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Chapter 18. Natural Convection, Evaporation, and Condensation

Practice Problems

1.

The density of 87% wet steam at 50 psia (350 kPa) is most nearly

(A)

0.75 lbm/ft^3 (12 kg/m^3)

(B)

0.89 lbm/ft^3 (14 kg/m^3)

(C)

0.94 lbm/ft^3 (15 kg/m^3)

(D)

1.07 lbm/ft^3 (17 kg/m^3)

2.

The viscosity of 100°F (38°C) water in units of lbm/hr-ft (kg/s·m) is most nearly

(A)

1.2 lbm/ft-hr (0.00052 kg/m·s)

(B)

1.4 lbm/ft-hr (0.00060 kg/m·s)

(C)

1.6 lbm/ft-hr (0.00068 kg/m·s)

(D)

1.8 lbm/ft-hr (0.00077 kg/m·s)

3.

A fluid in a tank is maintained at 85°F (29°C) by a copper tube carrying hot water. The water decreases in temperature from 190°F (88°C) to 160°F (71°C) as it flows through the tube. The fluid's film coefficient must be calculated at the average temperature differential of this system. The temperature that this film coefficient should be calculated at is most nearly

(A)

130°F (54°C)

(B)

160°F (71°C)

(C)

175°F (79°C)

(D)

190°F (88°C)
4.

A bare, horizontal conductor with a circular cross section with an outside diameter of 0.6 in (1.5 cm) dissipates 8.0 W/ft (25 W/m). The conductor is cooled by free convection, and the surrounding air temperature is 60°F (15°C). The film temperature is 100 °F (38°C), the heat capacity ratio (C) is 0.85, and the thermal expansion coefficient of air (β) can be estimated at 0.0018 1/°F (0.00318 1/°C). Using the given relation,

$$Nu = C(GrPr)^{0.25}$$

the conductor's surface temperature is most nearly

(A)

85°F (29°C)

(B)

110°F (43°C)

(C)

130°F (50°C)

(D)

160°F (67°C)

Solutions

1.

Customary U.S. Solution

The steam is 87% wet, so the quality is $x = 0.13$.

From appendixMERM24B (also *NCEES Handbook* "Saturated Steam (U.S. Units)—Temperature Table") at 50 psia,

$$\begin{aligned} v_f &= 0.01727 \text{ ft}^3/\text{lbm} \\ v_g &= 8.517 \text{ ft}^3/\text{lbm} \end{aligned}$$

From equationMERM24043 (also *NCEES Handbook:* Properties for Two-Phase (Vapor-Liquid) Systems), the specific volume of steam is

$$\begin{aligned} v &= v_f + x v_{fg} \\ &= 0.01727 \, \frac{\text{ft}^3}{\text{lbm}} + (0.13)\left(8.517 \, \frac{\text{ft}^3}{\text{lbm}} - 0.01727 \, \frac{\text{ft}^3}{\text{lbm}}\right) \\ &= 1.122 \text{ ft}^3/\text{lbm} \end{aligned}$$

The density is

$$
\begin{aligned}
\rho &= \frac{1}{v} \\
&= \frac{1}{1.122\ \frac{\text{ft}^3}{\text{lbm}}} \\
&= 0.891\ \text{lbm/ft}^3 \quad (0.89\ \text{lbm/ft}^3)
\end{aligned}
$$

The answer is (B).

SI Solution

The steam is 87% wet, so the quality is $x = 0.13$.

