Determination of hydraulic resistance of rough annular channels by resistance of rough pipes

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Abstract. According to the current calculation recommendations for turbulent flow, coefficient of hydraulic resistance of a smooth annular channel with an equivalent hydraulic diameter \(d_h\) is assumed to be equal to the coefficient of hydraulic resistance of a pipe with a diameter \(d_h\) multiplied by a conversion factor. The value of this conversion factor, depending on the Reynolds number and the ratio of the inner diameter of the annular channel to the outer diameter, varies from 1 to 1.07. That is, a smooth annular channel and a smooth pipe with the same hydraulic diameters have practically the same hydraulic resistance coefficients. In this paper, experiments were conducted to test the feasibility of such an approach to channels with rough walls. According to measurements of water flow and pressure gradient, the coefficients of hydraulic resistance of a rough annular channel and a pipe with hydraulic diameters \(d_h = 6\) mm were calculated and compared. A trapezoidal artificial roughness was applied to the surfaces, which are flowing with a liquid. The experiments were carried out on a water circuit in the Reynolds number range from \(10^3\) to \(10^5\) in the regime of full roughness. The obtained experimental results were compared with calculations of coefficients of hydraulic resistance of pipes with artificial roughness according to the existing recommendations. Conclusions are drawn on the possibility of determining the hydraulic resistance of rough annular channels through the resistance of rough pipes.

1. Introduction

One of the ways of intensification of heat transfer is the creation of artificial roughness on the heat transfer surface [1,2]. Thus for the thermal-hydraulic calculations of heat exchangers requires knowledge of heat transfer coefficients and coefficients of hydraulic resistance for the specific geometry of the channels. Annular channels are one of the most common geometries. In the literature there are recommendations for the calculation of hydraulic resistance of smooth circular channels using the hydraulic resistance of smooth tubes, but reliable guidelines to calculate a rough ring channels do not exist. Therefore, the aim of this work is to test the possibility of calculating the coefficient of hydraulic resistance of rough annular channels using a hydraulic resistance factor of rough pipes using the formula for smooth channels.

According to [3], the coefficients of hydraulic resistance of a smooth annular channel and smooth pipes of the same hydraulic diameter are related by (1)
\[ \xi_x = \xi_0 \left( \frac{1-\theta}{1+(1-\theta^2)/\ln\theta^2} \right)^{0.62} (1+0.04\theta) \]  

(1)

where \( \xi_0 \) - coefficient of hydraulic resistance of smooth pipe, \( \theta = d_1/d_2 \), \( d_1 \) - inner diameter of the annular channel, \( d_2 \) - outer diameter of the annular channel. In practice, the coefficients of hydraulic resistance of a smooth annular channel and pipe are not more than 7%. To check the applicability of formula (1) to calculate rough paths conducted hydraulic testing of the pipe and the annular channel with similar hydraulic diameters and the same artificial roughness in the full manifestation of roughness, were the corresponding coefficients of hydraulic resistance and compared their attitude with the attitude calculated by the formula (1).

2. Experimental system and work areas

The measurements were carried out on a water loop (figure 1), in which is mounted the work area. Water circulation was provided a multistage vertical pump Calpeda MXV 40-805 with a maximum flow rate \( 13 \text{ m}^3/\text{h} \) and a maximum outlet pressure of 0.6 MPa. During the experiments, was measured: water flow, water temperature, pressure drop along the length of the plot. To improve the accuracy of measuring the pressure drop along the length of the plot was made four tackles pressure. For hydrodynamic stabilization of the flow the first selection pressure was located at a distance of 130 mm from the entrance to the work area. Measurement of water flow produced by the ultrasonic flowmeter "Akron-01". The measurement error was 2%. The temperature was measured by thermocouple chromel-alumel with an error \( \pm 0.05 \degree \text{C} \). Pressure measurement was carried out exemplary pressure gauges with an accuracy of \( \pm 3 \cdot 10^3 \text{ Pa} \).

![Diagram of the water circuit](image)

1 – Tank with coolant, 2 – valve, 3 – pump, 4 – outer pipe, 5 – shank, 6 – manometer, 7 – rotameter, 8 – thermometer

Figure 1 – diagram of the water circuit.

