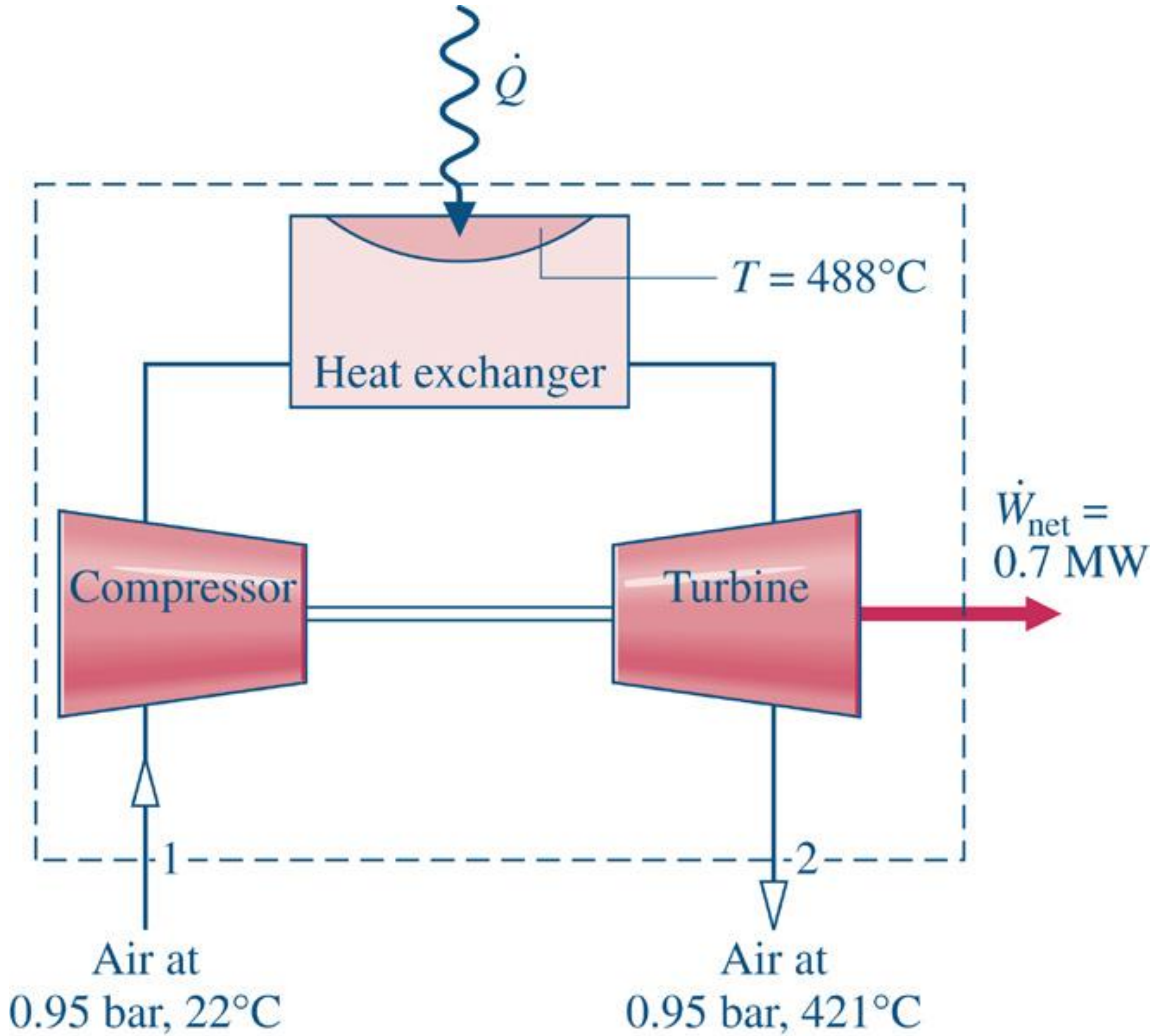

Q̇in
Heat exchanger
p2 = 5.7 bar
2
3
p3 = 5.7 bar
T3 = 1100 K
ηc = 82%
ηt = 85%
Compressor
Turbine
Ẇnet
ṁ1 = 5 kg/s
p1 = 0.95 bar
T1 = 22°C
1
4
p4 = 0.95 bar

