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Experimental determination of hydraulic characteristics of highly porous metal rubber material

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Experimental results are presented to determine the hydraulic characteristics of highly metal rubber in the porosity range from 70% to 85% for wire samples with a diameter of 0.1−0.8 mm. It is shown that with an increase in the diameter of the wire with a fixed porosity, the pressure loss of the working medium on the metal rubber decreases. The generalized empirical expressions found for determining the viscous and inertial resistance coefficients depending on the porosity and diameter of the wire from which the metallorisn is made are presented.

Keywords: porous metal materials, hydraulic, viscous coefficient of resistance, inertial coefficient of resistance, metal rubber.

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Introduction

The use of porous metallic materials (PMMs) as heat exchange intensifiers is an efficient method for improvement of heat removal performance in heat exchange units, which is because of a high degree of flow mixing and increase of the heat transfer coefficient through equalization of the speed and temperature within the section of the heat carrier flow in PMMs, as well as increase of the area of heat transferring surface. Regardless of a high potential of porous materials, one shall take into account that their installation into heat transferring channels leads to increase of hydraulic resistance, which is characterized by viscosity and inertia coefficients [1]. These parameters also define the effective thermal conductivity coefficient of the working medium in a porous body [2]. Therefore, the relevant problem is the correct definition of the values of the viscosity and inertia coefficients characterizing hydraulic and thermal physical parameters of porous materials. The pressure losses depend on the parameters of the working medium flow and on the characteristics of a porous structure [3], which are defined by the manufacturing technology.

A promising PMM, whose porosity can be preset and controlled in the process of manufacture, is metallic rubber (MR). MR manufactured of copper wire with silver coating, which is melted during heat treatment after pressing to form an element with the required shape and forms undetachable soldered joints at the nodes, is of especial interest [4]. Such technology allows manufacturing a high-porous MR with the porosity of up to 90% [3], having a good thermal contact between the spiral windings and body walls, where it is installed, which makes that type of PMMs attractive for the use as heat exchange intensifiers.

At the present time there are several calculation and experimental approaches for determination of the losses of the working medium pressure when flowing through MR. The experimental methods based on the theory of similarity and dimensional analysis have become the most popular. Since two dimensionless complexes are used in the simulation of hydraulic processes in MR: friction resistance coefficient per the unit of length of porous insert and Reynolds number of the working medium in pores [5]. In the study [6] the authors indicate the dependence of the coefficient of hydraulic friction per the unit of length on the Reynolds number for MR with the porosity of 75% and the wire diameter of 0.42 mm. The average pore diameter [5,7] is used as specific size in the study subject to the correction for probabilistic distribution of pores by sizes. The study [8] presents two semi-empirical procedures for determination of hydraulic losses in porous elements based on MR. In accordance with the first procedure, one must know a set of parameters of porous structure, which can only be determined experimentally from the statistical analysis of flat polished specimens of MR. The second procedure is based on the application of the viscosity and inertia coefficients of resistance, which are determined through permeability of the medium. In turn, permeability is derived by empirical expression [9] through the wire diameter and porosity. The use of the viscosity and inertia coefficients of resistance in calculations of hydraulic losses of pressure allows to exclude the error of determination of the specific pore size and, as a consequence, under- or overestimation of the hydraulic friction coefficient. The values of the viscosity and inertia coefficients of resistance, because of a complex structure of porous materials made of MR can only be defined experimentally by its hydraulic characteristic [3]. Technical publications deal with the empirical dependences of these parameters on the porosity (P) within the range $15\% \leq n\div \leq 67\%$ for pressed MR. Application of such MR in hydro- and gas dynamic channels of systems and plants of various purpose will lead to a significant increase of resistance, as a consequence, to great losses of pressure. Therefore, high-porous MR with the porosity of $> 70\%$ becomes interesting.

The objective of this study was experimental determination of generalized empirical dependence of the viscosity and inertia coefficient of resistance of high-porous MR on the porosity within the range $p\div = 70-85\%$, and the wire diameter $\delta = 0.1-0.8$ mm.

