
Nuclear Reactor Thermal-Hydraulics

NUGN520 - Homework

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HEAT TRANSFER AND FLUID FLOW, NONMETALLIC COOLANTS

Several exercises from the book written by M. M. El Wakil [1] are tackled in this homework. The problems in this section relate to the tenth chapter of the book, covering the subject of heat transfer and fluid flow, for metallic coolants.

1.1 [10-1] - Turbulent coolant tube

1.1.1 Problem

A hypothetical liquid metal has $Pr = 0$ and $k = 50 \text{ Btu} \cdot \text{h}^{-1} \cdot \text{ft}^{-1} \cdot ^\circ\text{F}^{-1}$. It flows through a 1-in.-diameter tube with a Reynolds number of 1000000. The tube-wall temperature is 1000°F . The temperature of the fluid halfway between the wall and the centerline is 900°F . Find (a) the temperature at the centerline of the tube, (b) the bulk temperature of the fluid and (c) the heat flux in $\text{Btu} \cdot \text{h}^{-1} \cdot \text{ft}^{-2}$.

1.1.2 Solution

Martinelli provides solutions for the temperature gradient in pipe flow for various Reynolds and Prandtl number (and conveniently, $Re = 10^6$ and $Pr = 0$ is one of these solutions), seen in Figure 9-3 of the book [1].

We thus obtain, for $Pr = 0$ and $Re = 10^6$:

$$(1.1) \quad \frac{T_w - T(y)}{T_w - T_c} = \frac{y}{r_0}$$

Knowing $T_w = 1000^\circ\text{F}$ and also knowing $T(y = r_0/2) = 900^\circ\text{F}$, we can now easily solve the next equation for T_c :

$$(1.2) \quad \frac{T_w - T(y = r_0/2)}{T_w - T_c} = \frac{1}{2}$$

$$(1.3) \quad T_c = 2 * (900 + 500 - 1000) = 800^\circ F$$

This is expected, we have a linear profile. In this case, the bulk temperature can be taken to be the average temperature in the channel, thus $T_f = 900^\circ F$. The book also states that (p. 236) "in highly turbulent flow, the temperature profile is fairly flat over much of the cross-section, and the bulk temperature is taken as equal to the temperature at the center of the channel", so T_f could also be taken as $800^\circ F$. Alternatively, the bulk temperature can be obtained from Figure 10-12. However, this requires to know the value of $\frac{q''' r_0^2}{k}$. This value can be obtained from Figure 10-11, by taking the temperature at the wall. Indeed:

$$(1.4) \quad 10 * \frac{T_w - T_c}{q''' r_0^2 / k} = 2 \implies \frac{q''' r_0^2}{k} = \frac{T_w - T_c}{0.2} = 1000$$

Plugging this into the data for Figure 10-12, we get:

$$(1.5) \quad \frac{T_w - T_f}{q''' r_0^2 / k} = 10^{-2} \implies T_f = 990^\circ F$$

So we have values of $800^\circ F$, $900^\circ F$ and $990^\circ F$ for the bulk temperature. The middle value will be used, arbitrarily.

Considering a constant heat flux along the tube wall, we can use the Lyon-Martinelli correlation:

$$(1.6) \quad Nu = 7 + 0.025 Pe^{0.8}$$

$Pe = Re.Pr = 0$ in our case, so, $Nu = \frac{h D_e}{k} = 7$.

From this, we can obtain $h = \frac{7k}{D_e} = \frac{7 * 50}{1/12} = 4200 \text{ Btu} \cdot \text{h}^{-1} \cdot \text{ft}^{-2} \cdot ^\circ F^{-1}$.

We can now calculate the heat flux, using:

$$(1.7) \quad q_w'' = h(T_f - T_w)$$

Consequently, $q_w'' = -4200 * (100) = -4.2 \times 10^6 \text{ Btu} \cdot \text{h}^{-1} \cdot \text{ft}^{-2}$

This value for the heat flux changes with the bulk temperature chosen.

1.2 [10-7] - Fluid-fueled reactor

1.2.1 Problem

A fast fluid-fueled reactor uses uranium metal dissolved in liquid bismuth with a U^{235} density of $1 \times 10^{20} \text{ n.cm}^{-3}$. The fuel thermal conductivity is $9 \text{ Btu.h}^{-1}.\text{ft}^{-1}.\text{°F}^{-1}$. The fission cross section is $5b$. The core can be approximated by a cylinder 3 ft in diameter. At a particular plane in the core, the neutron flux was flattened to 1×10^{13} and the fuel bulk temperature is 782.5°F . If the fuel flow is assumed to be laminar, find for that plane (a) the wall temperature in case the walls were adiabatic, (b) the centerline temperature for the preceding case, and (c) the percent heat generated that must be removed if, for structural reasons, the wall temperature should not exceed 700°F .

1.2.2 Solution

In order to compute the wall temperature T_w , we can use Equation 10-22 of the book [1].

$$(1.8) \quad T_w = T_f + \frac{q''' r_0^2}{k} \frac{11F - 8}{48}$$

In the case of an adiabatic wall, $F = 1$. The only unknown in this equation is the volumetric thermal source strength, q''' . It can be obtained using the equation:

$$(1.9) \quad q''' = G \sigma_f N \phi g = 180 * 5 \times 10^{-24} * 1 \times 10^{20} * 1 \times 10^{13} * 1.5477 \times 10^{-8} = 13929 \text{ Btu.h}^{-1}.\text{ft}^{-3}$$

T_w is thus 1000°F .

Using Figure 10-9, we can obtain that:

$$(1.10) \quad \frac{T_w - T_c}{q''' r_0^2 / 2k_f} = 0.25$$

Consequently, we can obtain $T_c = 565^\circ\text{F}$.

Using Equation 1.8, we can compute F , which is 1-fraction of heat generated that is transferred for a given maximum T_w .

In our case, $T_w = 700^\circ\text{F}$. And so:

$$(1.11) \quad \frac{48}{11} \left((T_w - T_f) \frac{k}{q''' r_0^2} + \frac{8}{48} \right) = F$$

This gives us $F = 0.2$. Consequently, the fraction of the heat generated within the moving fluid that needs to be removed is 0.8.

BIBLIOGRAPHY

- [1] M. M. EL-WAKIL, *Nuclear Heat Transport*, American Nuclear Society, 1993.