Fig07_P7



$\dot{Q}$
$T = 488°C$
Heat exchanger
Compressor
Turbine
$\dot{W}_{net} =$
0.7 MW
1
2
Air at
0.95 bar, 22°C
Air at
0.95 bar, 421°C

Fig07_P7

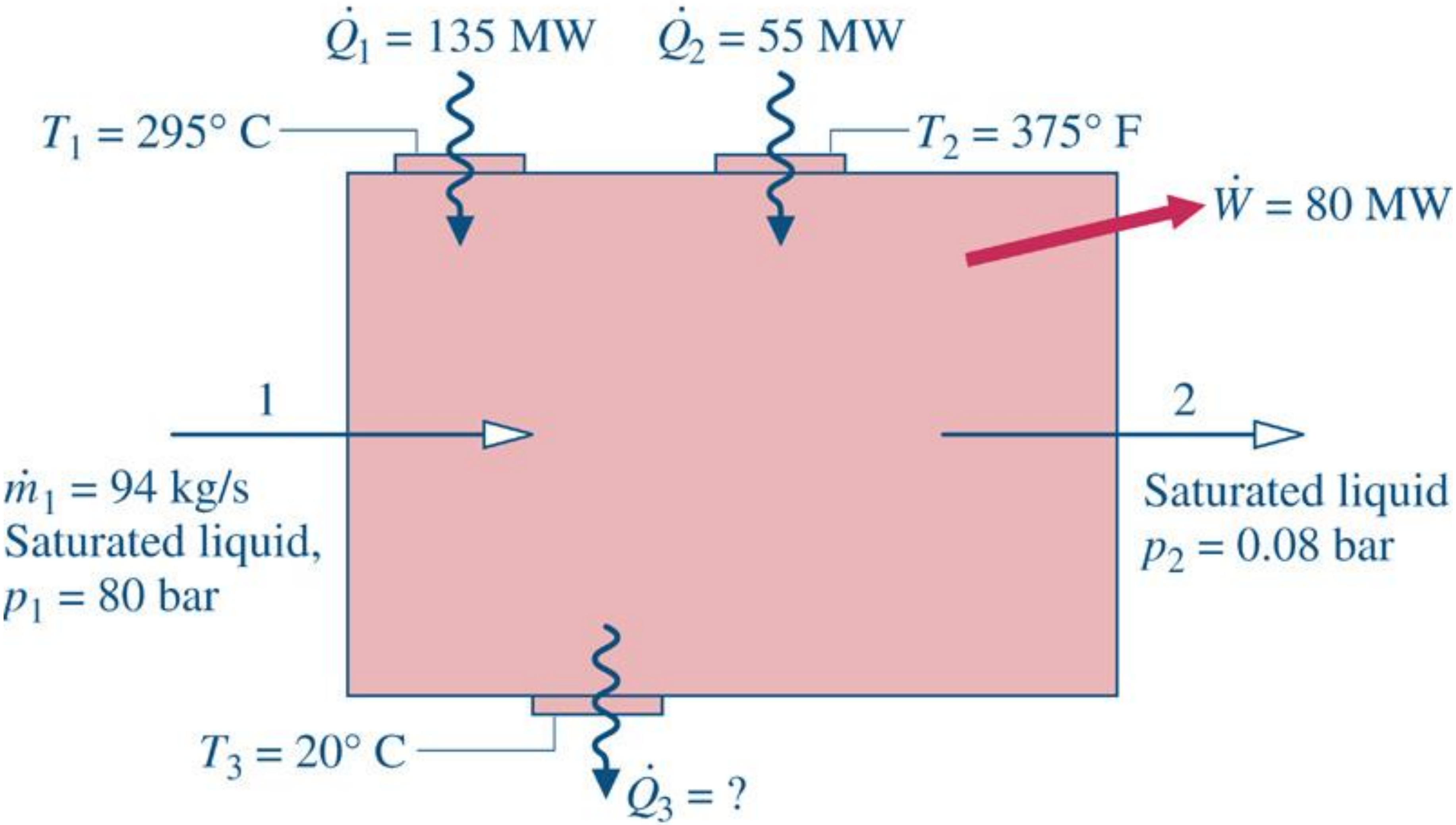

$\dot{Q}_1 = 135$ MW
$\dot{Q}_2 = 55$ MW
$T_1 = 295°$ C
$T_2 = 375°$ F
$\dot{W} = 80$ MW
1
2
$\dot{m}_1 = 94$ kg/s
Saturated liquid,
$p_1 = 80$ bar
Saturated liquid
$p_2 = 0.08$ bar
$T_3 = 20°$ C
$\dot{Q}_3 = ?$