1. Experimental studies of hydraulic characteristics of MR

The object of the studies were 16 cylindrical samples with MR. The samples referred to copper tubes with the outside diameter of $d_{tb} = 54$ mm with the wall thickness of $h_{wl} = 2$ mm and the length of $L_{tb} = 150$ mm. The thickness of MR pressed-in was $L_{MR} = 40$ mm. MR was made of wire with the diameters of δ 0.1, 0.21, 0.42 and 0.8 mm. Wherein, the samples porosity for every diameter lied within the range $p = 70-85\%$ with the pitch of 5%.

The studies were performed on an experimental bench designed for the measurement of the static pressure drop, dynamic component of the pressure and temperature of the air passing through the studied sample. Fig. 1 shows the diagram of the experimental bench.

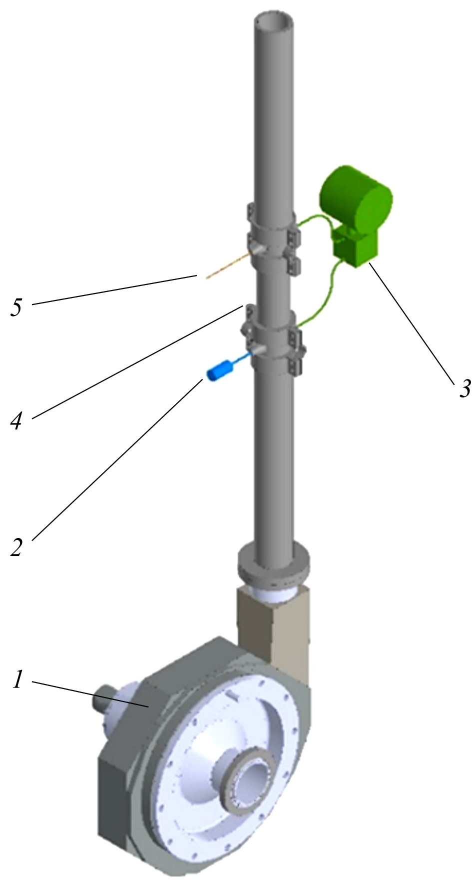

Figure 1. Diagram of the experimental bench: *1* — is the centrifugal charger; *2* — is the instrument KPDM-1 (Pitot-Prandtl tube connected to a micro pressure gage); *3* — ELEMER AIR-30 S3 CD-4 (differential pressure transducer); *4* — is the studied sample with porous element; *5* — is the thermocouple KTHA 02.01-062-K1-and-E310-1,5-100/2000.

The studies were performed in the air at the atmospheric pressure and temperature 20°C. The air flow rate Q, [m^3/s] through the sample varied. The value of dynamic component of the air pressure P_D, [Pa] was registered by using a micro pressure gage connected to the Pitot-Prandtl tube *2*. A microprocessor-based differential pressure smart transducer *3* registered the value of the static air pressure drop ΔP, [Pa] at the sample. The air temperature T_{air}, [°C] was controlled by means of the thermocouple *5*. The instrument error of the static air pressure drop measurement ΔP was 4% of the measured value, the instrument error of the air temperature measurement ΔT_{air} was 0.1°C, the instrument error of the dynamic air pressure component measurement ΔP_D was $(0.1 + 0.05 \cdot P_{Dmeasured})$, [Pa]. The bench enabled linear travel of the Pitot-Prandtl tube and the thermocouple within the measured sections of the air flow. The working medium flow rate was determined based on the values of dynamic air pressure component measured in seven points of the cross section of supply channel P_{Di} in accordance with the expression:

$$Q = V_{med} \cdot S = \left(\sum_i \sqrt{2 \cdot P_{Di}/\rho(T_i)} \cdot \pi \cdot d^2\right)/(4 \cdot n), \tag{1}$$

where V_{med} — is the average air speed, [m/s]; S — is the internal cross-section area of the channel, [m^2]; P_{Di} — is the measured value of dynamic component of the air pressure in the i-th point of the pipe cross-section, [Pa]; $\rho(T_i)$ — is the air density function of the temperature, [kg/m^3]; n — is the total number of measurements; d — is the inside diameter of the sample, [m].

Fig. 2 shows experimental hydraulic characteristics for all studied samples.

As is can be seen from Figure, with the increase of the wire diameter at constant air flow the pressure drop at MR with similar porosity is falling. The pressure losses also fall with the increase of porosity, with the fixed diameter of wire and air flow rate. Therefore, it was demonstrated experimentally that the working medium pressure losses when flowing through MR depend both on the porosity and on the wire diameter.

