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Friction Factor Correlations

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Summary

We describe in this note the friction factor correlations implemented in the `friction` *library.*

1. Introduction

Simulation of thermohydraulic transients in cables require the precise knowledge of the friction factor of the flow. We have created a series of dedicated functions that implement well-known correlations for smooth tubes, as well as dedicated correlations for Cable-in-Conduit Conductors (CICC's). These correlation can be used as a library and called from user's programs, or user's routines in programs. Here we describe in details the correlations and the functions implemented in the `friction` library.

2. Correlations

The definition of the friction factor that we use is such that the pressure drop per unit length along the flow direction x can be written as:

$$\frac{\partial p}{\partial x} = -2\rho \frac{f}{D_h} v|v| \qquad (1)$$

where p is the pressure, ρ is the density, f is the friction factor, D_h is the hydraulic diameter of the channel and v is the flow velocity. The friction factor will be given primarily as a function of the Reynolds number Re, in turn defined as:

$$Re = \frac{\rho v D_h}{\upsilon} \qquad (2)$$

where υ is the viscosity.

2.1. Laminar flow

For laminar flow we have the well-known relation:

$$f_{laminar} = \frac{16}{Re} \qquad (3)$$

2.2. Smooth tube correlation

A convenient correlation for a turbulent flow in a smooth tube is given by:

$$f_{smooth} = \frac{0.046}{Re^{0.2}} \qquad (4)$$

2.3. Blasius correlation

Blasius' correlation also holds for a turbulent flow in a smooth tube in the range of $3\ 10^3 < Re < 10^5$:

$$f_{Blasius} = \frac{0.079}{Re^{0.25}} \qquad (5)$$

2.4. Nikuradse-von Karman correlation

A better correlation for turbulent flow in smooth tube has been given by Nikuradse and von Karman in the range of $4\ 10^3 < Re < 3\ 10^6$:

$$\frac{1}{\sqrt{f_{Nikuradse}}} = 1.737\, ln\left(Re\sqrt{f_{Nikuradse}}\right) - 0.4 \qquad (6)$$

this correlation is non-linear in nature, and requires iterative solution to determine the value of the friction factor as a function of Re. It should therefore be used with caution to avoid excessive computational burden.

2.5. Westinghouse correlation for CICC's

Westinghouse developed a dedicated correlation for the friction factor measured in the CICC developed for the LCT project [1]. The correlation is the following:

$$f_{Westinghouse} = \frac{12.7}{Re} + \frac{0.0698}{Re^{0.25}} + 0.0146 \qquad (7)$$

that is valid in the range $50 < Re < 10^4$.

2.6. Adapted Nikuradse-von Karman correlation for the US-DPC CICC

The data from the US-DPC test [2] were used to modify the coefficient in the Nikuradse-von Karman correlation as follows:

$$\frac{1}{\sqrt{f_{US-DPC}}} = 1.74\, ln\left(Re\sqrt{f_{US-DPC}}\right) - 4.794 \qquad (8)$$

The fit was performed in the range $80 < Re < 8\ 10^3$. As for the Nikuradse-von Karman equation the above correlation is non-linear and requires iterative solution.

2.7. Katheder correlation for CICC's

The best correlation to a CICC friction factor, that takes into account the effect of variations in void fraction v_f, has been proposed by Katheder [3]. The formula originates in similar equations used for pebble beds. The best fit to six different sources is given by:

$$f_{Katheder} = \frac{1}{4v_f^{0.72}}\left(\frac{19.5}{Re^{0.88}} + 0.051\right) \qquad (9)$$

with best agreement found in a range $10^3 < Re < 10^4$.

3. Library

The correlations above have been implemented in the following `FORTRAN` functions available in the `friction.a` library. All functions must be declared as `real` in the calling program. The calling parameters (Reynolds number `Re` and void fraction `vf` for Katheder correlation) are also of `real` type.

correlation	equation	function	remarks
laminar	(3)	`f_Laminar(Re)`	
smooth tube	(4)	`f_Smooth(Re)`	
Blasius	(5)	`f_Blasius(Re)`	
Nikuradse-von Karman	(6)	`f_Nikuradse(Re)`	iterative function
Westinghouse	(7)	`f_Westinghouse(Re)`	
US-DPC	(8)	`f_US_DPC(Re)`	iterative function
Katheder	(9)	`f_Katheder(Re,vf)`	

4. References

[1] M.A. Janocko, R.D. Blaugher, P.W. Eckels, *Flow Characteristics of Forced Flow Nb3Sn Conductors for Toroidal Field Coils*, Proc. ICEC-7, 1978.

[2] T. Painter, et al., *Test Data from the US-Demonstration Poloidal Coil Experiment*, DOE/ER/54110-1, January 1992.

[3] H. Katheder, *Optimum Thermohydraulic Operation Regime for Cable in Conduit Superconductors (CICS)*, Cryogenics, **34**, 595-598, 1994.