Fig07_P7

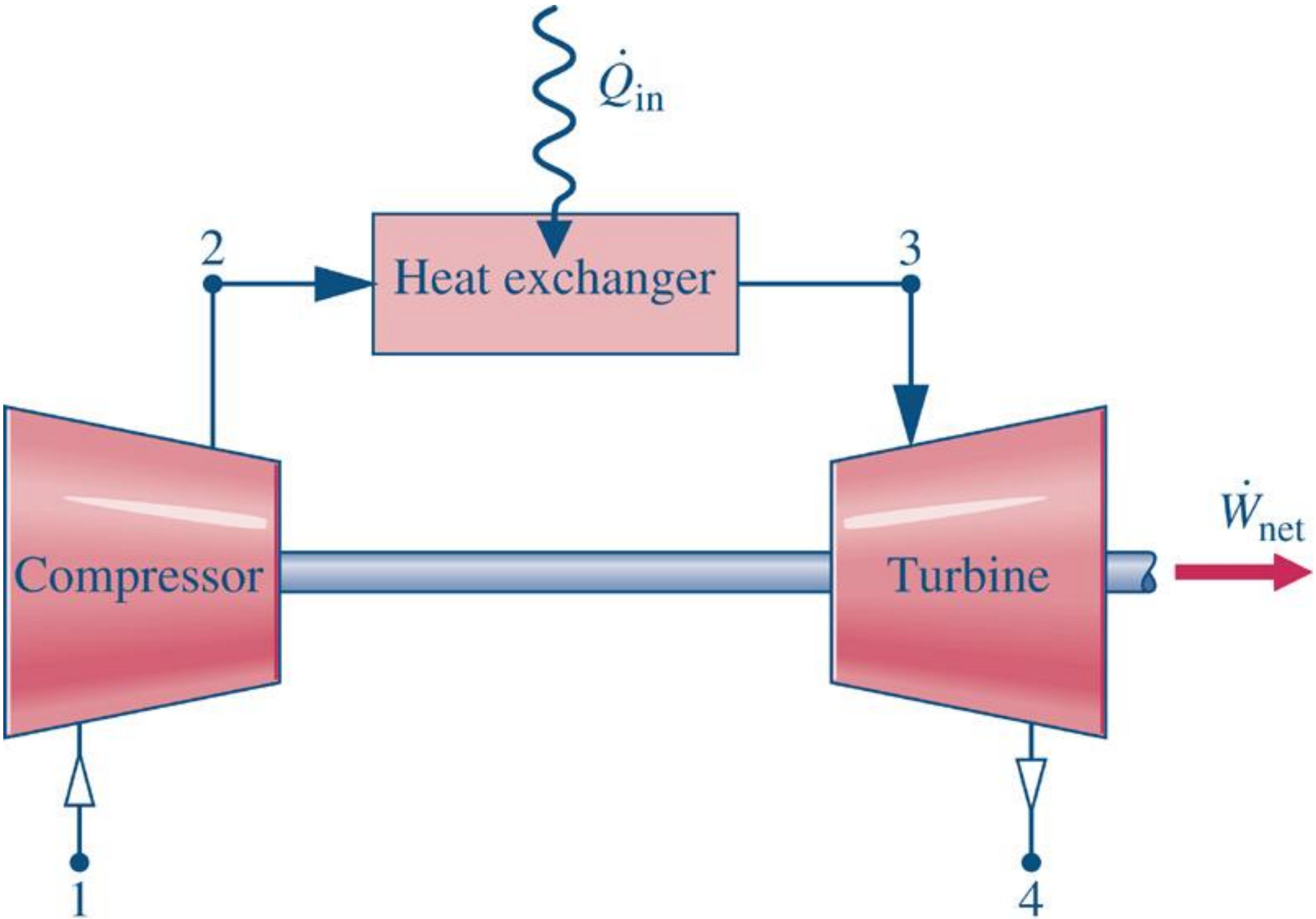


Fig07_P7

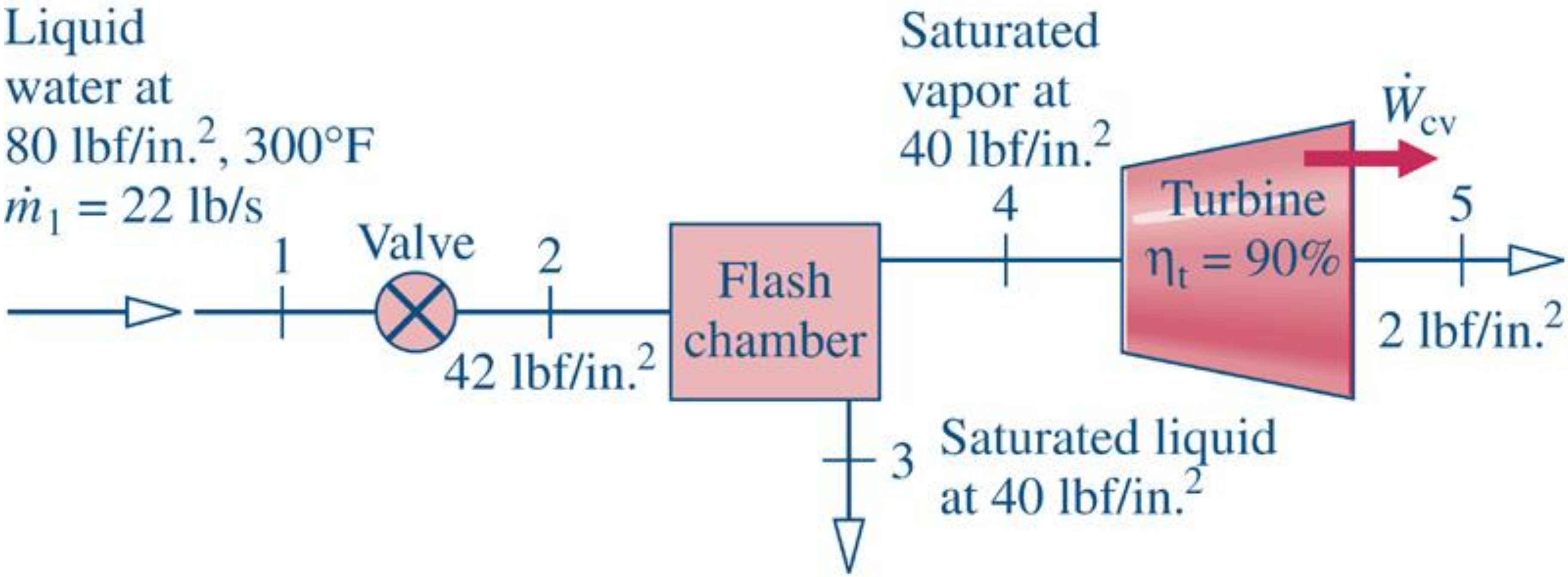

Liquid
water at
80 lbf/in.2, 300°F
ṁ1 = 22 lb/s
1
Valve
2
42 lbf/in.2
Flash
chamber
Saturated
vapor at
40 lbf/in.2
4
Turbine
ηt = 90%
Ẇcv
5
2 lbf/in.2
3
Saturated liquid
at 40 lbf/in.2

