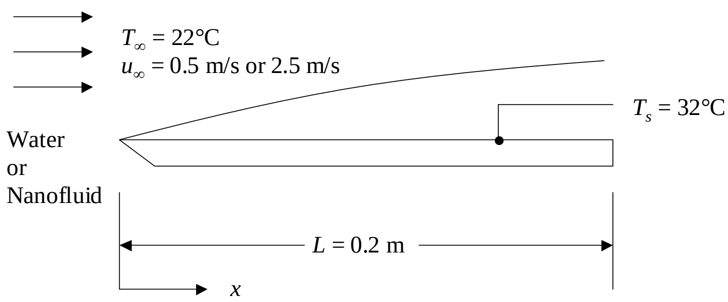
PROBLEM 7.26

KNOWN: Dimensions of flat plate in parallel flow. Plate and fluid temperatures, fluid velocities.

FIND: Average heat transfer coefficient, convection heat transfer rate, drag force for (a) water flowing at a velocity of 0.5 m/s, (b) nanofluid of Example 2.2 at a velocity of 0.5 m/s, (c) water at a velocity of 2.5 /m/s, (d) nanofluid at a velocity of 2.5 m/s.

SCHEMATIC:



ASSUMPTIONS: (1) Steady-state conditions, (2) Constant properties, $Re_{x,c} = 5 \times 10^5$.

PROPERTIES: *Table A.4*, water (300 K): ρ_{bf} = 997 kg/m^3, $\nu_{bf} = 857 \times 10^{-9}$ m^2/s, k_{bf} = 0.613 W/m·K, Pr_{bf} = 5.83. Example 2.2, nanofluid (300 K): ρ_{nf} = 1146 kg/m^3, $\mu_{nf} = 962 \times 10^{-6}$ m^2/s, $\nu_{nf} = \mu_{nf}/\rho_{nf} = 839 \times 10^{-9}$ m^2/s, k_{nf} = 0.705 W/m·K, $\alpha_{nf} = 171 \times 10^{-9}$ m^2/s $Pr_{nf} = \nu_{nf}/\alpha_{nf} = 4.91$.

ANALYSIS: (a) For water flowing over the plate at u_m = 0.5 m/s,

$$Re_L = \frac{u_\infty L}{\nu_{bf}} = \frac{0.5\text{m/s} \times 0.2\text{m}}{857 \times 10^{-9}\,\text{m}^2/\text{s}} = 117 \times 10^3$$

Since $Re_L < Re_{x,c}$ the flow is laminar and Eq. 7.30 yields

$$\bar{h}_L = \frac{k_{bf}}{L}\left[0.664 Re_L^{1/2}\right] Pr_{bf}^{1/3} = \frac{0.613\text{W/m}\cdot\text{K}}{0.2\text{m}}\left[0.664 \times 117{,}000^{1/2}\right] 5.83^{1/3} = 1253\ \text{W/m}^2\bullet\text{K}$$ $<$

and the convection heat transfer rate from the top of the plate is

$$q = wL\bar{h}_L(T_s - T_\infty) = 1\text{m} \times 0.2\text{m} \times 1253\text{W/m}^2\cdot\text{K} \times (32-22)°\text{C} = 2500\text{W} = 2.51\ \text{kW}$$ $<$

The drag force on the plate is

$$F = \bar{\tau}_{s,L} wL = \frac{\bar{C}_f \rho_{bf} u_\infty^2}{2} wL$$

$$= \frac{1.328 \rho_{bf} u_\infty^2}{2\sqrt{Re_L}} wL = \frac{1.328 \times 997\ \text{kg/m}^3 \times (0.5\ \text{m/s})^2}{2\sqrt{117 \times 10^3}} \times 1\ \text{m} \times 0.2\ \text{m}$$

$$= 0.097\ \text{N}$$ $<$

where Equation 7.29 has been used to determine the average friction coefficient.

