The relationship between dynamic and average flow rates of the coolant in the channels of complex shape

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Abstract. This paper presents interconnection of dynamic and average flow rates of the coolant in a channel of complex geometry that is a basis for a generalization model of experimental data on heat transfer in various porous structures. Formulas for calculation of heat transfer of fuel rods in transversal fluid flow are acquired with the use of the abovementioned model. It is shown that the model describes a marginal case of separated flows in twisting channels where coolant constantly changes its flow direction and mixes in the communicating channels with large intensity. Dynamic speed is suggested to be identified by power for pumping. The coefficient of proportionality in general case depends on the geometry of the channel and the Reynolds number (Re). A calculation formula of the coefficient of proportionality for the narrow line rod packages is provided. The paper presents a comparison of experimental data and calculated values, which shows usability of the suggested models and calculation formulas.

1. Introduction

The determination of the hydrodynamic resistance and heat transfer is the primary goal of considering the convective transfer in the heat exchanger. The heat transfer coefficient of rod assemblies depends on large list of parameters: the longitudinal and transversal steps of package, hydraulic diameter, flow velocity, flow properties and etc.

\[ Nu = f(Re, Pr, \frac{s_1}{d}, \frac{s_2}{d}, ...) \] (1)

Since the parameters in equation (1) are interconnected, a determination of this parameters separate and comprehensive influence on heat transfer becomes crucial objective. The correct choice of the equation structure could arise after numerical analysis of experimental data.

2. Construction of the model

Two factors have served as a basis for making new generalizations. The first factor is the construction of a unified physical model to summarize information about any structures. The second one is a good
agreement of the calculations, that is performed with the use of the recommended empirical formulas [1-7], with experimental data in in-line bundles of tubes with a large value of porosity ($\Pi \geq 0.3$). The difference in the experimental data and calculated values does not usually exceed 25 - 30 %. However, the recommended formulas are not appropriate for high-density line bundles. The difference in the experimental values and calculated data varies from 50 to 300 % (Fig.1). The high density bundles are supposed to be the ones with no more than 30 % porosity value ($\Pi < 0.3$).

![Figure 1. Dependence of heat transfer complex on Re number for line bundles: 1-1.053×1.053, 1-1.026×1.026, 3-1.020×1.020, 4-1.013×1.013, 5-1.008×1.008, 6-2.63×1.10, 7-2.00×2.00, 8-1.65×2.00, 9 - experimental values obtained by A.A. Zukauskas [1].](image)

In [6] the next dependence of heat transfer resistance in turbulent flow in smooth channels, which is constructed with the use of factor analogy, is recommended:

$$\frac{c_f}{2St} = k_1 + k_2 \sqrt{\frac{c_f}{2} (Pr^{2\xi} - 1)} \quad (2),$$

where $St = \frac{Nu}{RePr}$ is the Stanton number, $c_f = \frac{\xi}{4}$ – friction coefficient, $\xi$ – coefficient of hydraulic resistance, $k_1 = 0.93$, $k_2 = 12.5$. Assuming $k_1 = 1$, $k = k_2 = 12.7$, $n = \frac{2}{3}$, a general equation is obtained:

$$St = \frac{\frac{\xi}{8}}{1 + k \sqrt{\frac{\xi}{8} (Pr^n - 1)}} \quad (3)$$

In [10-11], the universality of equation (3) and its applicability to the calculation of average heat transfer in channels of complex shape with tear currents is assumed. The main task is to find the relationship between the dynamic and average coolant flow rates in the channel.
3. Interconnection of dynamic and average flow rates of the coolant

An important characteristic of coolant flow rate distribution near the wall of pipe is the dynamic flow rate \( v_* \) that is associated with the average speed \( \bar{V} \) and the coefficient of resistance \( \zeta \) by the equation:

\[
v_* = \bar{v} \sqrt{\frac{\zeta}{8}} = \bar{v} \sqrt{\frac{c_f}{2}}
\]

Considering this, the following equation appears:

\[
\frac{\bar{v}}{v_*} = \sqrt{\frac{8}{\zeta}} = f(Re_*)
\]

The dynamic flow rate is supposed to be determined through the cost of coolant pumping power. Then, with the consideration of dimensions:

\[
v_* = c \left( \frac{\nu \bar{V} P}{\rho} \right)^{0.25}
\]

(4)

where \( \nu \) - the kinematic viscosity coefficient, \( C \) – coefficient of proportionality, which depends in the General case on the geometry of the channel and \( Re \) number.

To determine the value of the constant «\( C \)» it is necessary to define function \( f(Re_*) \). Previously, this function was obtained for the pipe (the first equation of the following system) and the plate (second equation of the following system).

\[
f(Re_*) = \frac{\bar{v}}{v_*} = \sqrt{\frac{8}{\zeta}} = \left( \frac{2.5 \ln Re_*}{6.33 Re_*^{\frac{1}{5}}} \right)
\]

(5)

The obtained values give similar results after substitution of both functions in equation (5). The difference is less than 10%. In further generalization function \( f(Re_*) \) was used for the plate.

4. Data generalization

The calculation of the coefficient of proportionality «\( C \)» for a dense line bundles is implemented. It is shown that «\( C \)» does not depend on the \( Re \) number for each dense packing (figure2).

![Figure 2](image)

**Figure 2.** The dependence of coefficient «\( C \)» from \( Re \) number for narrow line bundles \((\Pi < 0.3)\): 1- \( 1.053 \times 1.053 \), 2- \( 1.026 \times 1.026 \), 3- \( 1.020 \times 1.020 \), 4- \( 1.013 \times 1.013 \), 5- \( 1.008 \times 1.008 \).
The formula (6) is recommended for calculations since the usage of this equation in (3) outputs good agreement with experimental data [1]. The deviation of calculated values from the experimental data does not exceed 15%.

\[ c = -45.6 + 350.5II - 635.9II^2 \]  

(6)

5. Conclusion

The paper presented interconnection of dynamic and average flow rates of the coolant and experimental data on heat transfer in various porous structures generalization model, which has several advantages. The first one is in fact that only one empirical constant presents in generalization. Additionally, new calculation formula is obtained, which has more accurate agreement with the experimental data [1].

Acknowledgments

The study was performed by the Russian Science Foundation (project No. 16-19-10548).

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