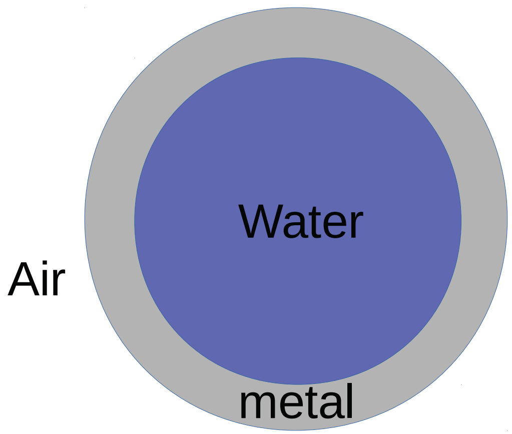
SH2706
Sustainable Energy Transformation Technologies

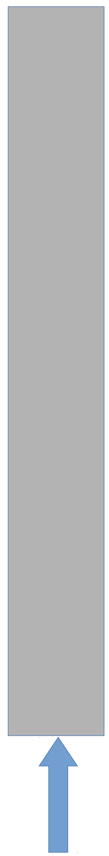
Exercise Session 03

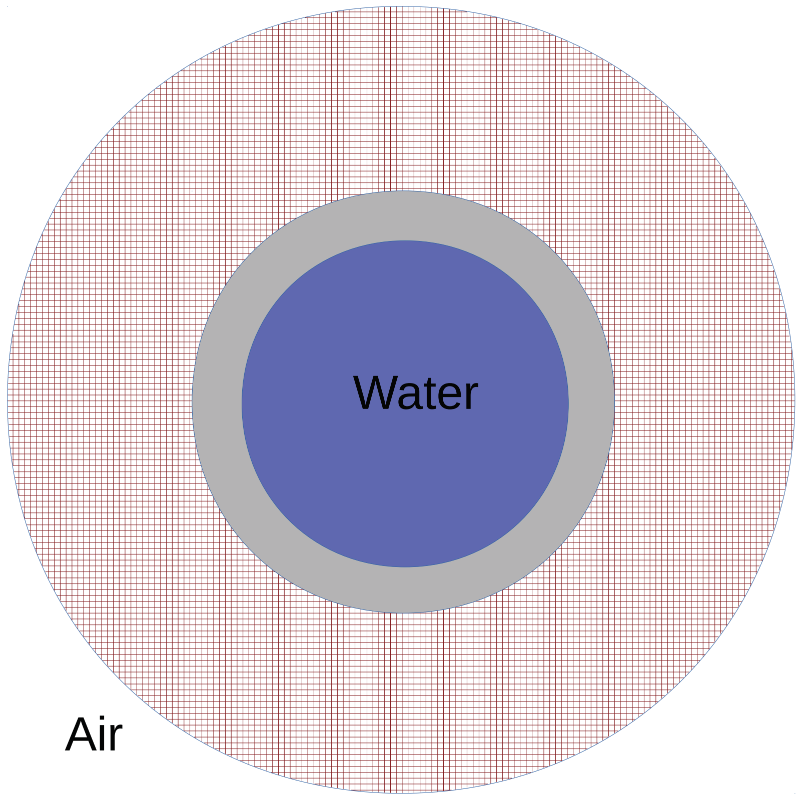
E03_P01

Water flows through a metal pipe with an outer diameter of 104 mm and wall thickness of 2 mm. The water temperature is 15℃ and the outside air temperature is -10℃. The thermal conductivity of the metal pipe is 50 W/m/K. The water side heat transfer coefficient is 30 kW/m^2/K and the outside heat transfer coefficient is 20 W/m^2/K. Calculate the heat flow rate per meter length of the pipe.

If the pipe is insulated with an outer diameter of 300 mm, and the thermal conductivity of the insulation materials is 0.05 W/m/K, calculate the new heat flow rate per meter.

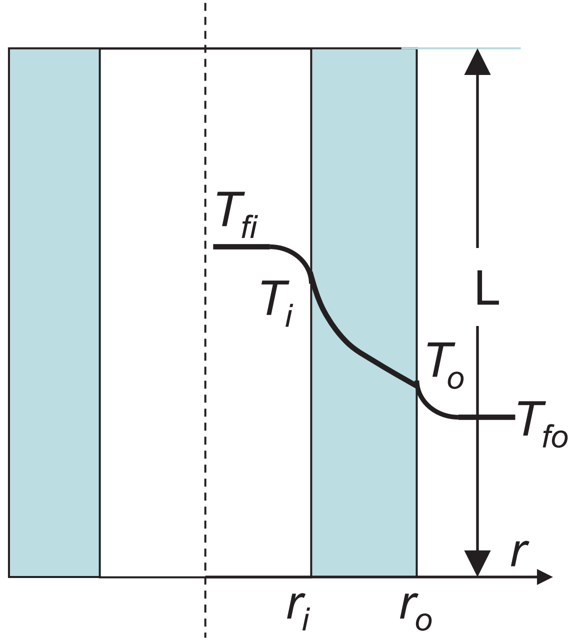






Infinite Hollow Cylinder (6)

