To print, please use the print page range feature within the application.

Chapter 19. Forced Convection and Heat Exchangers

Practice Problems

1.

Water is heated from 55°F to 87°F (15°C to 30°C) by stack gases that are cooled from 350°F to 270°F (175°C to 130°C). The logarithmic mean temperature difference is most nearly

(A)

190°F (105°C)

(B)

210°F (117°C)

(C)

235°F (130°C)

(D)

270°F (150°C)

2.

A fluid in a tank is maintained at 85°F (30°C) by an immersed hot water coil. The hot water enters at 190°F (90°C) and leaves at 160°F (70°C). The logarithmic mean temperature difference is most nearly

(A)

89°F (49°C)

(B)

96°F (53°C)

(C)

111°F (62°C)

(D)

127°F (71°C)

3.

Light no. 10 oil is heated from 95°F to 105°F (35°C to 41°C) in a 0.6 in (1.52 cm) inside diameter tube. The average velocity of the oil is 2.0 ft/sec (0.6 m/s). The viscosity of the oil at 100°F (38°C) is 45 centistokes (cS). The Reynolds number is most nearly

(A)

200

(B)

2500

(C)

4600

(D)

19,000
4.

A white, uninsulated, rectangular duct passes through a 50 ft (15 m) wide room. The duct is 18 in (45 cm) wide and 12 in (30 cm) high. The room and its contents are at 70°F (21°C). Air at 100°F (40°C) enters the duct flowing at 800 ft/min (4.0 m/s). The film coefficient for the outside of the duct is 2.0 Btu/hr-ft^2-°F (11 W/m^2·K). All theoretical hydraulic properties are applicable. What is most nearly the temperature of the air after it has traveled in the duct the full 50 ft (15 m)?

(A)

85°F (29°C)

(B)

88°F (31°C)

(C)

91°F (33°C)

(D)

94°F (36°C)

5.

A steel pipe carrying 350°F (175°C) air is 100 ft (30 m) long. The outside and inside diameters are 4.00 in and 3.50 in (10 cm and 9.0 cm), respectively. The pipe is covered with 2.0 in (5.0 cm) of insulation with a thermal conductivity of 0.05 Btu-ft/hr-ft^2-°F (0.086 W/m·K). The pipe passes through a 50°F (10°C) basement. Flow is laminar and fully developed. The heat loss is most nearly

(A)

3100 Btu/hr (0.93 kW)

(B)

3500 Btu/hr (1.1 kW)

(C)

4200 Btu/hr (1.3 kW)

(D)

8700 Btu/hr (2.0 kW)

6.

An uninsulated horizontal pipe with 4.00 in (10 cm) outside diameter carries saturated 300 psia (2.1 MPa) steam through a 70°F (21°C) room. The steam flow rate is 5000 lbm/hr (0.63 kg/s). The pipe emissivity is 0.80. Any thermal gradients within the pipe are negligible. Approximately what decrease in quality will occur in the first 50 ft (15 m) of length?

(A)

1.5%

(B)

2.2%

(C)

2.8%

(D)

4.3%
7.

A crossflow tubular feedwater heater is being designed to heat 2940 lbm/hr (0.368 kg/s) of water from 70°F (21°C) to 190°F (90°C). Saturated steam at 134 psia (923 kPa) is condensing on the outside of the tubes. The tubes are a copper alloy containing 70% Cu and 30% Ni. Each tube has a 1 in (2.54 cm) outside diameter and a 0.9 in (2.29 cm) inside diameter. The water velocity inside the tubes is 3 ft/sec (0.9 m/s). The outside tube surface area required is most nearly

(A)

3.5 ft^2 (0.30 m^2)

(B)

4.5 ft^2 (0.54 m^2)

(C)

10 ft^2 (0.97 m^2)

(D)

18 ft^2 (1.7 m^2)

8.

A U-tube surface feedwater heater with one shell pass and two tube passes is being designed to heat 500,000 lbm/hr (60 kg/s) of water from 200°F to 390°F (100°C to 200°C). The water flows at 5 ft/sec (1.5 m/s) through the tubes. Dry, saturated steam at 400°F (205°C) is to be used as the heating medium. The heater is to operate straight condensing (i.e., the condensed steam will not be mixed with the heated water). Saturated water at 400°F (205°C) is removed from the heater. The tubes in the heater are $^7/_8$ in (2.2 cm) outside diameter with $^1/_{16}$ in (1.6 mm) walls. The overall heat transfer coefficient is estimated as 700 Btu/hr-ft^2-°F (4 kW/m^2·°C). Approximately how many tubes are required?

(A)

80

(B)

110

(C)

140
(D)

170
9.

A single-pass heat exchanger is tested in a clean condition and is found to heat 100 gal/min (6.3 L/s) of 70°F (21°C) water to 140°F (60°C). The hot side uses 230°F (110°C) steam. The tube's inner surface area is 50 ft^2 (4.7 m^2). After being used in the field for several months, the exchanger heats 100 gal/min (6.3 L/s) of 70°F (21°C) water to 122°F (50°C). The fouling factor is most nearly

(A)

0.0004 hr-ft^2-°F/Btu (0.00008 m^2·K/W)

(B)

0.0008 hr-ft^2-°F/Btu (0.0001 m^2·K/W)

(C)

0.001 hr-ft^2-°F/Btu (0.0002 m^2·K/W)

(D)

0.002 hr-ft^2-°F/Btu (0.0004 m^2·K/W)

10.

Cold water is used to cool hot water in a single-pass, tube-in-tube, counterflow heat exchanger. Compared to a plot of heat transfer rate-versus-distance traveled for the hot water, the plot of heat transfer rate-versus-time traveled for the hot water is

(A)

identical

(B)

reversed end-to-end

(C)

shifted (delayed)

(D)

inverted top-to-bottom

11.

Cold water is used to cool hot water in a single-pass, tube-in-tube, counterflow heat exchanger. Compared to a plot of heat transfer rate-versus-distance traveled by the cold water, the heat transfer rate-versus-distance traveled plot for the hot water is

(A)

identical

(B)

reversed end-to-end

(C)

shifted (delayed)

(D)

inverted top-to-bottom
12.

Cold water is used to cool hot water in a single-pass, tube-in-tube, parallel-flow (co-current) heat exchanger. Compared to a plot of temperature-versus-location by the hot water, the temperature-versus-location traveled plot of the cold water is

(A)

identical

(B)

reversed end-to-end

(C)

shifted (delayed)

(D)

inverted top-to-bottom

13.

Cold water is used to cool hot water in a single-pass, tube-in-tube, counterflow heat exchanger. The temperature gradient experienced by the hot water along the length of the heat exchanger will

(A)

essentially be constant

(B)

decrease nonlinearly

(C)

increase nonlinearly

(D)

decrease linearly

14.

Cold water is used to condense saturated steam in a single-pass, tube-in-tube, counterflow heat exchanger without subcooling. The temperature of the steam along the length of the heat exchanger from entrance to exit

(A)

decreases linearly
(B)

decreases parabolically

(C)

decreases logarithmically

(D)

is constant
15.

Heat exchanger “duty” is best defined as the

(A)

entering enthalpy difference of hot and cold fluids

(B)

non-adiabatic heat loss

(C)

heat transfer rate per unit mass of cold fluid

(D)

heat transfer rate per unit time

16.

A 2 ft long cylindrical fin with a diameter of 0.5 in is attached at one end to a heat source. The temperature of the heat source is 350°F, and the temperature of the ambient air is 75°F. The thermal conductivity of the fin is 128 Btu/hr-ft-°F, and the average film coefficient along the length of fin is 1.3 Btu/hr-ft^2-°F. No heat is transferred from the exposed fin tip. Heat transfer from the heat source into the base of the fin is most nearly

(A)

22 Btu/hr

(B)

29 Btu/hr

(C)

36 Btu/hr

(D)

46 Btu/hr
17.

A heat-conducting rod has an outside diameter of 0.35 in (8.9 mm). Its uniform temperature is 100°F (38°C). The rod is inserted perpendicularly into a 100 ft/sec (30 m/s) airflow. The air temperature is 150°F (66°C). The film coefficient on the outside of the rod is most nearly

(A)

36 Btu/hr-ft^2-°F (210 W/m^2·K)

(B)

45 Btu/hr-ft^2-°F (260 W/m^2·K)

(C)

66 Btu/hr-ft^2-°F (380 W/m^2·K)

(D)

91 Btu/hr-ft^2-°F (530 W/m^2·K)

Solutions

1.

Customary U.S. Solution

The logarithmic mean temperature difference will be different for different types of flow.

Parallel flow:

$$\Delta T_A = 350^\circ\text{F} - 55^\circ\text{F} = 295^\circ\text{F}$$
$$\Delta T_B = 270^\circ\text{F} - 87^\circ\text{F} = 183^\circ\text{F}$$

From equationMERM36067 (also *NCEES Handbook:* Log-Mean Temperature Difference), the logarithmic mean temperature difference is

$$\begin{aligned}\Delta T_{\text{lm}} &= \frac{\Delta T_A - \Delta T_B}{\ln \frac{\Delta T_A}{\Delta T_B}} = \frac{295^\circ\text{F} - 183^\circ\text{F}}{\ln \frac{295^\circ\text{F}}{183^\circ\text{F}}} \\ &= 234.6^\circ\text{F}\end{aligned}$$

Counterflow:

$$\Delta T_A = 270^\circ\text{F} - 55^\circ\text{F} = 215^\circ\text{F}$$
$$\Delta T_B = 350^\circ\text{F} - 87^\circ\text{F} = 263^\circ\text{F}$$

From equationMERM36067 (also *NCEES Handbook:* Log-Mean Temperature Difference), the logarithmic mean temperature difference is

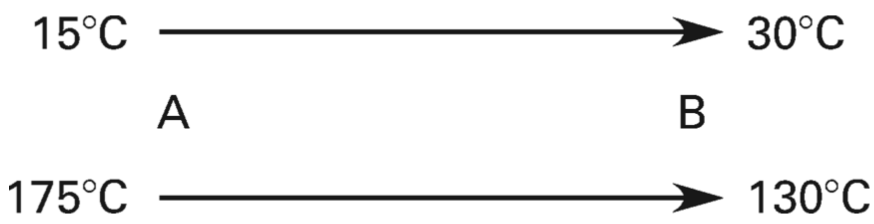
$$\begin{aligned}\Delta T_{\mathrm{lm}} &= \frac{\Delta T_A - \Delta T_B}{\ln \dfrac{\Delta T_A}{\Delta T_B}} = \frac{215^\circ\mathrm{F} - 263^\circ\mathrm{F}}{\ln \frac{215^\circ\mathrm{F}}{263^\circ\mathrm{F}}} \\ &= 238.2^\circ\mathrm{F} \quad (235^\circ\mathrm{F})\end{aligned}$$

The answer is (C).

SI Solution

The logarithmic mean temperature difference will be different for different types of flow.

Parallel flow:

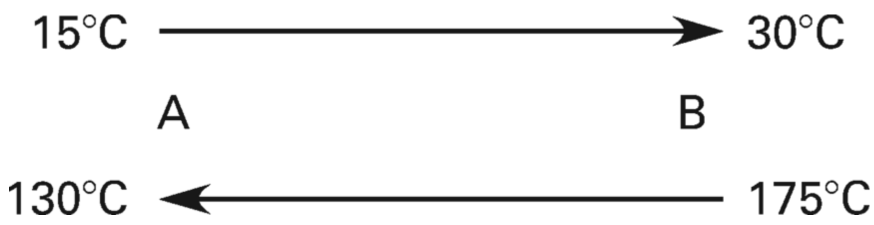


$$\begin{aligned}\Delta T_A &= 175^\circ\mathrm{C} - 15^\circ\mathrm{C} = 160^\circ\mathrm{C} \\ \Delta T_B &= 130^\circ\mathrm{C} - 30^\circ\mathrm{C} = 100^\circ\mathrm{C}\end{aligned}$$

From equationMERM36067 (also *NCEES Handbook:* Log-Mean Temperature Difference), the logarithmic mean temperature difference is

$$\begin{aligned}\Delta T_{\mathrm{lm}} &= \frac{\Delta T_A - \Delta T_B}{\ln \dfrac{\Delta T_A}{\Delta T_B}} \\ &= \frac{160^\circ\mathrm{C} - 100^\circ\mathrm{C}}{\ln \dfrac{160^\circ\mathrm{C}}{100^\circ\mathrm{C}}} \\ &= 127.7^\circ\mathrm{C}\end{aligned}$$

Counterflow:



$$\begin{aligned}\Delta T_A &= 130^\circ\mathrm{C} - 15^\circ\mathrm{C} = 115^\circ\mathrm{C} \\ \Delta T_B &= 175^\circ\mathrm{C} - 30^\circ\mathrm{C} = 145^\circ\mathrm{C}\end{aligned}$$

From equationMERM36067 (also *NCEES Handbook:* Log-Mean Temperature Difference), the logarithmic mean temperature difference is

$$\begin{aligned}\Delta T_{\mathrm{lm}} &= \frac{\Delta T_A - \Delta T_B}{\ln \dfrac{\Delta T_A}{\Delta T_B}} \\ &= \frac{115^\circ\mathrm{C} - 145^\circ\mathrm{C}}{\ln \frac{115^\circ\mathrm{C}}{145^\circ\mathrm{C}}} \\ &= 129.4^\circ\mathrm{C} \quad (130^\circ\mathrm{C})\end{aligned}$$

The answer is (C).
2.

Customary U.S. Solution

$$\Delta T_A = 190^\circ\text{F} - 85^\circ\text{F} = 105^\circ\text{F}$$
$$\Delta T_B = 160^\circ\text{F} - 85^\circ\text{F} = 75^\circ\text{F}$$

From equationMERM36067 (also *NCEES Handbook:* Log-Mean Temperature Difference), the logarithmic mean temperature difference is

$$\begin{aligned}\Delta T_{\text{lm}} &= \frac{\Delta T_A - \Delta T_B}{\ln \dfrac{\Delta T_A}{\Delta T_B}} \\ &= \frac{105^\circ\text{F} - 75^\circ\text{F}}{\ln \dfrac{105^\circ\text{F}}{75^\circ\text{F}}} \\ &= 89.2^\circ\text{F} \quad (89^\circ\text{F})\end{aligned}$$

The answer is (A).

