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Chapter 12. Vapor Power Equipment

Practice Problems

1.

“BLEVE” is an acronym that is used to describe

(A)

a boiler demand leveling valve

(B)

a catastrophic boiler explosion

(C)

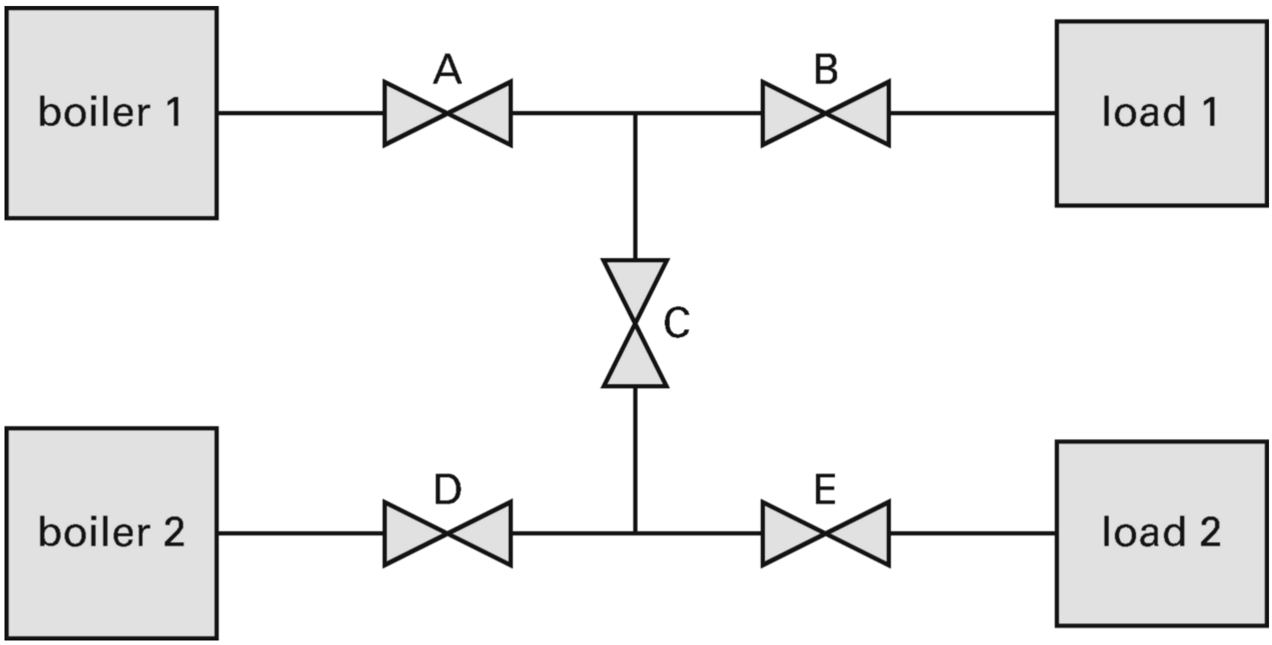
the vapor from a bleed valve

(D)

a burnout caused by insufficient feedwater

2.

A small power generating plant has two furnace boilers and two turbine generators. During long periods of low electrical demand, capacity is achieved with a single boiler. To achieve a functional cross-coupled configuration, which valves should be opened and which should be closed?



(A)

open: A, B, D, and E

closed: C

(B)

open: A, B, C, and D

closed: E
(C)

open: A, B, C, and E

closed: D

(D)

open: A, C, and E

closed: B, D
3.

A steam generator receives liquid water at 80°F and produces saturated steam at 300 psia. Most nearly, what is the ratio of boiler sensible to boiler latent heat supplied to the water and steam?

(A)

0.06

(B)

0.12

(C)

0.27

(D)

0.43

4.

What is most nearly the isentropic efficiency of a process that expands dry steam from 100 psia to 3 psia (700 kPa to 20 kPa) and 90% quality?

(A)

40%

(B)

50%

(C)

60%

(D)

70%

5.

A 5000 kW steam turbine uses 200 psia (1.4 MPa) steam with 100°F (40°C) of superheat. The condenser is at 1 in Hg (3.4 kPa) absolute. Assuming an ideal turbine, the water rate per kilowatt of generated power at full load is most nearly

(A)

4.7 lbm/kW-hr (0.0006 kg/kW·s)
(B)

8.8 lbm/kW-hr (0.0012 kg/kW·s)

(C)

25 lbm/kW-hr (0.0031 kg/kW·s)

(D)

37 lbm/kW-hr (0.0046 kg/kW·s)
6.

A 10,000 kW steam turbine operates on 400 psia (3.0 MPa), 750°F (420°C) dry steam, expanding to 2 in Hg (6.8 kPa) absolute. The maximum adiabatic heat drop available for power production is most nearly

(A)

450 Btu/lbm (1100 kJ/kg)

(B)

600 Btu/lbm (1400 kJ/kg)

(C)

750 Btu/lbm (1800 kJ/kg)

(D)

900 Btu/lbm (2200 kJ/kg)

7.

A 750 kW steam turbine has a water rate of 20 lbm/kW-hr (2.5×10^{-3} kg/kW·s). Steam with 50°F (30°C) of superheat is expanded from 165 psia (1.0 MPa absolute) to 26 in Hg (90 kPa) absolute. 65°F (18°C) cooling water is available. The terminal temperature difference is zero. The quantity of cooling water required is most nearly

(A)

45,000 lbm/hr (5.9 kg/s)

(B)

60,000 lbm/hr (7.8 kg/s)

(C)

80,000 lbm/hr (10 kg/s)

(D)

95,000 lbm/hr (12 kg/s)

8.

332,000 lbm/hr (41.8 kg/s) of 81°F (27°C) water enters a two-pass, counterflow heat exchanger. The heat exchanger is constructed of 1850 ft^2 (172 m^2) of $^5/_8$ in (15.9 mm) copper tubing. Saturated steam is bled from a turbine at 4.45 psia (30.6 kPa) and condenses to saturated liquid. The heated water leaves at 150°F (65.6°C) with an enthalpy of 1100 Btu/lbm (2.56 MJ/kg). The overall heat transfer coefficient is most nearly

(A)

1900 Btu/hr-ft^2-°F (11 kW/m^2·°C)

(B)

4400 Btu/hr-ft^2-°F (25 kW/m^2·°C)

(C)

6500 Btu/hr-ft^2-°F (37 kW/m^2·°C)

(D)

7700 Btu/hr-ft^2-°F (44 kW/m^2·°C)
9.

A two-pass surface condenser constructed of 1 in (25.4 mm) BWG tubing receives 82,000 lbm/hr (10.3 kg/s) of steam from a turbine. Steam enters the condenser with an enthalpy of 980 Btu/lbm (2.280 MJ/kg) The condenser operates at a pressure of 1 in Hg (3.4 kPa) absolute. Water is circulated at 8 ft/sec (2.4 m/s) through an equivalent length of 120 ft (36 m) of extra strong 30 in (76.2 cm) steel pipe. An additional head loss of 6 in wg (1.5 kPa) is incurred in the intake screens. If the water temperature increases 10°F (5.6°C) across the condenser, what is most nearly the circulation rate of cooling water?

(A)

9000 gal/min (34 kL/min)

(B)

11,000 gal/min (42 kL/min)

(C)

13,000 gal/min (49 kL/min)

(D)

15,000 gal/min (57 kL/min)

10.

100 lbm/hr (0.013 kg/s) of 60°F (16°C) water is turned into 14.7 psia (101.3 kPa) saturated steam in an electric boiler. Radiation losses are 35% of the supplied energy. If electricity is $0.04 per kW-hr, the cost is most nearly

(A)

$2/hr

(B)

$3/hr

(C)

$4/hr
(D)

$5/hr
11.

A gas burner produces 250 lbm/hr (0.032 kg/s) of 98% dry steam at 40 psia (300 kPa) from 60°F (16°C) feedwater. The fuel gas enters at 80°F (26°C) and 4 in Hg (13.6 kPa) and has a heating value of 550 Btu/ft^3 (20.5 MJ/m^3) at standard industrial conditions. The barometric pressure is 30.2 in Hg (102.4 kPa). 13.5 ft^3/min (6.4 L/s) of fuel gas is consumed. The efficiency of the boiler is most nearly

(A)

37%

(B)

43%

(C)

57%

(D)

66%

12.

A boiler evaporates 8.23 lbm (8.23 kg) of 120°F (50°C) water per pound (per kilogram) of coal fired, producing 100 psia (700 kPa) saturated steam. The coal is 2% moisture by weight as fired, and dry coal is 5% ash. 1% of the coal is removed from the ash pit. (The ash pit loss has the same composition as unfired, dry coal.) Coal is initially at 60°F (16°C), and combustion occurs at 14.7 psia (101.3 kPa). The combustion products leave at 600°F (315°C). The heating value of the dry coal is 12,800 Btu/lbm (29.80 MJ/kg). The efficiency of the boiler is most nearly

(A)

53%

(B)

68%

(C)

73%

(D)

82%

13.

500 psia (3.5 MPa) steam is superheated to 1000°F (500°C) before expanding through a 75% efficient turbine to 5 psia (30 kPa). No subcooling occurs. The pump work is negligible compared to the 200 MW generated. The quantity of steam required is most nearly

(A)

8.6×10^5 lbm/hr (120 kg/s)
(B)

1.4×10^6 lbm/hr (190 kg/s)

(C)

2.0×10^6 lbm/hr (270 kg/s)

(D)

4.2×10^6 lbm/hr (310 kg/s)
14.

191,000 lbm/hr (24 kg/s) of 635°F (335°C) combustion gases flow through a 20 ft (6 m) wide boiler stack whose front and back plates are 5 ft 10 in (1.78 m) apart. An integral crossflow economizer is being designed to heat water from 212°F to 285°F (100°C to 140°C) by dropping the stack gas temperature to 470°F (240°C). Layers of 24 tubes with dimensions 0.957 in (24.3 mm) ID, 1.315 in (33.4 mm) OD, and 20 ft (6 m) length will be placed on a 2.315 in (58.8 mm) pitch in horizontal banks. The overall coefficient of heat transfer for the tubes is 10 Btu/hr-ft^2-°F (57 W/m^2·°C). Assuming the heat capacity of the combustion gas can be approximated by that of Nitrogen, how many 24-tube layers are required?

(A)

5

(B)

9

(C)

12

(D)

17

15.