Hydrodynamics of the working medium flow in porous materials is determined by hydraulic resistance characterizing the pressure losses, which in the general case is represented as the superposition of viscosity and inertia components — modified Darcy equation (Dupuit-Reynolds-Forchheimer equation) [10–13]:

$$dP/dx = \alpha \cdot \mu \cdot V_f + \beta \cdot \rho \cdot V_f^2, \tag{2}$$

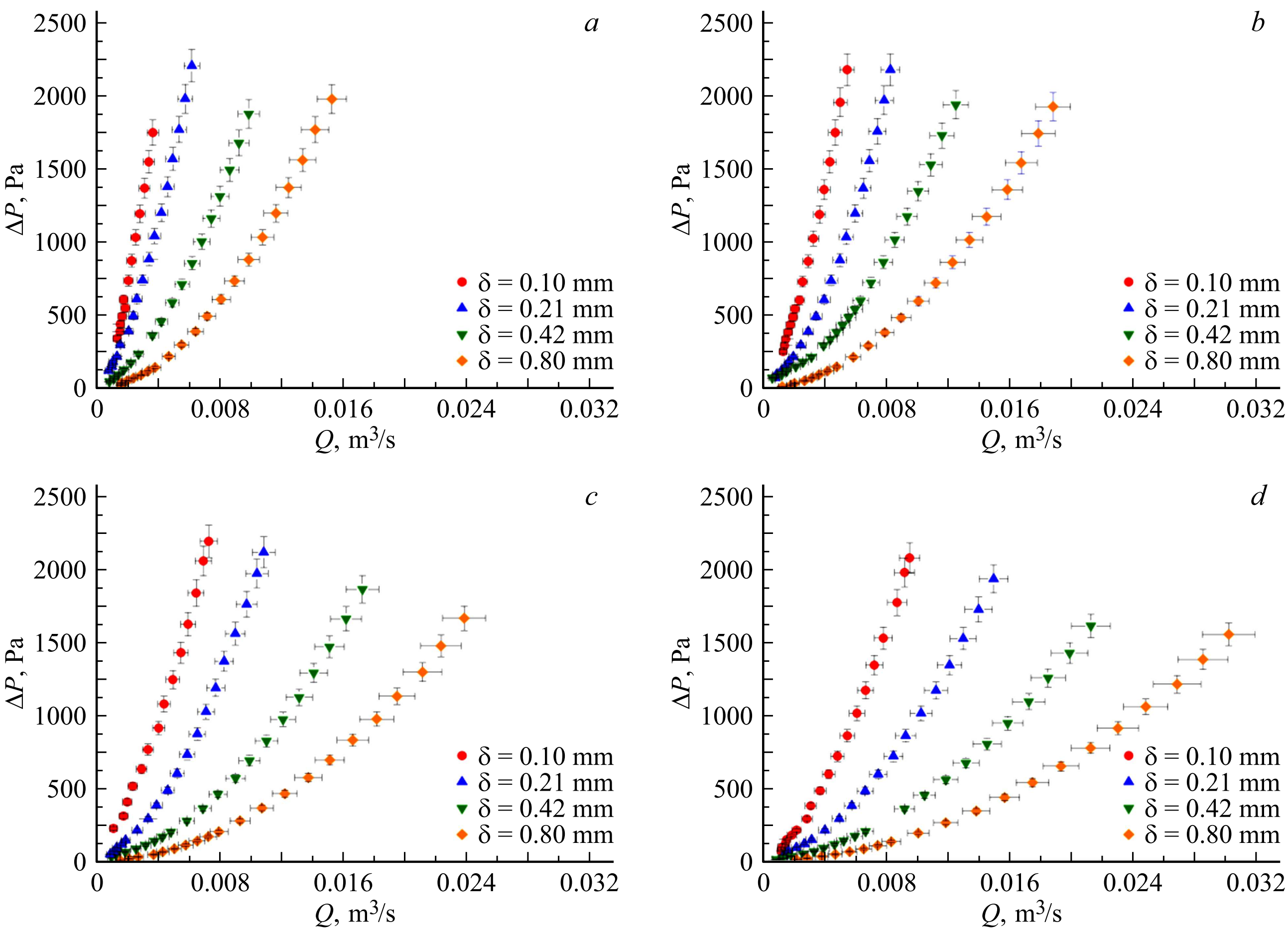

Figure 2. Experimental dependencies of the air pressure drop at MR on the flow rate for the samples differed by the wire diameter and the porosity: *a* — porosity of 70%; *b* — 75%; *c* — 80%; *d* — 85%.