SI Solution

$$\Delta T_A = 90^\circ\text{C} - 30^\circ\text{C} = 60^\circ\text{C}$$
$$\Delta T_B = 70^\circ\text{C} - 30^\circ\text{C} = 40^\circ\text{C}$$

From equationMERM36067 (also *NCEES Handbook:* Log-Mean Temperature Difference), the logarithmic mean temperature difference is

$$\begin{aligned}\Delta T_{\text{lm}} &= \frac{\Delta T_A - \Delta T_B}{\ln \dfrac{\Delta T_A}{\Delta T_B}} \\ &= \frac{60^\circ\text{C} - 40^\circ\text{C}}{\ln \dfrac{60^\circ\text{C}}{40^\circ\text{C}}} \\ &= 49.3^\circ\text{C} \quad (49^\circ\text{C})\end{aligned}$$

The answer is (A).
3.

Customary U.S. Solution

As in *NCEES Handbook* table “Dimensionless Numbers,” the Reynolds number is

$$\text{Re}_d = \frac{\text{v}D}{\nu}$$
$$D = \frac{0.6 \text{ in}}{12 \dfrac{\text{in}}{\text{ft}}} = 0.05 \text{ ft}$$
$$\text{v} = 2 \text{ ft/sec}$$

$$\begin{aligned}\nu &= \frac{45 \text{ cS}}{\left(100 \dfrac{\text{cS}}{\text{S}}\right)\left(929 \dfrac{\text{sec-stoke}}{\text{ft}^2}\right)} \\ &= 4.84 \times 10^{-4} \text{ ft}^2/\text{sec}\end{aligned}$$

$$\begin{aligned}\text{Re} &= \frac{\left(2 \dfrac{\text{ft}}{\text{sec}}\right)(0.05 \text{ ft})}{4.84 \times 10^{-4} \dfrac{\text{ft}^2}{\text{sec}}} \\ &= 206.6 \quad (200)\end{aligned}$$

The answer is (A).

SI Solution

As in *NCEES Handbook* table “Dimensionless Numbers,” the Reynolds number is

$$\begin{aligned}
\mathrm{Re}_d &= \frac{\mathrm{v}D}{\nu} \\
D &= \frac{1.52\ \mathrm{cm}}{100\ \frac{\mathrm{cm}}{\mathrm{m}}} = 0.0152\ \mathrm{m} \\
\mathrm{v} &= 0.6\ \mathrm{m/s} \\
\nu &= \frac{(45\ \mathrm{cS})\left(1\ \frac{\frac{\mu\mathrm{m}^2}{\mathrm{s}}}{\mathrm{cS{\cdot}s}}\right)}{10^6\ \frac{\mu\mathrm{m}^2}{\mathrm{m}^2}} \\
&= 45\times 10^{-6}\ \mathrm{m}^2/\mathrm{s} \\
\mathrm{Re}_d &= \frac{\left(0.6\ \frac{\mathrm{m}}{\mathrm{s}}\right)(0.0152\ \mathrm{m})}{45\times 10^{-6}\ \frac{\mathrm{m}^2}{\mathrm{s}}} \\
&= 202.7 \quad (200)
\end{aligned}$$

The answer is (A).

4.

Customary U.S. Solution

The exposed duct area is

$$\begin{aligned}
A &= (2W + 2H)\,L \\
&= \frac{\big((2)(18\ \mathrm{in}) + (2)(12\ \mathrm{in})\big)(50\ \mathrm{ft})}{12\ \frac{\mathrm{in}}{\mathrm{ft}}} \\
&= 250\ \mathrm{ft}^2
\end{aligned}$$

The duct is noncircular; therefore, the hydraulic diameter of the duct will be used. From equationMERM36048 (also *NCEES Handbook*: Free/Forced Heat-Transfer Coefficients/Correlations), the theoretical hydraulic diameter is

$$\begin{aligned}
d_H &= 4\left(\frac{\text{area in flow}}{\text{wetted perimeter}}\right) \\
&= 4\left(\frac{WH}{2\,(W+H)}\right) \\
&= \frac{(4)\left(\frac{(18\ \mathrm{in})(12\ \mathrm{in})}{(2)(18\ \mathrm{in} + 12\ \mathrm{in})}\right)}{12\ \frac{\mathrm{in}}{\mathrm{ft}}} \\
&= 1.2\ \mathrm{ft}
\end{aligned}$$

From appendixMERM35C, for air at 100°F,

$$\begin{aligned}
\nu &= 18.0\times 10^{-5}\ \mathrm{ft}^2/\mathrm{sec} \\
\rho &= 0.0710\ \mathrm{lbm/ft}^3 \\
\mathrm{Pr} &= 0.71
\end{aligned}$$

The Reynolds number is

$$
\begin{aligned}
\text{Re} &= \frac{\text{v}D}{\nu} \\
&= \frac{\left(800\ \frac{\text{ft}}{\text{min}}\right)(1.2\ \text{ft})}{\left(18.0\times 10^{-5}\ \frac{\text{ft}^2}{\text{sec}}\right)\left(60\ \frac{\text{sec}}{\text{min}}\right)} \\
&= 8.90\times 10^{4}
\end{aligned}
$$

This is a turbulent flow. The thermal conductivity for air can be found in *NCEES Handbook:* Temperature-Dependent Properties of Air (U.S. Customary Units). The correlation for forced convection in a pipe can be found in *NCEES Handbook:* Free/Forced Heat-Transfer Coefficients/Correlations. Rearrange the correlation to find the film coefficient for the inside of the duct. (Ignore the viscosity term for such a small temperature change.)

$$
\begin{aligned}
\text{Nu} &= 0.023\text{Re}^{0.8}\text{Pr}^{1/3}\left(\tfrac{\mu_\infty}{\mu_s}\right) = \tfrac{h_i d}{k} \\
h_i &= \left(\tfrac{k}{d}\right)0.023\text{Re}^{0.8}\text{Pr}^{1/3}\left(\tfrac{\mu_\infty}{\mu_s}\right) \\
&= \left(\frac{0.015\ \frac{\text{Btu}}{\text{hr-ft-}^\circ\text{F}}}{1.2\ \text{ft}}\right)(0.23)\left(8.9\times 10^{4}\right)^{0.8}(0.71)^{1/3} \\
&= 2.34\ \text{Btu/hr-ft}^2\text{-}^\circ\text{F}
\end{aligned}
$$

Disregarding the duct thermal resistance, the overall heat transfer coefficient from equationMERM36072 (also *NCEES Handbook:* Overall Heat-Transfer Coefficient) is

$$
\begin{aligned}
\frac{1}{U} &= \frac{1}{h_i}+\frac{1}{h_o} \\
&= \frac{1}{2.34\ \frac{\text{Btu}}{\text{hr-ft}^2\text{-}^\circ\text{F}}}+\frac{1}{2.0\ \frac{\text{Btu}}{\text{hr-ft}^2\text{-}^\circ\text{F}}} \\
&= 0.927\ \text{hr-ft}^2\text{-}^\circ\text{F/Btu} \\
U &= 1.08\ \text{Btu/hr-ft}^2\text{-}^\circ\text{F}
\end{aligned}
$$

The heat transfer to the room is

$$
Q = UA\left(T_\text{ave}-T_\infty\right) = UA\left(\frac{1}{2}\left(T_\text{in}+T_\text{out}\right)-T_\infty\right)
$$

Since T_out is unknown, an iteration procedure may be required. Assume $T_\text{out} \approx 95°\text{F}$.

$$
\begin{aligned}
Q &= \left(1.08\ \frac{\text{Btu}}{\text{hr-ft}^2\text{-}^\circ\text{F}}\right)\left(250\ \text{ft}^2\right) \\
&\quad\times\left(\left(\frac{1}{2}\right)\left(100^\circ\text{F}+95^\circ\text{F}\right)-70^\circ\text{F}\right) \\
&= 7425\ \text{Btu/hr}\quad (7400\ \text{Btu/hr})
\end{aligned}
$$

(Notice that ΔT (not ΔT_lm) is used in accordance with standard conventions in the HVAC industry.)

Temperature T_out can be verified by using

$$
\begin{aligned}
Q &= \dot{m}c_p\left(T_\text{in}-T_\text{out}\right) \\
\dot{m} &= GA_\text{flow} = GWH \\
&= \frac{\left(3408.0\ \frac{\text{lbm}}{\text{hr-ft}^2}\right)(18\ \text{in})(12\ \text{in})}{\left(12\ \frac{\text{in}}{\text{ft}}\right)^2} \\
&= 5112\ \text{lbm/hr} \\
c_p &= 0.240\ \text{Btu/lbm-}^\circ\text{F}
\end{aligned}
$$

As in *NCEES Handbook* table "Temperature-Dependent Properties of Air at 14.7 psia (U.S. Units),"

$$\begin{aligned} 7425\ \frac{\text{Btu}}{\text{hr}} &= \left(5112\ \frac{\text{lbm}}{\text{hr}}\right)\left(0.240\ \frac{\text{Btu}}{\text{lbm-}^\circ\text{F}}\right) \\ &\quad \times (100^\circ\text{F} - T_{\text{out}}) \\ T_{\text{out}} &= 94^\circ\text{F} \quad \text{[close enough]} \end{aligned}$$

The answer is (D).

SI Solution

The exposed duct area is

$$\begin{aligned} A &= (2W + 2H)\,L \\ &= \frac{\big((2)\,(45\ \text{cm}) + (2)\,(30\ \text{cm})\big)\,(15\ \text{m})}{100\ \frac{\text{cm}}{\text{m}}} \\ &= 22.5\ \text{m}^2 \end{aligned}$$

The duct is noncircular; therefore, the hydraulic diameter of the duct will be used. From equationMERM36048 (also *NCEES Handbook:* Free/Forced Heat-Transfer Coefficients/Correlations), the hydraulic diameter is

$$\begin{aligned} d_H &= 4\left(\frac{\text{area in flow}}{\text{wetted perimeter}}\right) = 4\left(\frac{WH}{2\,(W+H)}\right) \\ &= \frac{(4)\left(\frac{(45\ \text{cm})\,(30\ \text{cm})}{(2)\,(45\ \text{cm} + 30\ \text{cm})}\right)}{100\ \frac{\text{cm}}{\text{m}}} \\ &= 0.36\ \text{m} \end{aligned}$$

From appendixMERM35D (also *NCEES Handbook* table "Temperature-Dependent Properties of Air at 0.1 MPa (SI Units)"), for air at 40°C,

$$\begin{aligned} \mu &= 1.91 \times 10^{-5}\ \text{kg/m·s} \\ \rho &= 1.130\ \text{kg/m}^3 \\ c_p &= 1.0051\ \text{kJ/kg·K} \\ k &= 0.02718\ \text{W/m·K} \\ \text{Pr} &= 0.0709 \end{aligned}$$

As in *NCEES Handbook* table "Dimensionless Numbers," the Reynolds number is

$$\begin{aligned} \text{Re} &= \frac{\rho \text{v} D}{\mu} = \frac{\left(1.130\ \frac{\text{kg}}{\text{m}^3}\right)\left(4.0\ \frac{\text{m}}{\text{s}}\right)(0.36\ \text{m})}{1.91 \times 10^{-5}\ \frac{\text{kg}}{\text{m·s}}} \\ &= 8.52 \times 10^4 \end{aligned}$$

This is a turbulent flow. From equationMERM36034 (also *NCEES Handbook*: Free/Forced Heat-Transfer Coefficients/Correlations), the Nusselt number is

$$\text{Nu} = 0.023\,\text{Re}^{0.8}(\text{Pr})^{1/3}$$

The film coefficient is

$$
\begin{aligned}
h &= 0.023\,\mathrm{Re}^{0.8}\left(\frac{k}{d}\right)(\mathrm{Pr})^{1/3} \\
&= (0.023)\left(8.52\times 10^4\right)^{0.8}\left(\frac{0.02718\ \frac{\mathrm{W}}{\mathrm{m\cdot K}}}{0.36\ \mathrm{m}}\right)(0.709)^{1/3} \\
&= 13.6\ \mathrm{W/m^2\cdot K}
\end{aligned}
$$

Disregarding the duct thermal resistance, the overall heat transfer coefficient from equationMERM36072 (also *NCEES Handbook:* Overall Heat-Transfer Coefficient) is

$$
\begin{aligned}
\frac{1}{U} &= \frac{1}{h_i}+\frac{1}{h_o} \\
&= \frac{1}{11\ \frac{\mathrm{W}}{\mathrm{m^2\cdot K}}}+\frac{1}{13.6\ \frac{\mathrm{W}}{\mathrm{m^2\cdot K}}} \\
&= 0.1644\ \mathrm{m^2\cdot K/W} \\
U &= 6.08\ \mathrm{W/m^2\cdot K}
\end{aligned}
$$

The heat transfer to the room is

$$
Q = UA\left(T_{\mathrm{ave}}-T_\infty\right) = UA\left(\frac{1}{2}\left(T_{\mathrm{in}}+T_{\mathrm{out}}\right)-T_\infty\right)
$$

Since T_{out} is unknown, an iterative procedure may be required. Assume $T_{\mathrm{out}} = 36°\mathrm{C}$.

$$
\begin{aligned}
Q &= \left(6.08\ \frac{\mathrm{W}}{\mathrm{m^2\cdot K}}\right)\left(22.5\ \mathrm{m^2}\right) \\
&\quad\times\left(\left(\frac{1}{2}\right)\left(40^\circ\mathrm{C}+36^\circ\mathrm{C}\right)-21^\circ\mathrm{C}\right) \\
&= 2325\ \mathrm{W}\quad (2.4\ \mathrm{kW})
\end{aligned}
$$

(Notice that ΔT (not ΔT_{lm}) is used in accordance with standard conventions in the HVAC industry.)