Water is used in an adiabatic steam desuperheater. 1000 lbm/hr (0.13 kg/s) of 200 psia (1.5 MPa), 600°F (300°C) steam enters with negligible velocity. 50 lbm/hr (0.0063 kg/s) of 82°F (28°C) water enters with negligible velocity. 100 psia (700 kPa) steam leaves the desuperheater at 2000 ft/sec (600 m/s). The temperature of the leaving steam is most nearly

(A)

330°F (165°C)

(B)

360°F (180°C)

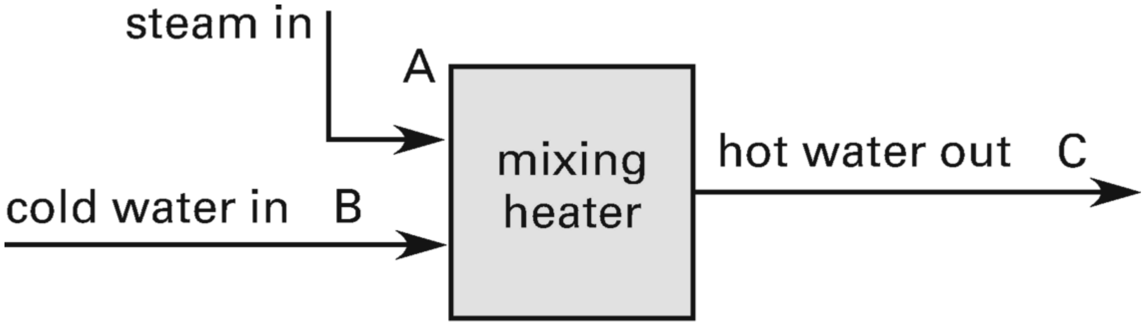
(C)

400°F (200°C)

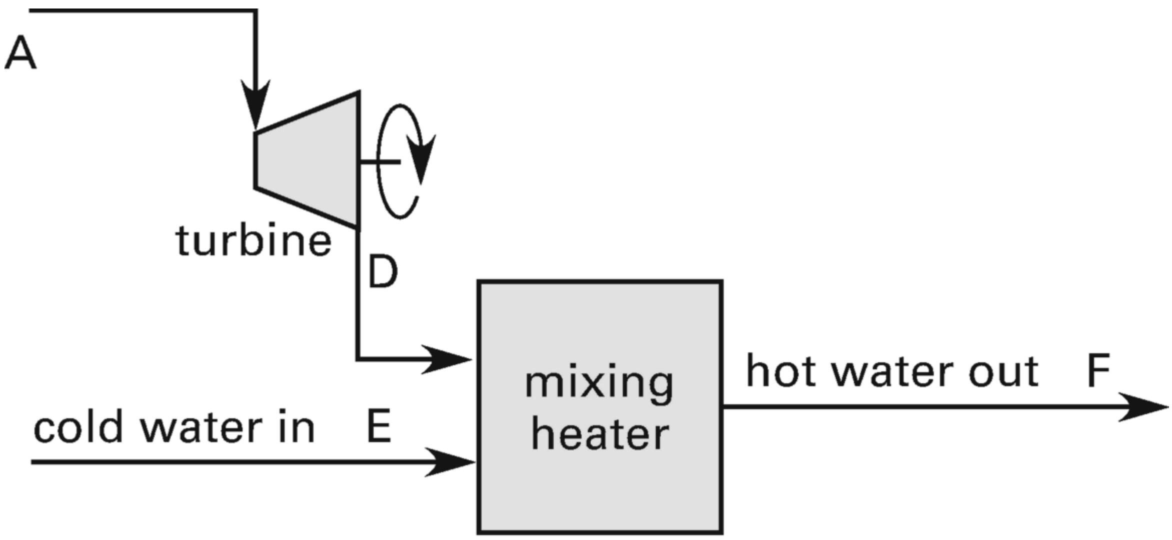
(D)

470°F (240°C)
16.

Waste steam at 400°F (200°C) and 100 psia (700 kPa) was originally used only for heating cold water. Cold water entered at 70°F (21°C) and 60 psia (400 kPa). 2000 lbm/hr (0.25 kg/s) of hot water at 180°F (80°C) and 20 psia (150 kPa) were produced. Now, the same quantity of steam is to be expanded through a low-pressure turbine. The low-pressure turbine has an isentropic efficiency of 60% and a mechanical efficiency of 96%. The steam will then flow through a mixing heater (see diagram). A pressure drop of 5 psi (30 kPa) occurs through the heater. The heater output must remain at 180°F (80°C) and 20 psia (150 kPa), but the output at point F may decrease.



original use



proposed use of waste steam

The steam flow is most nearly

(A)

160 lbm/hr (0.019 kg/s)

(B)

180 lbm/hr (0.022 kg/s)

(C)

210 lbm/hr (0.024 kg/s)

(D)

250 lbm/hr (0.029 kg/s)

Solutions

1.

"BLEVE" is the acronym for "boiling liquid-expanding vapor explosion," essentially the catastrophic failure of a container whose walls cannot withstand the pressure of vaporization. BLEVEs are caused when a leak allows the pressurized liquid contents to flash into a vapor. The term is most frequently used to describe explosions of tanks containing flammable liquids, but it is equally applicable to boilers. Common elements of BLEVE events are weakening of tank walls (usually by fire) and inadequate or nonfunctional pressure-relief valves.

The answer is (B).

2.

Cross-coupling provides flexibility integrating redundant, back-up, excess-capacity, and auxiliary units. Cross-coupling permits any available source to be connected to any load, facilitating operation when units are idle or down for maintenance. In addition, when both all loads are online, cross-coupling provides smoother transitions and faster response to fluctuating demand. With a two-two system (i.e., two sources and two loads) in cross-coupled mode, both sources are connected to both loads during periods of high demand, but only one source is connected to either one load or the other during periods of low demand.

It is unlikely (unnecessary) that both sources would be connected to a single load. Also, it is unlikely that a single source would be sufficient for two loads. Operation with all cross-control valves closed is not a cross-controlled configuration.

The answer is (D).

3.

Sensible heat changes temperature, while latent heat changes phase. The pressure throughout the steam generator is 300 psia. Water enters subcooled at 80°F and 300 psia. The water remains in liquid form as it is heated (sensible heat) to the saturation temperature corresponding to 300 psia, which (from appendixMERM24B and *NCEES Handbook:* Properties of Saturated Steam (U.S. Customary Units)) is 417.35°F. Additional energy (latent heat) converts the saturated water to saturated steam at 300 psia.

The enthalpy of 80°F liquid water is essentially a function of temperature only. From appendixMERM24A (also *NCEES Handbook:* Properties of Saturated Steam (U.S. Customary Units)), $h_{80°\text{F}}$ = 48.07 Btu/lbm. From appendixMERM24B (also *NCEES Handbook:* Properties of Saturated Steam (U.S. Customary Units)), $h_{f,300\text{ psia}}$ = 394.0 Btu/lbm, and $h_{fg,300\text{ psia}}$ = 809.4 Btu/lbm.

The ratio of sensible heat to latent heat is

$$\begin{aligned}\frac{q_{\text{sensible}}}{q_{\text{latent}}} &= \frac{h_{f,300\text{ psia}} - h_{80^\circ\text{F}}}{h_{fg,300\text{ psia}}} = \frac{394.0\ \frac{\text{Btu}}{\text{lbm}} - 48.07\ \frac{\text{Btu}}{\text{lbm}}}{809.4\ \frac{\text{Btu}}{\text{lbm}}} \\ &= 0.427 \quad (0.43)\end{aligned}$$

The answer is (D).

4.

Customary U.S. Solution

From appendixMERM24B (also *NCEES Handbook:* Properties of Saturated Steam (U.S. Customary Units)), for 100 psia, the enthalpy of dry steam is h_1 = 1187.2 Btu/lbm.

From *NCEES Handbook* figure "Temperature-Entropy (T-S) Diagram (U.S. Customary Units)," for an isentropic process from 100 psia to 3 psia, $h_2 = 950$ Btu/lbm.

From appendixMERM24B (also *NCEES Handbook:* Properties of Saturated Steam (U.S. Customary Units)), for 3 psia,

$$\begin{aligned} h_f &= 109.4\ \text{Btu/lbm} \\ h_g &= 1122.6\ \text{Btu/lbm} \\ h_{fg} &= 1122.6\ \frac{\text{Btu}}{\text{lbm}} - 109.4\ \frac{\text{Btu}}{\text{lbm}} = 1013.2\ \text{Btu/lbm} \\ h_2' &= h_f + x h_{fg} \\ &= 109.4\ \frac{\text{Btu}}{\text{lbm}} + (0.9)\left(1013.2\ \frac{\text{Btu}}{\text{lbm}}\right) \\ &= 1021.3\ \text{Btu/lbm} \end{aligned}$$

From equationMERM27017 (also *NCEES Handbook:* Open Thermodynamic Systems), the isentropic efficiency is

$$\begin{aligned} \eta_s &= \frac{h_1 - h_2'}{h_1 - h_2} = \frac{1187.2\ \frac{\text{Btu}}{\text{lbm}} - 1021.3\ \frac{\text{Btu}}{\text{lbm}}}{1187.2\ \frac{\text{Btu}}{\text{lbm}} - 950\ \frac{\text{Btu}}{\text{lbm}}} \\ &= 0.699 \quad (70\%) \end{aligned}$$

The answer is (D).

SI Solution

From appendixMERM24O (also *NCEES Handbook:* Saturated Steam (SI Units)), for 700 kPa, the enthalpy of dry steam is $h_1 = 2763.5$ kJ/kg.

From *NCEES Handbook* figure "Temperature-Entropy (T-S) Diagram (SI Units)," for an isentropic process from 700 kPa to 20 kPa, $h_2 = 2200$ kJ/kg.

From appendixMERM24O (also *NCEES Handbook:* Saturated Steam (SI Units)), for 20 kPa,

$$\begin{aligned} h_f &= 251.4\ \text{kJ/kg} \\ h_g &= 2609.7\ \text{kJ/kg} \\ h_{fg} &= 2609.7\ \frac{\text{kJ}}{\text{kg}} - 251.4\ \frac{\text{kJ}}{\text{kg}} = 2358.3\ \text{kJ/kg} \\ h_2' &= h_f + x h_{fg} \\ &= 251.4\ \frac{\text{kJ}}{\text{kg}} + (0.9)\left(2358.3\ \frac{\text{kJ}}{\text{kg}}\right) \\ &= 2373.9\ \text{kJ/kg} \end{aligned}$$

From equationMERM27017 (also *NCEES Handbook:* Open Thermodynamic Systems), the isentropic efficiency is

$$\begin{aligned} \eta_s &= \frac{h_1 - h_2'}{h_1 - h_2} = \frac{2763.5\ \frac{\text{kJ}}{\text{kg}} - 2373.9\ \frac{\text{kJ}}{\text{kg}}}{2763.5\ \frac{\text{kJ}}{\text{kg}} - 2200\ \frac{\text{kJ}}{\text{kg}}} \\ &= 0.691 \quad (70\%) \end{aligned}$$

The answer is (D).
5.

Customary U.S. Solution

From appendixMERM24A (also *NCEES Handbook:* Properties of Saturated Steam (U.S. Customary Units)), T_{sat} for 200 psia is 381.80°F.

The steam temperature is

$$381.80^\circ\text{F} + 100^\circ\text{F} = 481.80^\circ\text{F}$$

Interpolate from appendixMERM24C (also *NCEES Handbook:* Superheated Steam (U.S. Customary Units)), $h_1 = 1257.8$ Btu/lbm.

1 in Hg is approximately 0.5 psia. From *NCEES Handbook* figure "Temperature-Entropy (T-S) Diagram (U.S. Customary Units)," assuming isentropic expansion and dropping straight down to the 0.5 psia line, $h_2 \approx 870$ Btu/lbm.

For isentropic expansion, $\eta_{turbine} = 1$, and the steam mass flow rate through the turbine is given by equationMERM27022 (also *NCEES Handbook:* Turbines).

$$\begin{aligned}\dot{m} &= \frac{P_{turbine}}{h_1 - h_2} = \frac{(5000\text{ kW})\left(3412\ \dfrac{\text{Btu}}{\text{kW-hr}}\right)}{1257.8\ \dfrac{\text{Btu}}{\text{lbm}} - 870\ \dfrac{\text{Btu}}{\text{lbm}}} \\ &= 4.399 \times 10^4\text{ lbm/hr}\end{aligned}$$

The water rate per kilowatt of generated power at full load is

$$\begin{aligned}\text{WR} &= \frac{\dot{m}}{P_{turbine}} = \frac{4.399 \times 10^4\ \dfrac{\text{lbm}}{\text{hr}}}{5000\text{ kW}} \\ &= 8.798\text{ lbm/kW-hr} \quad (8.8\text{ lbm/kW-hr})\end{aligned}$$

The answer is (B).

