Module 2 : Convection

Lecture 20 : Heat Transfer Enhancement Evaluation in Roughened Heat Exchanger Tubes

Objectives

In this class:

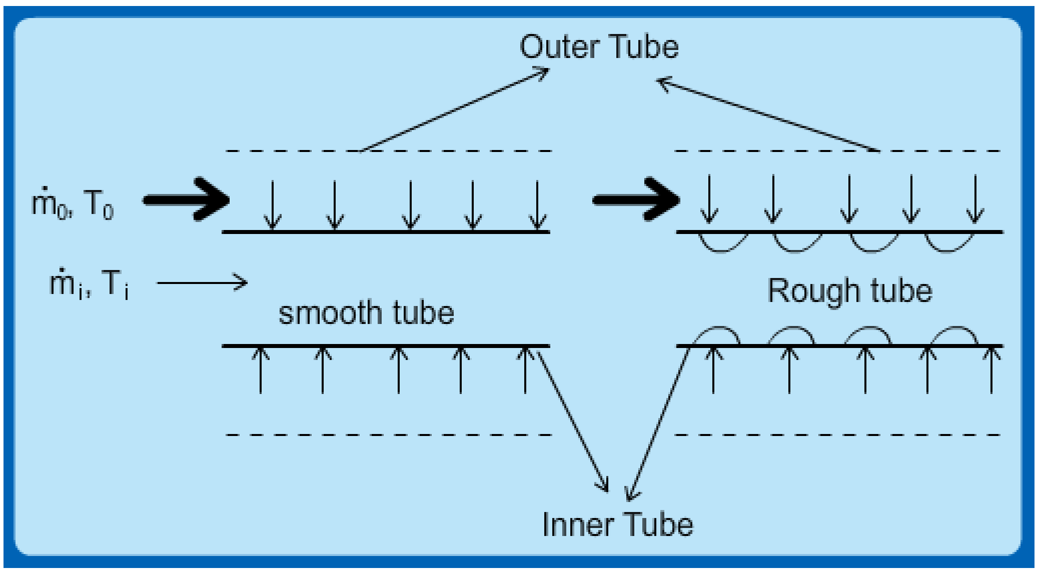
- Methodologies for evaluation of the performance of heat transfer enhancement devices in heat exchanger tubes of tube in tube type
- Material from "Application of Rough Surfaces to Heat Exchanger Design" R.L. Webb, R.L & Eckert, E.R.G" International Journal of Heat and Mass Transfer pg. 1647, 1972

Rough Surface Heat Exchanger tubes-1

- The analysis in Class 19 was one where a heat flux was assumed to have been supplied to the pipe. Only the internal heat transfer coefficients were considered.
- Now consider a situation where outer wall of the tube is exposed to a fluid that transfers heat to the inner tube.
- Only the inner tube is assumed to have been roughened.

Rough Surface Heat Exchanger tubes-2

- There is now an outer heat transfer coefficient also.



Rough Surface Heat Exchanger tubes-3

- Let:
- A_{os}, A_{or}, A_s, Ar = outer/inner surface of smooth/rough inner tube respectively.
- h_o, h_s, h_r = heat transfer coefficients for outer tube, inner smooth/rough tube.
- Notice that even though A_s and A_r are not necessarily equal:

$$\frac{A_s}{A_{0s}} = \frac{A_r}{A_{0r}} = 1$$

Rough Surface Heat Exchanger tubes-4

- In this case the resistance to heat transfer due to the outer tube also needs to be considered and using a 1D analogy:

$$\frac{1}{UA} = \frac{1}{h_s A_s} + \frac{1}{h_0 A_{0s}} = \frac{1}{h_s A_s}\left[1 + \frac{h_s A_s}{h_0 A_{0s}}\right] \qquad (20.1)$$

- U is the overall heat transfer coefficient. An equation like equ^n (20.1) can also be written for the rough tube.
- Assume that the outer tube is not modified for enhancement and h_0 remains constant

Rough Surface Heat Exchanger tubes-5

- The smooth and rough heat exchangers need to be compared

$$\frac{1}{U_s A_s} = \frac{1}{h_s A_s}[1+r]; \quad (20.2)$$

$$\frac{1}{U_r A_r} = \frac{1}{h_r A_r}\left(1 + r\frac{h_r}{h_s}\right) \quad (20.3)$$

$$r = \frac{h_s A_s}{h_0 A_{0s}} = \frac{h_s}{h_0} \quad (20.4)$$

- Now we can analyze in a manner similar to the previous situation.

Rough Surface Heat Exchanger tubes-6

- Conductance ratio therefore becomes:

$$\frac{k_r}{k_s} = \frac{U_r A_r}{U_s A_s} = \frac{A_r}{A_s}\frac{(1+r)}{(h_s/h_r + r)} \quad (20.5)$$

- Heat transfer coefficient ratio for the inner smooth and rough situations is:

$$\frac{h_r}{h_s} = \frac{h_r \rho c_p u_r}{\rho c_p u_r}\frac{\rho c_p u_s}{h_s \rho c_p u_s} = \frac{St_r}{St_s}\frac{1}{g^*};$$

$$\text{where } \frac{\rho\, u_r}{\rho\, u_s} = \frac{1}{g^*} \quad (20.6)$$

Rough Surface Heat Exchanger tubes-7

- Therefore

$$\frac{k_r}{k_s} = \frac{A_r}{A_s}\left[\frac{1+r}{g^*\dfrac{St_s}{St_r} + r}\right] \quad (20.7)$$

- Note that for r = 0 equ^{n}s (20.7) and (19.2) are identical; i.e. conductance in the previous case was infinite for the outer wall – this is alright since outer wall flux was specified i.e. resistance on outer wall is zero.
- Do the same manipulations as in the previous case and obtain the core equation.