Thus for a hollow cylinder with convecting heat transfer on both the inner and outer surfaces, the over-all thermal resistance is:



$$R_t = \frac{1}{h_i 2\pi r_i L} + \frac{\ln\left(r_o / r_i\right)}{2\pi\lambda L} + \frac{1}{h_o 2\pi r_o L}$$

where the linear heat transferred from inside to the outside of the hollow cylinder is:

$$q' = \frac{\left(T_{fi} - T_{fo}\right)}{R_t L}$$

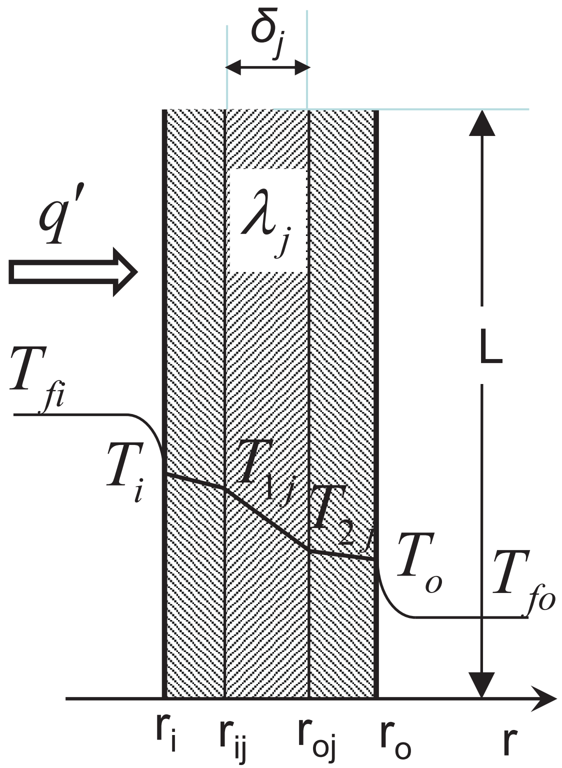
and the total heat is:

$$q = \frac{\left(T_{fi} - T_{fo}\right)}{R_t}$$

Composite Hollow Cylinder

- For a hollow cylinder with a composite wall we have

$$q' = \frac{T_{fi} - T_{fo}}{\dfrac{1}{h_i 2\pi r_i} + \sum_j \dfrac{\ln\left(r_{oj}/r_{ij}\right)}{2\pi\lambda_j} + \dfrac{1}{h_o 2\pi r_o}} = \frac{T_{fi} - T_{fo}}{R_t L}$$



- where

$$R_t = \frac{1}{h_i 2\pi r_i L} + \frac{1}{2\pi L}\sum_j \frac{\ln\left(r_{oj}/r_{ij}\right)}{\lambda_j} + \frac{1}{h_o 2\pi r_o L}$$

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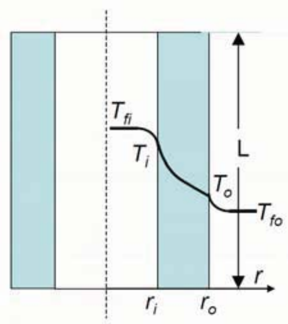
If the pipe is insulated with an outer diameter of 300 mm, and the thermal conductivity of the insulation materials is 0.05 W/m/K, calculate the new heat flow rate per meter.

Solution:

$$q = \frac{\left(T_{fi} - T_{fo}\right)}{R_t}$$

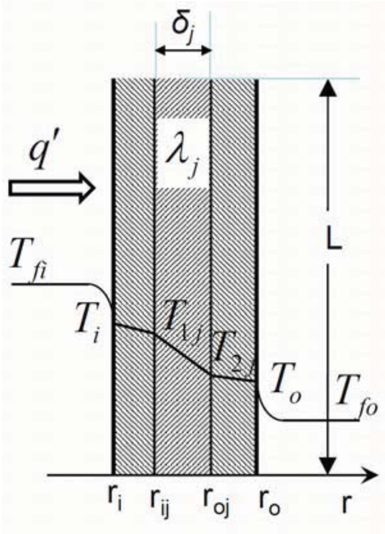
$$R_t = \frac{1}{h_i 2\pi r_i L} + \frac{\ln\left(r_o / r_i\right)}{2\pi\lambda L} + \frac{1}{h_o 2\pi r_o L}$$

