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PREDICTION OF FRICTIONAL LOSSES IN SLOTTED SIEVES

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Slotted sieves are used for separation of different phases and are applied in various engineering applications, including their widespread use in chemical and petrochemical industry. Physical features of sieves and dynamic properties of flow through a slotted sieve affect friction, which can be the cause of significant portion of flow resistance. Due to the fact that such research is scattered in literature, there is a need for more research in the field of prediction of friction for various operating parameters, which is needed to properly establish pipeline characteristics and which can lead to minimisation of losses for various set of values of slotted sieves design and operating parameters. The aim of the paper is to develop semi-empirical function describing frictional coefficient in a turbulent flow through slotted sieve. Experimental measurements of the frictional coefficient were conducted in three selected sieves, with a wide range of gaps from 0.22 mm to 1.02 mm, opening area ranging from 16.32% to 43.51% and shape coefficient of working rods from 0.17 to 0.24. A new function describing frictional coefficient has been developed and validated. The semi-empirical function depends on physical features of a slotted sieve, like opening area, shape coefficient, and dynamic properties of a flow represented by Reynolds number.

KEY WORDS: turbulent flow, slotted sieve, prediction, frictional coefficient.

1. INTRODUCTION

In the case of solid-liquid flow, there is often a need to separate solid and liquid phases, Rushton et al. (2000). Separation techniques are defined as operation that isolate solid phase from a hydro-mixture without a chemical reaction taking place. Several criteria are available to classify separation techniques. Most common are sedimentation, centrifugation, filtration and membrane separations, Poole (2009). Filtration is used in several engineering applications including water supply, wastewater, mining industry, aggregate processes, machine coolant, chemical and petrochemical industry, Priestman et al. (1996), Rawlins et al. (2000), Wakeman and Tarleton (2015).

In some engineering cases we are using slotted sieves in order to separate liquid or solid phase to further engineering processes or to prevent solid particles entering machines to avoid possible impeller damage. Slotted sieves can be stand-alone or take the form of parallel-flow trays incorporating slotted sieve tray decks. Losses in a flow through a slotted sieve are extremely important as they produce a substantial portion of total flow resistance. The width of the screen openings, called the gap width or slot size, depends on the grain size distribution and critical particles size. There is some research in literature dealing with

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head losses in open flow through sieve trays under different inclinations, as discussed by Li et al. (2013), Ping et al. (2014) and Hu et al. (2014). In order to predict hydraulic gradient on such sieve trays, researchers employ empirical methods to obtain reasonable agreement. However, there are hardly any measurements and simulations for a slotted sieve installed in a pipeline.

Friction plays a crucial role in determining pipeline characteristics, as it produces a substantial portion of a pipeline flow resistance, as described by Duffy et al. (1972) and Vlasak et al. (2014). The phenomenon of two-phase flow through a slotted sieve installed in a pipeline is very complex as there are many boundary layers affecting one another, Bird et al. (1960), Brodkey (1969). Therefore, predictions of such flow are very complex and difficult to implement, especially if CFD is considered. Due to such difficulties we focused the research on the development of semi-empirical function in order to predict frictional coefficient in each of the selected slotted sieves. If commercially used pipeline elements, such as bends, valves or fittings are considered, a local frictional coefficient depends on the Reynolds number. If a new construction, like a slotted sieve, is developed or the liquid is not Newtonian the frictional losses must be determined experimentally. We anticipated that any semi-empirical function, which predicts frictional losses, should depend on slotted sieve geometry and flow properties. The ability to predict the frictional coefficient on a slotted sieve can reduce the time and cost necessary to make measurements, which are required in the process of slotted sieves design. Therefore, the main objective of the paper is to develop a semi-empirical function describing frictional coefficient in turbulent flow through slotted sieve. Three different slotted sieves were selected for experiments, which correspond to a wide range of sieve geometry.

2. SLOTTED SIEVE GEOMETRY

In the process of slotted sieve design, attention must be paid to mechanical and geometrical features. They may include the ability to carry heavy loads, high precision of performance, low frictional losses, a smooth and flat plane structure, a self-cleaning surface, a long-life cycle, etc. The slotted sieve should be mechanically stable at extreme pressure and temperature conditions.

