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Numerical method effect on pressure drop estimation in the Koflo® static mixer

Introduction

In the last few years the interest on the practical use of static mixers has significantly increased. It is caused by many advantages which motionless mixers can show. The main benefits obtained by use of static mixers are for example: small maintenance requirements, no moving parts, short residence times, high efficiency and many others. What is more, in contrast to commonly used mechanically agitated vessels they have small space requirements. Nowadays, this is a very important feature due to high prices of usable area, which translate into high investment and operating system costs. Furthermore, because of their construction that consists several motionless inserts installed in pipes (mostly with a circular cross section) static mixers may be used in many branches of industry, providing a variety of functions which include (except of mixing) heat exchange, mass transfer, multiphase flows, chemical reactions, etc. [*Thakur et al., 2003*].

At present, there are many types of static mixers at the market, commercially available, which differ from each other mainly with the geometry (shape) and number of static elements. These elements play a key role during the mixing process. Their main objective is to divide the fluid into a smaller streams and redistributing them by changing the flow direction that leads to a high degree of mixing (homogenization). The selection of inserts is based on fluid type and its properties, flow regime and of course an application of the static mixer.

In the literature there are many reports about the static mixers [*Cybulski and Werner, 1986; Mayers et al., 1997; Bayer et al., 2003*], but they are focused mainly on commonly used types, like for example Kenics (with helical inserts) [*Joshi et al., 1995, Rahmani et al., 2004, Wageningen et al., 2004*], *Sulzer SMX* [*Pahl and Mushelknautz, 1979; Rauline et al., 1998*], Ross LPD [*Singh et al., 2009*], etc. where the flow regime is laminar [*Hobbs and Muzzio, 1988; Hobbs et al., 1998; Bakker et al., 2000*]. Turbulent flow due to the more complicated description and much more complex requirements it is not as well recognized [*Berkman and Calabrese, 1988; Kumar et al., 2008*]. Among the others, the main purpose was to take this subject under consideration and to create the above paper. For this reason it was chosen the custom design of a static mixer bought from an American corporation Koflo® (Fig.1), about which there was no literature reports. Moreover, aside from an experimental analysis the authors decided to run numerical simulations using Computational Fluid Dynamics methods (CFD). With them it will be possible to create a versatile model facilitating a quick check of a Koflo® mixer usage to another industrial applications and enable the selection of the optimal solution from many considered options without running the expensive experiments.

It should be mentioned that presented paper is just a small part of report series concentrated on numerical modelling of hydrodynamic flow conditions in the Koflo static mixer.

CFD modelling

In two words, the first stage of the turbulent flow modelling, considered in this work, was a prediction of pressure drops over the static mixer during a one-phase flow in the range of *Reynolds* number *Re* = (1000÷5000). The objective for the numerical simulation was the Koflo® static mixer with 12 motionless inserts, where the tube total length L was 280 mm (there was an empty piece of tube at the beginning and at the end with a length L_1 of 30 mm). The internal diameter of threaded inlet and outlet d equals 10 mm (with the length of each section L_2 of 10 mm) and the internal pipe diameter with installed static inserts d_{SM} = 15 mm. The elements thickness s was 1,7 mm. The parameters of the fluid flowing through the mixer – water were collected in the Tab. 1.

Fig. 1 Koflo® static mixer - clear PCV geometry

Tab. 1. Fluid properties

Parameter	Value
Temperature of measurements	t = 20°C
Density	ρ = 998,2 kg/m^3
Viscosity	η = 10,0008·10^{-4} Pa·s

At first, in order to run the numerical simulations the generation of computational domain was performed. This stage was based on a proper formation of the mixer geometry and a body fitted mesh that covers the mixer and divides the domain into a large number of computational cells. What is important, the mesh must be in accordance with applicable quality criteria (like orthogonal quality, skewness or aspect ratio) [*ANSYS Inc., 2013*]. The mixer geometry was prepared in the *Design Modeler* package for ANSYS-*Fluent 15* with the dimensions compatible with the real model (Fig.2)

