# HW Solution

**19-5C** Nusselt number is the dimensionless convection heat transfer coefficient, and it represents the enhancement of heat transfer through a fluid layer as a result of convection relative to conduction across the same fluid layer. It is defined as $Nu = \frac{hL_c}{k}$ where $L_c$ is the characteristic length of the surface and $k$ is the thermal conductivity of the fluid.

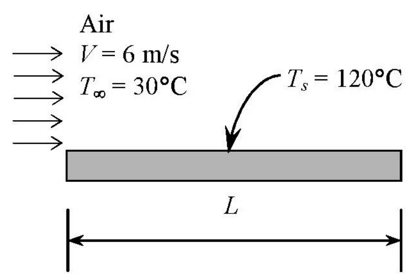
19-9

**19-16** The top surface of a hot block is to be cooled by forced air. The rate of heat transfer is to be determined for two cases.

***Assumptions*** **1** Steady operating conditions exist. **2** The critical Reynolds number is $\mathrm{Re}_{cr} = 5\times10^5$. **3** Radiation effects are negligible. **4** Air is an ideal gas with constant properties.

***Properties*** The atmospheric pressure in atm is

$$P = (83.4\text{ kPa})\frac{1\text{ atm}}{101.325\text{ kPa}} = 0.823\text{ atm}$$




For an ideal gas, the thermal conductivity and the Prandtl number are independent of pressure, but the kinematic viscosity is inversely proportional to the pressure. With these considerations, the properties of air at 0.823 atm and at the film temperature of (120+30)/2=75°C are (Table A-22)

$$k = 0.02917\text{ W/m.°C}$$

$$\nu = \nu_{@1atm} / P_{atm} = (2.046\times10^{-5}\text{ m}^2\text{/s}) / 0.823 = 2.486\times10^{-5}\text{ m}^2\text{/s}$$

$$\mathrm{Pr} = 0.7166$$

***Analysis*** (*a*) If the air flows parallel to the 8-m side, the Reynolds number in this case becomes

$$\mathrm{Re}_L = \frac{VL}{\nu} = \frac{(6\text{ m/s})(8\text{ m})}{2.486\times10^{-5}\text{ m}^2\text{/s}} = 1.931\times10^6$$

which is greater than the critical Reynolds number. Thus we have combined laminar and turbulent flow. Using the proper relation for Nusselt number, the average heat transfer coefficient and the heat transfer rate are determined to be

$$Nu = \frac{hL}{k} = (0.037\,\mathrm{Re}_L{}^{0.8} - 871)\,\mathrm{Pr}^{1/3} = [0.037(1.931\times10^6)^{0.8} - 871](0.7166)^{1/3} = 2757$$

$$h = \frac{k}{L}Nu = \frac{0.02917\text{ W/m.°C}}{8\text{ m}}(2757) = 10.05\text{ W/m}^2\text{.°C}$$

$$A_s = wL = (2.5\text{ m})(8\text{ m}) = 20\text{ m}^2$$

$$\dot{Q} = hA_s(T_\infty - T_s) = (10.05\text{ W/m}^2\text{.°C})(20\text{ m}^2)(120-30)\text{°C} = 18{,}100\text{ W} = \mathbf{18.10\text{ kW}}$$

(*b*) If the air flows parallel to the 2.5-m side, the Reynolds number is

$$\mathrm{Re}_L = \frac{VL}{\nu} = \frac{(6\text{ m/s})(2.5\text{ m})}{2.486\times10^{-5}\text{ m}^2\text{/s}} = 6.034\times10^5$$

which is greater than the critical Reynolds number. Thus we have combined laminar and turbulent flow. Using the proper relation for Nusselt number, the average heat transfer coefficient and the heat transfer rate are determined to be

$$Nu = \frac{hL}{k} = (0.037\,\mathrm{Re}_L{}^{0.8} - 871)\,\mathrm{Pr}^{1/3} = [0.037(6.034\times10^5)^{0.8} - 871](0.7166)^{1/3} = 615.1$$

$$h = \frac{k}{L}Nu = \frac{0.02917\text{ W/m.°C}}{2.5\text{ m}}(615.1) = 7.177\text{ W/m}^2\text{.°C}$$

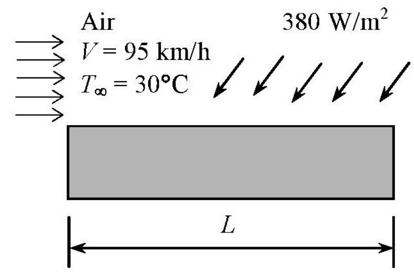
$$\dot{Q} = hA_s(T_\infty - T_s) = (7.177\text{ W/m}^2\text{.°C})(20\text{ m}^2)(120-30)\text{°C} = 12{,}920\text{ W} = \mathbf{12.92\text{ kW}}$$

**19-25** The top surface of the passenger car of a train in motion is absorbing solar radiation. The equilibrium temperature of the top surface is to be determined.

