Influence of flow conditions and foam parameters on pressure drop and heat transfer in flow of fluids through channels filled with metal foams

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Abstract. This paper reports the results of research into air, water and oil flow through pipes filled with open-cell metal foams, which form a material with a considerable potential for application in the design of process equipment. This study applied three metal foams with various geometrical parameters. The objective of the experiments involved the measurement of pressure drop within a relatively large range of the variability of the flow conditions. On the basis of data from the literature and analysis of the results of experiments, an assessment was undertaken concerned with the influence of the geometrical parameters of the foams as well as velocities and fluid properties on the flow regime and pressure drop. The results demonstrate that the theory concerned with the fluid flow through porous media has a limited application with regard to metal foams due to the considerable turbulence of the flow through such foams. If flow occurs in other conditions than laminar regime, the permeability of metal foams is relative not only to the geometrical structure of the foams but also depends on the properties and velocity of the fluid. The present study demonstrated that the assessment of the flow regime can apply the modified Reynolds number in which the characteristics dimension is defined on the basis of the parameters accounting for the geometrical foam structure. Three flow regimes were distinguished – laminar flow, transient Forchheimer and transient Froud flow. The ranges corresponding to the occurrence of the particular flow regimes were subsequently determined.

1 Introduction

Open cell metal foams form the type of cellular material that is relatively little known. Such foams consist of thin interwoven ligaments forming cellular materials, whose structure resembles a spatial skeleton comprising relatively large and hollow cells. The adjacent cells are connected by open “windows” – pores - located in the common walls. Such a spatial structure and the considerable porosity of the foams, which usually exceeds 90%, promote fluid flow through the foam skeleton and reduce the cost of fluid transport. The considerable thermal conductivity of the foam skeleton and continuous structure of the skeleton ligaments lead to the decrease of the thermal resistance. The technology of manufacturing open-cell foam provides adequate solutions needed to obtain this material from a variety of metal alloys. As a result, it is possible to utilize foams even in extreme operating conditions, in which high thermal and chemical resistance of material are required.

The above characteristics of open-cell metal foams have led to the identification of these materials as an alternative to more common structural packings applied in process equipment. The literature in the areas lists a number of potential applications of metal foams, such as

heat exchangers, heat storage tanks and heat recovery steam generators as well as chemical reactors, including catalytic reactors.

The practical use of open-cell metal foams in the design of process equipment is still at an initial stage, and the insight gained into the phenomena occurring in the spaces occupied by metal foams, including hydrodynamic phenomena, needs further research. The adequate design of the process equipment, in which the fluid is pumped through metal foams needs to involve a process in which the influence of fluid properties and foam parameters on the flow regimes and the value of the pressure drop are understood. The analysis of the results of research carried out in this area for more than a dozen years indicates the existence of many deficiencies and ambiguities, which have encouraged the experimental work and theoretical studies reported here.

2 Hydrodynamics of flow through – State of the art

Fluid flow through metal foams is often described on the basis of the theory of flow through porous media. If this approach is applied, the parameters characterizing the foams include permeability K and inertial coefficient β .

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Various reports in the literature contain a statement regarding the dependence of these quantities on the geometrical foam parameters, such as the foam structure, cell diameter, porosity and the specific surface [1–3]. However, we are not able to conclude unambiguously about the impact of these parameters on the value of permeability. For instance, as reported by Bonnet et al., [4], permeability of foams increases along with the square of the pore diameter, whereas the results gained by Bagci and Dukhan [5] as well as Wang and Guo [6] contain a conclusion that the relation is proportional. The authors of the work in [4] remarked about the effect of fluid properties on the permeability, whereas Kouidri and Madani [7] demonstrated that the permeability and inertial coefficient of foams are also relative to the fluid velocities. Although the results are less straightforward, similar observations were made by Medraj et al. [2] with regard to the transient and turbulent flows. The results found in [5] contain a statement that permeability of foams remains constant only in the conditions of laminar flow. Thus, the ranges corresponding to the occurrence of the particular flow regimes have not been explicitly demonstrated. The authors of papers in this area provide different values of the critical Reynolds number corresponding to the flow regime transitions. The reasons associated with this are related to various quantities which can be applied to define the hydraulic diameter d_h of the foam. A number of authors, including Bagci and Dukhan [5] postulate that the square root of the permeability should play the role of the hydraulic diameter. Other studies adopt various geometrical parameters of foam to represent d_h , such as the cell diameter [8, 9], pore diameter [10] and the specific surface [11].