SI Solution

From appendixMERM24O (also *NCEES Handbook:* Saturated Steam (SI Units)—Temperature Table), T_{sat} for 1.4 MPa is 195.1°C.

The steam temperature is

$$195.1^\circ\text{C} + 40^\circ\text{C} = 235.1^\circ\text{C}$$

Interpolate from appendixMERM24P (also *NCEES Handbook:* Superheated Steam (SI Units)), $h_1 =$ 2890 kJ/kg, and $s_1 = 6.6724$ kJ/kg·K.

Interpolate from appendixMERM24N (also *NCEES Handbook:* Saturated Steam (SI Units)—Temperature Table), for 3.4 kPa, the entropy of saturated liquid, s_f, the entropy of saturated vapor, s_g, the enthalpy of saturated liquid, h_f, and the enthalpy of vaporization, h_g, are

$$\begin{aligned}s_f &= 0.3817\text{ kJ/kg·K} \\ s_g &= 8.5364\text{ kJ/kg·K} \\ h_f &= 109.48\text{ kJ/kg} \\ h_g &= 2549.06\text{ kJ/kg}\end{aligned}$$

For isentropic expansion, $s_1 = s_2 = 6.6724$ kJ/kg·K.

Since $s_2 < s_g$, the expanded steam is in the liquid-vapor region. The quality of the mixture is given by equationMERM24041 (also *NCEES Handbook:* Properties for Two-Phase (Vapor-Liquid) Systems).

$$\begin{aligned} x &= \frac{s - s_f}{s_{fg}} = \frac{s - s_f}{s_g - s_f} \\ &= \frac{6.6724 \ \frac{\text{kJ}}{\text{kg·K}} - 0.3817 \ \frac{\text{kJ}}{\text{kg·K}}}{8.5364 \ \frac{\text{kJ}}{\text{kg·K}} - 0.3817 \ \frac{\text{kJ}}{\text{kg·K}}} \\ &= 0.7714 \end{aligned}$$

The final enthalpy is given by equationMERM24040 (also *NCEES Handbook:* Properties for Two-Phase (Vapor-Liquid) Systems).

$$\begin{aligned} h &= h_f + xh_{fg} = 109.48 \ \frac{\text{kJ}}{\text{kg}} + (0.7714)\left(2549.06 \ \frac{\text{kJ}}{\text{kg}}\right) \\ &= 2075.8 \ \text{kJ/kg} \end{aligned}$$

For isentropic expansion, $\eta_{\text{turbine}} = 1$, and the steam mass flow rate through a turbine is given by equationMERM27022 (also *NCEES Handbook:* Turbines).

$$\begin{aligned} \dot{m} &= \frac{P_{\text{turbine}}}{h_1 - h_2} = \frac{5000 \ \text{kW}}{2890 \ \frac{\text{kJ}}{\text{kg}} - 2075.8 \ \frac{\text{kJ}}{\text{kg}}} \\ &= 6.141 \ \text{kg/s} \end{aligned}$$

The water rate per kilowatt of generated power at full load is

$$\begin{aligned} \text{WR} &= \frac{\dot{m}}{P_{\text{turbine}}} = \frac{6.141 \ \frac{\text{kg}}{\text{s}}}{5000 \ \text{kW}} \\ &= 1.23 \times 10^{-3} \ \text{kg/kW·s} \quad (0.0012 \ \text{kg/kW·s}) \end{aligned}$$

The answer is (B).
6.

Customary U.S. Solution

From appendixMERM24C (also *NCEES Handbook:* Superheated Steam (U.S. Customary Units)), the enthalpy, h_1, of dry steam at 400 psia and 750°F is $h_1 = 1389.9$ Btu/lbm.

From *NCEES Handbook* figure "Temperature-Entropy (T-S) Diagram (U.S. Customary Units)," assuming isentropic expansion to 2 in Hg (about 1 psia), $h_2 = 935$ Btu/lbm.

The maximum adiabatic heat drop is

$$\begin{aligned} h_1 - h_2 &= 1389.9 \ \frac{\text{Btu}}{\text{lbm}} - 935 \ \frac{\text{Btu}}{\text{lbm}} \\ &= 454.9 \ \text{Btu/lbm} \quad (450 \ \text{Btu/lbm}) \end{aligned}$$

The answer is (A).

SI Solution

From appendixMERM24P (also *NCEES Handbook:* Superheated Steam (SI Units)), the enthalpy, h_1, of dry steam at 3.0 MPa and 420°C is $h_1 = 3277.1$ kJ/kg.

From *NCEES Handbook* figure "Temperature-Entropy (T-S) Diagram (SI Units)," assuming isentropic expansion, $h_2 \approx 2210$ kJ/kg.

The maximum adiabatic heat drop is

$$\begin{aligned} h_1 - h_2 &= 3277.1\ \frac{\text{kJ}}{\text{kg}} - 2210\ \frac{\text{kJ}}{\text{kg}} \\ &= 1067.1\ \text{kJ/kg} \quad (1100\ \text{kJ/kg}) \end{aligned}$$

The answer is (A).

7.

Customary U.S. Solution

The water rate is

$$\text{WR} = \frac{\dot{m}}{P_{\text{turbine}}}$$

The steam flow rate is

$$\begin{aligned} \dot{m}_{\text{steam}} &= (\text{WR})\, P_{\text{turbine}} \\ &= \left(20\ \frac{\text{lbm}}{\text{kW-hr}}\right)(750\ \text{kW}) \\ &= 15{,}000\ \text{lbm/hr} \end{aligned}$$

From appendixMERM24B, (also *NCEES Handbook:* Properties of Saturated Steam (U.S. Customary Units)), for 165 psia, $T_{\text{sat}} = 366°\text{F}$.

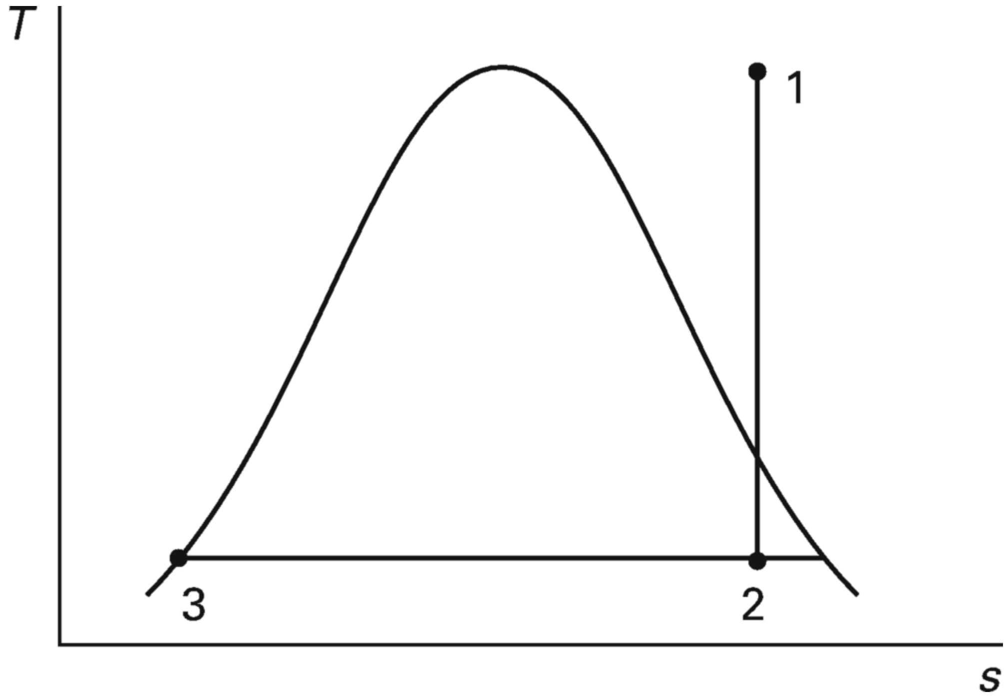
The steam temperature is

$$366^\circ\text{F} + 50^\circ\text{F} = 416^\circ\text{F}$$

From appendixMERM24C (also *NCEES Handbook:* Superheated Steam (U.S. Customary Units)), h_1 = 1226.0 Btu/lbm.

From equationMERM27022 (also *NCEES Handbook:* Turbines),

$$\begin{aligned} P_{\text{turbine}} &= \dot{m}\,(h_1 - h_2) \\ h_1 - h_2 &= \frac{P_{\text{turbine}}}{\dot{m}} = \frac{(750\ \text{kW})\left(3412\ \frac{\text{Btu}}{\text{kW-hr}}\right)}{15{,}000\ \frac{\text{lbm}}{\text{hr}}} \\ &= 170.6\ \text{Btu/lbm} \\ h_2 &= h_1 - 170.6\ \frac{\text{Btu}}{\text{lbm}} = 1226.0\ \frac{\text{Btu}}{\text{lbm}} - 170.6\ \frac{\text{Btu}}{\text{lbm}} \\ &= 1055.4\ \text{Btu/lbm} \\ p_2 &= (26\ \text{inHg})\left(0.491\ \frac{\text{lbf}}{\text{in}^2}\right) \\ &= 12.77\ \text{psia} \end{aligned}$$



From appendixMERM24B (also *NCEES Handbook:* Properties of Saturated Steam (U.S. Customary Units)), for $p_2 = 12.77$ psia,

$$\begin{aligned} T_{\text{sat}} &= T_2 = T_3 \approx 204^\circ\text{F} \\ h_{f,3} &\approx 172.3\ \text{Btu/lbm} \end{aligned}$$

From appendixMERM35A (also *NCEES Handbook:* Physical Properties of Water), the specific heat of water at 65°F is $c_{p,\text{water}} = 0.999$ Btu.

Assuming the water and steam leave in thermal equilibrium, the heat lost by steam is equal to the heat gained by water.

$$\dot{m}_{\text{water}} c_{p,\text{water}} \left(T_{\text{water,out}} - T_{\text{water,in}}\right) = \dot{m}_{\text{steam}} \left(h_2 - h_{f,3}\right)$$

Since the terminal temperature difference is zero, $T_{\text{water,out}} = T_3$.

$$\begin{aligned} \dot{m}_{\text{water}} \left(0.999\ \frac{\text{Btu}}{\text{lbm-}^\circ\text{F}}\right) (204^\circ\text{F} - 65^\circ\text{F}) \\ = \left(15{,}000\ \frac{\text{lbm}}{\text{hr}}\right) \left(1055.3\ \frac{\text{Btu}}{\text{lbm}} - 172.3\ \frac{\text{Btu}}{\text{lbm}}\right) \\ \dot{m}_{\text{water}} = 9.54 \times 10^4\ \text{lbm/hr} \quad (95{,}000\ \text{lbm/hr}) \end{aligned}$$

The answer is (D).

SI Solution

The steam flow rate is

$$\begin{aligned} \dot{m}_{\text{water}} &= (\text{WR})\, P_{\text{turbine}} \\ &= \left(2.5 \times 10^{-3}\ \frac{\text{kg}}{\text{kW·s}}\right) (750\ \text{kW}) \\ &= 1.875\ \text{kg/s} \end{aligned}$$

From appendixMERM24O (also *NCEES Handbook:* Saturated Steam (SI Units)), for 1 MPa, $T_{\text{sat}} = 179.9$°C.

The steam temperature is

$$179.9^\circ\text{C} + 30^\circ\text{C} = 209.9^\circ\text{C}$$

From appendixMERM24P (also *NCEES Handbook:* Superheated Steam (SI Units)), $h_1 = 2851.0$ kJ/kg.

