The experimental determination of the coefficient of hydraulic resistance of a perforated plate with a layer of balls adjoining to it

Yu V Smorchkova, A N Varava, A V Dedov, A V Zakharenkov and A T Komov

National Research University "Moscow Power Engineering Institute"
Russia, 111250 Moscow, Krasnokazarmennaya str., 14

Abstract. The results of an experimental study of the hydrodynamics of a perforated plate with a layer of balls adjoining to it are presented herein. The experiments were carried out in the fluid flow range from 0.1 to 0.6 kg/s, at a fluid temperature of 19 °C.

1. Introduction
For calculating the coefficient of hydraulic resistance of various elements, the manual [1] is traditionally used. The data in [1] are presented in the form of tables, diagrams, and the calculated ratios that generalize these data. However, when determining the coefficient of hydraulic resistance of a solitary perforated plate from the calculated ratios, tables and graphs on pages 410-413 [1], significant discrepancies were found. Comparison of calculations is shown in Fig. 1.

The following formulas are offered to be used for the perforated plate in [1]:

$$\zeta = \frac{1}{f_2^2} + e_0 Re \cdot \zeta_1,$$

$$\zeta_1 = 0.5(1 - f)^{0.75} + \tau(1 - f)^{1.375} + (1 - f)^2 + 1.375 \cdot \frac{l}{Re} \cdot \frac{l}{d_o} \cdot \frac{1}{f^2},$$

$$\tau = \left(2.4 - l_o\right)^{\varphi(l_o)}, \quad \varphi(l_o) = 0.25 + 0.535l_o^3 \left(0.05 + l_o^2\right), \quad l_o = l/d_o,$$

$$\zeta_\varphi = \left[18.78 - \frac{7.768}{f} + \frac{6.337}{f^2}\right] \cdot e^{-0.942 - 7.246f/3.878f^2} \log(Re).$$

(1)

$\zeta$ – coefficient of the effective cross-section of the plate; $Re = U_o d_o / \nu$ – Reynolds number, determined by the speed in the holes and the diameter of the hole in the plate; dependence $e_0 Re$ on number $Re$ is presented only in the form of a table.

Formulas (1) are valid for $30 < Re < 10^4$ and $l/d_o > 0.015.$
Figure 1. The coefficient of hydraulic resistance of a solitary plate according to [1].

Fig. 1 shows that both qualitative and quantitative discrepancies of the data is more than twofold. Such discrepancies in the data became one of the reasons for conducting our own experimental studies to determine the coefficient of hydraulic resistance of a perforated plate. The second reason is that all the calculated ratios described above are obtained for solitary plates, under the conditions of this work, on one side the layer of balls adjoins the plate, which leads to a change in the flow pattern behind the cover. As shown in [2], the total pressure losses occur at a certain distance behind the plate due to the zones of recurrent flow.

2. Experimental facility
2.1. Hydraulic circuit
The study was carried out on an open hydraulic circuit, which diagram is shown in Fig. 2. Distilled water was used as the working fluid, it is located in the tank (1). Circulation of the coolant is carried out by a multistage centrifugal pump Grundfos CRNE 1-4 (2). The water from the tank is injected by the pump through the filter (3) to the working area (6) and flows back to the tank. Since the water amount in the tank is large enough, the water temperature in the circuit does not change significantly during the experiments.
Consumption control was carried out in two ways: stepwise with the help of a frequency controller installed on the pump, and smoothly by means of a bypass line (BP) and valves (B1, B2). The flow rate through the working area was measured by an electromagnetic flowmeter (4) of the Vzlyot brand EM PROFI-212 model. To measure the pressure in the working area, the standard arrow gauges (5) at the input and output of the working area and the differential pressure sensor (7) Elemer-100 were used.

The experimental test-bed is designed for the following mode parameters: temperature in the circuit from 18 °C to 180 °C, pressure in the circuit up to 1.0 MPa, coolant flow rate (0.01-0.60) kg/s.