The calculation of pressure drop $\Delta P/\Delta L$ accompanying flow through metal foams is most commonly implemented by application of the Forchheimer equation,

$$\left(\frac{\Delta P}{\Delta L}\right)_f = \mu_f K^{-1} u_f + \rho_f \beta u_f^2, \quad (1)$$

which forms a development of the Darcy's law, describing laminar flow through porous media. The second term in the right hand side of Eq. (1) represents the component of the pressure drop resulting from the effect of inertia force exerted on the fluid flow. When inertia is accounted for, Forchheimer equation can be applied not only with regard to the laminar flow but also for transient flow. Along with the increase in the fluid velocity, the pressure drop associated with the inertia of the fluid determine the pressure drop to a much greater degree compared to the conditions when the fluid has a low velocity, and the term expressed as $\rho_f \beta u_f^2$ does not compensate for this increase in a sufficient manner. Hence, the pressure drop determined by the application of the Forchheimer equation can be characterized by a relatively high error if fluid is pumped through the foam with a considerable velocity. The reports in [6, 7, 12] suggest that the Forchheimer equation does not find application when the fluid velocity exceeds 10 m/s.

Pressure drop during flow through metal foams can be derived on the basis of the Ergun equation. It was originally developed for application to flows through a packed bed, but the potential for its use with regard to flows through foams was proposed e.g. by Liu et al. [13] and Beugre et al. [14]. Some authors suggest that the pressure drop accompanying the flow through metal foams on the basis of the correlations where the friction factor plays the measure of the pressure drop. Darcy-Weisbach equation forms an example of this, when it is applied with regard to foams in a number of studies [15–17].

The results of comparisons of the pressure drop derived on the basis of various correlations demonstrate that considerable differences are gained in terms of the calculated values. An opinion provided in [18] contains a suggestion that these discrepancies are due to the lack of the uniform and recognized definitions and approaches applied to determine cell and pore diameters, specific surface, porosity as well as other quantities characteristic for foams.

The majority of the research conducted to this date was realized by application of water or air.

In the own studies presented in this paper, oil was also used - in order to extend the range of viscosity changes of liquids - and the flow was carried out through foams with different geometrical structure.

3 Test stand and research methods

The research was conducted by application of three foams made of aluminum alloys (Fig. 1) – two from AlSi7Mg alloy and one made of Al 6101 alloy. The foams were characterized by the pore density of 20, 30 and 40 PPI (pores per inch). The analyzed foams varied in terms of the porosity ε , cell and pore sizes. The diameter of the pores d_p and cells d_c was derived on the basis of an analysis of microscopic images of the foam skeleton.

Fig. 1. Microscopic image of foams applied in the research: a) 20 PPI foam, b) 30 PPI foam, c) 40 PPI foam, d) cell and pore.

The fluid applied in the study included air, water and Velol-9Q machine oil. These fluids are distinct in terms of physical properties, including density ρ_{ol} and viscosity μ_{ol} . A summary of the basic parameters of the foams and the impact of temperature on the properties of the Velol-9Q oil is presented in Table 1.

Table 1. Foam parameters and oil properties.

Foam (alloy)	ε , –	$d_c \cdot 10^{-3}$, m	$d_p \cdot 10^{-3}$, m
20 PPI (AlSi7Mg)	0.9336	3.452	1.094
30 PPI (AlSi7Mg)	0.9435	2.255	0.712
40 PPI (Al 6101)	0.9292	2.386	0.824
density of Velol-9Q $\rho_{ol} = -0.669t + 872.76$ viscosity of Velol-9Q $\mu_{ol} = 0.117t^{-0.865}$			

The research was conducted by application of the experimental installation, whose diagram is presented in Fig. 2. Its main component is formed by a horizontal channel completely filled by a metal foam (a separate

channel was performed for each foam). The channel was in the form of a pipe with the internal diameter of 0.02 m and comprised three sections – a measurement section with the length of 1.27 m, a section with the length of 0.92 m preceding the measurement section and applied for flow development and an outlet section with the length of 0.42 m located behind the measurement section.

The installation was supplied by compressed air. The liquids were routed into the installation using pumps. The flow rates of the fluids were measured by application of a set of flowmeters with high measurement accuracy. For the case of air, two mass flowmeters were applied for the measurements.

