Boiling -2

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- Example.2 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.
- **Solution:** to calculate the critical heat flux on a large horizontal surface for boiling of Mercury, ethanol, and R-134a at 1atm.
- **Assumption:** 1- boiling is nucleate 2- steady state
- **Properties:** For Mercury h_{fg}=301kJ/kg, ρ_v=3.9kg/m^3, ρ_f=12740kg/m^3, σ=0.417N/m, T_s=630K
- For Ethanol h_{fg}=846kJ/kg, ρ_v=1.44kg/m^3, ρ_f=757kg/m^3, σ=0.0177N/m, T_{sat}=351K,

- For R-134a h_{fg}=217kJ/kg, ρ_v=5.26kg/m^3, ρ_f=1377kg/m^3, σ=0.0154N/m, T_{sat}=247K,
- And for water h_{fg}=2257kJ/kg, ρ_v=0.596kg/m^3, ρ_f=957.9kg/m^3, σ=0.0589N/m, T_{sat}=373K,
- **Analysis:** for determining the critical heat flux we can use the following relation.
- $\dot{q}_{max} = Ch_{fg}\rho_v \left[\frac{\sigma g(\rho_f - \rho_v)}{\rho_v^2}\right]^{1/4}$
- For Mercury $\dot{q}_{max} = Ch_{fg}\rho_v \left[\frac{\sigma g(\rho_f - \rho_v)}{\rho_v^2}\right]^{1/4}$ $= 0.149 \times 301 \times 10^3 \times 3.9 \left[\frac{0.417 \times 9.81(12740 - 3.9)}{(3.9)^2}\right]^{1/4} = 1338 \times 10^3 W$ /m^2=1.34MW/m^2

- For Ethanol

- $\dot{q}_{max} = C h_{fg} \rho_v \left[\frac{\sigma g(\rho_f - \rho_v)}{\rho_v^2}\right]^{1/4} = 0.149$

$\times 846 \times 10^3 \times 1.44 \left[\frac{0.0177 \times 9.81(757 - 1.44)}{(1.44)^2}\right]^{1/4}$

$= 511.9 \times 10^3 W/\text{m}^2 = 0.512\text{MW/m}^2$

- For R-134

- $\dot{q}_{max} = C h_{fg} \rho_v \left[\frac{\sigma g(\rho_f - \rho_v)}{\rho_v^2}\right]^{1/4} = 0.149$

$\times 217 \times 10^3 \times 5.26 \left[\frac{0.0154 \times 9.81(1377 - 5.26)}{(5.26)^2}\right]^{1/4}$

$= 281 \times 10^3 W/\text{m}^2 = 0.28\text{MW/m}^2$

- for water
- $\dot{q}_{max} = Ch_{fg}\rho_v \left[\frac{\sigma g(\rho_f - \rho_v)}{\rho_v^2}\right]^{1/4} = 0.149 \times 2257 \times 10^3 \times 0.596 \left[\frac{0.0589 \times 9.81(957.9 - 0.596)}{(0.596)^2}\right]^{1/4} = 1259 \times 10^3 W$ /m²=1.26MW/m²
- The ratio of heat flux at boiling
- For mercury to that of boiling water is
- $\frac{\dot{q}_{me}}{\dot{q}_w} = \frac{1.34}{1.26} = 1.063$
- For ethanol to water $\frac{\dot{q}_{eth}}{\dot{q}_w} = \frac{0.512}{1.26} = 0.406$
- For R-134a to water $\frac{\dot{q}_{R-134a}}{\dot{q}_w} = \frac{0.28}{1.26} = 0.222$
- And for water to water $\frac{\dot{q}_{me}}{\dot{q}_w} = \frac{1.26}{1.26} = 1.0$

- Example.3 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.
- Solution: Water boiling on the surface of a large copper tube $\dot{q}_{nuclear} = 0.9\dot{q}_{max}$. Scored associated with polished surface.

- **Properties:** water properties at 100ºC, $\rho_f = 957.9kg/m^3$ $\rho_v = 0.5978$kg/m³ h_{fg}=2257kJ/kg, cp_f=4217J/kg.K, k_f=0.679W/m.K, μ_f=0.282x10⁻³kg/m.s, Pr_f=1.75 σ=0.0589N/m.
- **Analysis:** the maximum heat flux where C=0.131
- $\dot{q}_{max} = Ch_{fg}\rho_v\left[\frac{\sigma g(\rho_f-\rho_v)}{\rho_v^2}\right]^{1/4} = 0.131 \times 2257 \times 10^3\left[\frac{0.0589\times9.81(957.9-0.5978)}{[0.5978]^2}\right]^{1/4} = 1854.53 \times 10^3 W/\text{m}^2$
- $\dot{q}_s = 0.9\dot{q}_{max} = 0.9(1854.53 \times 10^3) = 1669 \times 10^3 W/\text{m}^2$
- C_{sf}=0.0068 and n=1.0