From appendixMERM24O (also *NCEES Handbook* “Saturated Steam (SI Units)—Temperature Table”) at 350 kPa (350 bars),

$$
\begin{aligned}
v_f &= 1.0786\ \text{cm}^3/\text{g} \\
v_g &= 524.2\ \text{cm}^3/\text{g}
\end{aligned}
$$

From equationMERM24043 (also *NCEES Handbook:* Properties for Two-Phase (Vapor-Liquid) Systems), the specific volume of steam is

$$
\begin{aligned}
v &= v_f + x v_{fg} \\
&= 1.0786\ \frac{\text{cm}^3}{\text{g}} + (0.13)\left(524.2\ \frac{\text{cm}^3}{\text{g}}\right) \\
&= 69.22\ \text{cm}^3/\text{g}
\end{aligned}
$$

The density is

$$
\begin{aligned}
\rho &= \frac{1}{v} \\
&= \left(\frac{1}{69.22\ \frac{\text{cm}^3}{\text{g}}}\right)\left(\frac{\left(100\ \frac{\text{cm}}{\text{m}}\right)^3}{1000\ \frac{\text{g}}{\text{kg}}}\right) \\
&= 14.45\ \text{kg/m}^3 \quad (14\ \text{kg/m}^3)
\end{aligned}
$$

The answer is (B).
2.

Customary U.S. Solution

From appendixMERM35A (also *NCEES Handbook* table “Physical Properties of Liquid Water), the viscosity of water at 100°F is

$$
\begin{aligned}
\mu &= \left(0.458 \times 10^{-3}\ \frac{\text{lbm}}{\text{ft-sec}}\right)\left(3600\ \frac{\text{sec}}{\text{hr}}\right) \\
&= 1.6488\ \text{lbm/ft-hr} \quad (1.6\ \text{lbm/ft-hr})
\end{aligned}
$$

The answer is (C).

SI Solution

From appendixMERM35B (also *NCEES Handbook* table “Physical Properties of Liquid Water (SI Units)”), the viscosity of water at 38°C (use 37.8°C) is

$$
\mu = 0.682 \times 10^{-3}\ \text{kg/m·s} \quad (0.00068\ \text{kg/m·s})
$$

The answer is (C).

3.

Customary U.S. Solution

The midpoint tube temperature is

$$\begin{aligned} T_s &= \left(\frac{1}{2}\right)(190^\circ\mathrm{F} + 160^\circ\mathrm{F}) = 175^\circ\mathrm{F} \\ T_\infty &= 85^\circ\mathrm{F} \quad \text{[given]} \end{aligned}$$

Per equationMERM35011, the film coefficient should be evaluated at a temperature of

$$\begin{aligned} T_h &= \tfrac{1}{2}(T_s + T_\infty) \\ &= \left(\frac{1}{2}\right)(175^\circ\mathrm{F} + 85^\circ\mathrm{F}) \\ &= 130^\circ\mathrm{F} \end{aligned}$$

The answer is (A).

SI Solution

The midpoint tube temperature is

$$\begin{aligned} T_s &= \left(\frac{1}{2}\right)(88^\circ\mathrm{C} + 71^\circ\mathrm{C}) = 79.5^\circ\mathrm{C} \\ T_\infty &= 29^\circ\mathrm{C} \quad \text{[given]} \end{aligned}$$

Per equationMERM35011, the film coefficient should be evaluated at a temperature of

$$\begin{aligned} T_h &= \tfrac{1}{2}(T_s + T_\infty) \\ &= \left(\frac{1}{2}\right)(79.5^\circ\mathrm{F} + 29^\circ\mathrm{C}) \\ &= 54.3^\circ\mathrm{C} \quad (54^\circ\mathrm{C}) \end{aligned}$$

The answer is (A).
4.

Customary U.S. Solution

The heat loss per unit length is

$$\frac{Q}{L} = \left(8.0\ \frac{\mathrm{W}}{\mathrm{ft}}\right)\left(3.413\ \frac{\mathrm{Btu}}{\text{hr-W}}\right) = 27.3\ \text{Btu/hr-ft}$$

From appendixMERM35C (also *NCEES Handbook:* Temperature-Dependent Properties of Air (U.S. Customary Units)), the air properties at 100°F are

$$\begin{aligned} \mathrm{Pr} &= 0.72 \\ \frac{g\beta\rho^2}{\mu^2} &= 1.76 \times 10^6\ \frac{1}{\mathrm{ft}^3\text{-}^\circ\mathrm{F}} \end{aligned}$$