From equationMERM27022 (also *NCEES Handbook:* Turbines),

$$\begin{aligned} P_{\text{turbine}} &= \dot{m}\,(h_1 - h_2) \\ h_1 - h_2 &= \frac{P_{\text{turbine}}}{\dot{m}} = \frac{750\ \text{kW}}{1.875\ \frac{\text{kg}}{\text{s}}} \\ &= 400\ \text{kJ/kg} \\ h_2 &= h_1 - 400\ \frac{\text{kJ}}{\text{kg}} = 2851.0\ \frac{\text{kJ}}{\text{kg}} - 400\ \frac{\text{kJ}}{\text{kg}} \\ &= 2451.0\ \text{kJ/kg} \end{aligned}$$

From appendixMERM24O (also *NCEES Handbook:* Saturated Steam (SI Units)), for $p_2 = 90$ kPa,

$$\begin{aligned} T_{\text{sat}} &= T_2 = T_3 = 96.69^\circ\text{C} \\ h_{f,3} &= 405.20\ \text{kJ/kg} \end{aligned}$$

From appendixMERM35B (also *NCEES Handbook:* Physical Properties of Water), the specific heat of water at 18°C is $c_p = 4.186$ kJ/kg·K.

Assuming water and steam leave in thermal equilibrium, the heat lost by steam is equal to the heat gained by water.

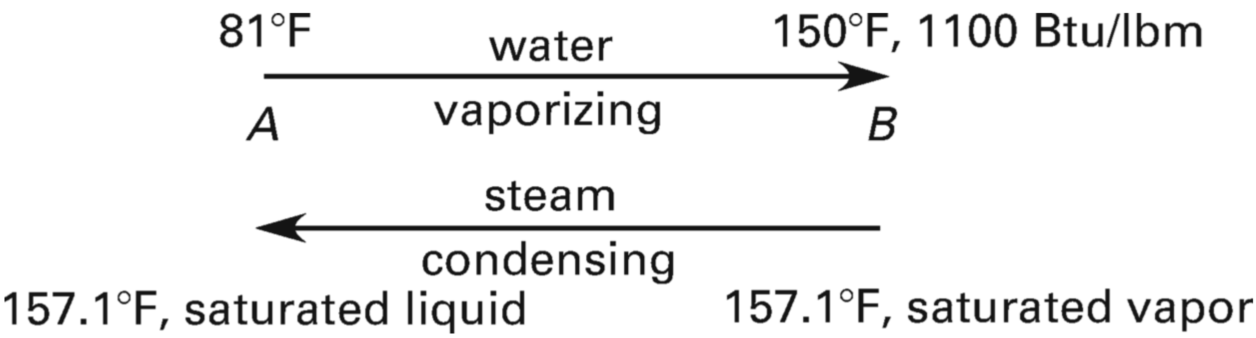
$$\dot{m}_{\text{water}}\, c_{p,\text{water}}\left(T_{\text{water,out}} - T_{\text{water,in}}\right) = \dot{m}_{\text{steam}}\left(h_2 - h_{f,3}\right)$$

Since the terminal difference is zero, $T_{\text{water,out}} = T_3$.

$$\begin{aligned} \dot{m}_{\text{water}} &\left(4.186\ \frac{\text{kJ}}{\text{kg·K}}\right)(96.71^\circ\text{C} - 18^\circ\text{C}) \\ &= \left(1.875\ \frac{\text{kg}}{\text{s}}\right)\left(2451.0\ \frac{\text{kJ}}{\text{kg}} - 405.20\ \frac{\text{kJ}}{\text{kg}}\right) \\ \dot{m}_{\text{water}} &= 11.64\ \text{kg/s} \quad (12\ \text{kg/s}) \end{aligned}$$

The answer is (D).
8.

Customary U.S. Solution



From appendixMERM24A (also *NCEES Handbook:* Saturated Steam (U.S. Units)—Temperature Table), at 81°F, $h_{\text{water},1} \approx 49.06$ Btu/lbm.

From appendixMERM24B (also *NCEES Handbook:* Saturated Steam (U.S. Units)—Temperature Table), for 4.45 psia, $T_{\text{sat}} = 157.1$°F.

The heat transferred to the water is

$$
\begin{aligned}
Q &= \dot{m}_{\text{water}}\left(h_{\text{water},2} - h_{\text{water},1}\right) \\
&= \left(332{,}000\ \frac{\text{lbm}}{\text{hr}}\right)\left(1100\ \frac{\text{Btu}}{\text{lbm}} - 49.06\ \frac{\text{Btu}}{\text{lbm}}\right) \\
&= 3.489 \times 10^{8}\ \text{Btu/hr}
\end{aligned}
$$

The two end temperature differences are

$$
\begin{aligned}
\Delta T_A &= 157.1^\circ\text{F} - 81^\circ\text{F} = 76.1^\circ\text{F} \\
\Delta T_B &= 157.1^\circ\text{F} - 150^\circ\text{F} = 7.1^\circ\text{F}
\end{aligned}
$$

The logarithmic mean temperature difference, T_{lm}, from equationMERM36067 (also *NCEES Handbook:* Log-Mean Temperature Difference), is

$$
\begin{aligned}
\Delta T_{\text{lm}} &= \frac{\Delta T_A - \Delta T_B}{\ln \dfrac{\Delta T_A}{\Delta T_B}} = \frac{76.1^\circ\text{F} - 7.1^\circ\text{F}}{\ln \dfrac{76.1^\circ\text{F}}{7.1^\circ\text{F}}} \\
&= 29.09^\circ\text{F}
\end{aligned}
$$

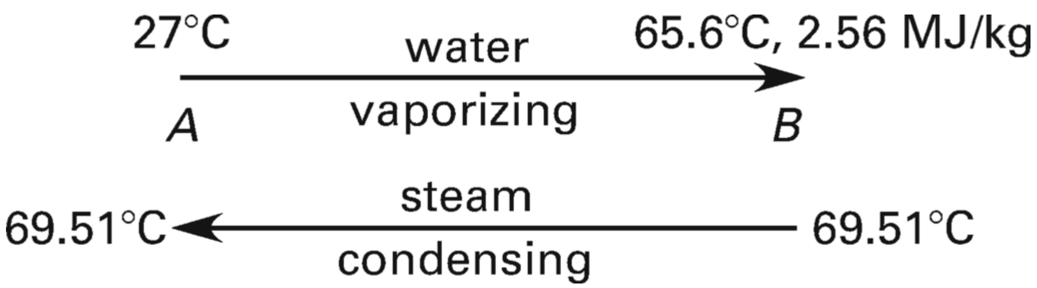
Since $T_{\text{steam},A} = T_{\text{steam},B}$, the correction factor, F_c, for ΔT_{lm} is 1.

The overall heat transfer coefficient is calculated from equationMERM36068 (also *NCEES Handbook:* Combination of Heat-Transfer Mechanisms).

$$
\begin{aligned}
Q &= U_o A_o F_c \Delta T_{\text{lm}} \\
U_o &= \frac{Q}{A_o F_c \Delta T_{\text{lm}}} = \frac{3.489 \times 10^{8}\ \dfrac{\text{Btu}}{\text{hr}}}{\left(1850\ \text{ft}^2\right)(1)\left(29.09^\circ\text{F}\right)} \\
&= 6483\ \text{Btu/hr-ft}^2\text{-}^\circ\text{F} \quad \left(6500\ \text{Btu/hr-ft}^2\text{-}^\circ\text{F}\right)
\end{aligned}
$$

The answer is (C).

SI Solution



From appendixMERM24N (also *NCEES Handbook:* Saturated Steam (SI Units)), at 27°C, $h_{\text{water},1} = 113.19$ kJ/kg.

From appendixMERM24O, for 30.6 kPa (0.306 bar), $T_{\text{sat}} = 69.51$°C.

The heat transferred to the water is

$$
\begin{aligned}
Q &= \dot{m}_{\text{water}}\left(h_{\text{water},2} - h_{\text{water},1}\right) \\
&= \left(41.8\ \frac{\text{kg}}{\text{s}}\right)\left(\left(2.56\ \frac{\text{MJ}}{\text{kg}}\right)\left(1000\ \frac{\text{kJ}}{\text{MJ}}\right) - 113.19\ \frac{\text{kJ}}{\text{kg}}\right) \\
&= 102\,277\ \text{kJ/s}
\end{aligned}
$$

The two end temperature differences are

$$
\begin{aligned}
\Delta T_A &= 69.51^\circ\text{C} - 27^\circ\text{C} = 42.5^\circ\text{C} \\
\Delta T_B &= 69.51^\circ\text{C} - 65.6^\circ\text{C} = 3.9^\circ\text{C}
\end{aligned}
$$

The logarithmic mean temperature difference, T_{lm}, from equationMERM36067 (also *NCEES Handbook:* Log-Mean Temperature Difference), is

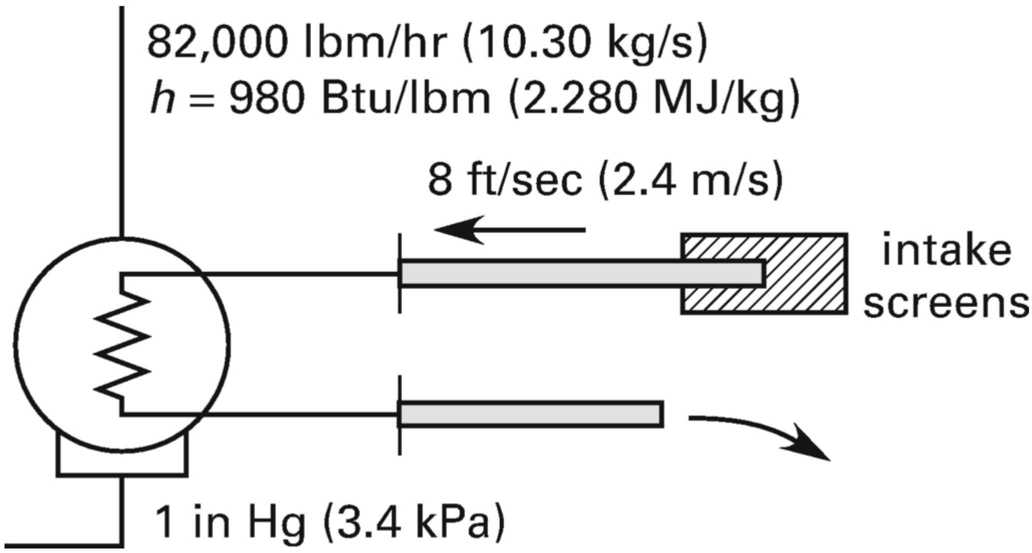
$$\begin{aligned}\Delta T_{\text{lm}} &= \frac{\Delta T_A - \Delta T_B}{\ln\dfrac{\Delta T_A}{\Delta T_B}} = \frac{42.5^\circ\text{C} - 3.9^\circ\text{C}}{\ln\dfrac{42.5^\circ\text{C}}{3.9^\circ\text{C}}}\\ &= 16.16^\circ\text{C}\end{aligned}$$

Since $T_{\text{steam},A} = T_{\text{steam},B}$, the correction factor, F_c, for ΔT_{lm} is 1.

The overall heat transfer coefficient is calculated from equationMERM36068 (also *NCEES Handbook:* Combination of Heat-Transfer Mechanisms).

$$\begin{aligned}Q &= U_o A_o F_c \Delta T_{\text{lm}}\\ U_o &= \frac{Q}{A_o F_c \Delta T_{\text{lm}}} = \frac{\left(102\,277\ \dfrac{\text{kJ}}{\text{s}}\right)\left(1000\ \dfrac{\text{W}}{\text{kW}}\right)}{(172\ \text{m}^2)(1)(16.16^\circ\text{C})}\\ &= 36\,797\ \text{W/m}^2\cdot{}^\circ\text{C} \quad (37\ \text{kW/m}^2\cdot{}^\circ\text{C})\end{aligned}$$

The answer is (C).
9.



