Heat Transfer and Pressure Drop Correlations

Heat Transfer Correlations

Coolant (Lead) Flow in Core (Ref. 8)

$$Nu = Nu_{lam} + \frac{0.041}{x^2}\left[1 - \frac{1}{\frac{x^{30}-1}{6} + \left(1.15 + 1.24\varepsilon_6\right)^{1/2}}\right]Pe^2$$

where

$$Nu_{lam} = 7.55x - \frac{6.3}{x^b}\left[1 - \frac{3.6x}{x^{20}\left(1 + 2.5\varepsilon_6^{0.86}\right) + 3.2}\right]$$

$$x = p/d$$

$$\varepsilon_6 = \frac{k_{cl}}{k_{bo}}\frac{X_{cl}\left(m_{bo} - X_{bo}\right)m_{cl} + X_{bo}\left(1 - X_{bo}m_{bo}\right)}{X_{bo}\left(m_{bo} + X_{bo}\right)m_{cl} + X_{bo}\left(1 + X_{bo}m_{bo}\right)}$$

$$X_{cl} = \left(\frac{D_{c,i}}{D_{rod}}\right)^{12}, \; X_{bo} = \left(\frac{D_{f,o}}{D_{rod}}\right)^{12}$$

$$m_{cl} = \frac{k_{cl} - k_f}{k_{cl} + k_f}, \; m_{bo} = \frac{k_{bo} - k_f}{k_{bo} + k_f}$$

$$Pe = \mathrm{Re}\,\mathrm{Pr}$$

$$a = 0.56 + 0.19x - 0.1/x^{80}$$

$$b = 17x\left(x - 0.81\right)$$

p = fuel pin pitch,
$d = D_{rod}$ = fuel pin diameter,
k = thermal conductivity,
$D_{c,i}$ = cladding inner diameter,
$D_{f,o}$ = fuel outer diameter,
subscripts *cl*, *bo*, and *f* denote cladding, bond, and fuel, respectively.

Lead Flow around Rods – LAR and FGP Regions (Ref. 9)

$$Nu = 24.15\log_{10}\left[-8.21 + 12.76\frac{p}{d} - 3.65\left(\frac{p}{d}\right)^2\right] + x$$

where

$$x = \begin{cases} 0.0174\left[1 - e^{-6.0\left(\frac{p}{d}-1\right)}\right](\mathrm{Re}\,\mathrm{Pr} - 200)^{0.9}, & \mathit{if}\ \mathrm{Re}\,\mathrm{Pr} \geq 200 \\ 0, \quad \mathit{if}\ \mathrm{Re}\,\mathrm{Pr} < 200 \end{cases}$$

Lead Flow in IRHX (Ref. 10)

$$Nu = 7.55\frac{p}{d} - 14\left(\frac{p}{d}\right)^5 + 0.007Pe^{0.64+0.246\frac{p}{d}}$$

Lead Flow along a Cylindrical Wall – IRHX wall and Downcomer (Ref 11)

$$Nu = \alpha + \beta(\psi\,\mathrm{Re}\,\mathrm{Pr})\gamma$$

where

	Outer wall	Inner wall
$\alpha =$	$5.54 - 0.023y$	$4.82 + 0.697y$
$\beta =$	$0.0189 + 0.00316y = 0.0000867y^2$	0.0222
$\gamma =$	$\frac{0.758}{y^{0.0204}}$	$0.758y^{0.053}$

$$y = \frac{R_o}{R_i} = \text{radius ratio},$$

$$\psi = 1 - \frac{1.82}{\mathrm{Pr}\left(\frac{\varepsilon_m}{\nu}\right)_{\max}^{1.4}},$$

$$\left(\frac{\varepsilon_m}{\nu}\right)_{\max}^{1.4} = 7.833 \cdot 10^{-4}\,\mathrm{Re}^{1.2}$$

Air Flow along Guard Vessel Wall (Ref. 12)

$$Nu = F_{enh} 0.0217 \mathrm{Re}^{0.8} \mathrm{Pr}^{0.4} \left(\frac{T_{air}}{T_w} \right)^{0.2}$$

where

F_{enh} = heat transfer enhancement factor,
T_{air}, T_w = air bulk and wall surface temperatures, respectively.