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

$$\mathrm{Gr} = L^3\left(\frac{g\beta\rho^2}{\mu^2}\right)\Delta T$$

The characteristic length is the wire diameter.

$$L = \frac{0.6\ \mathrm{in}}{12\ \dfrac{\mathrm{in}}{\mathrm{ft}}} = 0.05\ \mathrm{ft}$$

The temperature gradient is

$$\Delta T = T_s - T_\infty = T_{\text{wire}} - 60^\circ\text{F}$$

T_{wire} is unknown. Start by assuming $T_{\text{wire}} = 150°\text{F}$.

$$\begin{aligned}\text{Gr} &= (0.05\ \text{ft})^3 \left(1.76 \times 10^6\ \frac{1}{\text{ft}^3\text{-}^\circ\text{F}}\right)(150^\circ\text{F} - 60^\circ\text{F}) \\ &= 19{,}800 \\ \text{PrGr} &= (0.72)(19{,}800) = 14{,}256\end{aligned}$$

As in *NCEES Handbook* table “Forced Convection—External Flow,” the heat capacity ratio is $C = 0.85$ for this GrPr value. As in *NCEES Handbook* table “Temperature-Dependent Properties of Air at 14.7 psia (U.S. Units),” the thermal conductivity for air is $k = 0.015$ Btu/hr-ft-°F. The correlation equation 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. Use the diameter for the characteristic length.

$$\begin{aligned}\text{Nu} &= C(\text{GrPr})^{1/4} = \frac{hd}{k} \\ h &= \left(\frac{k}{d}\right) C(\text{GrPr})^{1/4} \\ &= \left(\frac{0.015\ \dfrac{\text{Btu}}{\text{hr-ft}^\circ\text{F}}}{0.05\ \text{ft}}\right)(0.85)(14{,}256)^{1/4} \\ &= 2.78\ \text{Btu/hr-ft}^2\text{-}^\circ\text{F}\end{aligned}$$

The heat transfer from the wire is found from equationMERM35001 (also *NCEES Handbook:* Convection).

$$\begin{aligned}Q &= \pi d L h\,(T_{\text{wire}} - T_\infty) \\ T_{\text{wire}} &= \frac{\frac{Q}{L}}{\pi d h} + T_\infty \\ &= \frac{27.3\ \dfrac{\text{Btu}}{\text{hr-ft}}}{\pi\,(0.05\ \text{ft})\left(2.78\ \dfrac{\text{Btu}}{\text{hr-ft}^2\text{-}^\circ\text{F}}\right)} + 60^\circ\text{F} \\ &= 122.5^\circ\text{F}\end{aligned}$$

Perform one more iteration with $T_{\text{wire}} = 122.5°\text{F}$.

$$\begin{aligned}\text{Gr} &= (0.05)^3 \left(1.76 \times 10^6\ \frac{1}{\text{ft}^3\text{-}^\circ\text{F}}\right)(122.5^\circ\text{F} - 60^\circ\text{F}) \\ &= 13\,750 \\ \text{PrGr} &= (0.72)(13\,750) = 9900\end{aligned}$$

As in *NCEES Handbook:* Free/Forced Heat-Transfer Coefficients/Correlations,

$$\begin{aligned}h &= \left(\tfrac{k}{d}\right) C(\text{GrPr})^{1/4} \\ &= \left(\frac{0.015\ \frac{\text{Btu}}{\text{hr-ft}^\circ\text{F}}}{0.05\ \text{ft}}\right)(0.85)(9900)^{1/4} \\ &= 2.55\ \text{Btu/hr-ft}^2\text{-}^\circ\text{F}\end{aligned}$$

$$
\begin{aligned}
T_{\text{wire}} &= \frac{\frac{Q}{L}}{\pi d h} + T_\infty \\
&= \frac{27.3\ \frac{\text{Btu}}{\text{hr-ft}}}{\pi\,(0.05\ \text{ft})\left(2.55\ \frac{\text{Btu}}{\text{hr-ft}^2\text{-}^\circ\text{F}}\right)} + 60^\circ\text{F} \\
&= 128.2^\circ\text{F} \quad (130^\circ\text{F})
\end{aligned}
$$

There is no need to repeat iterations since the assumed temperature and the calculated temperature are about the same.

