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Analysis of the pressure drop calculation method impact on the accuracy of the experimental results in the *Koflo*® static mixer

Introduction

Nowadays, CFD (*Computational Fluid Dynamics*) techniques are modern tools commonly used by engineers as so as manufacturers and project designers. They allow for the reduction of the designing time and what is more important, they contribute to the relieving of investment costs. However, numerical models require validation on the basis of experimental data. Otherwise, their value is considerably lower because they are not supported by the real terms [*Ansys Inc., 2013*]. That is why, the developed *Koflo*® static mixer numerical model (described fully in the previous paper [*Stec and Synowiec, 2015*] used for pressure drop predictions during one-phase turbulent flow was verified in addition to obtained experimental data performed on a specially designed laboratory setup.

Experimental

As previously mentioned, the pressure drop is one of the basic parameters used for assessing the validity of static mixers apply [*Thakur et al., 2003*]. Due to it, it is possible to make a correct system design and what is also really important to compare the costs of energy consumption with solutions based on use of mechanically agitated vessels. Furthermore, it should be emphasized that pressure drops will play a key role particularly in case of turbulent flows. It is expected that their values will be high, especially for large *Reynolds* number. Therefore, owing to the lack of a strict correlation between the pressure drop and *Reynolds* number in turbulent flow regime in accessible literature it was decided to research the subject in order to broaden the existing knowledge and to validate the prepared numerical model. For this purpose, the experimental study was performed. The scheme of an experimental setup is presented in Fig.1.

The water from the tank - *1* was pumped by centrifugal pump (with the automatic adjustment of the revolution number) - *2* to the static mixer - *3* with a differential pressure transducer. The pressure taps were located in the inlet and outlet connections of the mixer to enable the measurement of pressure drop during the flow of fluid. After the end of the experiment the water was directed to a storage tank - *4* and then with the use of the valve - *5a* to the sewage system (or recycled to the tank - 1 with mechanical agitator - *7* and used as a feed in the next measurement series).

The experimental setup was also equipped with two additional temperature sensors and thermostat - *6* providing a permanent control of the process medium and control valves - *5* which help to preserve the occupational safety.

All of the experiments were carried out in the range of *Reynolds* numbers Re = 1000÷5000 which were corresponding to flow rates F = 40÷200 l/h (liters per hour). The water flow rate was changed by increasing the rpm of the impeller in the pump. To increase the accuracy of the experiments the measurements were repeated four times each and the final result was averaged. The commonly existing measurement error was in the limit of 15 %.

Results and discussion

Numerical model validation

The experimental pressure drops were used for validation of the developed CFD model (described in details in the previous manuscript [*Stec and Synowiec, 2015*]. Obtained values were also

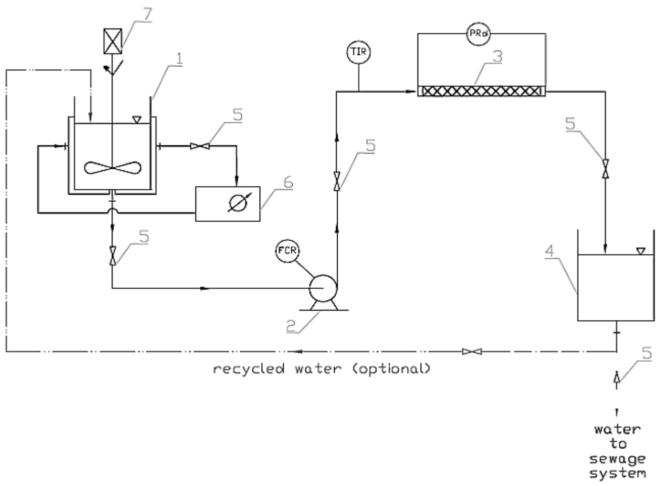

Fig. 1. Scheme of the experimental setup intended for pressure drop measurements: 1 – water tank, 2 – cenrtifugal pomp, 3 – *Koflo* static mixer, 4 – storage tank, 5 – valve, 6 – thermostat, 7 – mechanical agitator, FCR – flow rate automatic adjustment with registration, PRd – differential pressure measurement with registration, TIR – temperature measurement with the identification of a set point value and registration

compared with the pressure drops calculated from the manufacturer's correlation [*Koflo*® *Corporation*]. Achieved results were presented in Fig. 2 together with the experimental and numerical data (based on *k-ε* model). The design, experimental and computational points were fitted using a power function in accordance with Eq. (1).