- $\dot{q}_{nucleate} = \mu_f h_{fg} \left[\frac{g(\rho_f - \rho_v)}{\sigma}\right]^{1/2} \left[\frac{cp_f(T_w - T_{sat})}{C_{sf} h_{fg} Pr_f^n}\right]^3$
- $1669 \times 10^3 = 0.282 \times 10^{-3} \times 2257 \times 10^3 \left[\frac{9.81(957.9 - 0.5978)}{0.0589}\right]^{\frac{1}{2}} \left[\frac{4217(T_w - T_{sat})}{0.0068 \times 2257 \times 10^3 \times 1.75^{1.0}}\right]^3 \rightarrow$
- $(T_w - T_{sat}) = 11.93$° C→T_w=11.93+100=111.93°C
- After surface become polished then C_{sf}=0.0128
- Then $\Delta T_s = \frac{C_{sf(n)}}{C_{sf(o)}} \Delta T_{so} = \frac{0.0128}{0.0068} 11.93 = 22.45$

- Example 4. **The bottom of a copper pan, 0.3 m in diameter, is maintained at 118°C by an electric heater. Estimate the power required to boil water in this pan. What is the evaporation rate? Estimate the critical heat flux.**
- **Solution:** cooper pan D=0.3m T_w=118°C, T_{sat}=100°C
- **Requirement:** 1) power required to boiled water, 2) mass rate of evaporation 3) critical heat flux.

- Analysis $\dot{q}_s = \mu_f h_{fg}\left[\frac{g(\rho_f-\rho_v)}{\sigma}\right]^{1/2}\left[\frac{cp_f(T_w-T_{sat})}{C_{sf}h_{fg}Pr_f^n}\right]^3$
- $h_{fg}^* = h_{fg} + 0.68Cp_f(T_w - T_{sat}) = 2257 + 0.68 \times 4.217(118 - 100) = 2308.6 \times 10^3 J/kg$
- $\dot{q}_s = 0.279 \times 10^{-3} \times 2308.6 \times 10^3 \left[\frac{9.81(957.9-0.5956)}{0.0589}\right]^{1/2}\left[\frac{4217(118-100)}{0.0128\times2306.8\times10^3 1.76^{1.0}}\right]^3 = 291811.6 W/\text{m}^2$
- $\dot{Q} = \frac{\pi}{4}D^2\dot{q}_s = \frac{\pi}{4}0.3^2(291811.6) = 20626.95W$
- $\dot{m}_s = \frac{\dot{Q}_s}{h_{fg}} = \frac{20626.95}{2308.65\times10^3}$=0.009kg/sec=32.16kh/hr
- The critical heat flux is $\dot{q}_{max} = Ch_{fg}\rho_v\left[\frac{\sigma g(\rho_f-\rho_v)}{\rho_v^2}\right]^{1/4}$
- $\dot{q}_{max} = 0.149 \times 2257 \times 10^3 \times 0.5956\left[\frac{0.0589\times9.81(957.9-0.5956)}{(0.5956)^2}\right]^{1/4} = 1258646.5W$

- Example.5. **Water is boiled at 120°C in a mechanically polished stainless-steel pressure cooker placed on top of a heating unit. The inner surface of the bottom of the cooker is maintained at 130°C. Determine the heat flux on the surface.**
- **Solution**: T_{sat}=120^{o}C, T_w=130^{o}C
- **Properties:** For water at 120^{o}C
- μ_f=0.232x10^{-3}kg/m.sce, h_{fg}=2203kJ/kg, ρ_f=943.4kg/m^3, ρ_v=1.121kg/m^3, σ=0.055N/m, cp_f=4244J/kg.K, C_{sf}=0.13 n=1.0 Pr_f=1.44

- Requirements: Determine the heat flux on the surface.
- Analysis: to calculate the nucleate boiling heat
- Heat flux
- Find firstly modified latent heat of vaporation

$$h_{fg}^{*} = h_{fg} + 0.68Cp_f(T_w - T_{sat}) = 2203 + 0.68 \times 4.244(130 - 120) = 2246.84kJ/kg$$

Then the heat flux

$$\dot{q}_{nuceate} = \mu_f h_{fg}^{*} \left[\frac{g(\rho_f - \rho_v)}{\sigma}\right]^{1/2} \left[\frac{Cp_f(T_w - T_{sat})}{C_{sf} h_{fg}^{*} Pr_f^n}\right]^3$$

- $\dot{q}_{nuceate} = 0.232 \times 10^{-3} \times 2246.84 \times 10^{3} \left[\frac{9.81(943.4 - 1.121)}{0.055}\right]^{1/2} \left[\frac{4244(130 - 120)}{0.013 \times 2246.84 \times 10^{3} \times 1.44^{1}}\right]^{3}$ $= 219530.66 W/\mathrm{m}^2$.