The direct objective throughout the research was to measure the pressure drop. This value was recorded as the difference of the pressure in two points in the channel located at a distance of 1 m from each other. The measurements of the pressure drop were realized by the application of five piezoresistance sensors with the total measurement range of 0–150000 Pa. Overpressure was measured in the channel as there was a need to determine the air density.

Fig. 2. Scheme of experimental setup.

The measurements were performed within a considerable variability of the flow rates $\dot{V}_f$ so as to provide the results for the laminar and turbulent flows. For all three foams, research was realized in the conditions of the same fluid velocities. For the reason for the diverse foam porosity, the notion of the Darcy velocity was applied u_f ,

$$u_f = \dot{V}_f \frac{4}{\pi d^2}, \quad (2)$$

which denotes the mean velocity that is obtained by a fluid passing through an empty measurement channel with diameter d (i.e. not accounting for the presence of the foam).

Table 2. Conditions of the experiment.

fluid, f	u_f , m/s	Re_f^* , –
air, a	0.028–9.88	23–13244
water, w	0.003–0.270	30–4509
oil, ol	0.003–0.167	3–198

*Reynold number Re_f - Eq (3)

4 Results and discussion

During the flow of fluid through pipes filled with metal foams, the greatest pressure drop $(\Delta P/\Delta L)_f$ values were recorded for the case of the 40 PPI foam, whereas the lowest – for the case of the flow through 20 PPI foam. For the purposes of illustration, Fig. 3 contains the

results of the pressure drop during water flow through all three types of foam.

Fig. 3. Pressure drop during water flow.

As the foams applied in the research had similar levels of porosity, the differences in the pressure drop have to be attributed to the differences in the geometrical foam parameters. The 20 PPI foam has the largest cells, which results in the lower pressure drop of the fluid compared to foams with smaller cell diameters. Although the cell diameter in 40 PPI foams is only slightly greater than for the case of 30 PPI foam, the value of the pressure drop during flow through the first of them is considerably greater than for the case of the 30 PPI foams. The reason is likely to be associated with the specific geometrical structure of the 40 PPI foam skeleton. The cells of this foam form a more closed structure due to the occurrence of large nodes at the contact points between the fibers in the foam skeleton. Additionally, there are numerous deformations of the foam skeleton (Fig. 4), which leads to hinders the flow.

Fig. 4. Deformation of 40 PPI foam skeleton.

The value of the pressure drop is relative to the type and velocity of the fluid pumped through the foams. Under the assumption of the same velocity, the greatest pressure drop values were registered during the flow of oil, whereas the smallest for the air flow, as presented in Fig. 5 (in a logarithmic system due to the considerable variability of the fluid velocities). The pressure drop increase therefore as the viscosity of fluid increase.

The pressure drop also increases along with the increase of the fluid velocities, and the course of the variation of this drop can be described by the application of the Forchheimer equation, as illustrated in Fig. 3.

Fig. 5. Comparison of pressure drop during air, water and oil flow through 30 PPI foam.

The permeability K and inertial coefficient β were derived by the application of the measured pressure drop and the least squares method. The values of K and β for the analyzed cases of flows are presented in Fig. 6. The 20 PPI foam is characterized with the considerably greater permeability and lower inertial coefficient compared to the remaining foams. The permeability of the 30 and 40 PPI foams assumes similar values; however, the inertial coefficients of these foams are different. Both permeability and inertial coefficient assume different values for air, water and oil. These quantities are relative not only on the foam structure but also to the type of fluid pumped through the foams. For the case of the permeability, the differences for the particular fluids are in the range of 30%.

Fig. 6. Comparison of permeability (a) and inertial coefficient (b) of foams for air, water and oil flow.

In addition, the study offered the conclusion that the value of permeability is affected by the fluid velocity as presented in Fig. 7 on the basis of data gained with regard to 20 PPI foam. In a given range of the fluid velocities, permeability assumes a constant value, which is equal to below 0.12 m/s for water, and below 3.5 m/s

for the air. For higher fluid velocities, we can note an increase of the value K . For the case of flow through 30 and 40 PPI foams, similar results were gained. For the velocity for which an increase of permeability was recorded, the flow is likely to cease to demonstrate laminar characteristics. For the case of the flow of oil, the increase of permeability does not occur since the oil flow demonstrates laminar characteristics over the entire range of the velocities due to its greater viscosity.

