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Problems

General Considerations

10.1 Show that, for water at 1-atm pressure with $T_s - T_{sat} = 10°C$, the Jakob number is much less than unity. What is the physical significance of this result? Verify that this conclusion applies to other fluids.

10.2 The surface of a horizontal, 7-mm-diameter cylinder is maintained at an excess temperature of 5°C in saturated water at 1 atm. Estimate the heat flux using an appropriate free convection correlation and compare your result to the boiling curve of Figure 10.4. Repeat the calculation for a horizontal, 7-μm-diameter wire at the same excess temperature. What can you say about the general applicability of Figure 10.4 to all situations involving boiling of water at 1 atm?

10.3 The role of surface tension in bubble formation can be demonstrated by considering a spherical bubble of pure saturated vapor in *mechanical* and *thermal* equilibrium with its superheated liquid.

(a) Beginning with an appropriate free-body diagram of the bubble, perform a force balance to obtain an expression of the bubble radius,

$$r_b = \frac{2\sigma}{p_{sat} - p_l}$$

where p_{sat} is the pressure of the saturated vapor and p_l is the pressure of the superheated liquid outside the bubble.

(b) On a p–v diagram, represent the bubble and liquid states. Discuss what changes in these conditions will cause the bubble to grow or collapse.

(c) Calculate the bubble size under equilibrium conditions for which the vapor is saturated at 101°C and the liquid pressure corresponds to a saturation temperature of 100°C.

10.4 Estimate the heat transfer coefficient, h, associated with Points A, B, C, D, and E in Figure 10.4. Which point is associated with the largest value of h? Which point corresponds to the smallest value of h? Determine the thickness of the vapor blanket at the Leidenfrost point, neglecting radiation heat transfer through the blanket. Assume the solid is a flat surface.

Nucleate Boiling and Critical Heat Flux

10.5 A long, 1-mm-diameter wire passes an electrical current dissipating 3150 W/m and reaches a surface temperature of 126°C when submerged in water at 1 atm. What is the boiling heat transfer coefficient? Estimate the value of the correlation coefficient $C_{s,f}$.

10.6 Estimate the nucleate pool boiling heat transfer coefficient for water boiling at atmospheric pressure on the outer surface of a platinum-plated 10-mm-diameter tube maintained 10°C above the saturation temperature.

10.7 Plot the nucleate boiling heat flux for saturated water at atmospheric pressure on a large, horizontal polished copper plate, over the excess temperature range $5°C \le \Delta T_e \le 30°C$. Compare your results with Figure 10.4. Also find the excess temperature corresponding to the critical heat flux.

10.8 A simple expression to account for the effect of pressure on the nucleate boiling convection coefficient in water ($W/m^2 \cdot K$) is

$$h = C(\Delta T_e)^n \left(\frac{p}{p_a}\right)^{0.4}$$

where p and p_a are the system pressure and standard atmospheric pressure, respectively. For a horizontal plate and the range $15 < q_s'' < 235\ \text{kW/m}^2$, $C = 5.56$ and $n = 3$. Units of ΔT_e are kelvins. Compare predictions from this expression with the Rohsenow correlation ($C_{s,f} = 0.013$, $n = 1$) for pressures of 2 and 5 bars with $\Delta T_e = 10°\text{C}$.

10.9 In Example 10.1 we considered conditions for which vigorous boiling occurs in a pan of water, and we determined the electric power (heat rate) required to maintain a prescribed temperature for the bottom of the pan. However, the electric power is, in fact, the control (independent) variable, from which the temperature of the pan follows.

(a) For nucleate boiling in the copper pan of Example 10.1, compute and plot the temperature of the pan as a function of the heat rate for $1 \leq q \leq 100\ \text{kW}$.

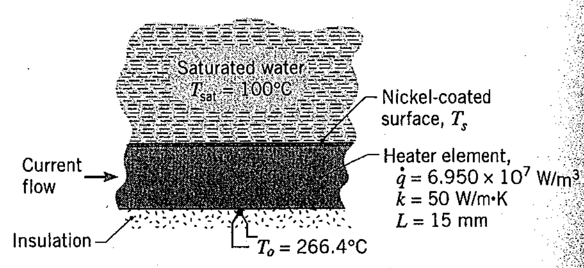
(b) If the water is initially at room temperature, it must, of course, be heated for a period of time before it will boil. Consider conditions shortly after heating is initiated and the water is at 20°C. Estimate the temperature of the pan bottom for a heat rate of 8 kW.