where P — is the working medium pressure, [Pa]; x — is the coordinate in the flow direction, [m]; μ — is the coefficient of dynamic viscosity of the working medium, [Pa/s]; ρ — is the density of the working medium, [kg/m^3]; V_f — is the filtration rate attributed to full cross-section of the channel without filling of the flow cross-section area with porous material, [m/s]; α — is the viscosity coefficient of the material resistance, [m^{-2}]; β — is the inertia coefficient of the porous material resistance, [m^{-1}].

For the purpose of determination of the value of the viscosity and inertia coefficients the expression (2) transformed to the following:

$$\Delta P/(L \cdot V_f) = \alpha \cdot \mu + \beta \cdot \rho \cdot V_f, \tag{3}$$

where L — is the length of the porous material in the direction of the working medium flow, [m].

Then, graphical dependence of the complex $A = \Delta P/(L \cdot V_f)$ on the filtration rate V_f, was built, which was approximated by the straight line

$$A(V_f) = B_0 + B_1 \cdot V_f. \tag{4}$$

The required values of the viscosity and intertia coefficients of MR were determined based on the coefficients of the approximation stright line:

$$\alpha = B_0/\mu; \quad \beta = B_1/\rho. \tag{5}$$

The obtained values of these coefficients and the ranges of Reynolds numbers, within whose limits they were found, are shown in Tables 1–3, accordingly. For the Reynolds number, the filtration rate V_f was used as the determinant rate, The hydraulic diameter of the channel, where MR is installed was used as the determinant size, and the gas temperature at the outlet from the porous element T_{air} was used as the determinant value of the kinematic viscosity μ. The Prandtl number in all measurements lied within the range $Pr = 0.733–0.745$. The gas temperature at the outlet from the porous element T_{air} was used as the temperature determining physical properties of the working medium.

Empirical dependencies of the viscosity and inertia coefficients of resistance of the studied MR samples on the porosity and diameter of wire, which they were made of, were found based on the obtained values by using the experimental data analysis method [14]:

$$\alpha = \delta^{-2} \cdot p \div^{-8} \cdot C, \tag{6}$$

$$\beta = 0.031 \cdot \delta^{-1} \cdot p \div^{-8}, \tag{7}$$

Table 1. Experimental values of the viscosity $\alpha\,[\mathrm{m}^{-2}]$ coefficients of resistance of the studied MR samples

Thickness of wire, mm	Porosity,%			
	70	75	80	85
0.1	$(6.5 \pm 0.3) \cdot 10^8$	$(4.48 \pm 0.11) \cdot 10^8$	$(2.09 \pm 0.16) \cdot 10^8$	$(1.71 \pm 0.07) \cdot 10^8$
0.21	$(3.67 \pm 0.13) \cdot 10^8$	$(1.89 \pm 0.07) \cdot 10^8$	$(1.36 \pm 0.05) \cdot 10^8$	$(6.6 \pm 0.3) \cdot 10^7$
0.42	$(1.83 \pm 0.03) \cdot 10^8$	$(1.02 \pm 0.01) \cdot 10^8$	$(5.31 \pm 0.04) \cdot 10^7$	$(3.18 \pm 0.03) \cdot 10^7$
0.8	$(2.97 \pm 0.04) \cdot 10^7$	$(1.93 \pm 0.02) \cdot 10^7$	$(1.26 \pm 0.02) \cdot 10^7$	$(6.94 \pm 0.01) \cdot 10^6$

Table 2. Experimental values of the inertia $\beta\,[\mathrm{m}^{-1}]$ coefficients of resistance of MR samples