Temperature T_{out} can be verified by using

$$
\begin{aligned}
Q &= \dot{m}c_p\left(T_{\mathrm{in}}-T_{\mathrm{out}}\right) \\
\dot{m} &= \rho A_{\mathrm{flow}}\mathrm{v} \\
&= \frac{\left(1.130\ \frac{\mathrm{kg}}{\mathrm{m^3}}\right)(45\ \mathrm{cm})(30\ \mathrm{cm})\left(4\ \frac{\mathrm{m}}{\mathrm{s}}\right)}{\left(100\ \frac{\mathrm{cm}}{\mathrm{m}}\right)^2} \\
&= 0.6102\ \mathrm{kg/s} \\
2325\ \mathrm{W} &= \left(0.6102\ \frac{\mathrm{kg}}{\mathrm{s}}\right)\left(1.0051\ \frac{\mathrm{kJ}}{\mathrm{kg\cdot K}}\right)\left(1000\ \frac{\mathrm{J}}{\mathrm{kJ}}\right) \\
&\quad\times\left(40^\circ\mathrm{C}-T_{\mathrm{out}}\right) \\
T_{\mathrm{out}} &= 36.2^\circ\mathrm{C}\qquad (36^\circ\mathrm{C})
\end{aligned}
$$

The answer is (D).
5.

Customary U.S. Solution

Refer to figureFERM31001b. The radii are

$$r_a = \frac{d_i}{2} = \frac{3.5\ \text{in}}{(2)\left(12\ \frac{\text{in}}{\text{ft}}\right)} = 0.1458\ \text{ft}$$

$$r_b = \frac{d_o}{2} = \frac{4\ \text{in}}{(2)\left(12\ \frac{\text{in}}{\text{ft}}\right)} = 0.1667\ \text{ft}$$

$$\begin{aligned} r_c &= r_b + t_{\text{insulation}} = 0.1667\ \text{ft} + \frac{2\ \text{in}}{12\ \frac{\text{in}}{\text{ft}}} \\ &= 0.3334\ \text{ft} \end{aligned}$$

From appendixMERM34B (also *NCEES Handbook* table "Physical Properties of Metals at 68°F (U.S. Units)"), for steel, $k_{\text{pipe}} \approx 24.8$ Btu-ft/hr-ft^2-°F.

Initially assume a typical value of $h_c = 1.5$ Btu/hr-ft^2-°F.

For fully developed laminar flow, from Eq. 19.28 (also *NCEES Handbook:* Free/Forced Heat-Transfer Coefficients/Correlations), $\text{Nu}_d = 3.658$.

From appendixMERM35C (also *NCEES Handbook* table "Temperature-Dependent Properties of Air at 14.7 psia (U.S. Units)"), for air at 350°F,

$$\begin{aligned} k_{\text{air}} &\approx 0.0203\ \text{Btu/hr-ft-}^\circ\text{F} \\ \text{Nu}_d &= \frac{h_a d_i}{k_{\text{air}}} = 3.658 \\ h_a &= \frac{3.658 k_{\text{air}}}{d_i} \\ &= \frac{(3.658)\left(0.0203\ \frac{\text{Btu}}{\text{hr-ft-}^\circ\text{F}}\right)\left(12\ \frac{\text{in}}{\text{ft}}\right)}{3.5\ \text{in}} \\ &= 0.255\ \text{Btu/hr-ft}^2\text{-}^\circ\text{F} \end{aligned}$$

Neglect thermal resistance between pipe and insulation. From equationMERM34034 (also *NCEES Handbook:* Combination of Heat-Transfer Mechanisms), the heat transfer is

$$\begin{aligned} Q &= \frac{2\pi L (T_i - T_\infty)}{\frac{1}{r_a h_a} + \frac{\ln\left(\frac{r_b}{r_a}\right)}{k_{\text{pipe}}} + \frac{\ln\left(\frac{r_c}{r_b}\right)}{k_{\text{insulation}}} + \frac{1}{r_c h_c}} \\ &= \frac{2\pi(100\ \text{ft})(350^\circ\text{F} - 50^\circ\text{F})}{\begin{array}{l} \frac{1}{(0.1458\ \text{ft})\left(0.255\ \frac{\text{Btu}}{\text{hr-ft}^2\text{-}^\circ\text{F}}\right)} + \frac{\ln\left(\frac{0.1667\ \text{ft}}{0.1458\ \text{ft}}\right)}{24.8\ \frac{\text{Btu-ft}}{\text{hr-ft}^2\text{-}^\circ\text{F}}} \\ \quad + \frac{\ln\left(\frac{0.3334\ \text{ft}}{0.1667\ \text{ft}}\right)}{0.05\ \frac{\text{Btu-ft}}{\text{hr-ft}^2\text{-}^\circ\text{F}}} + \frac{1}{(0.3334\ \text{ft})\left(1.5\ \frac{\text{Btu}}{\text{hr-ft}^2\text{-}^\circ\text{F}}\right)} \end{array}} \\ &= \frac{188{,}496\ \text{ft-}^\circ\text{F}}{\begin{array}{l} 26.90\ \frac{\text{hr-ft-}^\circ\text{F}}{\text{Btu}} + 0.00523\ \frac{\text{hr-ft-}^\circ\text{F}}{\text{Btu}} \\ \quad + 13.863\ \frac{\text{hr-ft-}^\circ\text{F}}{\text{Btu}} + 2.00\ \frac{\text{hr-ft-}^\circ\text{F}}{\text{Btu}} \end{array}} \\ &= 4408\ \text{Btu/hr} \end{aligned}$$

Use equationMERM34034 (also *NCEES Handbook:* Combination of Heat-Transfer Mechanisms) to find T_2 by using all resistances except the outer ($T_2 - T_\infty$) resistance.

$$
\begin{aligned}
T_i - T_2 &= \left(\frac{4408 \ \frac{\text{Btu}}{\text{hr}}}{2\pi\,(100 \text{ ft})} \right) \\
&\quad \times \left(\begin{array}{c} 26.9 \ \frac{\text{hr-ft-}^\circ\text{F}}{\text{Btu}} + 0.00523 \ \frac{\text{hr-ft-}^\circ\text{F}}{\text{Btu}} \\ +13.863 \ \frac{\text{hr-ft-}^\circ\text{F}}{\text{Btu}} \end{array} \right) \\
&= 286.0^\circ\text{F} \\
T_2 &= T_i - 286.0^\circ\text{F} = 350^\circ\text{F} - 286.0^\circ\text{F} \\
&= 64.0^\circ\text{F}
\end{aligned}
$$

To evaluate h_c, use film temperature.

$$
\begin{aligned}
T_{\text{film}} &= \tfrac{1}{2}(T_2 + T_\infty) = \left(\frac{1}{2}\right)(64.0^\circ\text{F} + 50^\circ\text{F}) \\
&= 57^\circ\text{F}
\end{aligned}
$$

From appendixMERM35C (also *NCEES Handbook* table "Temperature-Dependent Properties of Air at 14.7 psia (U.S. Units)"), for air at 57°F,

$$
\begin{aligned}
\text{Pr} &= 0.72 \\
\frac{g\beta\rho^2}{\mu^2} &= 2.645 \times 10^6 \ \frac{1}{\text{ft}^3\text{-}^\circ\text{F}}
\end{aligned}
$$

From equationMERM35004 (also *NCEES Handbook*: Similitude), the Grashof number is

$$
\text{Gr} = \frac{L^3 g\beta\rho^2\,(T_2 - T_\infty)}{\mu^2}
$$

For pipe,

$$
\begin{aligned}
L &= d_c = 2r_c = (2)\,(0.3334 \text{ ft}) = 0.6668 \text{ ft} \\
\text{Gr} &= (0.6668 \text{ ft})^3 \left(2.645 \times 10^6 \ \frac{1}{\text{ft}^3\text{-}^\circ\text{F}} \right) \\
&\quad \times (64.0^\circ\text{F} - 50^\circ\text{F}) \\
&= 1.1 \times 10^7 \\
\text{Gr Pr} &= \left(1.1 \times 10^7\right)(0.72) \\
&= 7.9 \times 10^6
\end{aligned}
$$

As in *NCEES Handbook* table "Forced Convection—External Flow," $C = 0.48$ for this GrPr value. The correlation for free convection over a horizontal cylinder can be found in *NCEES Handbook:* Free/Forced Heat-Transfer Coefficients/Correlations. Rearrange the correlation to find the film coefficient.

$$
\begin{aligned}
\text{Nu} &= C(\text{GrPr})^{1/4} = \tfrac{hd}{k} \\
h &= \left(\tfrac{k}{d}\right) C(\text{GrPr})^{1/4} \\
&= \left(\frac{0.0203 \ \frac{\text{Btu}}{\text{hr-ft-}^\circ\text{F}}}{0.6668 \text{ ft}} \right) (0.48) \left(7.9 \times 10^6\right)^{1/4} \\
&= 0.775 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}
\end{aligned}
$$

At the second iteration, the heat transfer is

$$
\begin{aligned}
Q &= \frac{188{,}496 \text{ ft-}^\circ\text{F}}{\begin{array}{l} 26.90 \ \frac{\text{hr-ft-}^\circ\text{F}}{\text{Btu}} + 0.00523 \ \frac{\text{hr-ft-}^\circ\text{F}}{\text{Btu}} \\ \quad + \ 13.863 \ \frac{\text{hr-ft-}^\circ\text{F}}{\text{Btu}} \\ \quad + \ \frac{1}{(0.3334 \text{ ft})\left(0.775 \ \frac{\text{Btu}}{\text{hr-ft-}^\circ\text{F}}\right)} \end{array}} \\
&= 4222 \text{ Btu/hr} \quad (4200 \text{ Btu/hr})
\end{aligned}
$$

Additional iterations will improve the accuracy further.

The answer is (C).

SI Solution

Refer to figureFERM31001b. The radii are

$$
\begin{aligned}
r_a &= \frac{d_i}{2} = \frac{9.0 \text{ cm}}{(2)\left(100 \ \frac{\text{cm}}{\text{m}}\right)} = 0.045 \text{ m} \\
r_b &= \frac{d_o}{2} = \frac{10 \text{ cm}}{(2)\left(100 \ \frac{\text{cm}}{\text{m}}\right)} = 0.050 \text{ m} \\
r_c &= r_b + t_{\text{insulation}} = 0.050 \text{ m} + \frac{5.0 \text{ cm}}{100 \ \frac{\text{cm}}{\text{m}}} \\
&= 0.100 \text{ m}
\end{aligned}
$$

From appendixMERM34B (also *NCEES Handbook:* Physical Properties of Metal at 20°C (SI Units), for steel, the thermal conductivity is 42.9 W/m·K.

Initially assume a typical value of $h_c = 3.5$ W/m^2·K.

For fully developed laminar flow from equationMERM36028 (also *NCEES Handbook:* Free/Forced Heat-Transfer Coefficients/Correlations), $\text{Nu}_d = 3.658$.

From appendixMERM35D (also *NCEES Handbook* table “Temperature-Dependent Properties of Air at 0.1 MPa (SI Units)”), for air at 175°C,

$$
\begin{aligned}
k_{\text{air}} &\approx 0.03709 \text{ W/m·K} \\
\text{Nu}_d &= \frac{h_a d_i}{k_{\text{air}}} = 3.658 \\
h_a &= \frac{3.658 k_{\text{air}}}{d_i} = \frac{(3.658)\left(0.03709 \ \frac{\text{W}}{\text{m·K}}\right)\left(100 \ \frac{\text{cm}}{\text{m}}\right)}{9.0 \text{ cm}} \\
&= 1.510 \text{ W/m}^2\text{·K}
\end{aligned}
$$

Neglect thermal resistance between pipe and insulation. From equationMERM34034 (also *NCEES Handbook:* Combination of Heat-Transfer Mechanisms), the heat transfer is

$$
\begin{aligned}
Q &= \frac{2\pi L\,(T_i - T_\infty)}{\dfrac{1}{r_a h_a} + \dfrac{\ln\left(\dfrac{r_b}{r_a}\right)}{k_{\text{pipe}}} + \dfrac{\ln\left(\dfrac{r_c}{r_b}\right)}{k_{\text{insulation}}} + \dfrac{1}{r_c h_c}} \\
&= \frac{2\pi(30\text{ m})(175^\circ\text{C} - 10^\circ\text{C})}{\begin{array}{l}\dfrac{1}{(0.045\text{ m})\left(1.510\ \dfrac{\text{W}}{\text{m}^2\cdot\text{K}}\right)} + \dfrac{\ln\left(\dfrac{0.050\text{ m}}{0.045\text{ m}}\right)}{42.9\ \dfrac{\text{W}}{\text{m}\cdot\text{K}}} \\ \quad + \dfrac{\ln\left(\dfrac{0.10\text{ m}}{0.050\text{ m}}\right)}{0.086\ \dfrac{\text{W}}{\text{m}\cdot\text{K}}} + \dfrac{1}{(0.10\text{ m})\left(3.5\ \dfrac{\text{W}}{\text{m}^2\cdot\text{K}}\right)}\end{array}} \\
&= \frac{31\,101.8\text{ m}\cdot{}^\circ\text{C}}{\begin{array}{l}14.74\ \dfrac{\text{m}\cdot\text{K}}{\text{W}} + 0.00238\ \dfrac{\text{m}\cdot\text{K}}{\text{W}} \\ \quad + 8.06\ \dfrac{\text{m}\cdot\text{K}}{\text{W}} + 2.86\ \dfrac{\text{m}\cdot\text{K}}{\text{W}}\end{array}} \\
&= 1212\text{ W}
\end{aligned}
$$

Use equationMERM34034 (also *NCEES Handbook:* Combination of Heat-Transfer Mechanisms) to find T_2 by using all resistances except the outer $(T_2 - T_\infty)$ resistance.

$$
\begin{aligned}
T_i - T_2 &= \left(\frac{1212\text{ W}}{2\pi\,(30\text{ m})}\right) \\
&\quad \times \left(14.74\ \frac{\text{m}\cdot\text{K}}{\text{W}} + 0.00238\ \frac{\text{m}\cdot\text{K}}{\text{W}} + 8.06\ \frac{\text{m}\cdot\text{K}}{\text{W}}\right) \\
&= 146.6^\circ\text{C} \\
T_2 &= T_i - 146.6^\circ\text{C} = 175^\circ\text{C} - 146.6^\circ\text{C} \\
&= 28.4^\circ\text{C}
\end{aligned}
$$