Customary U.S. Solution

The condenser pressure is

$$(1\ \text{in Hg})\left(0.491\ \frac{\dfrac{\text{lbf}}{\text{in}^2}}{\text{in Hg}}\right) = 0.5\ \text{psia}$$

From appendixMERM24B (also *NCEES Handbook:* Properties of Saturated Steam (U.S. Customary Units)), the enthalpy of the saturated liquid is $h_f = 47.08$ Btu/lbm.

As in *NCEES Handbook:* Physical Properties of Water, the specific heat of water is $c_{p,\text{water}} = 1$ Btu/lbm-°F.

The heat lost by the steam is equal to the heat gained by the water.

$$\begin{aligned}\dot{m}_{\text{water}} c_{p,\text{water}} \Delta T &= \dot{m}_{\text{steam}} (h_2 - h_f)\\ \dot{m}_{\text{water}} \left(1 \ \frac{\text{Btu}}{\text{lbm-}^\circ\text{F}}\right)(10^\circ\text{F}) &= \left(82{,}000 \ \frac{\text{lbm}}{\text{hr}}\right)\\ &\quad \times \left(980 \ \frac{\text{Btu}}{\text{lbm}} - 47.08 \ \frac{\text{Btu}}{\text{lbm}}\right)\\ \dot{m}_{\text{water}} &= 7.6499 \times 10^6 \ \text{lbm/hr}\end{aligned}$$

The density of water, ρ, is 62.4 lbm/ft^3.

$$\begin{aligned}Q = \frac{\dot{m}_{\text{water}}}{\rho} &= \frac{\left(7.6499 \times 10^6 \ \frac{\text{lbm}}{\text{hr}}\right)\left(7.48 \ \frac{\text{gal}}{\text{ft}^3}\right)}{\left(62.4 \ \frac{\text{lbm}}{\text{ft}^3}\right)\left(60 \ \frac{\text{min}}{\text{hr}}\right)}\\ &= 1.528 \times 10^4 \ \text{gal/min} \quad (15{,}000 \ \text{gal/min})\end{aligned}$$

(The flow rate can also be determined from the velocity and pipe area. However, this does not use the 10° data or perform an energy balance.)

The answer is (D).

SI Solution

The condenser pressure is 3.4 kPa.

From appendixMERM24N (also *NCEES Handbook:* Saturated Steam (SI Units)), the enthalpy of saturated liquid is h_f = 109.8 kJ/kg.

As in *NCEES Handbook:* Physical Properties of Water, the specific heat of water is $c_{p,\text{water}} = 4.187$ kJ/kg·K.

The heat lost by the steam is equal to the heat gained by the water.

$$\begin{aligned}\dot{m}_{\text{water}} c_{p,\text{water}} \Delta T &= \dot{m}_{\text{steam}} (h_2 - h_f)\\ \dot{m}_{\text{water}} \left(4.187 \ \frac{\text{kJ}}{\text{kg·K}}\right)(5.6^\circ\text{C}) &= \left(10.3 \ \frac{\text{kg}}{\text{s}}\right)\Bigg(\left(2.280 \ \frac{\text{MJ}}{\text{kg}}\right)\\ &\quad \times \left(1000 \ \frac{\text{kJ}}{\text{MJ}}\right) - 109.8 \ \frac{\text{kJ}}{\text{kg}}\Bigg)\\ \dot{m}_{\text{water}} &= 953.3 \ \text{kg/s}\end{aligned}$$

The density of water, ρ, is 1000 kg/m^3.

$$\begin{aligned}Q = \frac{\dot{m}_{\text{water}}}{\rho} &= \left(\frac{953.3 \ \frac{\text{kg}}{\text{s}}}{1000 \ \frac{\text{kg}}{\text{m}^3}}\right)\left(1000 \ \frac{\text{L}}{\text{m}^3}\right)\left(60 \ \frac{\text{s}}{\text{min}}\right)\\ &= 57\,200 \ \text{L/min} \quad (57 \ \text{kL/min})\end{aligned}$$

The answer is (D).
10.

Customary U.S. Solution

From appendixMERM24A (also *NCEES Handbook:* Properties of Saturated Steam (U.S. Customary Units)), the enthalpy of saturated liquid at 60°F is h_1 = 28.08 Btu/lbm.

From appendixMERM24B, the enthalpy of saturated steam at 14.7 psia is h_2 = 1150.3 Btu/lbm.

The heat transfer rate to the water is

$$
\begin{aligned}
Q &= \dot{m}(h_2 - h_1) \\
&= \left(100\ \frac{\text{lbm}}{\text{hr}}\right)\left(1150.3\ \frac{\text{Btu}}{\text{lbm}} - 28.08\ \frac{\text{Btu}}{\text{lbm}}\right) \\
&= 1.122 \times 10^5\ \text{Btu/hr} \\
&= \frac{1.122 \times 10^5\ \frac{\text{Btu}}{\text{hr}}}{\left(1000\ \frac{\text{W}}{\text{kW}}\right)\left(3.412\ \frac{\text{Btu}}{\text{W-hr}}\right)} \\
&= 32.89\ \text{kW}
\end{aligned}
$$

$$
\begin{aligned}
\text{cost} &= \frac{(32.89\ \text{kW})\left(\frac{\$0.04}{\text{kW-hr}}\right)}{1 - 0.35} \\
&= \$2.02/\text{hr} \quad (\$2/\text{hr})
\end{aligned}
$$

The answer is (A).

SI Solution

From appendixMERM24N (also *NCEES Handbook:* Saturated Steam (SI Units)—Temperature Table), for saturated liquid at 16°C, $h_1 = 67.17$ kJ/kg.

From appendixMERM24O, the enthalpy of saturated steam at 101.3 kPa is $h_2 = 2675.4$ kJ/kg.

The heat transfer rate to the water is

$$
\begin{aligned}
Q &= \dot{m}(h_2 - h_1) \\
&= \left(0.013\ \frac{\text{kg}}{\text{s}}\right)\left(2675.4\ \frac{\text{kJ}}{\text{kg}} - 67.17\ \frac{\text{kJ}}{\text{kg}}\right) \\
&= 33.907\ \text{kW}
\end{aligned}
$$

$$
\begin{aligned}
\text{cost} &= \frac{(33.907\ \text{kW})\left(\frac{\$0.04}{\text{kW·h}}\right)}{1 - 0.35} \\
&= \$2.09/\text{h} \quad (\$\ 2/\text{h})
\end{aligned}
$$

The answer is (A).
11.

Customary U.S. Solution

From appendixMERM24A (also *NCEES Handbook:* Properties of Saturated Steam (U.S. Customary Units)), the enthalpy of saturated liquid at 60°F is $h_1 = 28.08$ Btu/lbm.

From appendixMERM24B, for 40 psia steam, the enthalpy of saturated liquid, h_f, is 236.1 Btu/lbm. The heat of vaporization, h_{fg}, is 933.7 Btu/lbm. The enthalpy is given by equationMERM24040 (also *NCEES Handbook:* Properties for Two-Phase (Vapor-Liquid) Systems).

$$
\begin{aligned}
h_2 &= h_f + x h_{fg} \\
&= 236.1\ \frac{\text{Btu}}{\text{lbm}} + (0.98)\left(933.7\ \frac{\text{Btu}}{\text{lbm}}\right) \\
&= 1151.13\ \text{Btu/lbm}
\end{aligned}
$$

The heat transfer rate is

$$
\begin{aligned}
Q &= \dot{m}\,(h_2 - h_1) \\
&= \frac{\left(250\ \frac{\text{lbm}}{\text{hr}}\right)\left(1151.13\ \frac{\text{Btu}}{\text{lbm}} - 28.08\ \frac{\text{Btu}}{\text{lbm}}\right)}{60\ \frac{\text{min}}{\text{hr}}} \\
&= 4679.4\ \text{Btu/min}
\end{aligned}
$$

Find the volume of gas used at standard conditions for a heating gas (60°F).

$$
\begin{aligned}
\dot{V}_{\text{std}} &= \dot{V}\left(\frac{T_0}{T}\right)\left(\frac{p}{p_0}\right) \\
&= \left(13.5\ \frac{\text{ft}^3}{\text{min}}\right)\left(\frac{60^\circ\text{F} + 460^\circ}{80^\circ\text{F} + 460^\circ}\right) \\
&\quad \times \left(\frac{(4\ \text{in Hg} + 30.2\ \text{in Hg})\left(0.491\ \frac{\text{lbf}}{\text{in}^3}\right)}{14.7\ \frac{\text{lbf}}{\text{in}^2}}\right) \\
&= 14.85\ \text{ft}^3/\text{min}
\end{aligned}
$$

The efficiency of the boiler is

$$
\begin{aligned}
\eta &= \frac{Q}{\text{heat input}} = \frac{4679.4\ \frac{\text{Btu}}{\text{min}}}{\left(14.85\ \frac{\text{ft}^3}{\text{min}}\right)\left(550\ \frac{\text{Btu}}{\text{ft}^3}\right)} \\
&= 0.573 \quad (57\%)
\end{aligned}
$$

The answer is (C).

SI Solution

From appendixMERM24N (also *NCEES Handbook:* Saturated Steam (SI Units)), the enthalpy of saturated liquid at 16°C is $h_1 = 67.17$ kJ/kg.

From appendixMERM24O, for 300 kPa steam, the enthalpy of saturated liquid, h_f, is 561.43 kJ/kg. The enthalpy of vaporization, h_{fg}, is 2163.5 kJ/kg. The enthalpy is given by equationMERM24040 (also *NCEES Handbook:* Properties for Two-Phase (Vapor-Liquid) Systems).

$$
\begin{aligned}
h_2 &= h_f + x h_{fg} = 561.43\ \frac{\text{kJ}}{\text{kg}} + (0.98)\left(2163.5\ \frac{\text{kJ}}{\text{kg}}\right) \\
&= 2681.7\ \text{kJ/kg}
\end{aligned}
$$

The heat transfer rate is

$$
\begin{aligned}
Q &= \dot{m}\,(h_2 - h_1) \\
&= \left(0.032\ \frac{\text{kg}}{\text{s}}\right)\left(2681.7\ \frac{\text{kJ}}{\text{kg}} - 67.17\ \frac{\text{kJ}}{\text{kg}}\right) \\
&= 83.66\ \text{kJ/s}
\end{aligned}
$$

Find the volume of the gas used at standard conditions for a heating gas (16°C).

$$
\begin{aligned}
\dot{V}_{\text{std}} &= \dot{V}\left(\frac{T_0}{T}\right)\left(\frac{p}{p_0}\right) \\
&= \frac{\left(6.4\ \frac{\text{L}}{\text{s}}\right)\left(\frac{16^\circ\text{C} + 273^\circ}{26^\circ\text{C} + 273^\circ}\right)\left(\frac{13.6\ \text{kPa} + 102.4\ \text{kPa})}{101.3\ \text{kPa}}\right)}{1000\ \frac{\text{L}}{\text{m}^3}} \\
&= 0.00708\ \text{m}^3/\text{s}
\end{aligned}
$$

The efficiency of the boiler is

$$\begin{aligned}\eta &= \frac{Q}{\text{heat input}} \\ &= \frac{83.66\ \frac{\text{kJ}}{\text{s}}}{\left(0.00708\ \frac{\text{m}^3}{\text{s}}\right)\left(20.5\ \frac{\text{MJ}}{\text{m}^3}\right)\left(1000\ \frac{\text{kJ}}{\text{MJ}}\right)} \\ &= 0.576 \quad (57\%)\end{aligned}$$

The answer is (C).
12.