q = 163.3 W



$$R_t = \frac{1}{h_i 2\pi r_i L} + \frac{1}{2\pi L}\sum_j \frac{\ln\left(r_{oj} / r_{ij}\right)}{\lambda_j} + \frac{1}{h_o 2\pi r_o L}$$

q = 7.3 W



E03_P02

Water is flowing upward at 7 MPa in a vertical heated tube. The tube diameter is 25 mm and the mass flow rate is 0.22 kg/s. Calculate the wall heat flux at a position in the tube where the quality is 0.2 and the wall temperature is 290°C, using Chen correlation.

(Saturation pressure for water at 290°C is 7.44164 MPa;

Saturated temperature at 7 MPa is 285.83°C;

Enthalpy of saturated water at 7 MPa is 1.2674×10^6 J/kg;

Latent heat of water at 7 MPa is 1.5051×10^6 J/kg;

Density of saturated water at 7 MPa is 739.7 kg/m^3;

Density of saturated vapor at 7 MPa is 36.5 kg/m^3;

Viscosity of saturated water at 7 MPa is 9.1253×10^{-5} Pas;

Viscosity of saturated vapor at 7 MPa is 1.8961×10^{-5} Pas;

Specific heat of saturated water at 7 MPa is 5.4×10^3 J/kgK;

Specific heat of saturated vapor at 7 MPa is 5.354×10^3 J/kgK;

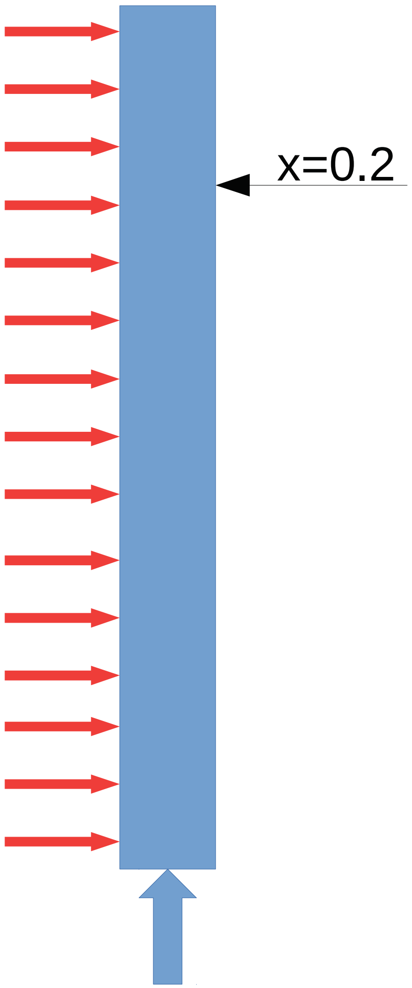
Thermal conductivity of saturated water at 7 MPa is 0.5687 W/mK;

Thermal conductivity of saturated vapor at 7 MPa is 0.0644 W/mK;

Surface tension at 7 MPa is 0.0176 N/m;

Critical pressure of water is 22.1 MPa;

Gravity acceleration is 9.8 m/s^2)



Saturated Flow Boiling (2)

- That is, in the Chen correlation

$$h = h_{mic} + h_{mac}$$

- Where

$$h_{mac} = 0.023\left(\frac{\lambda_f}{D}\right)\mathrm{Re}^{0.8}\,\mathrm{Pr}_f^{0.4}\cdot F \qquad \mathrm{Re} = \frac{G(1-x)D}{\mu_f} \qquad \mathrm{Pr}_f = \frac{\mu_f c_{pf}}{\lambda_f}$$

x – local quality

$$S = \left(1 + 2.56\cdot 10^{-6} F^{1.463}\cdot \mathrm{Re}^{1.17}\right)^{-1}$$

$$F = \begin{cases} 1 & X_{tt}^{-1} \le 0.1 \\ 2.35\left(0.213 + \dfrac{1}{X_{tt}}\right)^{0.736} & X_{tt}^{-1} \ge 0.1 \end{cases} \qquad X_{tt} = \left(\frac{1-x}{x}\right)^{0.9}\left(\frac{\rho_g}{\rho_f}\right)^{0.5}\left(\frac{\mu_f}{\mu_g}\right)^{0.1}$$

$$h_{mic} = 0.00122\left[\frac{\lambda_f^{0.79} c_{pf}^{0.45} \rho_f^{0.49}}{\sigma^{0.5}\mu_f^{0.29} i_{fg}^{0.24} \rho_g^{0.24}}\right]\Delta T_{\sup}^{0.24}\left(p_s(T_w) - p_f\right)^{0.75}\cdot S$$