Thickness of wire, mm	Porosity,%			
	70	75	80	85
0.1	$(5.6 \pm 0.4) \cdot 10^3$	$(3.59 \pm 0.11) \cdot 10^3$	$(2.60 \pm 0.09) \cdot 10^3$	$(1.35 \pm 0.04) \cdot 10^3$
0.21	$(3.04 \pm 0.11) \cdot 10^3$	$(1.82 \pm 0.04) \cdot 10^3$	$(1.07 \pm 0.03) \cdot 10^3$	$(5.80 \pm 0.14) \cdot 10^2$
0.42	$(1.05 \pm 0.05) \cdot 10^3$	$(7.5 \pm 0.2) \cdot 10^2$	$(4.13 \pm 0.07) \cdot 10^2$	$(2.40 \pm 0.04) \cdot 10^2$
0.8	$(6.52 \pm 0.06) \cdot 10^2$	$(4.11 \pm 0.03) \cdot 10^2$	$(2.19 \pm 0.02) \cdot 10^2$	$(1.29 \pm 0.01) \cdot 10^2$

Table 3. Ranges of Reynolds numbers for determination of the vallue of the viscosity and inertia coefficients

Thickness of wire, mm	Porosity,%			
	70	75	80	85
0.1	3300–5900	2400–8800	3300–12 000	2000–16000
0.21	1200–9900	1300–13 400	1400–17 900	2200–24 800
0.42	3600–16 100	4300–20 500	5200–28 200	1400–35 200
0.8	2600–25 200	3400–31 600	2500–39 900	3700–50 600

where δ — is the wire diameter, which MR was made of, [m]; P — is the MR porosity; C — is the coefficient selected experimentally for every sample. For MR made of the wire of 0.1 mm $C = 0.5$; for MR made of the wire of 0.21 mm $C = 1.25$; for MR made of the wire of 0.42 mm $C = 1.5$; for MR made of the wire of 0.8 mm $C = 1$.

The emperical expressions found describe the experimental data with the average deviations of 20 and 13% for the viscosity and inertia coefficients, accordingly, and are applicable within the ranges of the wire diameter $\delta = 0.1{-}0.8$ mm, porosity of $p\div = 70{-}85\%$ and the Reynolds numbers given in Table 3. In accordance with (3) the pressure losses from the air flow rate were calculated with its flow through the studied MR elements within the framework of the mode parameters corresponding to the experimental ones, wherein the calculation took into account the deviation of the porosity of $\pm 1\%$ caused by the manufacturing technology. Fig. 3 shows comparison of the calculation and experimental dependencies of the pressure drop on the flow rate. Experimentl data are represented as dots, and the region of calculation values of the pressure losses — as dashed lines.

By analyzing the obtained results, it can be said that the empirical dependencies of the viscosity (6) and inertia (7) coefficients of resistance found experimentally within the framework of the studied Reynolds number ranges enable assessment of the working medium pressure losses when it flows through the porous elements of MR within the range of porosity $0.7 \le p\div \le 0.85$ and wire diameter of 0.1 mm$\le \delta \le 0.8$ mm, wherein its maximum deviation of the calculation values of the pressure losses from the experimental ones does not exceed 20%.

Conclusion

The study shows results of experimental studies of hydraulic characteristics of high-porous elements made of MR within the range of porosity $70\% \le p\div \le 85\%$ of the wire with the diameter of 0.1, 0.21, 0.42 and 0.8 mm. It was proven experimentally, that with the fixed flow rate of the working medium and the same porosity the pressure losses at the MR elements made of thin wire exceed the losses at the elements made of thick wire.

The values of the viscosity and inertia coefficients of resistance were determined based on the hydraulic characteristics found experimentally for every studied sample, which allowed to find the dependence of these parameters on the porosity and diameter of wire. Empirical dependence of the viscosity coefficient of resistance is described by the expression $\alpha = \delta^{-2} \cdot p \div^{-8} \cdot C$, where C — is the constant