Two working area have been done. The first (A) is a rough pipe, the second (B) is a rough annular channel coaxially fixed to the rod inside a round tube (figure 2). On the inner surface of the pipe suffered a trapezoidal artificial roughness height \( h = 0.2 \text{ mm} \) and pitch \( S = 1 \text{ mm} \) (figure 2-A). The roughness of the same geometry was applied in the annular channel (figure 2-B).

The artificial roughness was chosen because of, first, it is technologically easier to put on the rod and the inner surface of the pipe; secondly, for it in the literature [4], the value of the equivalent sand roughness \( \Delta_{ecv} \) is given. Latter point is important for comparison of experimental data with existing
correlations for hydraulic design of the pipes with sand roughness. Outer diameter of the annular channel is $d_2 = 21.4$ mm, inner diameter of the annular channel is $d_1 = 14.3$ mm.

![Figure 2. Section of the working area: A - rough pipe, B - rough annular channel.](image)

3. Processing of the experimental data and results

The experimental data were carried out according to the formula Darcy – Weisbach [4], according to which the coefficient of hydraulic resistance of a channel is:

$$\xi_{\text{exp}} = \frac{2d_r \Delta P S^2}{G l \rho G^2},$$

where $\rho$ - density of water, kg/m$^3$; $G$ - water consumption, m$^3$/s; $S$ - area of flow section of the annular channel, m$^2$; $d_r$ - hydraulic diameter of the annular channel, m; $l$ - channel length, m; $\Delta P$ - pressure differential in the work area, Pa.

The coefficient of hydraulic resistance of a circular pipe with artificial roughness was calculated according to the recommended formulas Yaglom and Kader, Al'tshulya, Nikuradze, Kol'bruka-Uayta [4,5]. For used in experiments of artificial roughness in [4], the corresponding value of the equivalent sand roughness $\Delta_{\text{equiv}} = 0.343$ mm. The value of the dimensionless criterion $k_{so} = (\Delta/d)\sqrt{\xi / 8}$, responsible for the mode of manifestation of roughness in the experiments for the pipe and the annular channel was $k_{so} \geq 25$, that, according to [2,4], demonstrated the modes with the full manifestation of roughness.

Obtained experimental data for the rough tubes were compared with the calculated values according to the recommended formulas (figure 3). The experimental values lie below the calculated. The best fit is observed with the calculations according to the method Yaglom and Kader for pipes with an artificial roughness (difference is not more than 20%). It is also worth noting a significant difference calculated values obtained by Nikuradze and formulas Al'tshulya which is 29% at the same Re number and $\Delta_{\text{equiv}}$. By repeatedly conducted experiments obtained the mean value of the hydraulic resistance of rough tubes $\bar{\xi}_f = 0.0425$ (figure 3).

Technologically failed to produce channels with identical hydraulic diameters. They were equal to 6.4 mm for pipe and 7.1 mm for the annular channel. So a correction factor $k_1$ was introduced, which was defined as follows:
where $\xi_{d,6.4}$ and $\xi_{d,7.1}$ - coefficients of hydraulic resistance of rough pipes is calculated according to the formula Nikuradse, respectively, hydraulic diameters of 6.4 mm and 7.1 mm and the parameter of equivalent sand roughness $\Delta_{300} = 0.343$ mm. Further experimental average value $\xi_T = 0.0425$ divided by $k_1$ and the result was substituted into the formula (1). Finally the value of the coefficient of hydraulic resistance of rough annular channel was calculated: $\xi = 0.0433$. According to the experimental data the average value of the coefficient of hydraulic resistance for rough annular channel is equal to $\xi_{K.K.} = 0.0668$ (figure 4). The difference is 54%.

The result shows that use of formula (1) for hydraulic calculations of rough annular channels can give significantly lower values. In the experiments, the maximum error of measurement of the coefficient of hydraulic resistance of the channel was 12% and the maximum error of the Reynolds number -3.5%.

4. Conclusion
Experimental verification of the possibility to apply the formula for smooth channels for calculating the coefficient of hydraulic resistance of rough annular channels using the hydraulic resistance factor of rough pipes was carried out. For the studied roughness it was revealed that the coefficients of hydraulic resistance of rough annular channels and rough pipes with the same hydraulic diameters differ by 1.5 times, whereas for smooth channels, this difference does not exceed 7%. The result shows that the application of formula (1) for calculations of hydraulic resistance of rough annular channels can give significantly lower values and modification of this formula or search for new ratios are necessary.

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