Rough Surface Heat Exchanger tubes-8

- The pumping power equation is the same as derived previously (i.e. equ^n (19.8)):

$$\frac{P_r}{P_s} = \frac{f_r A_r}{f_s A_s}\left(\frac{1}{g^*}\right)^3 \quad (20.8)$$

- Substitute equ^n (20.8) in equ^n (20.7) to get:

$$\frac{k_r}{k_s} = \frac{A_r}{A_s}\left[\frac{(1+r)}{\dfrac{(f_r/f_s)^{1/3}(A_r/A_s)}{(P_r/P_s)^{1/3}}\dfrac{St_s}{St_r} + r}\right] \quad (20.9)$$

Rough Surface Heat Exchanger tubes-9

- Equ^n (20.9) is further simplified to yield

$$\frac{k_r}{k_s}\left(\frac{f_r}{f_s}\right)^{1/3}\left(\frac{A_r}{A_s}\right)^{1/3}\left(\frac{P_s}{P_r}\right)^{1/3}\frac{St_s}{St_r}+r\frac{k}{k_s}=(1+r)\frac{A_r}{A_s}$$

$$\frac{k_r}{k_s}\left(\frac{A_r}{A_s}\right)^{1/3}=\frac{(1+r)A_r/A_s-rk_r/k_s}{\frac{St_s}{St_r}\left(\frac{P_s}{P_r}\right)^{1/3}\left(\frac{f_r}{f_s}\right)^{1/3}} \qquad (20.10)$$

$$\Rightarrow\frac{\frac{k_r}{k_s}\left(\frac{A_r}{A_s}\right)^{1/3}}{\left(\frac{P_s}{P_r}\right)^{1/3}[(1+r)A_r/A_s-rk_r/k_s]}=\frac{\left(\frac{St_r}{St_s}\right)}{\left(\frac{f_r}{f_s}\right)^{1/3}}$$

Rough Surface Heat Exchanger tubes-10
Constant Pumping Power, Conductance

- Again do the same manipulations for the three cases. First consider $P/P_S = k/k_S = 1$. Start with equ^n (20.5) and simplify:

$$\frac{k_r}{k_s}=1=\frac{A_r}{A_s}\frac{(1+r)}{g^*(\frac{St_s}{St_r})+r} \qquad (20.11)$$

$$\Rightarrow\frac{A_r}{A_s}=\frac{g^*St_s/St_r+r}{1+r} \qquad (20.12)$$

- Start with equ^n (20.8) to get:

$$\frac{P_r}{P_s}=1=\frac{f_r}{f_s}\frac{A_r}{A_s}\frac{1}{g^{*3}}$$

Rough Surface heat Transfer: tubes-11
Constant Pumping Power, Conductance

- Use $k/k_S = 1 = P/P_S = 1$ in equ^n (20.10) and use equ^n (20.13) to get

$$\frac{(\frac{A_r}{A_s})^{1/3}}{\frac{1}{g^{*2}}\frac{A_r}{A_s}\left[(1+r)g^{*2}-r\frac{f_r}{f_s}\frac{1}{g^*}\right]}=\frac{St_r/St_s}{(f_r/f_s)^{1/3}}$$

$$\Rightarrow\frac{(A_s/A_r)^{2/3}g^{*2}}{(1+r)g^{*2}-r\frac{f_r}{f_s}\frac{1}{g^*}}=\frac{St_r/St_s}{(f_r/f_s)^{1/3}}$$

$$\Rightarrow\frac{\left[(f_r/f_s)^{2/3}1/g^{*2}\right]g^{*2}}{(1+r)g^{*2}-r\frac{f_r}{f_s}\frac{1}{g^*}}=\frac{St_r/St_s}{(f_r/f_s)^{1/3}} \qquad (20.14)$$

Rough Surface Heat Exchanger tubes-12
Constant Pumping Power, Conductance

- Equ^n (20.14) is simplified to yield the final expression:

$$\frac{f_r / St_r}{f_s / St_s} = g^{*2}(1+r) - \frac{r(f_r / f_s)}{g^*} \tag{20.15}$$

- Use equ^n (20.15) to obtain g*. Now use this in the A/As expression i.e. equ^n (20.12), to verify whether it is less than unity or not.

Rough Surface heat Transfer: tubes-13
Constant Pumping Power, Area

- Next case P/Ps = 1, A/As = 1. Use equ^n (20.13) to yield:

$$g^* = (f_r / f_s)^{1/3}$$

- Substitute in equ^n (20.11) to yield

$$\frac{k_r}{k_s} = \frac{1+r}{(f_r / f_s)^{1/3}(St_s / St_r) + r} \tag{20.16}$$

- Note that this is the same as equ^n (19.13) for r = 0 in equ^n (20.16).

Rough Surface heat Transfer: tubes-14
Constant Area, Conductance

- Last case k/ks=1, A/As=1
- Use equ^n (20.7)

$$1 = \frac{1+r}{\left(g^* St_s / St_r + r\right)} \Rightarrow g^* = St_r / St_s \tag{20.17}$$

- Use equ^n (20.8) to get:

$$g^* = \frac{(f_r / f_s)^{1/3}}{(P_r / P_s)^{1/3}} \tag{20.18}$$

- Equate equ^{n}s (20.17) and (20.18) to get:

$$\Rightarrow \frac{P_r}{P_s} = \frac{f_r / f_s}{(St_r / St_s)^3} \tag{20.19}$$

Recap

In this class:

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