To evaluate h_c, use film temperature.

$$
\begin{aligned}
T_{\text{film}} &= \tfrac{1}{2}(T_2 + T_\infty) = \left(\frac{1}{2}\right)(28.4^\circ\text{C} + 10^\circ\text{C}) \\
&= 19.2^\circ\text{C}
\end{aligned}
$$

From appendixMERM35D (also *NCEES Handbook* table “Temperature-Dependent Properties of Air at 0.1 MPa (SI Units)”), for air at 19.3°C,

$$
\begin{aligned}
\text{Pr} &= 0.710 \\
\frac{g\beta\rho^2}{\mu^2} &= 1.52 \times 10^8\ \frac{1}{\text{K}\cdot\text{m}^3}
\end{aligned}
$$

From equationMERM35004 (also *NCEES Handbook:* Similitude), the Grashof number is

$$
\text{Gr} = \frac{L^3 g\beta\rho^2\,(T_2 - T_\infty)}{\mu^2}
$$

For pipe,

$$
\begin{aligned}
L &= d_c = 2r_c = (2)\,(0.10\text{ m}) = 0.20\text{ m} \\
\text{Gr} &= (0.20\text{ m})^3\left(1.52 \times 10^8\ \frac{1}{\text{K}\cdot\text{m}^3}\right)(28.4^\circ\text{C} - 10^\circ\text{C}) \\
&= 2.24 \times 10^7 \\
\text{Gr}\,\text{Pr} &= \left(2.24 \times 10^7\right)(0.710) \\
&= 1.6 \times 10^7
\end{aligned}
$$

As in *NCEES Handbook* table "Forced Convection—External Flow," $C = 0.48$ for this GrPr value. The correlation for free convection over a horizontal cylinder can be found in *NCEES Handbook:* Free/Forced Heat-Transfer Coefficients/Correlations. Rearrange the correlation to find the film coefficient.

$$\begin{aligned}
\mathrm{Nu} &= C(\mathrm{GrPr})^{1/4} = \tfrac{hd}{k} \\
h &= \left(\tfrac{k}{d}\right) C(\mathrm{GrPr})^{1/4} \\
&= \left(\frac{0.03709\,\frac{\mathrm{W}}{\mathrm{m\cdot K}}}{0.2\ \mathrm{m}}\right)(0.48)\left(1.6\times 10^{7}\right)^{1/4} \\
&= 5.6\ \mathrm{W/m^2\cdot K}
\end{aligned}$$

Further iteration will improve accuracy.

$$\begin{aligned}
Q &= \frac{31\,101.8\ \mathrm{m\cdot{}^\circ C}}{\begin{array}{l}14.74\ \dfrac{\mathrm{m\cdot K}}{\mathrm{W}} + 0.00238\ \dfrac{\mathrm{m\cdot K}}{\mathrm{W}} \\ \quad + 8.06\ \dfrac{\mathrm{m\cdot K}}{\mathrm{W}} + \dfrac{1}{(0.10\ \mathrm{m})\left(5.6\ \dfrac{\mathrm{W}}{\mathrm{m^2\cdot K}}\right)}\end{array}} \\
&= 1264.9\ \mathrm{W} \qquad (1.3\ \mathrm{kW})
\end{aligned}$$

The answer is (C).

6.

Customary U.S. Solution

Neglecting pipe resistance (no information for pipe is given), $T_{\mathrm{pipe}} = T_{\mathrm{sat}}$.

From appendixMERM24B (also *NCEES Handbook* table "Saturated Steam (U.S. Units)—Temperature Table"), for 300 $\mathrm{lbf/in^2}$ steam, $T_{\mathrm{sat}} = 417.35°\mathrm{F}$. When a vapor condenses, the vapor and condensed liquid are at the same temperature. Therefore, the entire pipe is assumed to be at 417.35°F. The outside film coefficient should be evaluated from equationMERM36011.

$$\begin{aligned}
T_{\mathrm{film}} &= \tfrac{1}{2}(T_s + T_\infty) = \left(\frac{1}{2}\right)(417.35^\circ\mathrm{F} + 70^\circ\mathrm{F}) \\
&= 243.7^\circ\mathrm{F}
\end{aligned}$$

From appendixMERM35C (also *NCEES Handbook* table "Temperature-Dependent Properties of Air at 14.7 psia (U.S. Units)"), for air at 243.7°F,

$$\begin{aligned}
\mathrm{Pr} &= 0.715 \\
\frac{g\beta\rho^2}{\mu^2} &= 0.673\times 10^{6}\ \frac{1}{\mathrm{ft^3\text{-}{}^\circ F}}
\end{aligned}$$

From equationMERM35004 (also *NCEES Handbook:* Similitude), the Grashof number is

$$\begin{aligned}
\mathrm{Gr} &= \frac{L^3 g\beta\rho^2\,(T_s - T_\infty)}{\mu^2} \\
L = d_{\mathrm{outside}} &= \frac{4\ \mathrm{in}}{12\ \dfrac{\mathrm{in}}{\mathrm{ft}}} = 0.3333\ \mathrm{ft} \\
\mathrm{Gr} &= (0.3333\ \mathrm{ft})^3\left(0.673\times 10^{6}\ \frac{1}{\mathrm{ft^3\text{-}{}^\circ F}}\right) \\
&\quad \times (417.35^\circ\mathrm{F} - 70^\circ\mathrm{F}) \\
&= 8.66\times 10^{6} \\
\mathrm{Gr\,Pr} &= \left(8.66\times 10^{6}\right)(0.715) \\
&= 6.19\times 10^{6}
\end{aligned}$$

As in *NCEES Handbook* table "Forced Convection—External Flow," $C = 0.48$ for this GrPr value. The correlation for free convection over a horizontal cylinder can be found in *NCEES Handbook:* Free/Forced Heat-Transfer Coefficients/Correlations. Rearrange the correlation to find the film coefficient.

$$\begin{aligned}
\mathrm{Nu} &= C(\mathrm{GrPr})^{1/4} = \tfrac{hd}{k} \\
h &= \left(\tfrac{k}{d}\right) C(\mathrm{GrPr})^{1/4} \\
&= \left(\frac{0.019\ \frac{\mathrm{Btu}}{\mathrm{hr\text{-}ft\text{-}^\circ F}}}{0.3333\ \mathrm{ft}}\right)(0.48)\left(6.19\times 10^{6}\right)^{1/4} \\
&= 1.37\ \mathrm{Btu/hr\text{-}ft^2\text{-}^\circ F}
\end{aligned}$$

From equationMERM35001 (also *NCEES Handbook:* Convection), the heat transfer for the first 50 ft due to convection is

$$\begin{aligned}
Q &= h_c A_{\mathrm{outside}}\left(T_s - T_\infty\right) \\
&= h_c\left(\pi d_{\mathrm{outside}} L\right)\left(T_s - T_\infty\right) \\
&= \left(1.37\ \frac{\mathrm{Btu}}{\mathrm{hr\text{-}ft^2\text{-}^\circ F}}\right)\pi\,(0.3333\ \mathrm{ft})\,(50\ \mathrm{ft}) \\
&\quad \times (417.35^\circ\mathrm{F} - 70^\circ\mathrm{F}) \\
Q_{\mathrm{convection}} &= 24{,}914\ \mathrm{Btu/hr}
\end{aligned}$$

To determine heat transfer due to radiation, assume oxidized steel pipe, completely enclosed.

$$F_a = 1$$

As in *NCEES Handbook*: Temperature, the absolute temperatures are

$$\begin{aligned}
T_1 &= 417.35^\circ\mathrm{F} + 460^\circ = 877.35^\circ\mathrm{R} \\
T_2 &= 70^\circ\mathrm{F} + 460^\circ = 530^\circ\mathrm{R} \\
F_e &= \epsilon_{\mathrm{pipe}} = 0.80
\end{aligned}$$

The radiation heat transfer is from *NCEES Handbook:* Radiation.

$$\begin{aligned}
E_{\mathrm{net}} &= \sigma F_a F_e\left(T_1^4 - T_2^4\right) \\
&= \left(0.1713\times 10^{-8}\ \frac{\mathrm{Btu}}{\mathrm{hr\text{-}ft^2\text{-}^\circ R^4}}\right) \\
&\quad \times (1)\,(0.80)\left((877.35^\circ\mathrm{R})^4 - (530^\circ\mathrm{R})^4\right) \\
&= 704\ \mathrm{Btu/hr\text{-}ft^2} \\
Q_{\mathrm{radiation}} &= E_{\mathrm{net}} A = E_{\mathrm{net}}\left(\pi d_{\mathrm{outside}} L\right) \\
&= \left(704\ \frac{\mathrm{Btu}}{\mathrm{hr\text{-}ft^2}}\right)\pi\,(0.3333\ \mathrm{ft})\,(50\ \mathrm{ft}) \\
&= 36{,}858\ \mathrm{Btu/hr}
\end{aligned}$$

The total heat loss is

$$\begin{aligned}
Q_{\mathrm{total}} &= Q_{\mathrm{convection}} + Q_{\mathrm{radiation}} \\
&= 24{,}914\ \frac{\mathrm{Btu}}{\mathrm{hr}} + 36{,}858\ \frac{\mathrm{Btu}}{\mathrm{hr}} \\
&= 61{,}772\ \mathrm{Btu/hr} \\
Q_{\mathrm{total}} &= \dot{m}\Delta h
\end{aligned}$$

The enthalpy decrease per pound is

$$\Delta h = \frac{Q_{\mathrm{total}}}{\dot{m}_{\mathrm{steam}}} = \frac{61{,}772\ \frac{\mathrm{Btu}}{\mathrm{hr}}}{5000\ \frac{\mathrm{lbm}}{\mathrm{hr}}} = 12.35\ \mathrm{Btu/lbm}$$

This is a quality loss of

$$
\begin{aligned}
\Delta x &= \frac{\Delta h}{h_{fg}} = \frac{12.35\ \frac{\text{Btu}}{\text{lbm}}}{809.4\ \frac{\text{Btu}}{\text{lbm}}} \\
&= 0.0153 \quad (1.5\%)
\end{aligned}
$$

The answer is (A).

SI Solution

From the customary U.S. solution, T_{pipe} is the same for the entire length.

From appendixMERM24O (also *NCEES Handbook* table "Saturated Steam (SI Units)—Temperature Table") for 2.1 MPa, $T_{\text{sat}} = 214.72°\text{C}$. The outside film coefficient should be evaluated from equationMERM36011 as

$$
\begin{aligned}
T_{\text{film}} &= \tfrac{1}{2}(T_{\text{s}} + T_{\infty}) = \left(\frac{1}{2}\right)(214.72^{\circ}\text{C} + 21^{\circ}\text{C}) \\
&= 117.9^{\circ}\text{C}
\end{aligned}
$$

From appendixMERM35D (also *NCEES Handbook* table "Temperature-Dependent Properties of Air at 0.1 MPa (SI Units)"), for air at 117.9°C,

$$
\begin{aligned}
\text{Pr} &= 0.692 \\
\frac{g\beta\rho^2}{\mu^2} &= 0.403 \times 10^8\ \frac{1}{\text{K·m}^3}
\end{aligned}
$$

From equationMERM35004 (also *NCEES Handbook:* Similitude), the Grashof number is

$$
\begin{aligned}
\text{Gr} &= \frac{L^3 g\beta\rho^2\left(T_s - T_{\infty}\right)}{\mu^2} \\
L &= d_{\text{outside}} = \frac{10\ \text{cm}}{100\ \frac{\text{cm}}{\text{m}}} = 0.10\ \text{m} \\
\text{Gr} &= (0.10\ \text{m})^3 \left(0.403 \times 10^8\ \frac{1}{\text{K·m}^3}\right) \\
&\quad \times (214.72^{\circ}\text{C} - 21^{\circ}\text{C}) \\
&= 7.807 \times 10^6 \\
\text{Gr Pr} &= \left(7.807 \times 10^6\right)(0.692) \\
&= 5.40 \times 10^6
\end{aligned}
$$

As in *NCEES Handbook* table "Forced Convection—External Flow," $C = 0.48$ for this GrPr value. The correlation for free convection over a horizontal cylinder can be found in *NCEES Handbook:* Free/Forced Heat-Transfer Coefficients/Correlations. Rearrange the correlation to find the film coefficient.

$$
\begin{aligned}
\text{Nu} &= C(\text{GrPr})^{1/4} = \tfrac{hd}{k} \\
h &= \left(\tfrac{k}{d}\right) C(\text{GrPr})^{1/4} \\
&= \left(\frac{0.0328\ \frac{\text{W}}{\text{m·K}}}{0.1\ \text{m}}\right)(0.48)\left(5.4 \times 10^6\right)^{1/4} \\
&= 7.6\ \text{W/m}^2\text{·K}
\end{aligned}
$$

From equationMERM35001, the heat transfer for the first 15 m due to convection is

$$
\begin{aligned}
Q_{\text{convection}} &= h_c\left(\pi d_{\text{outside}} L\right)\left(T_s - T_{\infty}\right) \\
&= \left(7.6\ \frac{\text{W}}{\text{m}^2\text{·K}}\right)\pi\,(0.10\ \text{m})\,(15\ \text{m}) \\
&\quad \times (214.72^{\circ}\text{C} - 21^{\circ}\text{C}) \\
&= 6938\ \text{W}
\end{aligned}
$$

To determine heat transfer due to radiation, assume oxidized steel pipe, completely enclosed.

$$F_a = 1$$

As in *NCEES Handbook* table "Dimensionless Numbers," the absolute temperatures are

$$\begin{aligned} T_1 &= 214.72^\circ\text{C} + 273^\circ = 487.72\text{K} \\ T_2 &= 21^\circ\text{C} + 273^\circ = 294\text{K} \\ F_e &= \epsilon_{\text{pipe}} = 0.80 \end{aligned}$$

As in *NCEES Handbook:* Radiation, the radiation heat transfer is

$$\begin{aligned} E_{\text{net}} &= \sigma F_a F_e \left(T_1^4 - T_2^4\right) \\ &= \left(5.67 \times 10^{-8}\ \frac{\text{W}}{\text{m}^2{\cdot}\text{K}^4}\right) \\ &\quad \times (1)\,(0.80)\left((487.72\text{K})^4 - (294\text{K})^4\right) \\ &= 2228\ \text{W/m}^2 \\ Q_{\text{radiation}} &= E_{\text{net}}\left(\pi d_{\text{outside}} L\right) \\ &= \left(2228\ \frac{\text{W}}{\text{m}^2}\right)\pi\,(0.10\ \text{m})\,(15\ \text{m}) \\ &= 10\,499\ \text{W} \end{aligned}$$

The total heat loss is

$$\begin{aligned} Q_{\text{total}} &= Q_{\text{convection}} + Q_{\text{radiation}} = 6938\ \text{W} + 10\,499\ \text{W} \\ &= 17\,437\ \text{W} \\ Q_{\text{total}} &= \dot{m}\Delta h \end{aligned}$$

The enthalpy decrease per kilogram is

$$\begin{aligned} \Delta h &= \frac{Q_{\text{total}}}{\dot{m}_{\text{steam}}} = \frac{17\,437\ \text{W}}{\left(0.63\ \frac{\text{kg}}{\text{s}}\right)\left(1000\ \frac{\text{J}}{\text{kJ}}\right)} \\ &= 27.68\ \text{kJ/kg} \end{aligned}$$

This is a quality loss of

$$\begin{aligned} \Delta x &= \frac{\Delta h}{h_{fg}} = \frac{27.68\ \frac{\text{kJ}}{\text{kg}}}{1879.8\ \frac{\text{kJ}}{\text{kg}}} \\ &= 0.0147 \quad (1.5\%) \end{aligned}$$

The answer is (A).
7.