Figure 1 presents one of the slotted sieves used for experiments in a horizontal pipeline. Generally, the design of slotted sieve includes working rods welded to the supporting rods. The slots separate all the working rods whose size depends on the diameter of solid particles. Solid particles with diameter higher than a slot will not pass through the slot. In Figure 1, the photo to the left shows the front surface of the slotted sieve, which is attacked by solid particles flowing together with a carrier liquid. The photo to the right shows the backside of the slotted sieve. It can be seen that working rods look different from the back than from the front side. This is due to the fact that rods are triangular in shape, which is presented in Figure 2. Therefore, in the case of a hydro-mixture flowing through a single slot, the cross section of a stream is increasing towards the flow direction, which leads to the decrease in hydro-mixture velocity. As hydro-mixture velocity decreases, the static pressure increases. This phenomenon prevents solid particles from sticking to the front surface of the slotted sieve. In the case of horizontal flow in a pipeline, gravity will cause the accumulation of solid particles on the front side of the slotted sieve, at the bottom of a pipe. In order to prevent a pipeline clogging the sediment draining or periodic suction of solid particles is required. The frequency of sediment draining or periodic suction of solid particles depends mainly on concentration of solid phase and hydro-mixture flow rate.

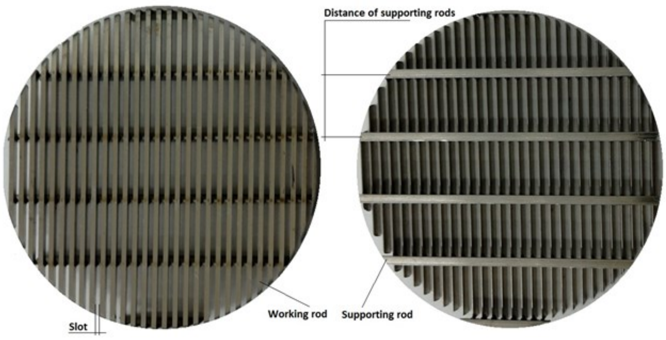

Figure 1. Slotted sieve used in experiments; to the left - front side; to the right - backside

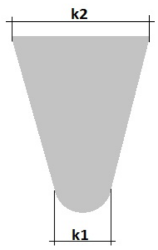

Figure 2. Working rod shape

As dimensions of working rods are different in all slotted sieves used in the experiments, the following parameters, which describe the slotted sieve geometry, were chosen:

- width of the front side of the working rod, denoted by k_2,
- width of the backside of the working rod, denoted by k_1.

Parameter k_1, however, determines the minimum width of the working rod on the backside, at the point where the working rod starts to become spherical. Taking into account k_1 and k_2 parameters we introduced the shape coefficient of working rods, defined as:

$$K = \frac{k_1}{k_2} \tag{1}$$

The active surface (open area) of the slotted sieve, denoted as A_S, plays a major role in energy dissipation. As a result, by introducing an open area coefficient, denoted as F_0, which expresses the percentage ratio of the open area to the cross-section area of a pipe, one can write:

$$F_0 = \frac{A_S}{A_T} \cdot 100\% \quad (2)$$

where A_S – the area of slots (open area), A_T – cross section area of the pipe

Three slotted sieves have been used in experiments, denoted as SLS_1, SLS_2 and SLS_3. Gap width ranged from 0.22 mm to 1.02 mm, which corresponds to open area coefficient from 16.32% to 43.51%, and shape coefficient ranged from 0.1751 to 0.2359. The main physical features of the slotted sieves used in the experiments are presented in Table 1.

Table 1

Physical features of slotted sieves used in experiments

Name of sieve	Gap width	K	F_0
-	mm	-	%
Slotted sieve 1 (SLS_1)	0.22	0.1751	16.32%
Slotted sieve 2 (SLS_2)	0.50	0.2300	28.95%
Slotted sieve 3 (SLS_3)	1.02	0.2359	43.51%

3. MEASUREMENTS

Measurements were performed on the experimental test rig, presented in Figure 3, consisting of a closed-loop pipeline with an inner diameter D=0.0545 m. The major components of an experimental test rig include a centrifugal pump, pressure transducers, a magnetic flow meter, a heat exchanger, a feeder with slurry mixing tank and valves. Drive inverter within the range of 0 - 3000 rpm controlled the centrifugal pump. The flow rate was measured with the magnetic flow meter Optiflux 1050 within the range from 0 to 60 m^3/h. Pressure drops p_2-p_3 and p_1-p_4 were measured using IP66 differential pressure transmitter. The pressure transmitter was examined before conducting the experiments by comparing its measurements with U-tube manometer results. Proper desaturation of the flowing carrier liquid and the pressure ducts have been performed. The temperature of the flowing liquid was measured via a thermocouple and was kept within the range 19.9^{o}C - 20.1^{o}C. A 12-byte data acquisition station recorded measured signals, like flow rate and pressure drops, Bartosik and Wojtyniak (2017).