$$\Delta p \propto \mathrm{Re}^{C} \tag{1}$$

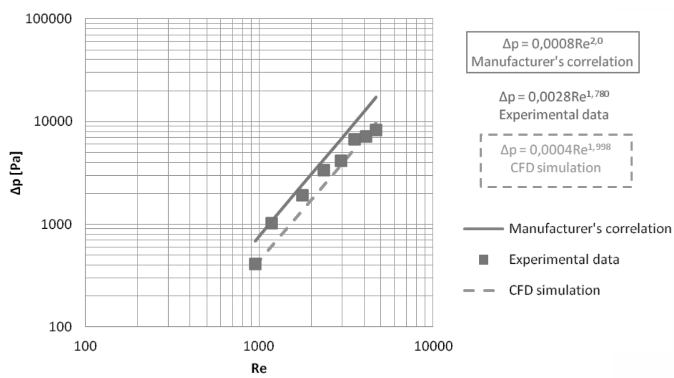

Fig. 2. Model validation for the flow in the range of Re = 1000÷5000

The comparison of the estimated exponent values C were presented in the Tab. 1.

From Fig. 2 it can be observed that pressure drop values obtained by use of numerical simulations stay in a good compatibility with experimental ones and those calculated from vendor's correlation. What is more, the influence of *Reynolds* number on an analyzed quantity powered by CFD is almost identical with one given by

Tab. 1.Values of C exponent from Eq. 1

Manufacturer's correlation	Experimental	CFD simulation
2,0	1,780	1,998

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manufacturer. Admittedly, with regard to the experimental results the exponent value at *Reynolds* number is lower than in two other cases (Tab. 1) but it stays within the normal range allowing for the safety margin and it is consistent with other literature data [*Thakur et al., 2003*].

New pressure drop correlation

In the basis of pressure drop results obtained from CFD computations and performed experiments, a new pressure drop correlation in the *Koflo*® static mixers was developed. For this purpose, the dimensional analysis was performed (due to well known procedure, only the most important assumptions were showed) and next (with the use of available computer software) equation parameters were calculated:

$$\Delta p = f(w, \rho, \eta, d_{SM}, L) \tag{2}$$

where:
Δp – pressure drop [Pa]
d_{SM} – inner diameter of the static mixer [m]
L – static mixer length [m]
w – fluid velocity [m/s]
ρ – fluid density [kg/m^3]
η – fluid dynamic viscosity [Pa·s]

$$Eu = Re^A \left(\frac{L}{d_{SM}}\right)^B \tag{3}$$

where:
Re – *Reynolds* number

$$Re = \frac{\rho w d_{SM}}{\eta} \tag{4}$$

Eu – *Euler* number

By use of *Euler* number definition

$$Eu = \frac{\Delta p}{w^2 \rho} \tag{5}$$

Eq. (3) may be also transformed to the following form:

$$\Delta p = Re^A \left(\frac{L}{d_{SM}}\right)^B w^2 \rho \tag{6}$$

Because of the fact that presented paper did not consider the influence of mixer diameter and length, it was adopted (according to the literature data [*Bayer et al., 2003*]) that *B* exponent in the relevant module $\left(\frac{L}{d_{SM}}\right)^B$ is equal to 1. Hence, the formula for pressure drop can be written as:

$$\Delta p = CRe^A \left(\frac{L}{d_{SM}}\right) w^2 \rho \tag{7}$$

After the data adjustment, the Koflo® static mixer empirical equation (from which the pressure drop calculations can be done) was presented in the following form:

$$Eu = 4{,}95 Re^{-0{,}22} \left(\frac{L}{d_{SM}}\right) \tag{8}$$

and it can be use for Re ϵ (1000; 5000).