***Assumptions*** **1** Steady operating conditions exist. **2** The critical Reynolds number is $Re_{cr} = 5\times10^5$. **3** Radiation heat exchange with the surroundings is negligible. **4** Air is an ideal gas with constant properties.

***Properties*** The properties of air at 30°C are (Table A-22)

$$k = 0.02588 \text{ W/m.°C}$$
$$\nu = 1.608\times10^{-5} \text{ m}^2\text{/s}$$
$$\Pr = 0.7282$$




***Analysis*** The rate of convection heat transfer from the top surface of the car to the air must be equal to the solar radiation absorbed by the same surface in order to reach steady operation conditions. The Reynolds number is

$$\mathrm{Re}_L = \frac{VL}{\nu} = \frac{[95\times1000/3600)\text{ m/s}](8\text{ m})}{1.608\times10^{-5}\text{ m}^2\text{/s}} = 1.313\times10^7$$

which is greater than the critical Reynolds number. Thus we have combined laminar and turbulent flow. Using the proper relation for Nusselt number, the average heat transfer coefficient and the heat transfer rate are determined to be

$$Nu = \frac{hL}{k} = (0.037\,\mathrm{Re}_L{}^{0.8} - 871)\Pr^{1/3} = [0.037(1.313\times10^7)^{0.8} - 871](0.7282)^{1/3} = 1.569\times10^4$$

$$h = \frac{k}{L}Nu = \frac{0.02588\text{ W/m.°C}}{8\text{ m}}(1.569\times10^4) = 50.77\text{ W/m}^2\text{.°C}$$

The equilibrium temperature of the top surface is then determined by taking convection and radiation heat fluxes to be equal to each other

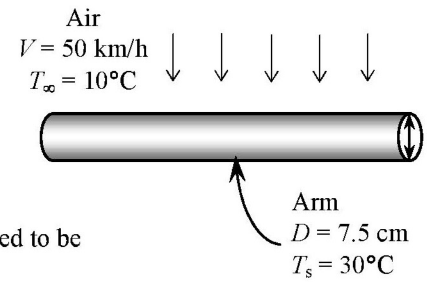
$$\dot{q}_{rad} = \dot{q}_{conv} = h(T_s - T_\infty) \longrightarrow T_s = T_\infty + \frac{\dot{q}_{conv}}{h} = 30°\text{C} + \frac{380\text{ W/m}^2}{50.77\text{ W/m}^2\text{.°C}} = \mathbf{37.5°C}$$

**19-42** A person extends his uncovered arms into the windy air outside. The rate of heat loss from the arm is to be determined.

***Assumptions*** **1** Steady operating conditions exist. **2** Radiation effects are negligible. **3** Air is an ideal gas with constant properties. 4 The arm is treated as a 0.6-m-long and 7.5-cm-diameter cylinder with insulated ends. **5** The local atmospheric pressure is 1 atm.

***Properties*** The properties of air at 1 atm and the film temperature of $(T_s + T_\infty)/2 = (30+10)/2 = 20°C$ are (Table A-15)

$$k = 0.02514 \text{ W/m.°C}$$
$$\nu = 1.516\times10^{-5} \text{ m}^2/\text{s}$$
$$\text{Pr} = 0.7309$$




***Analysis*** The Reynolds number is

$$\text{Re} = \frac{VD}{\nu} = \frac{[(50\times1000/3600)\text{ m/s}](0.075\text{ m})}{1.516\times10^{-5}\text{ m}^2/\text{s}} = 6.871\times10^4$$