Customary U.S. Solution

step 1: Determine the actual gravimetric analysis of the coal as fired. 1 lbm of coal contains 0.02 lbm moisture, leaving 0.98 lbm dry coal. 1% is lost to the ash pit. The remainder is 0.98 lbm − 0.01 lbm = 0.97 lbm.

step 2: Calculate the heating value of the remaining coal.

$$\text{HV} = (0.97\ \text{lbm})\left(12{,}800\ \frac{\text{Btu}}{\text{lbm}}\right) = 12{,}416\ \text{Btu}$$

step 3: Find the energy, Q, required to produce steam. From appendixMERM24A (also *NCEES Handbook:* Properties of Saturated Steam (U.S. Customary Units)), the enthalpy of water at 120°F is h_1 = 88.00 Btu/lbm.

From appendixMERM24B, the enthalpy of saturated steam at 100 psia is h_2 = 1187.5 Btu/lbm.

$$\begin{aligned}Q &= m(h_2 - h_1) \\ &= (8.23\ \text{lbm})\left(1187.5\ \frac{\text{Btu}}{\text{lbm}} - 88.00\ \frac{\text{Btu}}{\text{lbm}}\right) \\ &= 9048.9\ \text{Btu}\end{aligned}$$

step 4: The combustion efficiency is

$$\eta = \frac{Q}{\text{HV}} = \frac{9048.9\ \text{Btu}}{12{,}416\ \text{Btu}} = 0.729 \quad (73\%)$$

The answer is (C).

SI Solution

Since boiler data are based on 1 unit mass of coal fired, step 1 will be the same as for the customary U.S. solution. Repeat the rest of the steps as follows.

step 2: Calculate the heating value of the remaining coal.

$$\text{HV} = (0.97\ \text{kg})\left(29.80\ \frac{\text{MJ}}{\text{kg}}\right)\left(1000\ \frac{\text{kJ}}{\text{MJ}}\right) = 28\,906\ \text{kJ}$$

step 3: Find the energy, Q, required to produce steam. From appendixMERM24N (also *NCEES Handbook:* Saturated Steam (SI Units)), the enthalpy of water at 50°C is h_1 = 209.34 kJ/kg.

From appendixMERM24O, the enthalpy of saturated steam at 700 kPa is h_2 = 2762.8 kJ/kg.

$$\begin{aligned}Q &= m(h_2 - h_1) \\ &= (8.23\ \text{kg})\left(2762.8\ \frac{\text{kJ}}{\text{kg}} - 209.34\ \frac{\text{kJ}}{\text{kg}}\right) \\ &= 21\,015\ \text{kJ}\end{aligned}$$

step 4: The combustion efficiency is

$$\eta = \frac{Q}{\text{HV}} = \frac{21\,015\ \text{kJ}}{28\,906\ \text{kJ}} = 0.727 \quad (73\%)$$

The answer is (C).
13.

Customary U.S. Solution

Refer to figureMERM28001. Leaving the superheater and entering the turbine, the enthalpy, h_D, and entropy, s_D, can be obtained from appendixMERM24C (also *NCEES Handbook:* Superheated Steam (U.S. Customary Units)).

$$\begin{aligned} h_{\text{D}} &= 1521.0\ \text{Btu/lbm} \\ s_{\text{D}} &= 1.7376\ \text{Btu/lbm-}^\circ\text{F} \end{aligned}$$

For isentropic expansion through the turbine, $s_E = s_D$. From appendixMERM24B (also *NCEES Handbook:* Properties of Saturated Steam (U.S. Customary Units)), the enthalpy of saturated liquid, h_f, the enthalpy of evaporation, h_{fg}, the entropy of saturated liquid, s_f, and the entropy of evaporation, s_{fg}, are

$$\begin{aligned} h_f &= 130.2\ \text{Btu/lbm} \\ h_{fg} &= 1000.5\ \text{Btu/lbm} \\ s_f &= 0.2349\ \text{Btu/lbm-}^\circ\text{F} \\ s_{fg} &= 1.6089\ \text{Btu/lbm-}^\circ\text{F} \end{aligned}$$

The quality of the mixture for an isentropic process (at point E) is given by equationMERM24041 (also *NCEES Handbook:* Properties for Two-Phase (Vapor-Liquid) Systems).

$$\begin{aligned} x_{\text{E}} &= \frac{s_{\text{E}} - s_f}{s_{fg}} = \frac{1.7376\ \frac{\text{Btu}}{\text{lbm-}^\circ\text{F}} - 0.2349\ \frac{\text{Btu}}{\text{lbm-}^\circ\text{F}}}{1.6089\ \frac{\text{Btu}}{\text{lbm-}^\circ\text{F}}} \\ &= 0.9340 \end{aligned}$$

The isentropic enthalpy (at point E) is given by equationMERM24040 (also *NCEES Handbook:* Properties for Two-Phase (Vapor-Liquid) Systems).

$$\begin{aligned} h_{\text{E}} &= h_f + x_{\text{E}} h_{fg} \\ &= 130.2\ \frac{\text{Btu}}{\text{lbm}} + (0.9340)\left(1000.5\ \frac{\text{Btu}}{\text{lbm}}\right) \\ &= 1064.7\ \text{Btu/lbm} \end{aligned}$$

From equationMERM27019 (also *NCEES Handbook:* Open Thermodynamic Systems), the actual enthalpy of steam at point E is

$$\begin{aligned} h'_{\text{E}} &= h_{\text{D}} - \eta_s (h_{\text{D}} - h_{\text{E}}) \\ &= 1521\ \frac{\text{Btu}}{\text{lbm}} - (0.75)\left(1521\ \frac{\text{Btu}}{\text{lbm}} - 1064.7\ \frac{\text{Btu}}{\text{lbm}}\right) \\ &= 1178.8\ \text{Btu/lbm} \end{aligned}$$

Since the pump work is negligible, the mass flow rate of steam is

$$
\begin{aligned}
\dot{m} &= \frac{P}{W_{\text{turbine}}} = \frac{P}{h_{\mathrm{D}} - h_{\mathrm{E}}'} \\
&= \frac{(200\ \mathrm{MW})\left(10^6\ \frac{\mathrm{W}}{\mathrm{MW}}\right)\left(3.412\ \frac{\mathrm{Btu}}{\mathrm{W\text{-}hr}}\right)}{1521\ \frac{\mathrm{Btu}}{\mathrm{lbm}} - 1178.8\ \frac{\mathrm{Btu}}{\mathrm{lbm}}} \\
&= 1.994 \times 10^6\ \mathrm{lbm/hr} \quad (2.0 \times 10^6\ \mathrm{lbm/hr})
\end{aligned}
$$

The answer is (C).

SI Solution

Refer to figureMERM28001. Leaving the superheater and entering the turbine, the enthalpy, h_{D}, and entropy, s_{D}, can be obtained from the Mollier figure (also *NCEES Handbook* figure "Temperature-Entropy (T-S) Diagram (SI Units)").

$$
\begin{aligned}
h_{\mathrm{D}} &\approx 3430\ \mathrm{kJ/kg} \\
s_{\mathrm{D}} &\approx 7.25\ \mathrm{kJ/kg{\cdot}K}
\end{aligned}
$$

For isentropic expansion through the turbine, $s_{\mathrm{E}} = s_{\mathrm{D}}$. From appendixMERM24O (also *NCEES Handbook:* Saturated Steam (SI Units)), the enthalpy of saturated liquid, h_f, the enthalpy of evaporation, h_{fg}, the entropy of saturated liquid, s_f, and the entropy of saturated vapor, s_g, are

$$
\begin{aligned}
h_f &= 289.27\ \mathrm{kJ/kg} \\
h_{fg} &= 2335.3\ \mathrm{kJ/kg} \\
s_f &= 0.9441\ \mathrm{kJ/kg{\cdot}K} \\
s_g &= 7.7675\ \mathrm{kJ/kg{\cdot}K}
\end{aligned}
$$

The quality of the mixture for an isentropic process (at point E) is given by equationMERM24041 (also *NCEES Handbook:* Properties for Two-Phase (Vapor-Liquid) Systems) as

$$
\begin{aligned}
x_{\mathrm{E}} &= \frac{s_{\mathrm{E}} - s_f}{s_{fg}} = \frac{s_{\mathrm{E}} - s_f}{s_g - s_f} \\
&= \frac{7.25\ \frac{\mathrm{kJ}}{\mathrm{kg{\cdot}K}} - 0.9441\ \frac{\mathrm{kJ}}{\mathrm{kg{\cdot}K}}}{7.7675\ \frac{\mathrm{kJ}}{\mathrm{kg{\cdot}K}} - 0.9441\ \frac{\mathrm{kJ}}{\mathrm{kg{\cdot}K}}} \\
&= 0.9242
\end{aligned}
$$

The isentropic enthalpy (at point E) is given by equationMERM24040 (also *NCEES Handbook:* Properties for Two-Phase (Vapor-Liquid) Systems) as

$$
\begin{aligned}
h_{\mathrm{E}} &= h_f + x_{\mathrm{E}} h_{fg} \\
&= 289.27\ \frac{\mathrm{kJ}}{\mathrm{kg}} + (0.9242)\left(2335.3\ \frac{\mathrm{kJ}}{\mathrm{kg}}\right) \\
&= 2447.6\ \mathrm{kJ/kg}
\end{aligned}
$$

From equationMERM27019 (also *NCEES Handbook:* Open Thermodynamic Systems), the actual enthalpy of steam at point E is

$$
\begin{aligned}
h_{\mathrm{E}}' &= h_{\mathrm{D}} - \eta_s\,(h_{\mathrm{D}} - h_{\mathrm{E}}) \\
&= 3430\ \frac{\mathrm{kJ}}{\mathrm{kg}} - (0.75)\left(3430\ \frac{\mathrm{kJ}}{\mathrm{kg}} - 2447.6\ \frac{\mathrm{kJ}}{\mathrm{kg}}\right) \\
&= 2693.2\ \mathrm{kJ/kg}
\end{aligned}
$$

Since the pump work is negligible, the mass flow rate of steam is

$$\dot{m} = \frac{P}{W_{\text{turbine}}} = \frac{P}{h_D - h_E'} = \frac{(200\ \text{MW})\left(10^3\ \frac{\text{kW}}{\text{MW}}\right)}{3430\ \frac{\text{kJ}}{\text{kg}} - 2693.2\ \frac{\text{kJ}}{\text{kg}}}$$

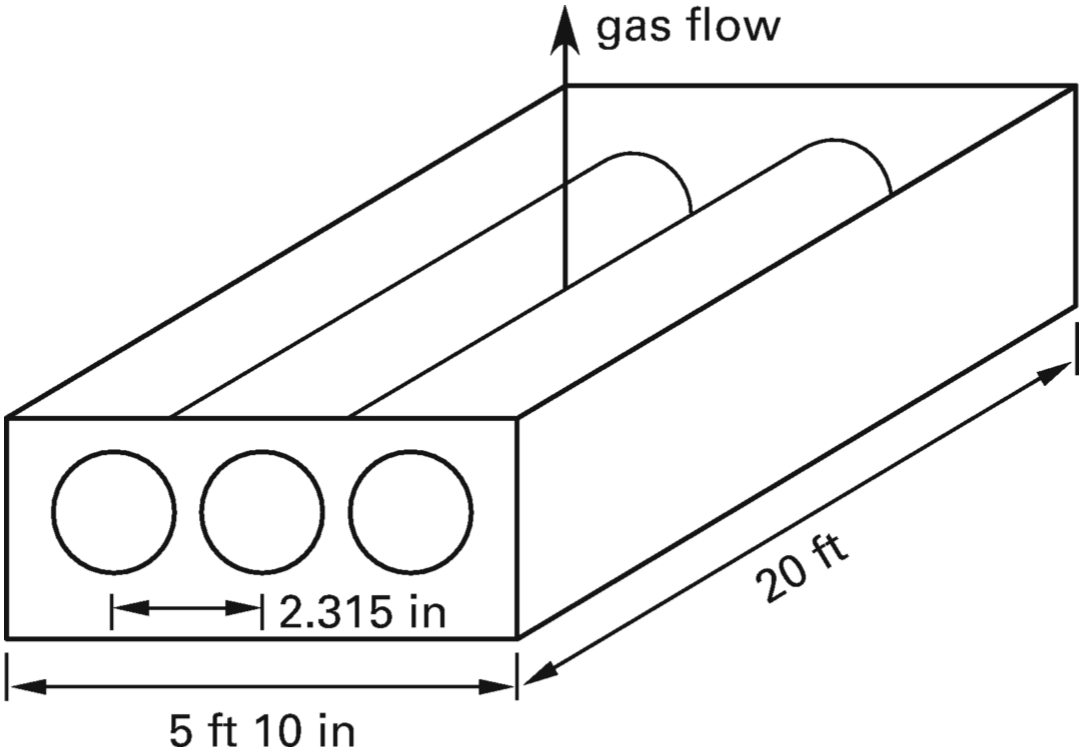
$$= 271.4\ \text{kg/s} \quad (270\ \text{kg/s})$$

The answer is (C).