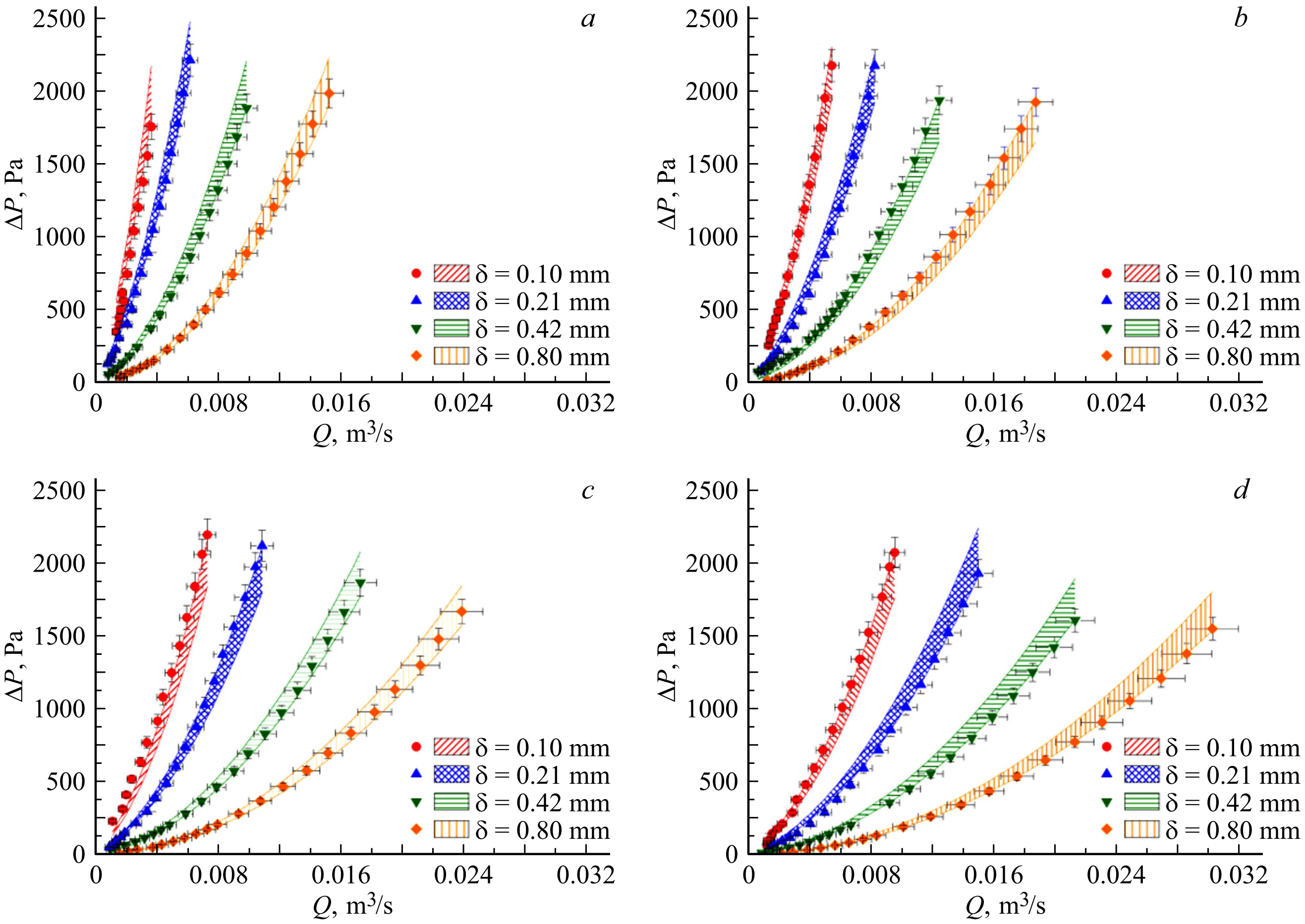

Figure 3. Experimental and calculation dependencies of the air pressure drops at MR on the flow rate for the samples differed by the wire diameter and porosity: *a* — porosity of 70%; *b* — 75%; *c* — 80%; *d* — 85%.

determined by the diameter of the MR wire. Empirical dependence of the inertia coefficient of resistance is described as the expression $\beta = 0.031 \cdot \delta^{-1} \cdot p\div^{-8}$. The maximum deviaion of the calculated losses of the pressure by using the found empirical coefficients does not exceed 20% within the studied dynamic range of Reynolds numbers and the MR parameters.

The obtained results are of a practical interest, because the emperical expressions found can be used in engineering hydraulic and thermal calculations when designing structural elements based on MR for the plants and systems of various purpose.

Conflict of interest

The authors declare that they have no conflict of interest.

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