Customary U.S. Solution

The bulk temperature of the water is

$$\begin{aligned} T_b &= \tfrac{1}{2}(T_{\text{in}} + T_{\text{out}}) = \left(\frac{1}{2}\right)(70^\circ\text{F} + 190^\circ\text{F}) \\ &= 130^\circ\text{F} \end{aligned}$$

From appendixMERM35A (also *NCEES Handbook* table "Physical Properties of Liquid Water (U.S. Units)") the properties of water at 130°F are

$$
\begin{aligned}
c_p &= 0.999\ \text{Btu/lbm-}^\circ\text{F} \\
\nu &= 0.582 \times 10^{-5}\ \text{ft}^2/\text{sec} \\
\text{Pr} &= 3.45 \\
k &= 0.376\ \text{Btu/hr-ft-}^\circ\text{F}
\end{aligned}
$$

The heat transfer is found from the temperature gain of the water.

$$
\begin{aligned}
Q &= \dot{m} c_p \Delta T \\
&= \left(2940\ \frac{\text{lbm}}{\text{hr}}\right)\left(0.999\ \frac{\text{Btu}}{\text{lbm-}^\circ\text{F}}\right)(190^\circ\text{F} - 70^\circ\text{F}) \\
&= 352{,}447\ \text{Btu/hr}
\end{aligned}
$$

As in *NCEES Handbook*: Similitude, the Reynolds number is

$$
\begin{aligned}
\text{Re} = \frac{\text{v}D}{\nu} &= \frac{\left(3\ \frac{\text{ft}}{\text{sec}}\right)(0.9\ \text{in})}{\left(0.582 \times 10^{-5}\ \frac{\text{ft}^2}{\text{sec}}\right)\left(12\ \frac{\text{in}}{\text{ft}}\right)} \\
&= 3.87 \times 10^4
\end{aligned}
$$

From equationMERM36033 (also *NCEES Handbook:* Free/Forced Heat-Transfer Coefficients/Correlations), the film coefficient is

$$
\begin{aligned}
h &= 0.023\text{Re}^{0.8}\text{Pr}^n\left(\frac{k}{d}\right) \\
&= (0.023)\left(3.87 \times 10^4\right)^{0.8}(3.45)^{1/3} \\
&\quad \times \left(\frac{\left(0.376\ \frac{\text{Btu}}{\text{hr-ft-}^\circ\text{F}}\right)\left(12\ \frac{\text{in}}{\text{ft}}\right)}{0.9\ \text{in}}\right) \\
&= 815\ \text{Btu/hr-ft}^2\text{-}^\circ\text{F}
\end{aligned}
$$

The saturation temperature for 134 psia steam is approximately 350°F. Assume the wall is 20°F lower (≈ 330°F). The film properties are evaluated at the average of the wall and saturation temperatures.

$$
\begin{aligned}
T_h &= \tfrac{1}{2}(T_{\text{sat},v} + T_s) = \left(\frac{1}{2}\right)(350^\circ\text{F} + 330^\circ\text{F}) \\
&= 340^\circ\text{F}
\end{aligned}
$$

Film properties are obtained from appendixMERM35A (also *NCEES Handbook* table “Physical Properties of Liquid Water (U.S. Units)”) for liquid water and from appendixMERM24A and appendixMERM24B (also *NCEES Handbook* table “Saturated Steam (U.S. Units)—Temperature Table”) for vapor.

$$
\begin{aligned}
k_{340^\circ\text{F}} &= 0.392\ \text{Btu/hr-ft-}^\circ\text{F} \\
\mu_{340^\circ\text{F}} &= \left(0.109 \times 10^{-3}\ \frac{\text{lbm}}{\text{sec-ft}}\right)\left(3600\ \frac{\text{sec}}{\text{hr}}\right) \\
&= 0.392\ \text{lbm/ft-hr} \\
\rho_{l,340^\circ\text{F}} &= \frac{1}{\upsilon_{f,340^\circ\text{F}}} = \frac{1}{0.01787\ \frac{\text{ft}^3}{\text{lbm}}} \\
&= 55.96\ \text{lbm/ft}^3 \\
\rho_{v,340^\circ\text{F}} &= \frac{1}{\upsilon_{g,340^\circ\text{F}}} = \frac{1}{3.788\ \frac{\text{ft}^3}{\text{lbm}}} \\
&= 0.2640\ \text{lbm/ft}^3
\end{aligned}
$$

$$h_{fg,134\text{ psia}} = 871.3\text{ Btu/lbm}$$

$$d = \frac{1.0\text{ in}}{12\ \frac{\text{in}}{\text{ft}}} = 0.083\text{ ft}$$

$$\begin{aligned} g &= \left(32.2\ \frac{\text{ft}}{\text{sec}^2}\right)\left(3600\ \frac{\text{sec}}{\text{hr}}\right)^2 \\ &= 4.17\times 10^8\text{ ft/hr}^2 \end{aligned}$$

From equationMERM35027 (also *NCEES Handbook:* Condensation), the film coefficient is

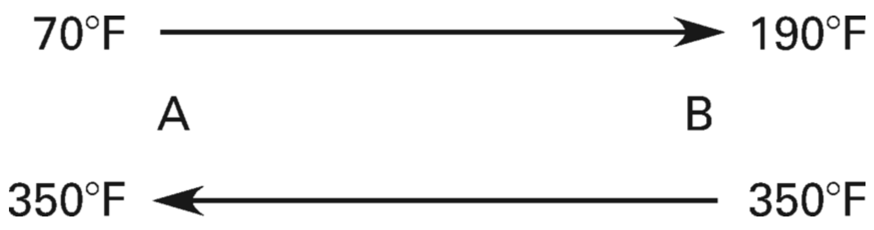
$$\begin{aligned} h_o &= 0.725\left(\frac{\rho_l(\rho_l-\rho_v)gh_{fg}k_l^3}{d\mu_l(T_{\text{sat},v}-T_s)}\right)^{1/4} \\ &= (0.725) \\ &\quad\times\left(\frac{\begin{array}{c}\left(55.96\ \frac{\text{lbm}}{\text{ft}^3}\right)\left(55.96\ \frac{\text{lbm}}{\text{ft}^3} - 0.2640\ \frac{\text{lbm}}{\text{ft}^3}\right) \\ \times\left(4.17\times 10^8\ \frac{\text{ft}}{\text{hr}^2}\right)\left(871.3\ \frac{\text{Btu}}{\text{lbm}}\right) \\ \times\left(0.392\ \frac{\text{Btu}}{\text{hr-ft-}^\circ\text{F}}\right)^3\end{array}}{(0.083\text{ ft})\left(0.392\ \frac{\text{lbm}}{\text{ft-hr}}\right)(350^\circ\text{F} - 330^\circ\text{F})}\right)^{1/4} \\ &= 2320\text{ Btu/hr-ft}^2\text{-}^\circ\text{F} \end{aligned}$$

From tableMERM36007 (also *NCEES Handbook* table “Physical Properties of Metals at 68°F (U.S. Units)”), for constantan, $k = 13.1$ Btu-ft/hr-ft^2-°F.

From equationMERM36069 (also *NCEES Handbook:* Combination of Heat-Transfer Mechanisms), the overall heat transfer coefficient based on the outside area is

$$\begin{aligned} \frac{1}{U_o} &= \frac{1}{h_o} + \left(\frac{r_o}{k_{\text{tube}}}\right)\ln\frac{r_o}{r_i} + \frac{r_o}{r_i h_i} \\ r_o &= \frac{d_o}{2} = \frac{1\text{ in}}{(2)\left(12\ \frac{\text{in}}{\text{ft}}\right)} = 0.0417\text{ ft} \\ r_i &= \frac{d_i}{2} = \frac{0.9\text{ in}}{(2)\left(12\ \frac{\text{in}}{\text{ft}}\right)} = 0.0375\text{ ft} \\ U_o &= \frac{1}{\begin{array}{l}\frac{1}{2320\ \frac{\text{Btu}}{\text{hr-ft}^2\text{-}^\circ\text{F}}} \\ \quad + \left(\frac{0.0417\text{ ft}}{13.1\ \frac{\text{Btu-ft}}{\text{hr-ft}^2\text{-}^\circ\text{F}}}\right)\ln\left(\frac{0.0417\text{ ft}}{0.0375\text{ ft}}\right) \\ \quad + \frac{0.0417\text{ ft}}{(0.0375\text{ ft})\left(815\ \frac{\text{Btu}}{\text{hr-ft}^2\text{-}^\circ\text{F}}\right)}\end{array}} \\ &= 469\text{ Btu/hr-ft}^2\text{-}^\circ\text{F} \end{aligned}$$

For crossflow operation,



$$\Delta T_A = 350^\circ\text{F} - 70^\circ\text{F} = 280^\circ\text{F}$$
$$\Delta T_B = 350^\circ\text{F} - 190^\circ\text{F} = 160^\circ\text{F}$$

From equationMERM36067 (also *NCEES Handbook:* Log-Mean Temperature Difference), the logarithmic mean temperature difference is

$$\Delta T_{\text{lm}} = \frac{\Delta T_A - \Delta T_B}{\ln \dfrac{\Delta T_A}{\Delta T_B}} = \frac{280^\circ\text{F} - 160^\circ\text{F}}{\ln \dfrac{280^\circ\text{F}}{160^\circ\text{F}}} = 214.4^\circ\text{F}$$

The heat transfer is known; therefore, the outside area can be calculated from equationMERM36068 (also *NCEES Handbook:* Combination of Heat-Transfer Mechanisms).

$$Q = U_o A_o F_c \Delta T_{\text{lm}}$$

For steam condensation, the temperature of steam remains constant. Therefore, $F_c = 1$.

$$\begin{aligned} A_o &= \frac{352{,}447 \ \dfrac{\text{Btu}}{\text{hr}}}{\left(469 \ \dfrac{\text{Btu}}{\text{hr-ft}^2\text{-}^\circ\text{F}}\right)(1)(214.4^\circ\text{F})} \\ &= 3.5 \ \text{ft}^2 \end{aligned}$$

At this point, the assumption that $T_{\text{sat},v} - T_s = 20°\text{F}$ could be checked using $Q = U_{\text{partial}} A_o \Delta T_{\text{partial}}$, working from the inside (at 130°F) to the outside (at T_s).

The answer is (A).

SI Solution

The bulk temperature of the water is

$$T_b = \tfrac{1}{2}(T_{\text{in}} + T_{\text{out}}) = \left(\frac{1}{2}\right)(21^\circ\text{C} + 90^\circ\text{C}) = 55.5^\circ\text{C}$$

From appendixMERM35B (also *NCEES Handbook* table “Physical Properties of Liquid Water (SI Units)”), the properties of water at 55.5°C are

$$\begin{aligned} c_p &= 4.186 \ \text{kJ/kg·K} \\ \rho &= 986.6 \ \text{kg/m}^3 \\ \mu &= 0.523 \times 10^{-3} \ \text{kg/m·s} \\ k &= 0.6503 \ \text{W/m·K} \\ \text{Pr} &= 3.37 \end{aligned}$$

The heat transfer is found from the temperature gain of the water.

$$\begin{aligned} Q &= \dot{m} c_p \Delta T \\ &= \left(0.368 \ \frac{\text{kg}}{\text{s}}\right)\left(4.186 \ \frac{\text{kJ}}{\text{kg·K}}\right)\left(1000 \ \frac{\text{J}}{\text{kJ}}\right) \\ &\quad \times (90^\circ\text{C} - 21^\circ\text{C}) \\ &= 106\,291 \ \text{W} \end{aligned}$$

As in *NCEES Handbook* table “Dimensionless Numbers,” the Reynolds number is

$$
\begin{aligned}
\mathrm{Re} &= \frac{\rho \mathrm{v} D}{\mu} \\
&= \frac{\left(986.6\ \frac{\mathrm{kg}}{\mathrm{m}^3}\right)\left(0.9\ \frac{\mathrm{m}}{\mathrm{s}}\right)(2.29\ \mathrm{cm})}{\left(0.523 \times 10^{-3}\ \frac{\mathrm{kg}}{\mathrm{m}\cdot\mathrm{s}}\right)\left(100\ \frac{\mathrm{cm}}{\mathrm{m}}\right)} \\
&= 3.89 \times 10^4
\end{aligned}
$$