The Nusselt number corresponding to this Reynolds number is determined to be

$$Nu = \frac{hD}{k} = 0.3 + \frac{0.62\,\text{Re}^{0.5}\,\text{Pr}^{1/3}}{\left[1+\left(\frac{0.4}{\text{Pr}}\right)^{2/3}\right]^{1/4}}\left[1+\left(\frac{\text{Re}}{282{,}000}\right)^{5/8}\right]^{4/5}$$

$$= 0.3 + \frac{0.62(6.871\times10^4)^{0.5}(0.7309)^{1/3}}{\left[1+\left(\frac{0.4}{0.7309}\right)^{2/3}\right]^{1/4}}\left[1+\left(\frac{6.871\times10^4}{282{,}000}\right)^{5/8}\right]^{4/5} = 170.2$$

Then the heat transfer coefficient and the heat transfer rate from the arm becomes

$$h = \frac{k}{D}Nu = \frac{0.02514\text{ W/m.°C}}{0.075\text{ m}}(170.2) = 57.05\text{ W/m}^2.°\text{C}$$

$$A_s = \pi DL = \pi(0.075\text{ m})(0.6\text{ m}) = 0.1414\text{ m}^2$$

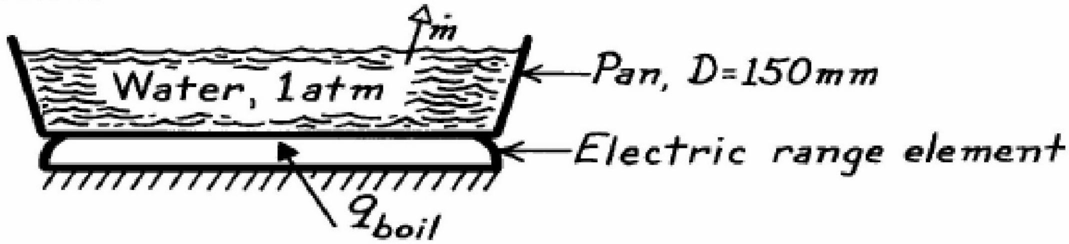
$$\dot{Q}_{conv} = hA_s(T_s - T_\infty) = (57.05\text{ W/m}^2.°\text{C})(0.1414\text{ m}^2)(30-10)°\text{C} = \mathbf{161\text{ W}}$$

# PROBLEM 10.10

**KNOWN:** Copper pan, 150 mm diameter and filled with water at 1 atm, is maintained at 115°C.

**FIND:** Power required to boil water and the evaporation rate; ratio of heat flux to critical heat flux; pan temperature required to achieve critical heat flux.

**SCHEMATIC:**




**ASSUMPTIONS:** (1) Nucleate pool boiling, (2) Copper pan is polished surface.

**PROPERTIES:** *Table A-6*, Water (1 atm): $T_{sat} = 100°C$, $\rho_\ell = 957.9\ kg/m^3$, $\rho_v = 0.5955\ kg/m^3$, $c_{p,\ell} = 4217\ J/kg\cdot K$, $\mu_\ell = 279 \times 10^{-6}\ N\cdot s/m^2$, $Pr_\ell = 1.76$, $h_{fg} = 2257\ kJ/kg$, $\sigma = 58.9 \times 10^{-3}\ N/m$.

**ANALYSIS:** The power requirement for boiling and the evaporation rate can be expressed as follows,

$$q_{boil} = q_s'' \cdot A_s \qquad \dot{m} = q_{boil} / h_{fg}.$$

The heat flux for nucleate pool boiling can be estimated using the Rohsenow correlation.

$$q_s'' = \mu_\ell h_{fg}\left[\frac{g(\rho_\ell - \rho_v)}{\sigma}\right]^{1/2}\left(\frac{c_{p,\ell}\Delta T_e}{C_{s,f}\, h_{fg}\, Pr_\ell^n}\right)^3.$$

Selecting $C_{s,f} = 0.0128$ and $n = 1$ from Table 10.1 for the polished copper finish, find

$$q_s'' = 279\times10^{-6}\,\frac{N\cdot s}{m^2}\times 2257\times10^3\,\frac{J}{kg}\left[\frac{9.8\,\frac{m}{s^2}(957.9-0.5955)\frac{kg}{m^3}}{58.9\times10^{-3}\,N/m}\right]^{1/2}\left(\frac{4217\,\frac{J}{kg\cdot K}\times 15°C}{0.0128\times 2257\times10^3\,\frac{J}{kg}\times 1.76}\right)^3$$

$$q_s'' = 4.839\times10^5\ W/m^2.$$

The power and evaporation rate are

$$q_{boil} = 4.839\times10^5\ W/m^2 \times \frac{\pi}{4}(0.150m)^2 = 8.55\,kW \qquad <$$

$$\dot{m}_{boil} = 8.55\,kW / 2257\times10^3\,J/kg = 3.79\times10^{-3}\,kg/s = 14\,kg/h. \qquad <$$