14.

Customary U.S. Solution

The illustration shows one of N layers. Each layer consists of $n = 24$ tubes, only 3 of which are shown.



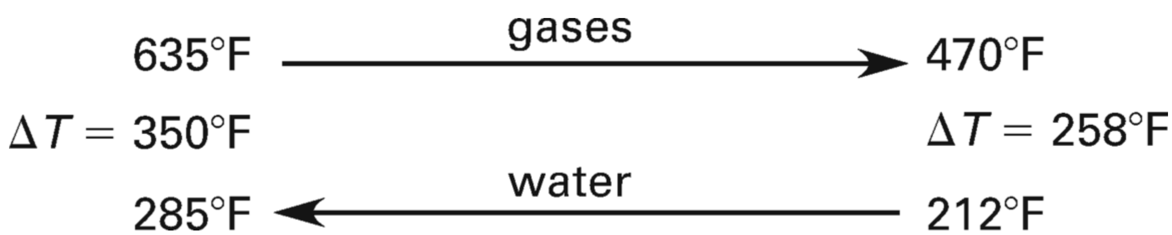
Assume stack gases consist primarily of nitrogen. The average gas temperature is

$$T_{\text{ave}} = \left(\frac{1}{2}\right)(635^\circ\text{F} + 470^\circ\text{F}) + 460^\circ = 1012.5^\circ\text{R}$$

From equationMERM24094 (also *NCEES Handbook* table "Temperature-Dependent Physical Properties of Gases at 14.7 psia (U.S. Units)"), the specific heat of nitrogen is 0.2554 Btu/lbm-°R using constants given in tableMERM24009.

For the purpose of calculating the logarithmic temperature difference, assume counterflow operation. The two end temperature differences are

$$\Delta T_A = 635^\circ\text{F} - 285^\circ\text{F} = 350^\circ\text{F}$$
$$\Delta T_B = 470^\circ\text{F} - 212^\circ\text{F} = 258^\circ\text{F}$$



The logarithmic temperature difference (see equationMERM36067 and *NCEES Handbook:* Log-Mean Temperature Difference) is

$$
\begin{aligned}
\Delta T_{\mathrm{lm}} &= \frac{\Delta T_A - \Delta T_B}{\ln \dfrac{\Delta T_A}{\Delta T_B}} = \frac{350^\circ\mathrm{F} - 258^\circ\mathrm{F}}{\ln \dfrac{350^\circ\mathrm{F}}{258^\circ\mathrm{F}}} \\
&= 301.7^\circ\mathrm{F}
\end{aligned}
$$

Determine F_c for crossflow.

$$
\begin{aligned}
R &= \frac{635^\circ\mathrm{F} - 470^\circ\mathrm{F}}{285^\circ\mathrm{F} - 212^\circ\mathrm{F}} = 2.26 \\
x &= \frac{285^\circ\mathrm{F} - 212^\circ\mathrm{F}}{635^\circ\mathrm{F} - 212^\circ\mathrm{F}} = 0.17
\end{aligned}
$$

From appendixMERM36F (also *NCEES Handbook:* F-Factor Charts), F_c for all heat exchanger configurations is close to 1.0 for this set of parameters.

The heat transfer from the temperature gain of water is equal to the heat transfer based on the logarithmic mean temperature difference. From equationMERM36068 (also *NCEES Handbook:* Overall Heat-Transfer Coefficient),

$$
\begin{aligned}
Q &= \dot{m}c_p\Delta T = U_oA_oF_c\Delta T_{\mathrm{lm}} \\
&\left(191{,}000\ \frac{\mathrm{lbm}}{\mathrm{hr}}\right)\left(0.2554\ \frac{\mathrm{Btu}}{\mathrm{lbm}\text{-}^\circ\mathrm{R}}\right)(635^\circ\mathrm{F} - 470^\circ\mathrm{F}) \\
&= \left(10\ \frac{\mathrm{Btu}}{\mathrm{hr}\text{-}\mathrm{ft}^2\text{-}^\circ\mathrm{F}}\right)A_o(1.0)(301.7^\circ\mathrm{F}) \\
A_o &= 2667.9\ \mathrm{ft}^2
\end{aligned}
$$

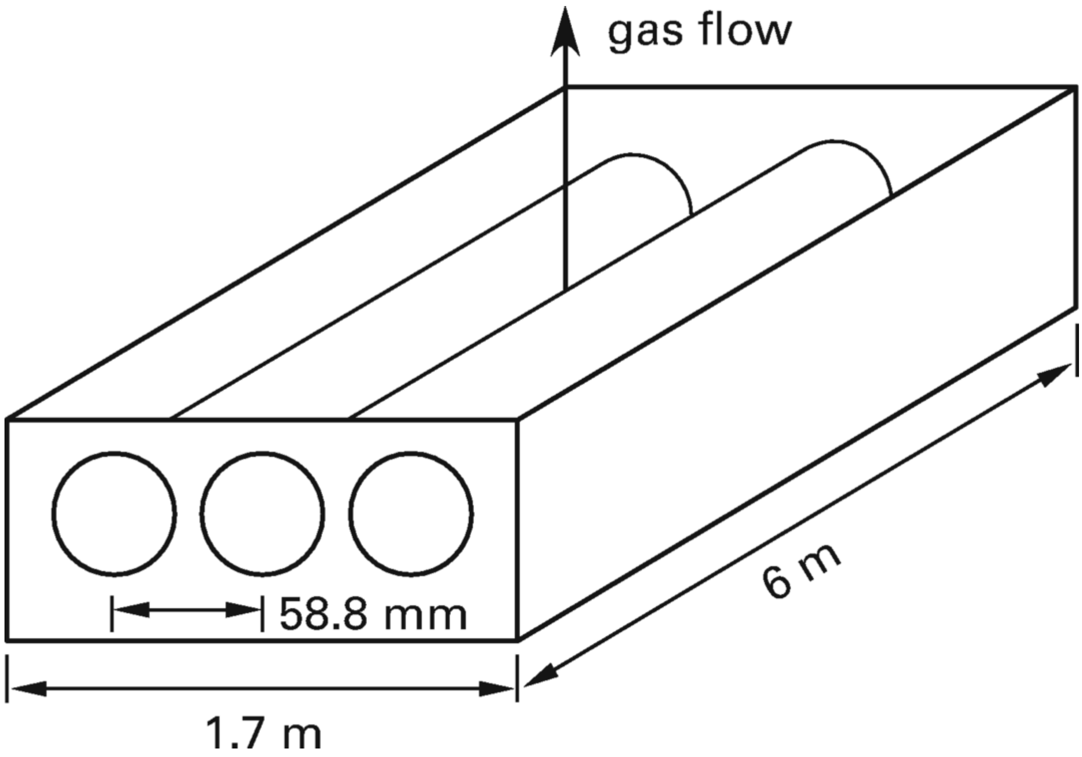
The tube area per bank is

$$
\begin{aligned}
A_{\mathrm{bank}} &= n\pi D_oL = \frac{24\pi(1.315\ \mathrm{in})\,(20\ \mathrm{ft})}{12\ \dfrac{\mathrm{in}}{\mathrm{ft}}} = 165.2\ \mathrm{ft}^2 \\
N &= \frac{A_o}{A_{\mathrm{bank}}} = \frac{2667.9\ \mathrm{ft}^2}{165.2\ \mathrm{ft}^2} = 16.1 \quad (17)
\end{aligned}
$$

The answer is (D).

SI Solution

The illustration shows one of *N* layers. Each layer consists of *n* = 24 tubes, only 3 of which are shown.



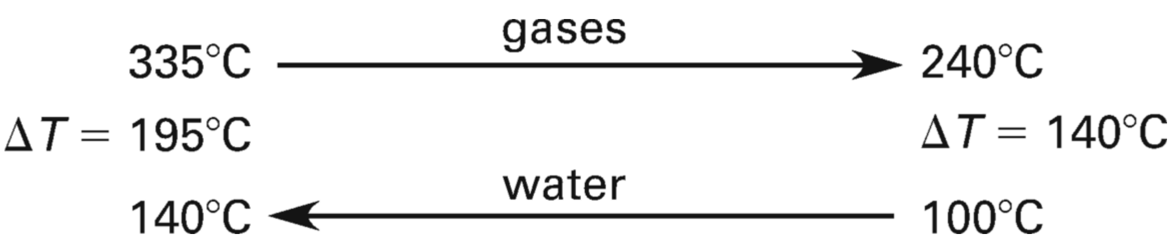
Assume stack gas consists primarily of nitrogen. The average gas temperature is

$$\begin{aligned} T_{\text{ave}} &= \left(\frac{1}{2}\right)(335^\circ\text{C} + 240^\circ\text{C}) + 273^\circ \\ &= 560.5\text{K} \quad (1009^\circ\text{R}) \end{aligned}$$

From tableMERM24009 (also *NCEES Handbook* table "Temperature-Dependent Physical Properties of Gases at 0.1 MPa (SI Units)"), the specific heat of nitrogen is 1069 J/kg·°C.

For the purpose of calculating the logarithmic temperature difference, assume counterflow operation. The two end temperature differences are

$$\begin{aligned} \Delta T_A &= 335^\circ\text{C} - 140^\circ\text{C} = 195^\circ\text{C} \\ \Delta T_B &= 240^\circ\text{C} - 100^\circ\text{C} = 140^\circ\text{C} \end{aligned}$$



The logarithmic mean temperature difference is (see equationMERM36067 and *NCEES Handbook:* Log-Mean Temperature Difference)

$$\begin{aligned} \Delta T_{\text{lm}} &= \frac{\Delta T_A - \Delta T_B}{\ln \dfrac{\Delta T_A}{\Delta T_B}} = \frac{195^\circ\text{C} - 140^\circ\text{C}}{\ln \dfrac{195^\circ\text{C}}{140^\circ\text{C}}} \\ &= 166.0^\circ\text{C} \\ R &= \frac{335^\circ\text{C} - 240^\circ\text{C}}{140^\circ\text{C} - 100^\circ\text{C}} = 2.38 \\ x &= \frac{140^\circ\text{C} - 100^\circ\text{C}}{335^\circ\text{C} - 100^\circ\text{C}} = 0.17 \end{aligned}$$

From appendixMERM36F (also *NCEES Handbook:* F-Factor Charts), F_c for all heat exchanger configurations is close to 1.0 for this set of conditions.