Continued…

(b) For the nanofluid flowing over the plate at u_m = 0.5 m/s,

$$Re_L = \frac{u_\infty L}{\nu_{\text{nf}}} = \frac{0.5\text{m/s} \times 0.2\text{m}}{839 \times 10^{-9}\text{m}^2/\text{s}} = 119 \times 10^3$$

The flow is laminar and Eq. 7.30 yields

$$\bar{h}_L = \frac{k_{\text{nf}}}{L}\left[0.664 Re_L^{1/2}\right] Pr_{\text{nf}}^{1/3} = \frac{0.705\text{W/m}\cdot\text{K}}{0.2\text{m}}\left[0.664 \times 119{,}000^{1/2}\right] 4.91^{1/3} = 1372\ \text{W/m}^2\bullet\text{K}$$

<

and the convection heat transfer rate from the top of the plate is

$$q = wL\bar{h}_L(T_s - T_\infty) = 1\text{m} \times 0.2\text{m} \times 1372\text{W/m}^2\cdot\text{K}(32-22)°\text{C} = 2740\text{W} = 2.74\ \text{kW}$$

<

The drag force on the plate is

$$\begin{aligned} F &= \bar{\tau}_{s,L} wL = \frac{\bar{C}_f \rho_{\text{nf}} u_\infty^2}{2} wL \\ &= \frac{1.328 \rho_{\text{nf}} u_\infty^2}{2\sqrt{Re_L}} wL = \frac{1.328 \times 1146\ \text{kg/m}^3 \times (0.5\ \text{m/s})^2}{2\sqrt{119 \times 10^3}} \times 1\ \text{m} \times 0.2\ \text{m} \\ &= 0.110\ \text{N} \end{aligned}$$

<

(c) For water flowing over the plate at u_m = 2.5 m/s,

$$Re_L = \frac{u_\infty L}{\nu_{\text{bf}}} = \frac{2.5\text{m/s} \times 0.2\text{m}}{857 \times 10^{-9}\text{m}^2/\text{s}} = 5.83 \times 10^5$$

Therefore, the flow at the end of the plate is turbulent and Eq. 7.38 yields

$$\begin{aligned} \bar{h}_L &= \frac{k_{\text{bf}}}{L}\left[0.037 Re_L^{4/5} - 871\right] Pr_{\text{bf}}^{1/3} \\ &= \frac{0.613\text{W/m}\cdot\text{K}}{0.2\text{m}}\left[0.037(5.83 \times 10^5)^{4/5} - 871\right] 5.83^{1/3} = 3562\ \text{W/m}^2\bullet\text{K} \end{aligned}$$

<

and the convection heat transfer rate from the top of the plate is

$$q = wL\bar{h}_L(T_s - T_\infty) = 1\text{m} \times 0.2\text{m} \times 3562\text{W/m}^2\cdot\text{K}(32-22)°\text{C} = 7120\text{W} = 7.12\ \text{kW}$$

<

The drag force on the plate is

Continued…

$$F = \bar{\tau}_{s,L} wL = \bar{C}_f \frac{\rho_{\text{bf}} u_\infty^2}{2} wL$$

$$= \left(0.074 Re_L^{-1/5} - \frac{2 \times 871}{Re_L}\right) \frac{\rho_{\text{bf}} u_\infty^2}{2} wL$$

$$= \left(0.074 \times \left(5.83 \times 10^5\right)^{-1/5} - \frac{2 \times 871}{5.83 \times 10^5}\right) \frac{997 \text{ kg/m}^3 \times (2.5 \text{ m})^2}{2} \times 1 \text{ m} \times 0.2 \text{ m}$$

$$= 1.379 \text{ N}$$ <

where Equation 7.40 has been used to determine the average friction coefficient.

(d) For the nanofluid flowing over the plate at u_m = 2.5 m/s, $Re_L = 5.96 \times 10^5$, $\bar{h}_L$ = 4024 W/m^2·K, q = 8050 W = 8.05 kW, and F = 1.615 N. <

COMMENTS: (1) The convection heat transfer rate is greater for the nanofluid than for the base fluid (water). For the laminar case, the nanofluid convection heat transfer rate is 9.5% larger when the nanofluid is used. For the turbulent flow case the convection heat transfer rate is 13% higher for the nanofluid. The higher efficacy of the nanofluid in the turbulent flow case is associated with its larger Reynolds number, $Re_{L,\text{nf}} > Re_{L,\text{bf}}$. Hence more of the plate experiences turbulent flow when the nanofluid is used. (2) The drag force is always greater when the nanofluid is used. For the laminar flow case, the drag force is 13.6% larger when the nanofluid is used, while for the turbulent flow case the drag force associated with the nanofluid is 17.1% larger than for the base fluid. Larger drag forces are expected due to the larger viscosity associated with the nanofluid. (c) For many cases involving nanofluids, a tradeoff exists between potentially increasing the heat transfer rates, but at a cost of experiencing larger friction losses.