The maximum or critical heat flux was found in Example 10.1 as

$$q''_{max} = 1.26\,MW/m^2.$$

Hence, the ratio of the operating to maximum heat flux is

$$\frac{q_s''}{q''_{max}} = 4.619\times10^5\ W/m^2 / 1.26\,MW/m^2 = 0.384. \qquad <$$

From the boiling curve, Fig. 10.4, $\Delta T_e \approx 30°C$ will provide the maximum heat flux. <

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**Al-Wakil 9.6.**

$$Nu = \frac{hL}{k} \qquad Re = \frac{DV}{\nu}$$

$$Nu = 0.023\, Re^{0.8}\, Pr^{0.4} \quad \text{- Dittus Boelter}$$

$$h = \frac{Nu\, k}{L} \qquad Pr = \frac{\nu}{\alpha} = \frac{C_p \mu}{k} \qquad \mu = \nu\rho$$

Identify variables which is affected by temperature change

$$h = \frac{Nu\, k}{L} = 0.023\, Re^{0.8}\, Pr^{0.4}$$

$$h = 0.023 \left(\frac{DV}{\nu}\right)^{0.8} \left(\frac{C_p \mu}{k}\right)^{0.4} \frac{k}{L} \quad \text{—(1)}$$

$$\frac{w'}{q} = 7.07\times10^{-14} \left(\frac{1}{D_e^{0.2}}\right)\left(\frac{V^{2.8}}{h\,\Delta T_m}\right)\left(\rho^{0.8}\mu^{0.2}\right)$$

Temperature change affects only $h, \rho, \mu$. Others treated as constant.

Substitute (1) into $\frac{w'}{q}$

$$\frac{w'}{q} = [\text{const.}] \frac{1}{\left(\frac{1}{\nu}\right)^{0.8}\left(\frac{C_p\mu}{k}\right)^{0.4} k} \left(\rho^{0.8}\mu^{0.2}\right)$$

$$= [\ldots] \frac{\nu^{0.8}}{\left(\frac{C_p}{k}\frac{\mu}{\rho}\right)^{0.4}\rho^{0.4} k}\left(\rho^{0.8}\mu^{0.2}\right)$$

$$= [\ldots] \frac{\mu^{0.8}\mu^{0.2}}{(C_p \nu)^{0.4}\rho^{0.4} k^{0.6}} = [\ldots] \frac{\mu}{(C_p\mu)^{0.4} k^{0.6}}$$

$$= [\ldots] \frac{\mu^{0.6}}{C_p^{0.4} k^{0.6}} = [\ldots] \underbrace{\left(\frac{\mu}{k}\right)^{0.6} \frac{1}{C_p^{0.6}}}_{\text{at different temperatures}}$$

% change of $\frac{w'}{q}$ : $$\frac{\Delta\left(\frac{w'}{q}\right)}{\frac{w'}{q}} = \frac{\cancel{[\ldots]}\left\{(\ )_{2} - (\ )_{1}\right\}}{\cancel{[\ldots]}\,(\ )_{1}} \ \%$$

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Table values:

Sat. liq

200°F : $\rho = 60.132$ lbm/ft$^3$

$\mu = 0.738$ lbm/hr.ft

$k = 0.3935$ Btu/hr.ft.°F

$C_p = 1.0047$ Btu/lbm.R

300°F : $\mu = 0.452$

$k = 0.3952$

$C_p = 1.0289$

400°F : $\mu = 0.327$

$k = 0.3809$

$C_p = 1.0794$

200°F : $\left(\frac{\mu}{k}\right)^{0.6} \frac{1}{C_p^{0.4}} = \left(\frac{0.738}{0.3935}\right)^{0.6} \frac{1}{1.0047^{0.4}} = 1.4556$