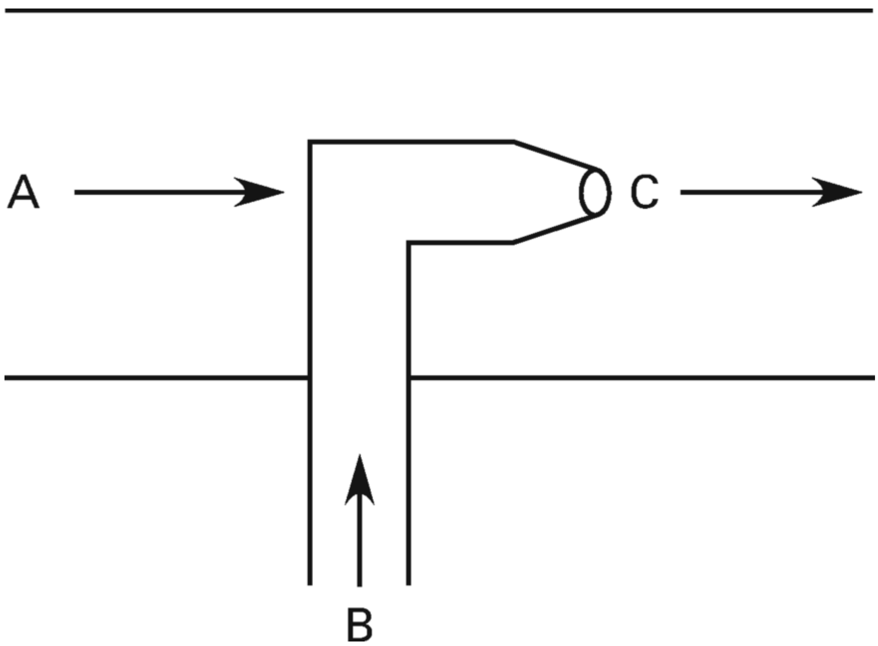
The heat transfer from the temperature gain of water is equal to the heat transfer based on the logarithmic mean temperature difference. From equationMERM36068 (also *NCEES Handbook:* Log-Mean Temperature Difference),

$$
\begin{aligned}
Q &= \dot{m}c_p\Delta T = U_oA_oF_c\Delta T_{\mathrm{lm}} \\
&\left(24\ \frac{\mathrm{kg}}{\mathrm{s}}\right)\left(1069\ \frac{\mathrm{J}}{\mathrm{kg}\cdot{}^\circ\mathrm{C}}\right)(335^\circ\mathrm{C} - 240^\circ\mathrm{C}) \\
&= \left(57\ \frac{\mathrm{W}}{\mathrm{m}^2\cdot{}^\circ\mathrm{C}}\right)A_o(1.0)(166.0^\circ\mathrm{C}) \\
A_o &= 257.6\ \mathrm{m}^2
\end{aligned}
$$

The tube area per bank is

$$
\begin{aligned}
A_{\mathrm{bank}} &= n\pi D_oL = \frac{24\pi(33.4\ \mathrm{mm})\,(6\ \mathrm{m})}{1000\ \frac{\mathrm{mm}}{\mathrm{m}}} \\
&= 15.1\ \mathrm{m}^2 \\
N &= \frac{A_o}{A_{\mathrm{bank}}} = \frac{257.6\ \mathrm{m}^2}{15.1\ \mathrm{m}^2} = 17.1 \quad (17)
\end{aligned}
$$

The answer is (D).
15.



Customary U.S. Solution

The enthalpy, h_A, and entropy, s_A, for steam at 600°F and 200 psia can be obtained from appendixMERM24C (also *NCEES Handbook:* Superheated Steam (U.S. Customary Units)).

$$
\begin{aligned}
h_{\mathrm{A}} &= 1322.3\ \mathrm{Btu/lbm} \\
s_{\mathrm{A}} &= 1.6771\ \mathrm{Btu/lbm}\text{-}^\circ\mathrm{R}
\end{aligned}
$$

For water at 82°F, enthalpy can be obtained for saturated water from appendixMERM24A (also *NCEES Handbook:* Properties of Saturated Steam (U.S. Customary Units)).

$$
h_{\mathrm{B}} = 50.06\ \frac{\mathrm{Btu}}{\mathrm{lbm}}
$$

From appendixMERM24A, $s_B = 0.09697$ Btu/lbm-°F. From an energy balance equation (with $Q = 0$, $v_1 = 0$, $\Delta z = 0$, and $W = 0$), equationMERM25030(b) can be written as

$$
\begin{aligned}
0 &= h_C(m_A+m_B) - (h_A m_A + h_B m_B) \\
&\quad + \left(\frac{v_C^2}{2g_cJ}\right)(m_A+m_B) \\
&= h_C\left(1000\ \frac{\text{lbm}}{\text{hr}} + 50\ \frac{\text{lbm}}{\text{hr}}\right) \\
&\quad - \left(\begin{array}{l}\left(1322.3\ \frac{\text{Btu}}{\text{lbm}}\right)\left(1000\ \frac{\text{lbm}}{\text{hr}}\right) \\ \quad + \left(50.06\ \frac{\text{Btu}}{\text{lbm}}\right)\left(50\ \frac{\text{lbm}}{\text{hr}}\right)\end{array}\right) \\
&\quad + \frac{\left(2000\ \frac{\text{ft}}{\text{sec}}\right)^2\left(1000\ \frac{\text{lbm}}{\text{hr}} + 50\ \frac{\text{lbm}}{\text{hr}}\right)}{(2)\left(32.2\ \frac{\text{lbm-ft}}{\text{lbf-sec}^2}\right)\left(778\ \frac{\text{ft-lbf}}{\text{Btu}}\right)}
\end{aligned}
$$

$$
\begin{aligned}
h_C &= 1181.9\ \text{Btu/lbm} \\
p_C &= 100\ \text{psia}
\end{aligned}
$$

Since the enthalpy of saturated steam at 100 psia, h_g, from appendixMERM24B (also *NCEES Handbook:* Properties of Saturated Steam (U.S. Customary Units)), is greater than h_C, steam leaving the desuperheater is not 100% saturated. From appendixMERM24B, the temperature of the saturated steam mix is 327.81°F (330°F).

The answer is (A).

SI Solution

(a) The enthalpy, h_A, and entropy, s_A, for steam at 300°C and 1.5 MPa can be obtained from appendixMERM24P (also *NCEES Handbook:* Superheated Steam (SI Units)).

$$
\begin{aligned}
h_A &= 3038.2\ \text{kJ/kg} \\
s_A &= 6.9198\ \text{kJ/kg·K}
\end{aligned}
$$

From appendixMERM24N (also *NCEES Handbook:* Saturated Steam (SI Units)), for water at 28°C, h_B = 117.37 kJ/kg.

Similarly, from appendixMERM24N, $s_B = 0.4091$ kJ/kg·K.

From an energy balance equation (with $Q=0$, $v_1=0$, $\Delta z=0$, and $W=0$), equationMERM25030(a) (also *NCEES Handbook:* Open Thermodynamic Systems) can be written as

$$
\begin{aligned}
0 &= h_C(m_A+m_B) - (m_A h_A + m_B h_B) \\
&\quad + \left(\frac{v_C^2}{2}\right)(m_A+m_B) \\
&= h_C\left(0.13\ \frac{\text{kg}}{\text{s}} + 0.0063\ \frac{\text{kg}}{\text{s}}\right) \\
&\quad - \left(\begin{array}{l}\left(0.13\ \frac{\text{kg}}{\text{s}}\right)\left(3038.2\ \frac{\text{kJ}}{\text{kg}}\right) \\ \quad + \left(0.0063\ \frac{\text{kg}}{\text{s}}\right)\left(117.37\ \frac{\text{kJ}}{\text{kg}}\right)\end{array}\right) \\
&\quad + \left(\frac{\left(600\ \frac{\text{m}}{\text{s}}\right)^2}{2}\right)\left(0.13\ \frac{\text{kg}}{\text{s}} + 0.0063\ \frac{\text{kg}}{\text{s}}\right) \\
&\quad \times \left(\frac{1\ \text{kJ}}{1000\ \text{J}}\right)
\end{aligned}
$$

$$
\begin{aligned}
h_C &= 2723.2\ \text{kJ/kg} \\
p_C &= 700\ \text{kPa}
\end{aligned}
$$

Since the enthalpy of saturated steam at 700 kPa, from appendixMERM24O (also *NCEES Handbook:* Saturated Steam (SI Units)), is greater than h_C, steam leaving the desuperheater is not 100% saturated. From appendixMERM24O (also *NCEES Handbook:* Saturated Steam (SI Units)), the temperature of the steam mix is 164.9°C (165°C).

The answer is (A).
16.

Customary U.S. Solution

Work with the original system to find the steam flow.

From appendixMERM24C (also *NCEES Handbook:* Superheated Steam (U.S. Customary Units)), at 100 psia and 400°F, $h_A = 1227.7$ Btu/lbm.

From appendixMERM24A (also *NCEES Handbook:* Properties of Saturated Steam (U.S. Customary Units)) at 70°F, $h_B = 38.08$ Btu/lbm.

From appendixMERM24A (also *NCEES Handbook:* Properties of Saturated Steam (U.S. Customary Units)) at 180°F, $h_C = 148.04$ Btu/lbm.

Let x = fraction of steam in mixture.

From the energy balance equation,

$$\begin{aligned} m_A h_A + m_B h_B &= m_C h_C \\ x\left(1227.7\ \frac{\text{Btu}}{\text{lbm}}\right) \\ +(1-x)\left(38.08\ \frac{\text{Btu}}{\text{lbm}}\right) &= (1)\left(148.04\ \frac{\text{Btu}}{\text{lbm}}\right) \\ x &= 0.0924 \end{aligned}$$

The steam flow is

$$\begin{aligned} \dot{m} &= x\left(2000\ \frac{\text{lbm}}{\text{hr}}\right) = (0.0924)\left(2000\ \frac{\text{lbm}}{\text{hr}}\right) \\ &= 184.8\ \text{lbm/hr} \quad (180\ \text{lbm/hr}) \end{aligned}$$

The answer is (B).

SI Solution

Work with the original system to find the steam flow.

From appendixMERM24P (also *NCEES Handbook:* Superheated Steam (SI Units)), at 700 kPa and 200°C, $h_A = 2845.3$ kJ/kg.

From appendixMERM24N (also *NCEES Handbook:* Saturated Steam (SI Units)), at 21°C, $h_B = 88.10$ kJ/kg.

From appendixMERM24N (also *NCEES Handbook:* Saturated Steam (SI Units)), at 80°C, $h_C = 335.01$ kJ/kg.

Let x = fraction of steam in mixture.

From the energy balance equation,

$$
\begin{aligned}
m_{\mathrm{A}} h_{\mathrm{A}} + m_{\mathrm{B}} h_{\mathrm{B}} &= m_{\mathrm{C}} h_{\mathrm{C}} \\
x\left(2845.3\ \frac{\mathrm{kJ}}{\mathrm{kg}}\right) & \\
+(1-x)\left(88.10\ \frac{\mathrm{kJ}}{\mathrm{kg}}\right) &= (1)\left(335.01\ \frac{\mathrm{kJ}}{\mathrm{kg}}\right) \\
x &= 0.0896
\end{aligned}
$$

The steam flow is

$$
\begin{aligned}
\dot{m} &= x\left(0.25\ \frac{\mathrm{kg}}{\mathrm{s}}\right) = (0.0896)\left(0.25\ \frac{\mathrm{kg}}{\mathrm{s}}\right) \\
&= 0.0224\ \mathrm{kg/s} \quad (0.022\ \mathrm{kg/s})
\end{aligned}
$$

The answer is (B).