From equationMERM36033 (also *NCEES Handbook:* Free/Forced Heat-Transfer Coefficients/Correlations), the film coefficient is

$$
\begin{aligned}
h &= 0.023\,\mathrm{Re}^{0.8}\mathrm{Pr}^n\left(\frac{k}{d}\right) \\
&= (0.023)\left(3.89 \times 10^4\right)^{0.8}(3.37)^{1/3} \\
&\quad \times \left(\frac{\left(0.6503\ \frac{\mathrm{W}}{\mathrm{m}\cdot\mathrm{K}}\right)\left(100\ \frac{\mathrm{cm}}{\mathrm{m}}\right)}{2.29\ \mathrm{cm}}\right) \\
&= 4601\ \mathrm{W/m^2\cdot K}
\end{aligned}
$$

The saturation temperature for 923 kPa steam is 176.4°C. Assume the wall is 10°C lower (or 166.4°C). The film properties are evaluated at the average of the wall and saturation temperatures.

$$
\begin{aligned}
T_h &= \tfrac{1}{2}(T_{\mathrm{sat},v} + T_s) = \left(\frac{1}{2}\right)(176.4^\circ\mathrm{C} + 166.4^\circ\mathrm{C}) \\
&= 171.4^\circ\mathrm{C}
\end{aligned}
$$

Film properties are obtained from appendixMERM35B (also *NCEES Handbook* table “Physical Properties of Liquid Water (SI Units)”), for liquid water and appendixMERM24N (also *NCEES Handbook* table “Saturated Steam (SI Units)—Temperature Table”) for vapor.

$$
\begin{aligned}
k_{171.4^\circ\mathrm{C}} &= 0.6745\ \mathrm{W/m\cdot K} \\
\mu_{171.4^\circ\mathrm{C}} &= 0.1712 \times 10^{-3}\ \mathrm{kg/m\cdot s} \\
\rho_{l,171.4^\circ\mathrm{C}} &= \frac{1}{v_{f,171.4^\circ\mathrm{C}}} \\
&= \frac{(1)\left(100\ \frac{\mathrm{cm}}{\mathrm{m}}\right)^3}{\left(1.1161\ \frac{\mathrm{cm}^3}{\mathrm{g}}\right)\left(1000\ \frac{\mathrm{g}}{\mathrm{kg}}\right)} \\
&= 896.0\ \mathrm{kg/m^3} \\
\rho_{v,171.4^\circ\mathrm{C}} &= \frac{1}{v_{g,171.4^\circ\mathrm{C}}} \\
&= \frac{(1)\left(100\ \frac{\mathrm{cm}}{\mathrm{m}}\right)^3}{\left(235.3\ \frac{\mathrm{cm}^3}{\mathrm{g}}\right)\left(1000\ \frac{\mathrm{g}}{\mathrm{kg}}\right)} \\
&= 4.25\ \mathrm{kg/m^3}
\end{aligned}
$$

$$
\begin{aligned}
h_{fg,923\ \mathrm{kPa}} &= \left(2026.8\ \frac{\mathrm{kJ}}{\mathrm{kg}}\right)\left(1000\ \frac{\mathrm{J}}{\mathrm{kg}}\right) \\
&= 2.0268 \times 10^6\ \mathrm{J/kg} \\
d &= \frac{2.54\ \mathrm{cm}}{100\ \frac{\mathrm{cm}}{\mathrm{m}}} = 0.0254\ \mathrm{m}
\end{aligned}
$$

From equationMERM35027 (also *NCEES Handbook:* Condensation), the film coefficient is

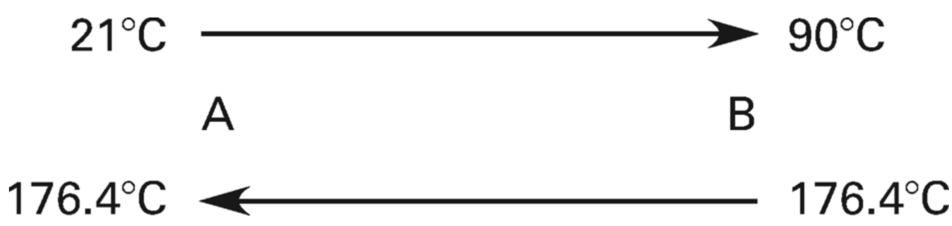
$$
\begin{aligned}
h_o &= 0.725\left(\frac{\rho_l\left(\rho_l-\rho_v\right) g h_{fg} k_l^3}{d \mu_l\left(T_{\text{sat},v}-T_s\right)}\right)^{1/4} \\
&= (0.725) \\
&\quad \times\left(\frac{\begin{array}{c}\left(896\ \frac{\text{kg}}{\text{m}^3}\right)\left(896\ \frac{\text{kg}}{\text{m}^3}-4.25\ \frac{\text{kg}}{\text{m}^3}\right)\left(9.81\ \frac{\text{m}}{\text{s}^2}\right) \\ \times\left(2.0268\times 10^6\ \frac{\text{J}}{\text{kg}}\right)\left(0.6745\ \frac{\text{W}}{\text{m}\cdot\text{K}}\right)^3\end{array}}{\begin{array}{c}(0.0254\ \text{m})\left(0.1712\times 10^{-3}\ \frac{\text{kg}}{\text{m}\cdot\text{s}}\right) \\ \times\left(176.4^\circ\text{C}-166.4^\circ\text{C}\right)\end{array}}\right)^{1/4} \\
&= 13\,266\ \text{W/m}^2\cdot\text{K}
\end{aligned}
$$

From tableMERM36007 and the table footnote (also *NCEES Handbook* table "Physical Properties of Metals at 20°C (SI Units)"), for constantan, the thermal conductivity is 22.7 W/m·K.

From equationMERM36069 (also *NCEES Handbook:* Combination of Heat-Transfer Mechanisms), the overall heat transfer coefficient based on outside area is

$$
\begin{aligned}
\frac{1}{U_o} &= \frac{1}{h_o}+\left(\frac{r_o}{k_{\text{tube}}}\right)\ln\frac{r_o}{r_i}+\frac{r_o}{r_i h_i} \\
r_o &= \frac{d_o}{2} = \frac{2.54\ \text{cm}}{(2)\left(100\ \frac{\text{cm}}{\text{m}}\right)} = 0.0127\ \text{m} \\
r_i &= \frac{d_i}{2} = \frac{0.0229\ \text{m}}{2} = 0.0115\ \text{m} \\
U_o &= \frac{1}{\begin{array}{c}\dfrac{1}{13\,266\ \frac{\text{W}}{\text{m}^2\cdot\text{K}}}+\left(\dfrac{0.0127\ \text{m}}{33.93\ \frac{\text{W}}{\text{m}\cdot\text{K}}}\right)\ln\left(\dfrac{0.0127\ \text{m}}{0.0115\ \text{m}}\right) \\ +\dfrac{0.0127\ \text{m}}{(0.0115\ \text{m})\left(4601\ \frac{\text{W}}{\text{m}^2\cdot\text{K}}\right)}\end{array}} \\
&= 2836\ \text{W/m}^2\cdot\text{K}
\end{aligned}
$$

For crossflow operation,



$$
\begin{aligned}
\Delta T_A &= 176.4^\circ\text{C} - 21^\circ\text{C} = 155.4^\circ\text{C} \\
\Delta T_B &= 176.4^\circ\text{C} - 90^\circ\text{C} = 86.4^\circ\text{C}
\end{aligned}
$$

From equationMERM36067 (also *NCEES Handbook:* Log-Mean Temperature Difference), the logarithmic mean temperature difference is

$$
\begin{aligned}
\Delta T_{\text{lm}} &= \frac{\Delta T_A-\Delta T_B}{\ln\dfrac{\Delta T_A}{\Delta T_B}} = \frac{155.4^\circ\text{C}-86.4^\circ\text{C}}{\ln\dfrac{155.4^\circ\text{C}}{86.4^\circ\text{C}}} \\
&= 117.5^\circ\text{C}
\end{aligned}
$$

The heat transfer is known; therefore, the outside area can be calculated from equationMERM36068 (also *NCEES Handbook:* Combination of Heat-Transfer Mechanisms).

$$Q = U_o A_o F_c \Delta T_{\text{lm}}$$

For steam condensation, the temperature of steam remains constant. Therefore, $F_c = 1$.

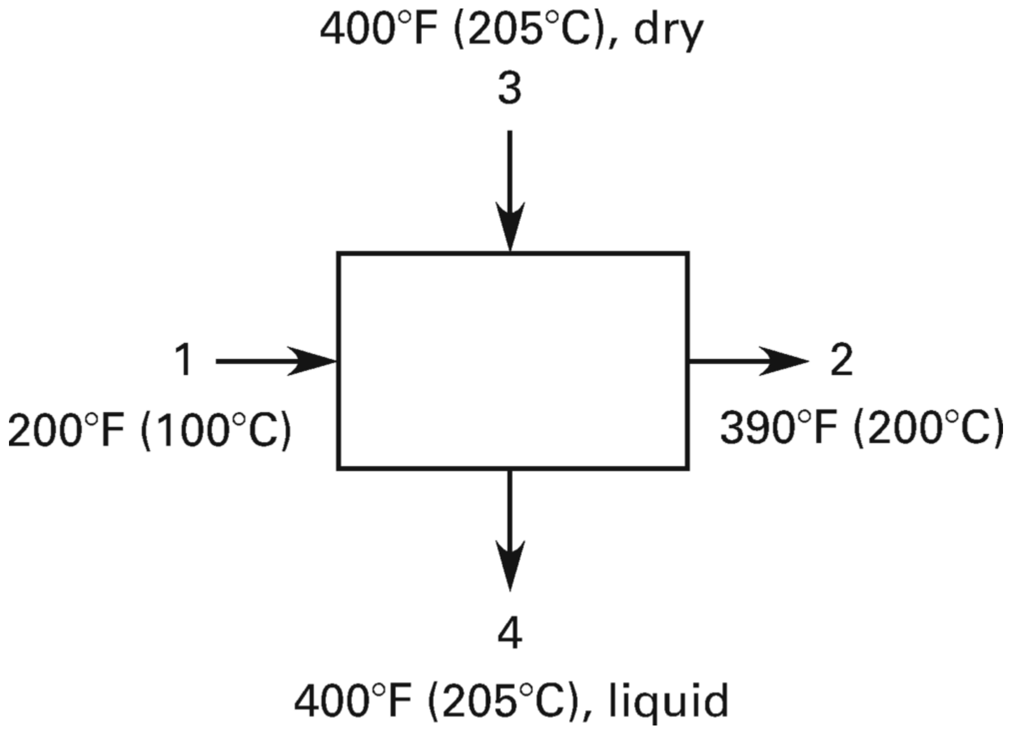
$$\begin{aligned} A_o &= \frac{106\,291 \text{ W}}{\left(2836 \ \frac{\text{W}}{\text{m}^2\cdot\text{K}}\right)(1)\,(117.5^\circ\text{C})} \\ &= 0.319 \text{ m}^2 \quad (0.30 \text{ m}^2) \end{aligned}$$

At this point, the assumption that $T_{\text{sat},\upsilon} - T_s = 10°\text{C}$ could be checked using $Q = U_{\text{partial}} A_o \Delta T_{\text{partial}}$, working from the inside (at 55°C) to the outside (at T_s).

The answer is (A).

8.

Use the illustration shown for both the customary U.S. and SI solutions.



Customary U.S. Solution

From appendixMERM24A (also *NCEES Handbook* table "Saturated Steam (U.S. Units)—Temperature Table") the enthalpy of each point is

$$\begin{aligned} h_1 &= 168.13 \text{ Btu/lbm} \\ h_2 &= 364.3 \text{ Btu/lbm} \\ h_3 &= 1201.4 \text{ Btu/lbm} \\ h_4 &= 375.1 \text{ Btu/lbm} \end{aligned}$$

The heat transfer is due to the temperature gain of water.

$$\begin{aligned} Q &= \dot{m}\,(h_2 - h_1) \\ &= \left(500{,}000 \ \frac{\text{lbm}}{\text{hr}}\right)\left(364.3 \ \frac{\text{Btu}}{\text{lbm}} - 168.13 \ \frac{\text{Btu}}{\text{lbm}}\right) \\ &= 9.809 \times 10^7 \text{ Btu/hr} \end{aligned}$$

The mass flow rate per tube is

$$\dot{m}_{\text{tube}} = \rho A_{\text{tube}} \text{v}$$

Select ϱ where the specific volume is greatest (at 390°F). From appendixMERM24A (also *NCEES Handbook* table "Saturated Steam (U.S. Units)—Temperature Table"),

$$\begin{aligned} \upsilon_f &= 0.01850\ \text{ft}^3/\text{lbm} \\ \rho &= \frac{1}{\upsilon_f} = \frac{1}{0.01850\ \frac{\text{ft}^3}{\text{lbm}}} \\ &= 54.05\ \text{lbm/ft}^3 \end{aligned}$$

The inside diameter of the tube is

$$\begin{aligned} d_i &= d_o - 2\,(\text{wall}) \\ &= \frac{7}{8}\ \text{in} - (2)\left(\frac{1}{16}\ \text{in}\right) \\ &= 0.750\ \text{in} \end{aligned}$$

The area per tube is

$$\begin{aligned} A_{\text{tube}} &= \left(\frac{\pi}{4}\right) d_i^2 = \frac{\left(\frac{\pi}{4}\right)(0.750\ \text{in})^2}{\left(12\ \frac{\text{in}}{\text{ft}}\right)^2} \\ &= 0.003068\ \text{ft}^2 \\ \dot{m}_{\text{tube}} &= \left(54.05\ \frac{\text{lbm}}{\text{ft}^3}\right)\left(0.003068\ \text{ft}^2\right) \\ &\quad \times \left(5\ \frac{\text{ft}}{\text{sec}}\right)\left(3600\ \frac{\text{sec}}{\text{hr}}\right) \\ &= 2985\ \text{lbm/hr} \end{aligned}$$

The required number of tubes is

$$N = \frac{500{,}000\ \frac{\text{lbm}}{\text{hr}}}{2985\ \frac{\text{lbm}}{\text{hr}}} = 167.5 \quad (170)$$

The answer is (D).