300°F : $= \qquad = 1.0716$

400°F : $= \qquad = 0.8851$

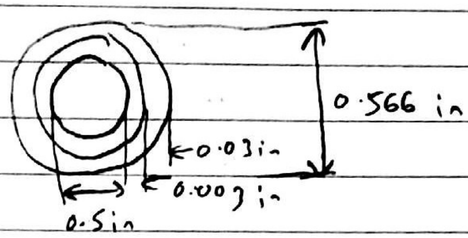
(% Δ)

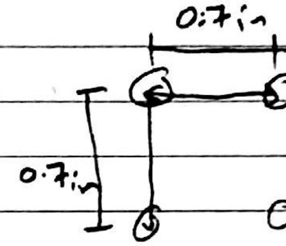
$\%\Delta\Big|_{300-200°F} = \frac{1.4556 - 1.0716}{1.0716} = 35.8\ \%$

$\%\Delta\Big|_{300-400°F} = \frac{1.0716 - 0.8851}{1.0716} = 17.4\ \%$ //

El-Wakil 9.7

PWR.




square lattice

$T_b = 520\,°F$ $\qquad V = 15 \frac{ft}{s}$

$$q''' = 5\times10^{7} \frac{Btu}{hr.\,ft^3}$$

(a) find h : PWR, assume no boiling, assume Weisman

$$\frac{q}{\text{ft length of pellet}} = q''' V = 5\times10^{7} \frac{Btu}{hr.\,ft^3}\left(\pi\left(\frac{0.25}{12}\right)^2\right) 1\,ft$$

$$= 68176.9 \frac{Btu}{hr}$$

$$\frac{\text{Surface area of fuel pin}}{\text{ft length}} = \left(\pi \frac{0.566}{12}\right) 1 = 0.1482\ ft^2$$

$$\therefore q'' = \frac{68176.9}{0.1482} = 460033.2 \frac{Btu}{hr.\,ft^2}$$

Weisman : $\quad Nu = C\, Re^{0.8}\, Pr^{1/3}$

$$C = 0.042 \frac{s}{D} - 0.024$$

$$Re = \frac{DV}{\nu}$$

$D = \frac{4A_c}{P}$ for square lattice

$$= \frac{4\left(\left(\frac{0.7}{12}\right)^2 - \pi\left(\frac{0.566}{2(12)}\right)^2\right)}{\pi \frac{0.566}{12}}$$

$$= 0.04469\ ft$$

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at 520 °F : $\mu = 0.246 \ \text{lbm/hr.ft}$

$P_r = 0.8907$

$k = 0.3397 \ \text{Btu/hr.ft.F}$

$\rho = 47.847 \ \text{lbm/ft}^3$

$C_p = 1.23 \ \text{Btu/lbm.R}$

$$P_r = \frac{C_p \mu}{k} = 0.8907$$

$$Re = \frac{DV}{\nu} = \frac{\rho D V}{\mu} = \frac{47.847 \ (0.04469)(15 \times 3600 \ \text{s/hr})}{0.246}$$

$$= 4.6937 \times 10^5$$

Weisman: $Nu = C \ Re^{0.8} \ P_r^{1/3}$

$$C = 0.042 \ \frac{S}{D} - 0.024$$

$$\frac{S}{D} = \frac{0.7}{0.566} = 1.237$$

$$\therefore \ C = 0.0279$$

$$\therefore Nu = 0.0279 (4.6937 \times 10^5)^{0.8} (0.8907)^{1/3}$$

$$= 924.84$$

$$\therefore h = \frac{Nu \, k}{D} = \frac{924.84 \ (0.3397) \ \text{Btu/hr.ft.F}}{0.04469 \ \text{ft}}$$

$$= 7030 \ \frac{\text{Btu}}{\text{hr. ft}^2 \ \text{F}}$$

(b) Minimum system pressure to prevent boiling.

- determine surface temperature (the determining temp.)

$$q'' = h \ (T_s - T_b)$$

$$460033.2 \ \frac{\text{Btu}}{\text{hr.ft}^2} = 7030 \ \frac{\text{Btu}}{\text{hr.ft}^2 \ \text{F}} \ (T_s - 520 \ \text{F})$$

$$\therefore \ T_s = 585.45 \ °\text{F}$$

From steam table : $P_{sat}\big|_{T_{580°F}} = 1325.8$ psia

$P_{sat}\big|_{600°F} = 1542.9$ psia

$P_{max} \doteq 1500$ psia to prevent boiling.