Next, in the aim of checking the accuracy between the values calculated on the basis of Eq. (8) and other given data an appropriate graph was created (Fig. 3), showing the pressure drop as a function of *Reynolds* number.

From presented Fig. 3 it can be concluded that thedeveloped correlation stays in a good agreement with bothexperimental and simulation data (calculated relative error was in the range of 3,4÷8,6 % and it can be successfully used for *Koflo*® static mixer pressure drop predictions.

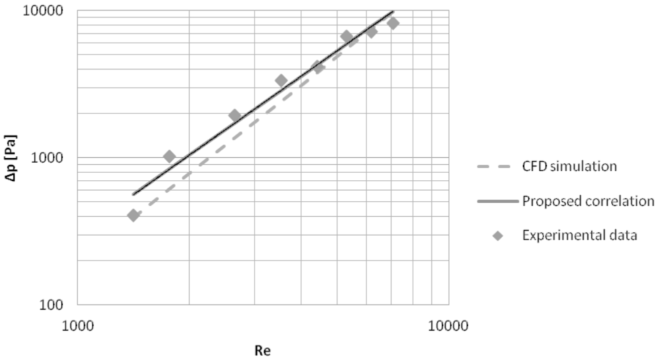

Fig. 3. Validation of the developer pressure drop correlation

Pressure drop as a function of Newton number

Well known is that the equation for pressure drop can be also presented in another form as a function of *Newton* number. The starting point used for presenting it in that kind of form is always the *Darcy – Weisbach* equation [*Çengel, Cimbala, 2006*] presented below

$$\Delta p = (2CRe^A)\frac{w^2}{2}\rho\left(\frac{L}{d_{SM}}\right) \tag{9}$$

where the first term in brackets is defined as the friction factor *f*, which included into Eq. (9) gives:

$$\Delta p = f\frac{w^2}{2}\rho\left(\frac{L}{d_{SM}}\right) \tag{10}$$

Next, knowing that the expression *f/2* represents the *Newton* number [*Bayer et al., 2003*] the pressure drop equation can be written as:

$$\Delta p = Ne\, w^2 \rho\left(\frac{L}{d_{SM}}\right) \tag{11}$$

The transformation of Eq. (11) gave the expression for *Newton* number

$$Ne = \frac{\Delta p}{w^2 \rho}\left(\frac{d_{SM}}{L}\right) \tag{12}$$

which can be also written as:

$$Ne = Eu\left(\frac{d_{SM}}{L}\right) \tag{13}$$

and that form (Eq. 13) was subsequently used for calculations in order to compare *Newton* number values for experimental and CFD computations as so as results of developed correlation (Eq. 8). The obtained data presented as a function of *Reynolds* number was showed in Fig. 4.

It can be seen from Fig. 4 that the *Newton* number (and so the friction factor *f*) in the turbulent flow computed on the basis of CFD