In order to examine measurements method, two separate experiments, which used direct and indirect methods, were performed by Bartosik and Wojtyniak (2017). In the case of the direct method, the pressure drop on the slotted sieve was measured between two taps situated at the inlet and the outlet of the slotted sieve (p_2 and p_3 in Figure 3). In the indirect method, two additional pressure taps were installed in order to measure the pressure difference $\Delta p = p_1 - p_4$. In conclusion, the results of measurements performed using two different methods, direct and indirect, did not confirm significant differences, Bartosik and Wojtyniak (2017). For this reason, the paper presents the results of measurements of the frictional coefficient on slotted sieves using the direct method, which is simpler than the indirect one.

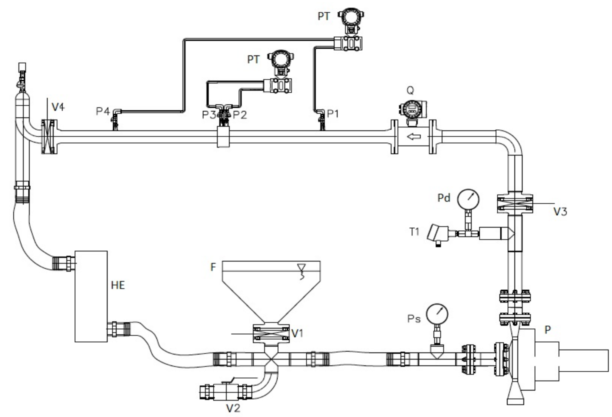

Figure 3. Experimental test rig. HE – heat exchanger; P – centrifugal pump; Ps, Pd – suction and discharge pressure; PT – pressure transducer; p1, p2, p3, p4 – pressure taps; Q – magnetic flow meter; T1 – thermocouple; V1, V2, V3, V4 –feeder, drain, discharge and check valves

In order to measure the frictional coefficient on the slotted sieve, situated between taps p_2 and p_3, we adopted the Bernoulli equation for the horizontal pipeline for cross section 2, which constitutes an inlet to the slotted sieve, and cross sections 3, which constitutes an outlet from the slotted sieve - Figure 3. Therefore, we can write:

$$\frac{\rho U_2^2}{2} + p_2 = \frac{\rho U_3^2}{2} + p_3 + \sum \Delta p_{2-3} \tag{3}$$

The last term of equation 3 corresponds to the frictional losses in the slotted sieve. Taking into account that pipeline has a constant inner diameter, the averaged velocities U_2 and U_3 are the same. Therefore, we can write:

$$p_2 - p_3 = \xi \frac{\rho U^2}{2} \tag{4}$$

where ρ is a hydro-mixture density and $U_2=U_3=U$.

Taking into account the measured pressure drops, $\Delta p_{2-3} = p_2 - p_3$, and volumetric flow rate, we can obtain frictional coefficient for slotted sieve, taking the form:

$$\xi = \frac{\Delta p_{2-3}\, \pi^2 D^4}{8 \rho Q^2} \tag{5}$$

where D is inner pipe diameter, and Q is volumetric flow rate.

Equation (5) was used to calculate the frictional coefficient of the slotted sieve based on the experimental data. We selected three different slotted sieves for the experiments, which represent various physical features. The physical features of the slotted sieves are summarized in Table 1. The experiments were performed with the use of water as a carrier liquid. The reason for selecting water, as a research medium, is that slotted sieves of this type are designed mainly for diluted solutions. Therefore, we can expect that the differences between frictional coefficient for the carrier liquid and a solid-liquid flow will not be significant.