2.2. Test section
The diagram of the test section (TS) is shown in Fig. 3. The TS consists of two coaxially arranged polycarbonate tubes (2, 4) with a diameter of 54 and 47 mm. The inner tube holds the ball backfill. The outer tube ensures the strength and impermeability of the structure. The backfill (5) is held by the lower (3) and upper (6) perforated plates made of caprolon. The perforation of the plates was carried out by drilling, the diameter of the perforation holes was 1.5 mm, the number of holes in each plate was 316. Balls with a diameter of 2.0 mm are made of steel AISI 420 grade.

The pressure loss was measured with a help of capillaries (1, 7). The lower capillary (1) was placed in front of the grating (3), the upper capillary (7) is movable to measure the pressure in different coordinates.

![Figure 3. Diagram of the test section.](image_url)

3. Experimental data
3.1. Coefficient of hydraulic resistance of a solitary perforated plate
The first series of experiments to develop the methodology and refine the directory data [1] was carried out at the working area with no ball backfill. The primary experimental data (Fig. 4) were obtained in the form of losses, depending on the coordinate of the upper capillary. The experiments were performed in the fluid flow range from 0.3 to 0.6 kg/s, at a fluid temperature of 19 °C.
Based on the experimental data obtained, the coefficients of hydraulic resistance of the perforated plate were calculated:

\[ \xi = \frac{\Delta p}{\rho U^2 / 2}, \]  

where \( U \) is fluid velocity in the tube.

The pressure loss was determined at the steady flow area behind the grating, as the average value of magnitudes measured in the coordinates of the upper capillary (pressure sampling) from 20 to 85 mm (Fig. 3).

The dependence of the coefficient of hydraulic resistance on the Reynolds number is shown in Fig. 5. For comparison, the figure shows the values obtained using tables and diagrams (pages 410-413 [1]). There is a qualitative coincidence of the results, quantitatively the discrepancy of the results is 8%. The results obtained show the correctness of the measurement procedure, and at the same time they confirm the correctness of the determination of the coefficient of hydraulic resistance according to the tables and graphs presented in [1] on pages 410-413, simultaneously indicating the errors in formulas (1).
3.2. Coefficient of hydraulic resistance of a perforated plate with a layer of balls adjoining to it

At the next stage, experiments were carried out to determine the pressure loss on a plate with a ball backfill. The height of the backfill in the experiments was 100 mm, its porosity – 0.383. The capillary of the upper pressure sampling shifted axially from the lower plate (3) to a coordinate of 50 mm. The primary experimental data are shown in Fig. 6 a, b. The comparison of Fig. 4 and Fig. 6 b) shows significant differences. In Fig. 6 b), the dependencies are linear and have no peculiarities, which indicates different patterns of fluid flow behind a solitary plate and in the case of an adjacent layer of balls. Consequently, to account the plate resistance in the presence of a layer of balls behind it, the use of the recommendations in [1] is incorrect.

Figure 5. Dependence of the coefficient of hydraulic resistance on the Reynolds number.

Figure 6. a) Dependence of pressure losses on the fluid mass flow rate. b) Dependence of pressure loss on the coordinate of the upper capillary.
To determine the coefficient of hydraulic resistance, the data in Fig. 5 b) were approximated by linear dependencies and expressions for each flow rate were obtained. According to these equations, pressure losses in the coordinate of 2.5 mm are determined to calculate the coefficient of hydraulic resistance of the grating together with one layer of balls. The coefficient of hydraulic resistance was calculated by formula (2).

The dependence of the coefficient of hydraulic resistance on the Reynolds number is shown in Fig. 7.

![Figure 7. The dependence of the coefficient of hydraulic resistance on the Reynolds number.](image)

**Figure 7.** The dependence of the coefficient of hydraulic resistance on the Reynolds number.

**Conclusion**

The coefficients of hydraulic resistance of a solitary perforated plate were experimentally determined. As well as of a perforated plate with a layer of balls behind it. The discrepancies when determining the resistance coefficients from the calculated ratios, tables and graphs given in the handbook [1] were identified. On the basis of our own experimental data, it has been shown that the determination of the coefficients of hydraulic resistance from the tables and diagrams on pages 410-413 [1] is correct.

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**References**

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