The answer is (C).

SI Solution

From appendixMERM35D (also *NCEES Handbook:* Temperature-Dependent Properties of Air (SI Units)), the air properties at 38°C are

$$
\begin{aligned}
\text{Pr} &= 0.705 \\
\frac{g\beta\rho^2}{\mu^2} &= 1.12\times 10^8\ \frac{1}{\text{K}\cdot\text{m}^3}
\end{aligned}
$$

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

$$
\text{Gr} = L^3\left(\frac{g\beta\rho^2}{\mu^2}\right)\Delta T
$$

The characteristic length is the wire diameter.

$$
L = \frac{1.5\ \text{cm}}{100\ \frac{\text{cm}}{\text{m}}} = 0.015\ \text{m}
$$

The temperature gradient is

$$
\begin{aligned}
\Delta T &= T_s - T_\infty = T_{\text{wire}} - 15^\circ\text{C} \\
\text{Gr} &= (0.015\ \text{m})^3\left(1.12\times 10^8\ \frac{1}{\text{K}\cdot\text{m}^3}\right)(T_{\text{wire}} - 15^\circ\text{C})
\end{aligned}
$$

T_{wire} is unknown. Start by assuming $T_{\text{wire}} = 50°\text{C}$.

$$
\begin{aligned}
\text{Gr} &= (0.015\ \text{m})^3\left(1.12\times 10^8\ \frac{1}{\text{K}\cdot\text{m}^3}\right)(50^\circ\text{C} - 15^\circ\text{C}) \\
&= 13\,230 \\
\text{PrGr} &= (0.705)\,(13\,230) \\
&= 9327
\end{aligned}
$$

As in *NCEES Handbook* table “Forced Convection—External Flow,” the heat capacity ratio is $C = 0.85$ for this GrPr value. As in *NCEES Handbook* table “Temperature-Dependent Properties of Air at 0.1 MPa (SI Units),” the thermal conductivity for air is $k = 0.03\ \text{W/m}\cdot\text{k}$. The correlation for free convection over a horizontal cylinder can be found in *NCEES Handbook:* Free/Forced Heat-Transfer Coefficients/Correlations. Rearrange the correlation equation to find the film coefficient. Use the diameter for the characteristic length.

$$
\begin{aligned}
\mathrm{Nu} &= C(\mathrm{GrPr})^{1/4} = \frac{hd}{k} \\
h &= \left(\frac{k}{d}\right) C(\mathrm{GrPr})^{1/4} \\
&= \left(\frac{0.03\ \dfrac{\mathrm{W}}{\mathrm{m}\cdot\mathrm{K}}}{0.015\ \mathrm{m}}\right)(0.85)\,(9327)^{1/4} \\
&= 16.7\ \mathrm{W/m^2{\cdot}K}
\end{aligned}
$$

The heat transfer from the wire is found from equationMERM35001 (also *NCEES Handbook:* Free/Forced Heat-Transfer Coefficients/Correlations).

$$
\begin{aligned}
Q &= \pi dLh\,(T_{\mathrm{wire}} - T_\infty) \\
T_{\mathrm{wire}} &= \frac{\dfrac{Q}{L}}{\pi dh} + T_\infty \\
&= \frac{25\ \dfrac{\mathrm{W}}{\mathrm{m}}}{\pi\,(0.015\ \mathrm{m})\left(16.7\ \dfrac{\mathrm{W}}{\mathrm{m^2{\cdot}K}}\right)} + 15^\circ\mathrm{C} \\
&= 46.8^\circ\mathrm{C} \quad (50^\circ\mathrm{C})
\end{aligned}
$$

There is no need to perform another iteration since the assumed temperature and the calculated temperature are about the same.

The answer is (C).