Fig07_P7

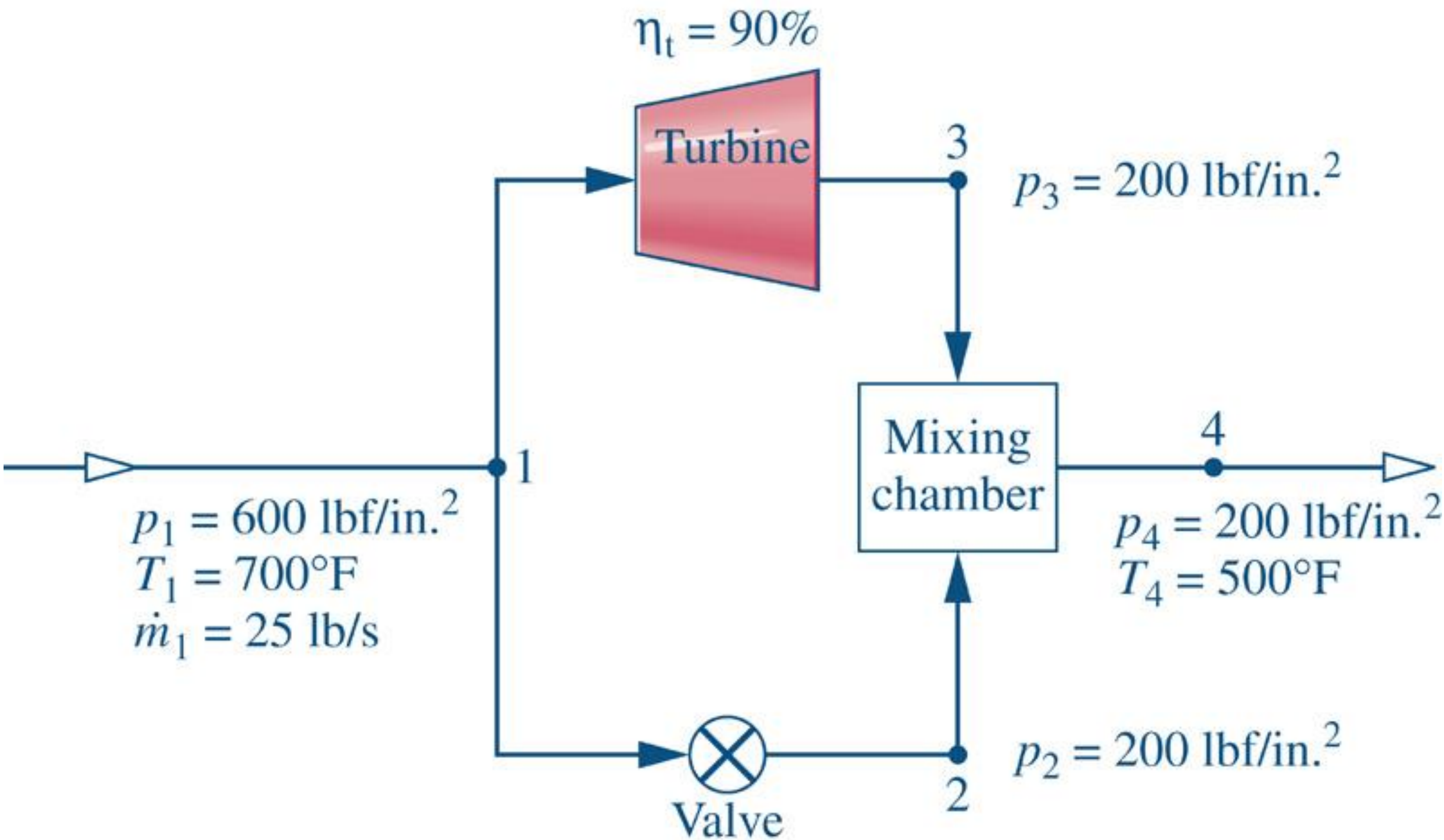
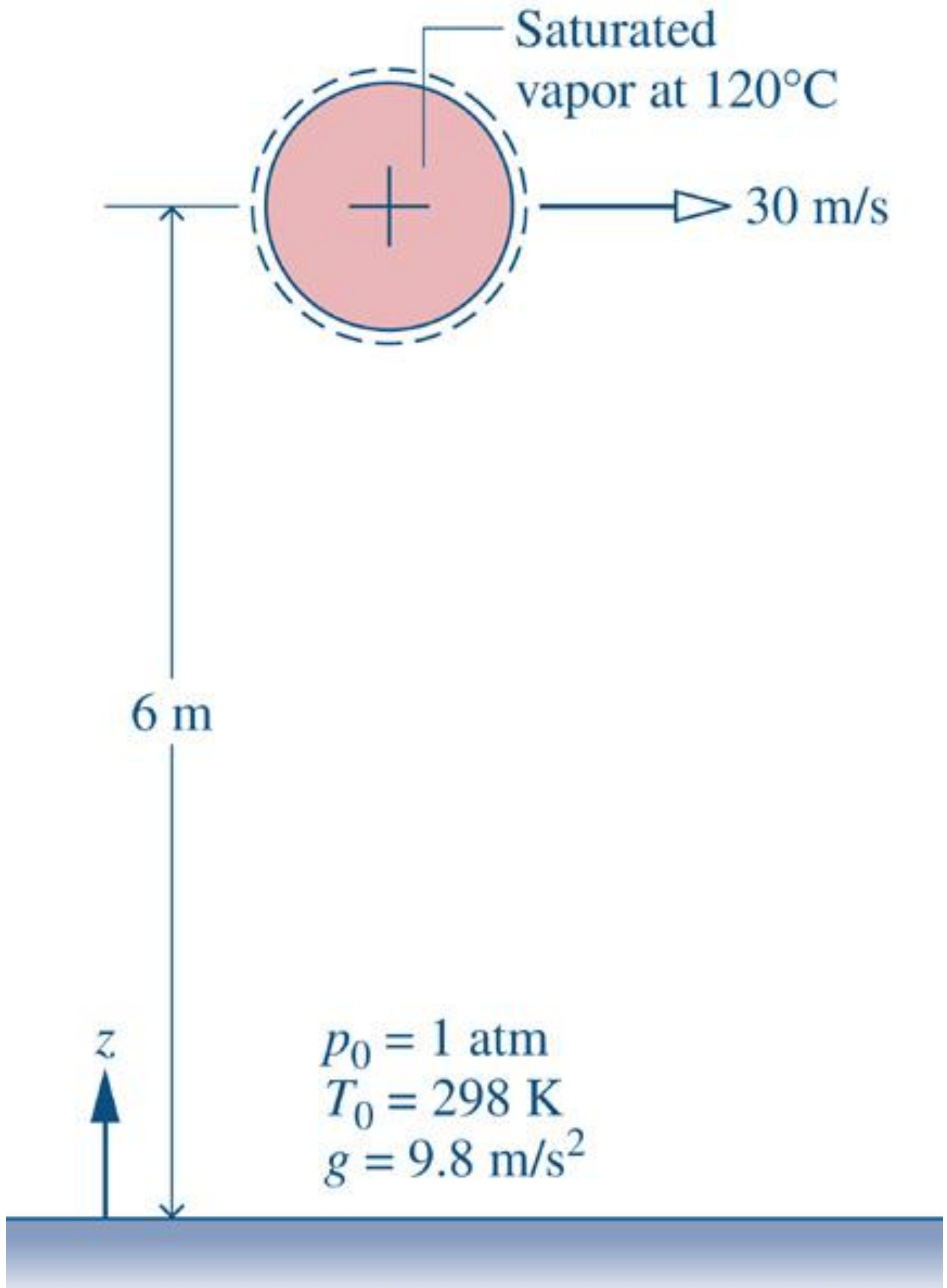
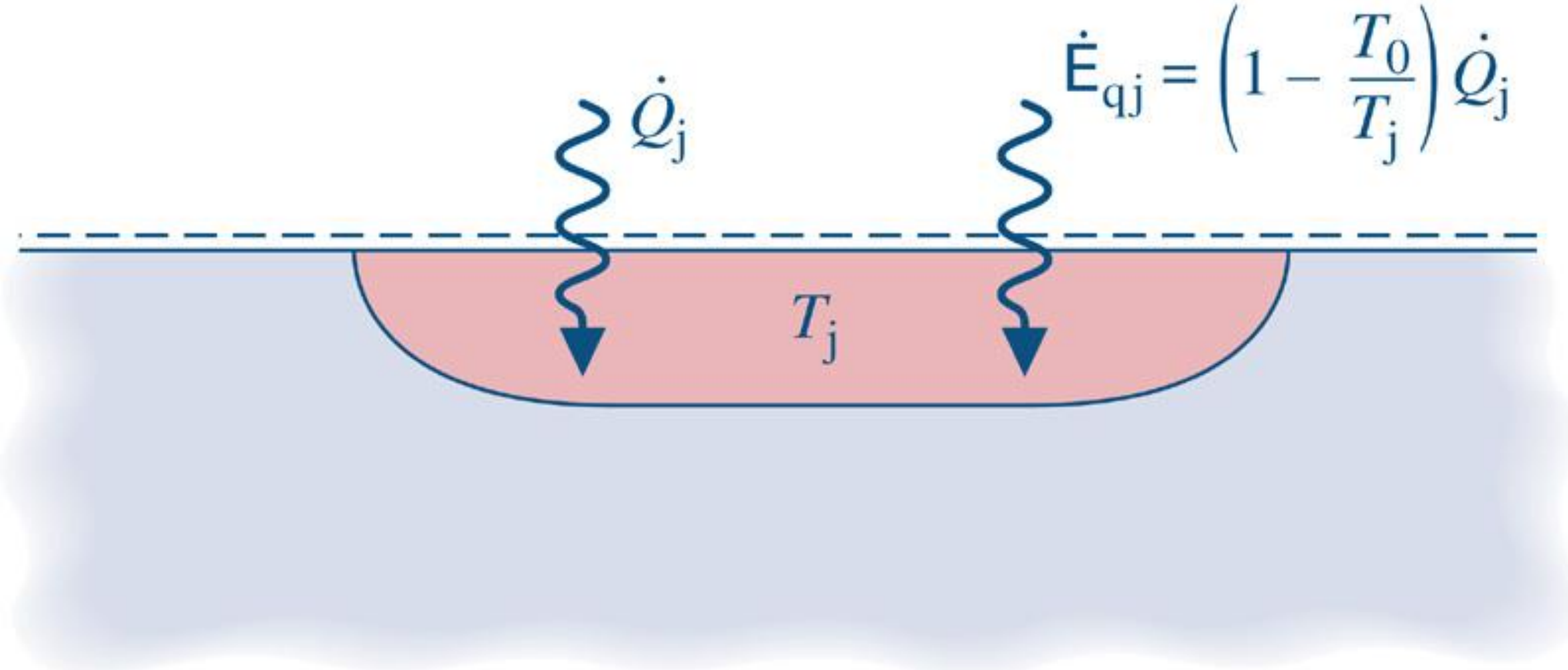

$\eta_t = 90\%$
Turbine
3
$p_3 = 200$ lbf/in.^{2}
Mixing chamber
4
1
$p_1 = 600$ lbf/in.^{2}
$T_1 = 700°F$
$\dot{m}_1 = 25$ lb/s
$p_4 = 200$ lbf/in.^{2}
$T_4 = 500°F$
$p_2 = 200$ lbf/in.^{2}
2
Valve

Fig07_P7



UnFig07_01_pg336



UnFig07_02_pg343