10.10 Calculate the critical heat flux on a large horizontal surface for the following fluids at 1 atm: mercury, ethanol, and refrigerant R-134a. Compare these results to the critical heat flux for water at 1 atm.

10.11 Water at atmospheric pressure boils on the surface of a large horizontal copper tube. The heat flux is 90% of the critical value. The tube surface is initially scored; however, over time the effects of scoring diminish and the boiling eventually exhibits behavior similar to that associated with a polished surface. Determine the tube surface temperature immediately after installation and after prolonged service.

10.12 The bottom of a copper pan, 150 mm in diameter, is maintained at 115°C by the heating element of an electric range. Estimate the power required to boil the water in this pan. Determine the evaporation rate. What is the ratio of the surface heat flux to the critical heat flux? What pan temperature is required to achieve the critical heat flux?

10.13 A nickel-coated heater element with a thickness of 15 mm and a thermal conductivity of $50\ \text{W/m}\cdot\text{K}$ is exposed to saturated water at atmospheric pressure. A thermocouple is attached to the back surface, which is well insulated. Measurements at a particular operating condition yield an electrical power dissipation in the heater element of $6.950 \times 10^7\ \text{W/m}^3$ and a temperature of $T_o = 266.4°\text{C}$.



(a) From the foregoing data, calculate the surface temperature, T_s, and the heat flux at the exposed surface.

(b) Using the surface heat flux determined in part (a), estimate the surface temperature by applying an appropriate boiling correlation.

10.14 Advances in very large scale integration (VLSI) of electronic devices on a chip are often restricted by the ability to cool the chip. For mainframe computers, an array of several hundred chips, each of area $25\ \text{mm}^2$, may be mounted on a ceramic substrate. A method of cooling the array is by immersion in a low boiling point fluid such as refrigerant R-134a. At 1 atm and 247 K, properties of the saturated liquid are $\mu = 1.46 \times 10^{-4}\ \text{N}\cdot\text{s/m}^2$, $c_p = 1551\ \text{J/kg}\cdot\text{K}$, and $Pr = 3.2$. Assume values of $C_{s,f} = 0.004$ and $n = 1.7$.

(a) Estimate the power dissipated by a single chip if it is operating at 50% of the critical heat flux. What is the corresponding value of the chip temperature?

(b) Compute and plot the chip temperature as a function of surface heat flux for $0.25 \leq q_s''/q_{max}'' \leq 0.90$.

10.15 Saturated ethylene glycol at 1 atm is heated by a horizontal chromium-plated surface which has a diameter of 200 mm and is maintained at 480 K. Estimate the heating power requirement and the rate of evaporation. What fraction is the power requirement of the maximum power associated with the critical heat flux? At 470 K, properties of the saturated liquid are $\mu = 0.38 \times 10^{-3}\ \text{N}\cdot\text{s/m}^2$, $c_p = 3280\ \text{J/kg}\cdot\text{K}$, and $Pr = 8.7$. The saturated vapor density is $\rho = 1.66\ \text{kg/m}^3$. Assume nucleate boiling constants of $C_{s,f} = 0.01$ and $n = 1.0$.

10.16 Copper tubes 25 mm in diameter and 0.75 m long are used to boil saturated water at 1 atm.

(a) If the tubes are operated at 75% of the critical heat flux, how many tubes are needed to provide a vapor production rate of 750 kg/h? What is the corresponding tube surface temperature?

(b) Compute and plot the tube surface temperature as a function of heat flux for $0.25 \leq q_s''/q_{max}'' < 0.90$. On the same graph, plot the corresponding number of tubes needed to provide the prescribed vapor production rate.

this result with the condensate formed by a *vertical* plate of the same dimensions for the same period of time.

10.46 Saturated steam at 1 atm condenses on the outer surface of a vertical, 100-mm-diameter pipe 1 m long, having a uniform surface temperature of 94°C. Estimate the total condensation rate and the heat transfer rate to the pipe.

10.47 Determine the total condensation rate and the heat transfer rate for Problem 10.46 when the steam is saturated at 1.5 bars.