SI Solution

From appendixMERM24N (also *NCEES Handbook* table "Saturated Steam (SI Units)—Temperature Table"), the enthalpy of each point is

$$\begin{aligned} h_1 &= 419.17\ \text{kJ/kg} \\ h_2 &= 852.27\ \text{kJ/kg} \\ h_3 &= 2794.8\ \text{kJ/kg} \\ h_4 &= 874.88\ \text{kJ/kg} \end{aligned}$$

The heat transfer is due to the temperature gain of water.

$$\begin{aligned} Q &= \dot{m}\,(h_2 - h_1) \\ &= \left(60\ \frac{\text{kg}}{\text{s}}\right)\left(852.27\ \frac{\text{kJ}}{\text{kg}} - 419.17\ \frac{\text{kJ}}{\text{kg}}\right) \\ &= 25\,986\ \text{kW} \end{aligned}$$

The mass flow rate per tube is

$$\dot{m}_{\text{tube}} = \rho A_{\text{tube}} \text{v}$$

Select ϱ where the specific volume is greatest (at 200°C). From appendixMERM24N (also *NCEES Handbook* table "Saturated Steam (SI Units)—Temperature Table"),

$$\begin{aligned} v_f &= \frac{\left(1.1565\ \frac{\mathrm{cm}^3}{\mathrm{g}}\right)\left(1000\ \frac{\mathrm{g}}{\mathrm{kg}}\right)}{\left(100\ \frac{\mathrm{cm}}{\mathrm{m}}\right)^3} \\ &= 1.1565 \times 10^{-3}\ \mathrm{m}^3/\mathrm{kg} \\ \rho &= \frac{1}{v_f} = \frac{1}{1.1565 \times 10^{-3}\ \frac{\mathrm{m}^3}{\mathrm{kg}}} \\ &= 864.7\ \mathrm{kg}/\mathrm{m}^3 \end{aligned}$$

The inside diameter of the tube is

$$\begin{aligned} d_i &= d_o - 2\,(\mathrm{wall}) \\ &= \frac{2.2\ \mathrm{cm} - \frac{(2)\,(1.6\ \mathrm{mm})}{10\ \frac{\mathrm{mm}}{\mathrm{cm}}}}{100\ \frac{\mathrm{cm}}{\mathrm{m}}} \\ &= 0.0188\ \mathrm{m} \end{aligned}$$

The area per tube is

$$\begin{aligned} A_{\mathrm{tube}} &= \left(\frac{\pi}{4}\right) d_i^2 = \left(\frac{\pi}{4}\right)(0.0188\ \mathrm{m})^2 \\ &= 2.776 \times 10^{-4}\ \mathrm{m}^2 \\ \dot{m}_{\mathrm{tube}} &= \left(864.7\ \frac{\mathrm{kg}}{\mathrm{m}^3}\right)\left(2.776 \times 10^{-4}\ \mathrm{m}^2\right)\left(1.5\ \frac{\mathrm{m}}{\mathrm{s}}\right) \\ &= 0.360\ \mathrm{kg/s} \end{aligned}$$

The required number of tubes is

$$N = \frac{60\ \frac{\mathrm{kg}}{\mathrm{s}}}{0.360\ \frac{\mathrm{kg}}{\mathrm{s}}} = 166.7 \quad (170)$$

The answer is (D).
9.

Customary U.S. Solution

The water's bulk temperature is

$$T_{b,\mathrm{water}} = \left(\frac{1}{2}\right)(70^\circ\mathrm{F} + 140^\circ\mathrm{F}) = 105^\circ\mathrm{F}$$

The fluid properties at 105°F are obtained from appendixMERM35A (also *NCEES Handbook* table "Physical Properties of Liquid Water (U.S. Units)").

$$\begin{aligned} \rho_{105^\circ\mathrm{F}} &= 61.92\ \mathrm{lbm/ft}^3 \\ c_{p,105^\circ\mathrm{F}} &= 0.998\ \mathrm{Btu/lbm\text{-}^\circ F} \end{aligned}$$

The mass flow rate of water is

$$\begin{aligned}\dot{m}_{\text{water}} &= \dot{V}\rho \\ &= \frac{\left(100\ \frac{\text{gal}}{\text{min}}\right)\left(60\ \frac{\text{min}}{\text{hr}}\right)\left(61.92\ \frac{\text{lbm}}{\text{ft}^3}\right)}{7.48\ \frac{\text{gal}}{\text{ft}^3}} \\ &= 49{,}668\ \text{lbm/hr}\end{aligned}$$

The heat transfer is found from the temperature gain of the water.

$$\begin{aligned}Q_{\text{clean}} &= \dot{m}c_p\Delta T \\ &= \left(49{,}668\ \frac{\text{lbm}}{\text{hr}}\right)\left(0.998\ \frac{\text{Btu}}{\text{lbm-}^\circ\text{F}}\right) \\ &\quad \times (140^\circ\text{F} - 70^\circ\text{F}) \\ &= 3.470 \times 10^6\ \text{Btu/hr} \\ \Delta T_A &= 230^\circ\text{F} - 70^\circ\text{F} = 160^\circ\text{F} \\ \Delta T_B &= 230^\circ\text{F} - 140^\circ\text{F} = 90^\circ\text{F}\end{aligned}$$

From equationMERM36067 (also *NCEES Handbook:* Log-Mean Temperature Difference), the logarithmic mean temperature difference is

$$\Delta T_{\text{lm}} = \frac{\Delta T_A - \Delta T_B}{\ln \frac{\Delta T_A}{\Delta T_B}} = \frac{160^\circ\text{F} - 90^\circ\text{F}}{\ln \frac{160^\circ\text{F}}{90^\circ\text{F}}} = 121.66^\circ\text{F}$$

The heat transfer is known. Therefore, the overall heat transfer coefficient can be calculated from equationMERM36068 (also *NCEES Handbook:* Combination of Heat-Transfer Mechanisms).

$$Q_{\text{clean}} = U_{\text{clean}} A F_c \Delta T_{\text{lm}}$$

For steam condensation, the temperature of steam remains constant. Therefore, $F_c = 1$.

$$\begin{aligned}U_{\text{clean}} &= \frac{Q_{\text{clean}}}{AF_c\Delta T_{\text{lm}}} = \frac{3.470 \times 10^6\ \frac{\text{Btu}}{\text{hr}}}{(50\ \text{ft}^2)(1)(121.66^\circ\text{F})} \\ &= 570.4\ \text{Btu/hr-ft}^2\text{-}^\circ\text{F}\end{aligned}$$

After fouling,

$$\begin{aligned}Q_{\text{fouled}} &= \left(49{,}668\ \frac{\text{lbm}}{\text{hr}}\right)\left(0.998\ \frac{\text{Btu}}{\text{lbm-}^\circ\text{F}}\right) \\ &\quad \times (122^\circ\text{F} - 70^\circ\text{F}) \\ &= 2.578 \times 10^6\ \text{Btu/hr} \\ \Delta T_B &= 230^\circ\text{F} - 122^\circ\text{F} = 108^\circ\text{F} \\ \Delta T_A &= 230^\circ\text{F} - 70^\circ\text{F} = 160^\circ\text{F}\end{aligned}$$

From equationMERM36067 (also *NCEES Handbook:* Combination of Heat-Transfer Mechanisms), the logarithmic mean temperature difference is

$$\begin{aligned}\Delta T_{\text{lm}} &= \frac{\Delta T_A - \Delta T_B}{\ln \frac{\Delta T_A}{\Delta T_B}} = \frac{160^\circ\text{F} - 108^\circ\text{F}}{\ln \frac{160^\circ\text{F}}{108^\circ\text{F}}} = 132.3^\circ\text{F} \\ U_{\text{fouled}} &= \frac{2.578 \times 10^6\ \frac{\text{Btu}}{\text{hr}}}{(50\ \text{ft}^2)(1)(132.3^\circ\text{F})} = 389.7\ \text{Btu/hr-ft}^2\text{-}^\circ\text{F}\end{aligned}$$

From equationMERM36074 (also *NCEES Handbook:* Fouling Factors), the fouling factor is

$$
\begin{aligned}
R_f &= \frac{1}{U_{\text{fouled}}} - \frac{1}{U_{\text{clean}}} \\
&= \frac{1}{389.7\ \dfrac{\text{Btu}}{\text{hr-ft}^2\text{-}^\circ\text{F}}} - \frac{1}{570.4\ \dfrac{\text{Btu}}{\text{hr-ft}^2\text{-}^\circ\text{F}}} \\
&= 0.000813\ \text{hr-ft}^2\text{-}^\circ\text{F/Btu} \quad (0.0008\ \text{hr-ft}^2\text{-}^\circ\text{F/Btu})
\end{aligned}
$$

The answer is (B).

SI Solution

The water's bulk temperature is

$$
T_{b,\text{water}} = \left(\frac{1}{2}\right)(21^\circ\text{C} + 60^\circ\text{C}) = 40.5^\circ\text{C}
$$

The fluid properties at 40.5°C are obtained from appendixMERM35B (also *NCEES Handbook* table “Physical Properties of Liquid Water (SI Units)”).

$$
\begin{aligned}
\rho_{40.5^\circ\text{C}} &= 993.5\ \text{kg/m}^3 \\
c_{p,40.5^\circ\text{C}} &= 4.183\ \text{kJ/kg·K}
\end{aligned}
$$

The mass flow rate of water is

$$
\dot{m}_{\text{water}} = \dot{V}\rho = \frac{\left(6.3\ \dfrac{\text{L}}{\text{s}}\right)\left(993.5\ \dfrac{\text{kg}}{\text{m}^3}\right)}{1000\ \dfrac{\text{L}}{\text{m}^3}} = 6.26\ \text{kg/s}
$$

The heat transfer is found from the temperature gain of the water.

$$
\begin{aligned}
Q_{\text{clean}} &= \dot{m}c_p\Delta T \\
&= \left(6.26\ \frac{\text{kg}}{\text{s}}\right)\left(4.183\ \frac{\text{kJ}}{\text{kg·K}}\right)\left(1000\ \frac{\text{J}}{\text{kJ}}\right) \\
&\quad \times (60^\circ\text{C} - 21^\circ\text{C}) \\
&= 1.021 \times 10^6\ \text{W} \\
\Delta T_A &= 110^\circ\text{C} - 21^\circ\text{C} = 89^\circ\text{C} \\
\Delta T_B &= 110^\circ\text{C} - 60^\circ\text{C} = 50^\circ\text{C}
\end{aligned}
$$

From equationMERM36067 (also *NCEES Handbook:* Log-Mean Temperature Difference), the logarithmic mean temperature difference is

$$
\Delta T_{\text{lm}} = \frac{\Delta T_A - \Delta T_B}{\ln \dfrac{\Delta T_A}{\Delta T_B}} = \frac{89^\circ\text{C} - 50^\circ\text{C}}{\ln \dfrac{89^\circ\text{C}}{50^\circ\text{C}}} = 67.64^\circ\text{C}
$$

The heat transfer is known. Therefore, the overall heat transfer coefficient can be calculated from equationMERM36068 (also *NCEES Handbook:* Combination of Heat-Transfer Mechanisms).

$$
Q_{\text{clean}} = U_{\text{clean}} A F_c \Delta T_{\text{lm}}
$$

For steam condensation, the temperature of steam remains constant. Therefore, $F_c = 1$.

$$
\begin{aligned}
U_{\text{clean}} &= \frac{Q_{\text{clean}}}{AF_c\Delta T_{\text{lm}}} \\
&= \frac{1.021 \times 10^6\ \text{W}}{(4.7\ \text{m}^2)(1)(67.64^\circ\text{C})} \\
&= 3211.6\ \text{W/m}^2\text{·K}
\end{aligned}
$$

After fouling,

$$Q_{\text{fouled}} = \left(6.26\ \frac{\text{kg}}{\text{s}}\right)\left(4.183\ \frac{\text{kJ}}{\text{kg·K}}\right)\left(1000\ \frac{\text{J}}{\text{kJ}}\right) \times (50^\circ\text{C} - 21^\circ\text{C})$$

$$= 7.594 \times 10^5\ \text{W}$$

$$\Delta T_A = 110^\circ\text{C} - 21^\circ\text{C} = 89^\circ\text{C}$$

$$\Delta T_B = 110^\circ\text{C} - 50^\circ\text{C} = 60^\circ\text{C}$$

From equationMERM36067 (also *NCEES Handbook:* Log-Mean Temperature Difference), the logarithmic mean temperature difference is

$$\Delta T_{\text{lm}} = \frac{\Delta T_A - \Delta T_B}{\ln \frac{\Delta T_A}{\Delta T_B}} = \frac{89^\circ\text{C} - 60^\circ\text{C}}{\ln \frac{89^\circ\text{C}}{60^\circ\text{C}}} = 73.55^\circ\text{C}$$

$$U_{\text{fouled}} = \frac{7.594 \times 10^5\ \text{W}}{(4.7\ \text{m}^2)(1)(73.55^\circ\text{C})} = 2196.8\ \text{W/m}^2\text{·K}$$

From equationMERM36074 (also *NCEES Handbook:* Fouling Factors), the fouling factor is

$$R_f = \frac{1}{U_{\text{fouled}}} - \frac{1}{U_{\text{clean}}}$$

$$= \frac{1}{2196.8\ \frac{\text{W}}{\text{m}^2\text{·K}}} - \frac{1}{3211.6\ \frac{\text{W}}{\text{m}^2\text{·K}}}$$

$$= 0.000144\ \text{m}^2\text{·K/W} \quad (0.0001\ \text{m}^2\text{·K/W})$$

The answer is (B).

10.

Heat exchanger tubing has a constant cross-sectional area, so the flow velocity within a heat exchanger is constant. Since distance traveled at constant velocity is proportional to time, and since both fluids have the same specific heat, the heat transfer rate-distance and heat transfer rate-time profiles are identical.

The answer is (A).