- Example-6 **A platinum-plated rod with a diameter of 10 mm is submerged horizontally in water at 110ºC. If the surface of the rod is maintained at 10°C above the saturation temperature, determine the nucleate pool boiling heat transfer rate per unit length and the rate of evaporation per unit length (in kg/s·m).**

- **Solution**: A platinum-plated Rod
- D=10mm=0.01m at atmospheric pressure $T_{sat}=110^oC$, $T_w=T_{sat}+10=110+10=120^oC$
- **Requirements**: heat transfer per unit length and mass evaporated per unit length.
- **Properties**: For water at 110^oC
- $\mu_f=0.255\times10^{-3}$kg/m.sce, $h_{fg}=2230$kJ/kg, $\rho_f=950.6$kg/m^3, $\rho_v=0.8263$kg/m^3, $\sigma=0.0569$N/m, $cp_f=4229$J/kg.K, $C_{sf}=0.013$ n=1.0 $Pr_f=1.58$
- Analysis: at beginning calculate h_{fg}^*

- $h_{fg}^{*} = h_{fg} + 0.68Cp_f(T_w - T_{sat}) = 2230 + 0.68 \times 4.229(120 - 110) = 2258.76kJ/kg$

- $\dot{q}_{nuceate} = \mu_f h_{fg}^{*} \left[\frac{g(\rho_f - \rho_v)}{\sigma}\right]^{1/2} \left[\frac{Cp_f(T_w - T_{sat})}{C_{sf} h_{fg}^{*} Pr_f^{n}}\right]^{3}$
- $\dot{q}_{nuceate} = 0.255 \times 10^{-3} \times 2258.76 \times 10^{3} \left[\frac{9.81(950.6 - 0.8263)}{0.0569}\right]^{1/2} \left[\frac{4229(120 - 110)}{0.013 \times 2258.76 \times 10^{3} \times 1.44^{1}}\right]^{3} = 233.176kW/\text{m}^2$.
- Heat transfer per unit length is
- $\dot{q}_L = \dot{q}_{nucleate} \times d\pi = 233.176 \times 0.01\pi = 7.325kW/m$
- $\dot{m} = \frac{\dot{q}_L}{h_{fg}^{*}} = \frac{7.325}{2258.76} = \frac{0.00324kg}{(m.s)} = \frac{11.675kg}{m.hr}$

- **Example-7- A 65-cm-long, 2-cm-diameter brass heating element is to be used to boil water at 120°C. If the surface temperature of the heating element is not to exceed 125°C, determine the highest rate of steam production in the boiler, in kg/h.**
- **Solution**: tube of D=2cm=0.02m and L=65cm=0.65m T_{sat}=120°C, and T_w=125°C.
- **Properties:** σ=0.0589N/m, ρ_f=957.9kg/m^3, ρ_v=0.5978kg/m^3, h_{fg}=2237kJ/kg
- **Analysis:** for maximum heat flux

- $\dot{q}_{max} = C_{cr} h_{fg} \rho_v \left[\frac{\sigma g(\rho_f - \rho_v)}{\rho_v^2} \right]^{1/4}$
- $\dot{q}_{max} = 0.15 \times 2257 \times 10^3 \times 0.5978 \left[\frac{0.0589 \times 9.81 \times (957.90 - 0.5978)}{(0.5978)} \right]^{\frac{1}{4}} = 1269.43 kW/m^2$
- A=$\pi DL = \pi \times 0.02 \times 0.65 = 0.408 m^2$
- $\dot{Q}_{mxa} = A\dot{q}_{max} = 0.408 \times 1269.43 = 517.93 kW$

- Example.8. **Water is boiled at atmospheric pressure by a horizontal platinum-plated rod with diameter of 10 mm. If the surface temperature of the rod is maintained at 110°C, determine the nucleate pool boiling heat transfer coefficient.**
- **Solution:** A horizontal platinum-plated rod with D=10mm T_w=110°C and T_{sat}=100°C.
- **Requirements:** the nucleate pool boiling heat transfer coefficient
- The heat transfer coefficient
- $h_{nucleat} = \frac{\dot{q}_{nucleat}}{\Delta T}$

- Properties: Properties of water at 100°C, ρ_f=957.9kg/m^3, ρ_v=0.5958kg/m^3, h_{fg}=2257kJ/kg, cp_f=4212J/kg.K, k_f=0.679W/m.K, μ_f=0.282x10^{-3}N/m.sec, Pr=1.75, σ=0.0589N/m, C_{sf}=0.013 and n=1
- Solution: The nucleate heat flux is
- $h^*_{fg} = h_{fg} + 0.68Cp_f(T_w - T_{sat}) = 2257 + 0.68 \times 4.212(110 - 100) = 2285.64kJ/kg$
- $\dot{q}_{nuceate} = \mu_f h^*_{fg}\left[\frac{g(\rho_f - \rho_v)}{\sigma}\right]^{1/2}\left[\frac{Cp_f(T_w - T_{sat})}{C_{sf}h^*_{fg}Pr_f^n}\right]^3$

- $\dot{q}_{nuceate} = 0.282 \times 10^{-3} \times 2285.64 \times 10^{3} \left[\frac{9.81(957.9-0.5958)}{0.0589}\right]^{\frac{1}{2}} \left[\frac{4212(110-100)}{0.013 \times 2285.64 \times 10^{3} \times 1.75^{1}}\right]^{3} = \frac{136790.58W}{m^2} = \frac{136.79kW}{m^2}$

- Then $h_{nucleate} = \frac{\dot{q}_{nucleate}}{(T_w - T_{sat})} = \frac{136790.58}{110-100}$=13679.5W/$m^{2o}C$