10.48 Consider wave-free laminar condensation on a vertical isothermal plate of length L, providing an average heat transfer coefficient of $\overline{h}_L$. If the plate is divided into N smaller plates, each of length $L_N = L/N$, determine an expression for the ratio of the heat transfer coefficient averaged over the N plates to the heat transfer coefficient averaged over the single plate, $\overline{h}_{L,N}/\overline{h}_{L,1}$.

10.49 A vertical plate 500 mm high and 200 mm wide is to be used to condense saturated steam at 1 atm.

(a) At what surface temperature must the plate be maintained to achieve a condensation rate of $\dot{m} = 25$ kg/h?

(b) Compute and plot the surface temperature as a function of condensation rate for $15 \leq \dot{m} \leq 50$ kg/h.

(c) On the same graph and for the same range of $\dot{m}$, plot the surface temperature as a function of condensation rate if the plate is 200 mm high and 500 mm wide.

10.50 A 2 m × 2 m vertical plate is exposed on one side to saturated steam at atmospheric pressure and on the other side to cooling water that maintains a plate temperature of 50°C.

(a) What is the rate of heat transfer to the coolant? What is the rate at which steam condenses on the plate?

(b) For plates inclined at an angle θ from the vertical, the average convection coefficient for condensation on the upper surface, $\overline{h}_{L(\text{incl})}$, may be approximated by an expression of the form, $\overline{h}_{L(\text{incl})} \approx (\cos\theta)^{1/4} \cdot \overline{h}_{L(\text{vert})}$, where $\overline{h}_{L(\text{vert})}$ is the average coefficient for the vertical orientation. If the 2 m × 2 m plate is inclined 45° from the normal, what are the rates of heat transfer and condensation?

10.51 Saturated ethylene glycol vapor at 1 atm is exposed to a vertical plate 300 mm high and 100 mm wide having a uniform temperature of 420 K. Estimate the heat transfer rate to the plate and the condensation rate. Approximate the liquid properties as those corresponding to saturated conditions at 373 K (Table A.5).

10.52 A vertical plate 2.5 m high, maintained at a uniform temperature of 54°C, is exposed to saturated steam at atmospheric pressure.

(a) Estimate the condensation and heat transfer rates per unit width of the plate.

(b) If the plate height were halved, would the flow regime stay the same or change?

(c) For $54 \leq T_s \leq 90$°C, plot the condensation rate as a function of plate temperature for the two plate heights of parts (a) and (b).

10.53 Two configurations are being considered in the design of a condensing system for steam at 1 atm employing a vertical plate maintained at 90°C. The first configuration is a single vertical plate $L \times w$ and the second consists of two vertical plates $(L/2) \times w$, where L and w are the vertical and horizontal dimensions, respectively. Which configuration would you choose?

10.54 The condenser of a steam power plant consists of a square (in-line) array of 625 tubes, each of 25-mm diameter. Consider conditions for which saturated steam at 0.105 bars condenses on the outer surface of each tube, while a tube wall temperature of 17°C is maintained by the flow of cooling water through the tubes. What is the rate of heat transfer to the water per unit length of the tube array? What is the corresponding condensation rate?

10.55 The condenser of a steam power plant consists of AISI 302 stainless steel tubes ($k_s = 15$ W/m·K), each of outer and inner diameters $D_o = 30$ mm and $D_i = 26$ mm, respectively. Saturated steam at 0.135 bar condenses on the outer surface of a tube, while water at a mean temperature of $T_m = 290$ K is in fully developed flow through the tube.

(a) For a water flow rate of $\dot{m} = 0.25$ kg/s, what is the outer surface temperature $T_{s,o}$ of the tube and the rates of heat transfer and steam condensation per unit tube length? As a first estimate, you may evaluate the properties of the liquid film at the saturation temperature. If one wishes to increase the transfer rates, what is the limiting factor that should be addressed?

(b) Explore the effect of the water flow rate on $T_{s,o}$ and the rate of heat transfer per unit length.

10.56 Saturated vapor from a chemical process condenses at a slow rate on the inner surface of a vertical, thin-walled cylindrical container of length L and diameter D. The container wall is maintained at a uniform temperature T_s by flowing cold water across its outer surface.