Fig. 7. Influence of fluid velocity on the permeability of 20 PPI foam.

The experimental data confirms the fact reported in the literature that for the case of metal foams, permeability and inertial coefficient do not have the characteristics of material constants. This, in turn, forms an impediment in the application of the Forchheimer equation in the description of the pressure drop through metal foams. In addition, the theory of flow through porous media accounts for the factors associated with the flow turbulence only to a limited degree. It seems that a more universal quantity characterizing the pressure drop through metal foams can be based on an adequately defined friction factor f .

The analysis of the value of the friction factor defined on the basis of the measured pressure drop and Darcy-Weisbach equation (f_{exp} - Fig. 8) confirms the possibility to define the friction factor by means of a relation that is common for various foams and fluids. The key role in this is attributed to an adequate statement of the Reynolds number Re_f . It was demonstrated that the Reynolds number should be derived on the basis of a mean actual fluid velocity (u_f/ε) and accounting for the geometrical foam parameters – i.e. porosity and pore diameter, in accordance with the relation,

$$Re_f = \frac{u_f d_h \rho_f}{\varepsilon \mu_f}, \quad (3)$$

where hydraulic diameter d_h :

$$d_h = \frac{\varepsilon d_p}{1 - \varepsilon}. \quad (4)$$

The values of the friction factor presented in Fig. 8 assume similar values for the equivalent flow conditions, which confirm the assumptions adopted for the purposes of calculating the friction factor. Concurrently, the characteristic course of the variations in the friction

factor confirms the occurrence of a variety of flow regimes. When the Reynolds number does not exceed the value of around 150, the friction factor decreases linearly (in a dual logarithmic system) along with an increase in Re_f , which demonstrates that the flow is laminar. For the case of oil, laminar flow occupies the entire range of the research that was conducted by application of this liquid.

Fig. 8. Value of friction factor for investigated cases of flow.

Along with an increase of the fluid velocity and the Reynolds number corresponding to it, the flow gradually takes on the characteristics of turbulent flow. This is demonstrated by a considerable deviation of the friction factor from a straight line for the case when $Re_f > 150$. For the range of $Re_f \approx 150 - 1300$ the turbulence of the fluid stream are small and the flow has the characteristics of the transient Forchheimer flow. When $Re_f > 1300$, the friction factor demonstrates a tendency to take on a constant value in an asymptotic manner. This indicates that the fluid stream demonstrates a considerable level of instability. The turbulence of the of fluid remains in the range of the transient flow; however, due to the considerable effect of the inertial force, which prevails over the viscosity forces, this type of flow should be considered as a separate regime – called the transient Froud flow.

5 Conclusions

In this study, an assessment of the effect of flow conditions, including geometrical foam parameters, velocities and fluid properties on the flow regimes and pressure drop in channels filled with metal foams was performed on the basis of insight from the literature and results of experimental studies. In addition, the potential for the application of the flow theory through porous media in the description of flow through metal foams.

The following conclusions were derived from the study:

- Pressure drop is considerably relative to the foam porosity, cell size and structure of the cellular skeleton.
- Except for laminar flow, transient flow was observed within a considerable range of the variable fluid flow velocities – Forchheimer flow and Froud flow. The Forchheimer flow is characterized by a

small degree of stream disturbance while the Froude flow shows turbulent flow characteristics.

- A similarity was demonstrated in terms of hydrodynamic parameters during flow of fluids through foams with distinct geometrical structure. The role of a similarity criterion can be taken on by the Reynolds number, in which the hydraulic diameter is defined on the basis of the geometrical foam parameters, i.e. porosity and pore diameter (Eq. (4)).
- Flow is laminar when $Re < 150$. In the range of $Re = 150\text{--}1300$, transient Forchheimer flow is recorded, and when $Re > 1300$, we have to do with the Froude flow.
- Permeability and inertial coefficient of metal foams are relative to the geometrical structure of the foam skeleton as well as properties and velocities of the fluids pumped through them. Hence, these quantities cannot be directly derived on the basis of the geometrical foam parameters.
- Influence of flow conditions on permeability forms an impediment in the application of the standard laws with regard to flows through porous media, including the use of Forchheimer law for the description of the flow through metal foams.

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