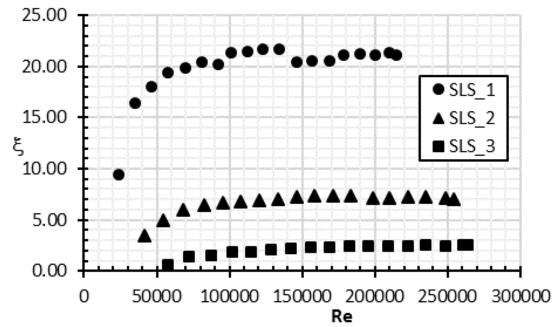

Figure 4. Frictional coefficients measured on slotted sieves versus Reynolds number

The frictional coefficient measured on each of the three selected slotted sieves versus the Reynolds number is presented in Figure 4. Experimental data correspond to turbulent flow, as the lowest Reynolds number amounts to about Re=24,000. As we expected, Figure 4 shows that as slots area (open area) increases, the frictional coefficient decreases. For the low Reynolds number, the frictional coefficient increases substantially as the Reynolds number increases, which is clearly seen for SLS_1. However, for $Re>10^5$, the coefficient is almost constant.

4. PREDICTION OF FRICTIONAL COEFFICIENT

In order to develop a semi-empirical function describing the frictional coefficient in turbulent flow through a slotted sieve, the major physical features of all three slotted sieves were determined. We took into account the open area coefficient F_0, defined by Equation 1, and shape coefficient K defined by Equation 2. We neglected roughness of slotted sieve elements, as all of them were smooth.

Considering frictional losses in the slotted sieve, it is obvious that flow properties are also very important, as they generate a substantial portion of the energy inverted partially into heat and losses of potential energy. For this reason, the Reynolds number was used in the semi-empirical function. Finally, we developed the following function:

$$\xi = Log_{12}(Re - 2C) - \frac{6C}{(Re-2C)} + \frac{4}{F_0} + 75 \cdot (K - 0.52)^2 - 17.3 \qquad (6)$$

where constant C in Equation 6 is equal to 10^4, and Re is the Reynolds number for carrier liquid.

The semi-empirical formula, described by Equation 6, has certain limitations, however, as Reynolds number has to be $Re > 2 \cdot 10^4$, which can be concluded by analysing the Equation 6. Equation 6 was validated by comparing the results of predictions with the measurements. Figure 5 shows experimental data compared to predictions. It can be seen that the accuracy is high, as maximum relative error is equal to -6,9% for the slotted sieve 1. This is due mainly to uncertainty of measurements, as experimental data are not perfectly arranged along a smooth line.

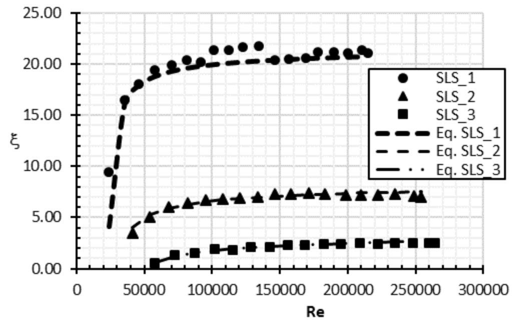

Figure 5. Measured and predicted frictional coefficient of slotted sieves versus Reynolds number

The measured and the computed frictional coefficients for each of the three selected slotted sieves demonstrate the importance of Reynolds number and the importance of the sieve geometry. The friction losses of the slotted sieve 1 are almost 10 times higher compared to the slotted sieve 3, although the gap width of the slotted sieves 1 and 3 is almost 5 times smaller, and the corresponding open area is less than 3 times smaller.

Equation (6) enables the prediction of the frictional coefficient in turbulent flow through a slotted sieve. Equation (6) is dedicated for slotted sieves in which working rods are triangular in shape. However, this is not a limitation, as slotted sieves should be triangular in shape in order to prevent solid particles from sticking to a slot.

5. CONCLUSIONS

Slotted sieves installed in a pipeline were investigated. Three different slotted sieves were selected in order to develop a semi-empirical function describing the frictional coefficient in turbulent flow. The geometrical parameters of slotted sieves were defined. On the basis of the measured frictional coefficient, the semi-empirical function has been proposed. The predicted and measured frictional coefficient shows high accuracy, as maximum relative error does not exceed -7%. The function is able to predict the frictional coefficient if geometrical parameters, like the open area coefficient (F_0), shape coefficient (K), and Reynolds number will be changing in the design process. Experimental data proved that for the Reynolds number $Re>10^5$, the frictional coefficient of each of the three slotted sieves is almost constant. However, it should be noted that coefficient of open area plays a major role while the shape coefficient has a less significant effect. It should be stated that the experiments for slotted sieves for pipe diameters other than those used in the experiments are required to ensure that the Reynolds number is a proper and sufficient parameter in Equation 6. Otherwise, additional parameter or parameters in Equation 6 will be required.

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