$p_s(T_w)$ is the saturation pressure at wall temperature

Saturated Flow Boiling (3)

given q”, x, p, G, D; guess ΔT_{sup}

$$X_{tt} = \left(\frac{1-x}{x}\right)^{0.9}\left(\frac{\rho_g}{\rho_f}\right)^{0.5}\left(\frac{\mu_f}{\mu_g}\right)^{0.1}$$

$$\mathrm{Re} = \frac{G(1-x)D}{\mu_f}$$

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$$h_{mac} = 0.023\left(\frac{\lambda_f}{D}\right)\mathrm{Re}^{0.8}\,\mathrm{Pr}_f^{0.4} \cdot F$$

$$h_{mic} = 0.00122\left[\frac{\lambda_f^{0.79} c_{pf}^{0.45} \rho_f^{0.49}}{\sigma^{0.5}\mu_f^{0.29} i_{fg}^{0.24} \rho_g^{0.24}}\right]\Delta T_{sup}^{0.24}\left(p_s(T_w) - p_f\right)^{0.75} \cdot S$$

$$h = h_{mic} + h_{mac}$$

$$\Delta T_{sup}^{new} = q'' / h$$

$$\left\|\Delta T_{sup}^{new} - \Delta T_{sup}\right\| < \varepsilon$$

Yes

No

$$\Delta T_{sup} = \Delta T_{sup}^{new}$$

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Solution:

The wall heat flux can be calculated as

$$q'' = h_{Chen} \Delta T_{\sup}$$

where

$$h_{Chen} = h_{mac} + h_{mic}$$

The Martinelli parameter is given by

$$X_{tt} = \left(\frac{1-x}{x}\right)^{0.9} \left(\frac{\rho_g}{\rho_f}\right)^{0.5} \left(\frac{\mu_f}{\mu_g}\right)^{0.1} = 0.9054$$

The enhance factor F is therefore

$$F = 2.8787$$

The liquid Reynolds number is

$$\mathrm{Re}_f = \frac{G(1-x)D_h}{\mu_f} = 9.82 \times 10^4$$

The suppression factor S is

$$S = 1/\left(1 + 2.56 \times 10^{-6} F^{1.463} \mathrm{Re}_f^{1.17}\right) = 0.1071$$

The convective heat transfer coefficient is

$$h_{mac} = 0.023 \left(\frac{\lambda_f}{D_h}\right) \mathrm{Re}_f^{0.8} \mathrm{Pr}_f^{0.4} F = 1.4021 \times 10^4 \ \ W/m^2K$$

The nucleate boiling heat transfer coefficient is

$$h_{mic} = 0.00122 \left(\frac{\lambda_f^{0.79} C_{pf}^{0.45} \rho_f^{0.49}}{\sigma^{0.5} \mu_f^{0.29} i_{fg}^{0.24} \rho_g^{0.24}}\right) \Delta T_{\sup}^{0.24} \left(p_{sat}(T_w) - p_f\right)^{0.75} S = 3.814 \times 10^3 \ \ W/m^2K$$

Therefore the total heat transfer coefficient is

$$h_{Chen} = h_{mac} + h_{mic} = 1.7835 \times 10^4 \ \ W/m^2K$$

The wall heat flux is then

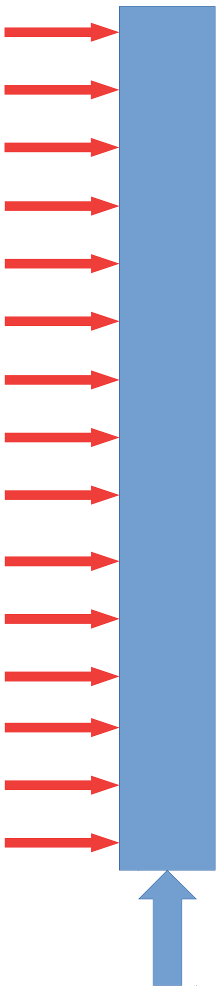
$$q'' = h_{Chen} \Delta T_{\sup} = 7.4372 \times 10^4 \ \ W/m^2$$

E03_P03

Water is flowing upward at 7 MPa in a vertical tube, with diameter of 10 mm and height of 3.6 m. The tube is uniformly heated with heat flux of 0.8 MW/m^2. The mass flux is 1250 kg/m^{2}s and the inlet subcooling is 10 K. Determine if dryout will occur in the tube.