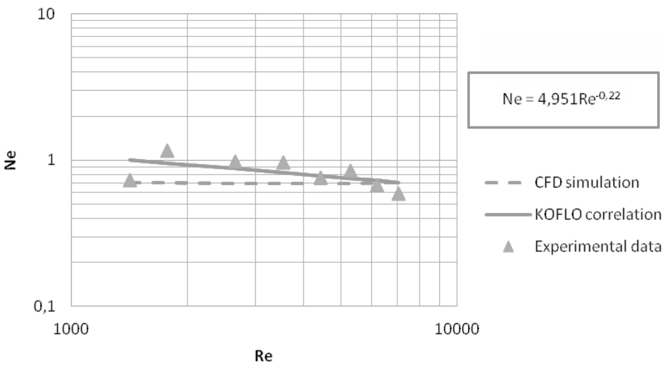

Fig. 4. *Newton* number as a function of *Reynolds* number

techniques has a constant value which is consistent with the literature references [*Kumar et al., 2008*] and proves the correctness of performed analysis. Furthermore, Fig. 4 shows a very good agreement between the developed pressure drop correlation (Eq. 8) and obtained experimental data. In turn, with regard to the test results, some discrepancies were observed (*Newton* number shows a slight downward trend). However, there is an expectation that the slope will decrease with the *Reynolds* number increase until the moment when the considered dependence (Ne = f(Re)) becomes linear. That is why occurred deviations may be regarded as staying within the acceptable limits and were found to be correct.

It should be also mentioned that equation describing the *Newton* and *Reynolds* number comparative dependence (presented in Fig. 4) shows clearly that the friction factor f is proportional to *Reynolds* number in the power of -0,22

$$f \propto Re^{-0,22} \tag{14}$$

That fact complies with the *Nikuradse* Equation [*Çengel, Cimbala, 2006*] used for friction factor calculations during the flow in the turbulent regime and it also demonstrates the rightness of the performed tests:

$$f = 0{,}0032 + \frac{0{,}221}{Re^{0,237}} \tag{15}$$

If the comparison of *Newton* number as a function of *Reynolds* number will be made for different commercially available static mixers [*Bayer et al., 2003*], adding the line corresponding to analyzed *Koflo*® type (Fig. 5), it can be concluded that it shows the smallest *Newton* number value which results in obtaining the smallest pressure drops (in comparison to considered geometries).

This allows for the conclusion that use of *Koflo*® static mixer may be a competitive solution in respect to commonly used mixer types and it's worth considering.

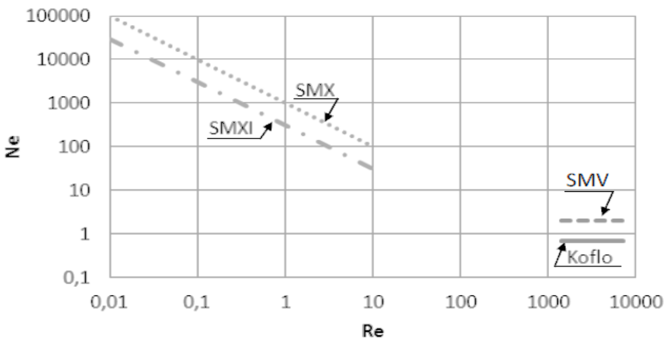

Fig. 5. The comparison of *Reynolds* number dependence on *Newton* number for different static mixers

Conclusions

The paper deals with the validation of the developed *Koflo*® static mixer numerical model (described in the earlier report [*Stec and Synowiec, 2015*] in addition to experimental data of pressure drops made on the built experimental setup as so as the values calculated from the manufacturer's correlation.

From the presented study it can be concluded that the pressure drop values obtained by performed experiments are consistient to both: CFD simulation results and values calculated from equation given by the vendor. It should be mentioned that there were some slight discrepancies (especially between the calculated from Eq. (1) exponent C values, however they stayed within the limits of acceptability and were related to the commonly occurring measurement errors.

On the basis of obtained results, the new pressure drop correlation was developed (Eq.8). The equation proposed by the authors stayed in a good agreement with both experimental and simulation data and it can be successfully used for *Koflo*® static mixer pressure drop predictions.

Furthermore, the analysis of *Newton* number presented in the Fig. 5, which includes different static mixers geometries shows that the use of *Koflo*® static mixer results in obtaining the smallest pressure drops. That stands a very important feature which makes the *Koflo*® type an interesting alternative to other well known used constructions.

All in all, the experiments connected to pressure drops acquired during the flow in the range of 40÷200 l/h confirmed that the numerical model of *Koflo*® static mixer was prepared in the proper way and means that CFD techniques can be successfully intended for pressure drop predictions. What is more, the *Koflo*® static mixer, unrecognized in the literature, provides a great base to other experiments that may affirm its superiority to another, commonly used types.

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