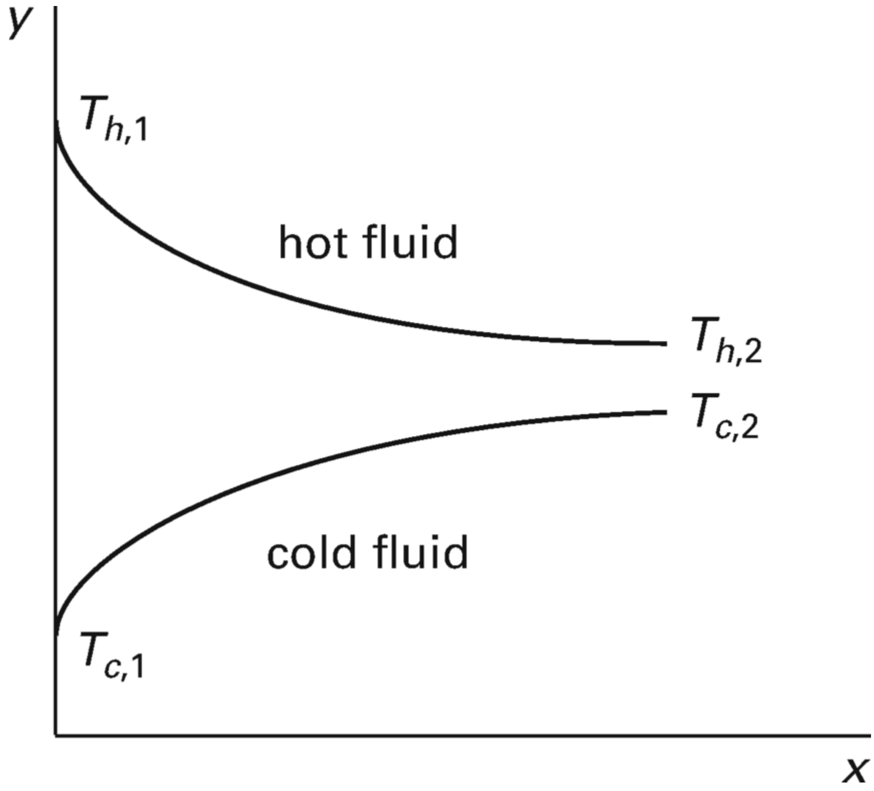
11.

At any point in the heat exchanger, the instantaneous heat gain by the cold water is equal to the instantaneous heat loss by the hot water. The heat transfer rates are the same. At that point, the two fluids will have traveled different distances. For example, at one entrance, the hot water will have traveled very little distance, while the cold water will have traveled almost the entire length of the heat exchanger (e.g., reversed end-to-end). However, the heat transfer rates will be the same. (It could be argued that from the standpoint of the thermodynamic sign convention, hot water has a negative heat transfer rate while cold water has a positive heat transfer rate. In that case, the temperature profiles would be reversed end-to-end *and* inverted top-to-bottom. However, that is not one of the options.)

The answer is (B).

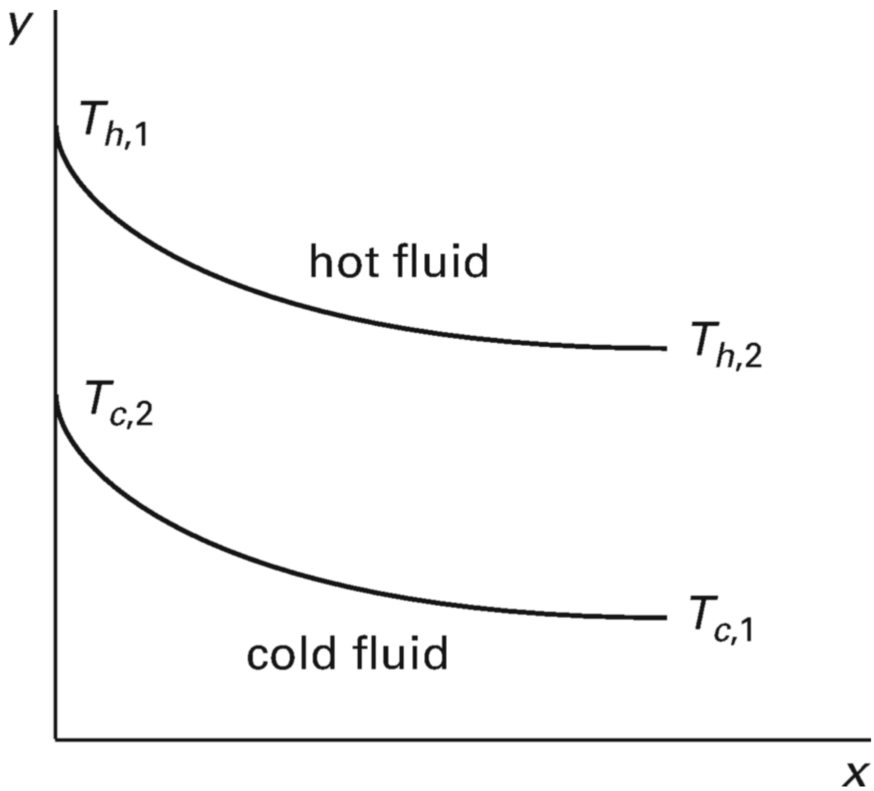
12.

At the entrance, as a result of the large temperature difference, the hot water loses heat rapidly, and the cold water gains heat rapidly. At the exit, the hot water loses heat more slowly while the cold water gains heat more slowly. Thus, the plot is inverted top-to-bottom.



The answer is (D).
13.

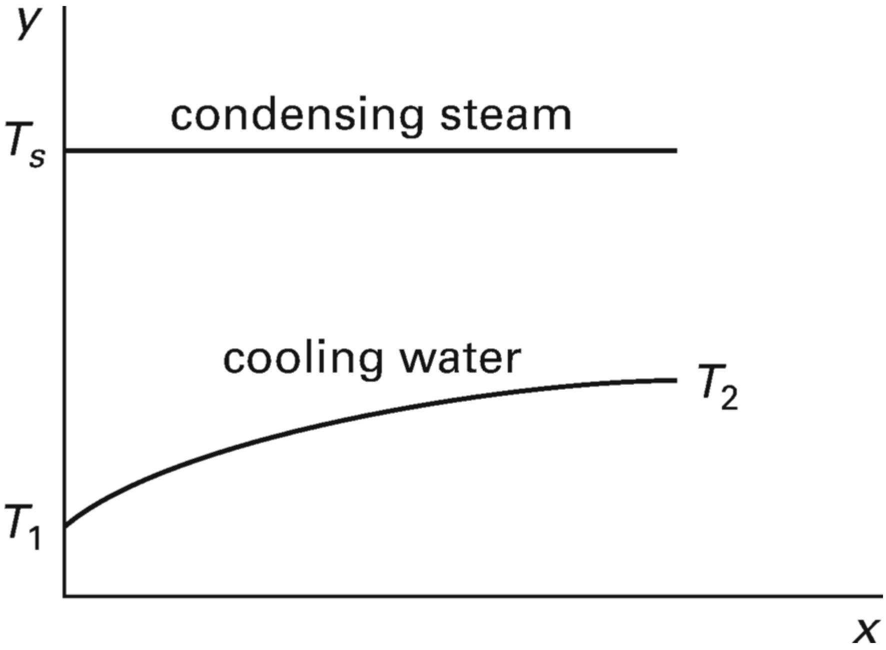
The temperature difference between the two water flows will essentially be constant.



The answer is (A).

14.

Since the steam enters the heat exchanger saturated and is not subcooled, the steam temperature remains constant at the saturation temperature throughout.



The answer is (D).

15.

"Duty" is the amount of energy that the heat exchanger transfers per unit time.

The answer is (D).

16.

The perimeter of the cylindrical fin is

$$P = \pi d = \frac{\pi\,(0.5\ \text{in})}{12\ \frac{\text{in}}{\text{ft}}} = 0.13\ \text{ft}$$

The cross-sectional area at the base of the cylindrical fin is

$$A_b = \frac{\pi d^2}{4} = \frac{\pi(0.5\ \text{in})^2}{(4)\left(12\ \frac{\text{in}}{\text{ft}}\right)^2} = 0.0014\ \text{ft}^2$$

From equationMERM34071 (also *NCEES Handbook:* Combination of Heat-Transfer Mechanisms), the heat transfer is

$$\begin{aligned} Q &= \sqrt{hPkA}\,(T_b - T_\infty)\tanh\left(\left(L + \tfrac{A}{P}\right)\sqrt{\tfrac{hP}{kA}}\right) \\ &= \sqrt{\left(1.3\ \frac{\text{Btu}}{\text{hr-ft}^2\text{-}^\circ\text{F}}\right)(0.13\ \text{ft})\left(128\ \frac{\text{Btu}}{\text{hr-ft-}^\circ\text{F}}\right)\left(0.0014\ \text{ft}^2\right)} \\ &\quad \times (350^\circ\text{F} - 75^\circ\text{F}) \\ &\quad \times \left(\tanh\left(\left(2\ \text{ft} + \frac{\left(0.0014\ \text{ft}^2\right)}{(0.13\ \text{ft})}\right)\sqrt{\frac{\left(1.3\ \frac{\text{Btu}}{\text{hr-ft}^2\text{-}^\circ\text{F}}\right)\times(0.13\ \text{ft})}{\left(128\ \frac{\text{Btu}}{\text{hr-ft-}^\circ\text{F}}\right)\times\left(0.0014\ \text{ft}^2\right)}}\right)\right) \\ &= 45.9\ \text{Btu/hr} \quad (46\ \text{Btu/hr}) \end{aligned}$$

The answer is (D).

17.

Customary U.S. Solution

From equationMERM35011, the film temperature of the air is

$$T_h = \frac{1}{2}(T_s + T_\infty) = \left(\frac{1}{2}\right)(100^\circ\text{F} + 150^\circ\text{F}) = 125^\circ\text{F}$$

From appendixMERM35C (also *NCEES Handbook* table "Temperature-Dependent Properties of Air at 14.7 psia (U.S. Units)"), the air properties at 125°F are

$$\begin{aligned} \nu &= 0.195 \times 10^{-3}\ \text{ft}^2/\text{sec} \\ k &= 0.0159\ \text{Btu/hr-ft-}^\circ\text{F} \\ \text{Pr} &= 0.72 \end{aligned}$$

As in *NCEES Handbook* table "Dimensionless Numbers," the Reynolds number based on the diameter, d, is

$$\begin{aligned} \text{Re}_d &= \frac{\text{v}d}{\nu} = \frac{\left(100\ \frac{\text{ft}}{\text{sec}}\right)(0.35\ \text{in})}{\left(0.195 \times 10^{-3}\ \frac{\text{ft}^2}{\text{sec}}\right)\left(12\ \frac{\text{in}}{\text{ft}}\right)} \\ &= 1.50 \times 10^4 \end{aligned}$$

From equationMERM36050 (also *NCEES Handbook:* Free/Forced Heat-Transfer Coefficients/Correlations), the film coefficient is

$$h = C_1(\text{Re}_d)^n\text{Pr}^{1/3}\left(\frac{k}{d}\right)$$

From tableMERM36003 (also *NCEES Handbook:* Free/Forced Heat-Transfer Coefficients/Correlations), $C_1 = 0.193$ and $n = 0.618$.

$$\begin{aligned} h &= (0.193)\left(1.50 \times 10^4\right)^{0.618}(0.72)^{1/3} \\ &\quad \times \left(\frac{\left(0.0159\ \frac{\text{Btu}}{\text{hr-ft-}^\circ\text{F}}\right)\left(12\ \frac{\text{in}}{\text{ft}}\right)}{0.35\ \text{in}}\right) \\ &= 35.9\ \text{Btu/hr-ft}^2\text{-}^\circ\text{F} \quad (36\ \text{Btu/hr-ft}^2\text{-}^\circ\text{F}) \end{aligned}$$

The answer is (A).

SI Solution

From equationMERM35011, the film temperature of the air is

$$T_h = \frac{1}{2}(T_s + T_\infty) = \left(\frac{1}{2}\right)(38^\circ\text{C} + 66^\circ\text{C}) = 52^\circ\text{C}$$

From appendixMERM35D (also *NCEES Handbook* table "Temperature-Dependent Properties of Air at 0.1 MPa (SI Units)"), the air properties at 52°C are

$$\begin{aligned} \rho &= 1.09\ \text{kg/m}^3 \\ \mu &= 1.966 \times 10^{-5}\ \text{kg/m·s} \\ k &= 0.02815\ \text{W/m·K} \\ \text{Pr} &= 0.703 \end{aligned}$$

As in *NCEES Handbook* table "Dimensionless Numbers," the Reynolds number based on the diameter, d, is

$$
\begin{aligned}
\mathrm{Re}_d &= \frac{\rho \mathrm{v} d}{\mu} \\
&= \frac{\left(1.09\ \frac{\mathrm{kg}}{\mathrm{m}^3}\right)\left(30\ \frac{\mathrm{m}}{\mathrm{s}}\right)(8.9\ \mathrm{mm})}{\left(1.966\times 10^{-5}\ \frac{\mathrm{kg}}{\mathrm{m{\cdot}s}}\right)\left(1000\ \frac{\mathrm{mm}}{\mathrm{m}}\right)} \\
&= 1.48\times 10^4
\end{aligned}
$$

From equationMERM36050 (also *NCEES Handbook:* Free/Forced Heat-Transfer Coefficients/Correlations), the film coefficient is

$$
h = C_1(\mathrm{Re}_d)^h \mathrm{Pr}^{1/3}\left(\frac{k}{d}\right)
$$

From tableMERM36003 (also *NCEES Handbook:* Free/Forced Heat-Transfer Coefficients/Correlations), $C_1 = 0.193$ and $n = 0.618$.

$$
\begin{aligned}
h &= (0.193)\left(1.48\times 10^4\right)^{0.618}(0.703)^{1/3} \\
&\quad\times\left(\frac{\left(0.02815\ \frac{\mathrm{W}}{\mathrm{m{\cdot}K}}\right)\left(1000\ \frac{\mathrm{mm}}{\mathrm{m}}\right)}{8.9\ \mathrm{mm}}\right) \\
&= 205.0\ \mathrm{W/m^2{\cdot}K} \quad (210\ \mathrm{W/m^2{\cdot}K})
\end{aligned}
$$

The answer is (A).