(Use the Levitan-Lantsman correlation for critical quality calculation;

Assume specific heat of water at 7 MPa is 5.4x10^3 J/kgK and is constant)



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Occurrence of Critical Heat Flux (5)

- Examples of correlations:
  - Levitan and Lantsman correlation for DNB in 8mm pipes

$$q''_{cr} = \left[10.3 - 7.8\frac{p}{98} + 1.6\left(\frac{p}{98}\right)^2\right]\left(\frac{G}{1000}\right)^{1.2\{[0.25(p-98)/98]-x\}} e^{-1.5x}$$

750<G<5000
29.4<p<196

  - Levitan and Lantsman correlation for dryout in 8 mm pipes

$$x_{cr} = \left[0.39 + 1.57\frac{p}{98} - 2.04\left(\frac{p}{98}\right)^2 + 0.68\left(\frac{p}{98}\right)^3\right]\left(\frac{G}{1000}\right)^{-0.5}$$

750<G<3000
9.8<p<166.6

q_{cr} [MW/m^2], p [bar], G [kg/m^2.s], x – equilibrium quality, x_{cr} – critical quality

Occurrence of Critical Heat Flux (6)

- Levitan and Lantsman correlations can be used for other pipe diameters using the following corrections:

  - For DNB

$$q''_{cr} = q''_{cr}\Big|_{8mm} \cdot \left(\frac{8}{D}\right)^{0.5}$$

  - For dryout

$$x_{cr} = x_{cr}\Big|_{8mm} \cdot \left(\frac{8}{D}\right)^{0.15}$$

D – diameter, mm

E03_P03

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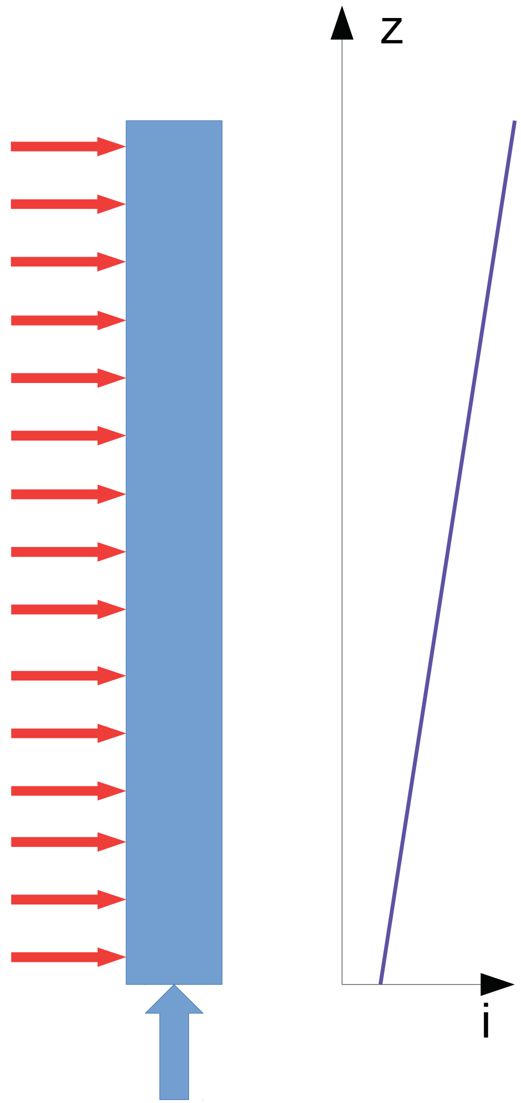
Solution:



Given the pressure and the mass flux, the critical quality can be calculated using Levitan-Lantsman correlation as

$$x_{cr,8mm}=\left[0.39+1.57\left(\frac{p}{98}\right)-2.04\left(\frac{p}{98}\right)^{2}+0.68\left(\frac{p}{98}\right)^{3}\right]\left(\frac{G}{1000}\right)^{-0.5}=0.6426$$

$$x_{cr}=x_{cr,8mm}\left(\frac{8}{D}\right)^{0.15}=0.6214$$

The maximum enthalpy and quality of the tube is at the exit. The exit enthalpy is calculated as

$$i_{ex}=i_{in}+\frac{q}{W}=i_{f}-C_{pf}\Delta T_{sub}+\frac{q}{W}=2.135\times10^{6}\;[J/kg]$$

The exit quality is

$$x_{ex}=\frac{i_{ex}-i_{f}}{i_{fg}}=0.5764$$

Since the exit quality is lower than the critical quality, there is no dryout occurrence in the tube.