CO_2 Flows

A user can select in input files which correlation to use in each component. The code supports two correlations:

- Dittus-Boelter [13]

$$Nu = 0.023 \mathrm{Re}^{0.8} \mathrm{Pr}^{n}$$

where

n = 0.4 for heated flow and 0.3 for cooled flow.

- Petukhov-Gnielinski [14]

$$Nu = \frac{\frac{f}{2}(\mathrm{Re} - 1000)\mathrm{Pr}}{1 + 12.7\left(\frac{f}{2}\right)^{1/2}\left(\mathrm{Pr}^{2/3} - 1\right)} \left[1 + \left(\frac{D}{L} \right)^{2/3} \right]$$

where

f = friction factor, found from $1/\sqrt{f} = 4.0 \log_{10}\left(\mathrm{Re} \cdot \sqrt{f}\right) - 0.4$

D = hydraulic diameter,
L = channel length.

Both correlations above are applicable to turbulent flow (Re>2300) only. In laminar flow the following correlation is used [15].

$$Nu_{lam} = 4.364$$

Pressure Drop Correlations

Turbulent Flow (Re>2300, Except Air, Ref. 16)

$$f = \frac{1}{4X^2}$$

where

X =hydraulic resistance found from $X = 1.74 - 2\log_{10}\left(\frac{2k_s}{D_h} + \frac{18.7X}{\text{Re}}\right)$

k_s = wall roughness (10 mkm is assumed),
D_h = hydraulic diameter.

Laminar Flow (Re≤2300, Except Air, Ref. 5)

$$f = \frac{16}{\text{Re}}$$

Air Flow

$$f = \frac{0.0791}{\text{Re}^{0.25}}$$

References

8. Kirillov, P.L. and Ushakov, P.A., "*Liquid-Metal Heat Transfer in Rod Bundles*," Thermal Engineering, Vol. 48, No. 2, 2001, pp. 127-133.

9. Borishanski, V.M. and Firsova, E.V., "*Heat Transfer in Liquid Metals*," Chapter 2.5.13 of Volume 2, Fluid Mechanics and Heat Transfer, of Heat Exchanger Design Handbook, Hemisphere Publishing Corporation, New York, 1990.

10. Zhukov, A.V., et. al., "*An Experimental Study of Heat Transfer in the Core of Brest-OD-300 Reactor with Lead Cooling on Models*," Thermal Engineering, Vol. 49, No. 3, 2002, pp. 175-184.

11. Dwyer, O.E., "*Liquid-Metal Heat Transfer*," Chapter 2 of Sodium-NaK Engineering Handbook, Volume II Sodium Flow, Heat Transfer, Intermediate Heat Exchangers, and Steam Generators, Science Publisher, Inc., New York, 1976.

12. Dalle Donne, M. and Meerwarld, E., "*Heat Transfer and Friction Coefficients for Turbulent Flow of Air in Smooth Annuli at High Temperatures*," International Journal of Heat and Mass Transfer, Vol. 16, p. 787, 1973

13. Todreas, N. E and Kazimi M.S., Nuclear Systems, Hemisphere Publishing Corp., New York, 1990.

14. Olson, D.A. and Allen, D., "*Heat Transfer in Turbulent Supercritical Carbon Dioxide Flowing in a Heated Horizontal Tube*," National Institute of Standards and Technology, NISTIR 6234, 1998.

15. VanSant, J.H., "*Conduction Heat Transfer Solutions*," UCRL-52863 Rev. 1, Lawrence Livermore National Laboratory, 1983.

16. Schlichting, H., Boundary Layer Theory, Fourth Edition, p. 525, McGraw-Hill Book Company, Inc., New York, 1960.