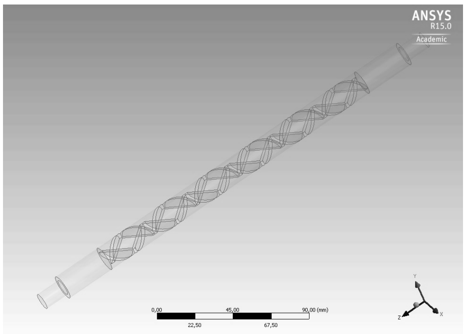

Fig. 2 Geometry of the Koflo® static mixer

In turn, the geometry of the Koflo® mixer was laid out using the hybrid grids (block and non-structured) with a variable number of elements (453K, 491K, 616K, 874K, 1,7M). For them a number of preliminary (initial) simulations were carried to determine the influence of grid density on the solution sensitivity and to choose the mesh with an optimal number of computational cells. From the obtained results the grid density tests were performed for all of the constructed meshes, using as a criteria the *Grid Convergence Index* (GCI) which is defined as [*Roache, 1994*]:

$$GCI = F_S \frac{\left|\dfrac{\Delta p_{h_2} - \Delta p_{h_1}}{\Delta p_{h_1}}\right|}{r^p - 1} 100\% \tag{1}$$

where: F_s = 3 – safety factor [*Roache, 1994*]; p = 2 – rate of convergence [*Roache, 1994*]; r – grid refinement ratio; Δp_{h1} – pressure drop obtained by use of coarse mesh [Pa]; Δp_{h2} – pressure drop obtained by use of finer mesh [Pa].

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Subsequently, guided by the lowest possible value of GCI coefficient (which must consider the computational resources of used computers) a mesh showing the smallest grid density effect on the numerical simulation sensitivity has been selected (Fig. 3).

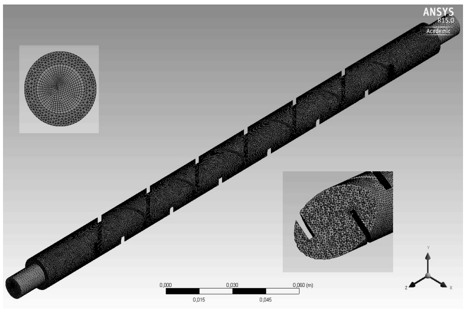

Fig. 3 Computational hybrid mesh of Koflo® static mixer
(number of elements 874 K)

After the successfully ended stage associated with computational domain preparation, there was a time to start the work aimed at performing numerical simulations. The first taken step was the selection of an appropriate modeling method. According to the review of turbulent flow modeling methods available in ANSYS-FLUENT software [*ANSYS Inc., 2013*] and computer parameters analysis (working memory and computing power) there was a decision on the choice of RANS method. Numerical computations were performed by use all of the viscous models (*k-ε, k-ω, k-ω* SST) with the aim of finding a suitable one allowing for reliable results obtain.

All in all, RANS modeling is based on *Navier-Stokes* equations averaged by *Reynolds* method (that is time-averaging) and enables the simulation of the flow in the whole range of the turbulence scales. What is important, it does not need a high computational efforts and resources and for these purposes it is often used for practical engineering applications giving solutions closely corresponding to the real conditions. However, due to the averaging process the transport equations must introduce a new term, known as *Reynolds* Stresses, which need to be provided by suitable turbulence model. In ANSYS *Fluent* there is a large variety of closure models but the most popular are:

- *k-ε* – an algorithm that introduces to N-S model two more transport equations which are the turbulent kinetic energy equation *k* and the dissipation rate equation *ε*. In *Fluent* software it occurs in three forms: as the Standard *k-ε* suitable for initial numerical computations, which poorly performs complex flows, RNG *k-ε* proper for complex shear flows and Realizable k-ε that has almost the same advantages as RNG but with greater accuracy and faster convergence. Use of *k-ε* model ensures the accurate modeling in the fluid core which can be also expanded to the near-wall area by use of additional functions (like for example enhanced wall treatment).
- *k-ω* – a two-equation model consists of equations for the turbulent kinetic energy *k* and the specific dissipation rate *ω* (that is defined as the rate at which the turbulence kinetic energy is converted into thermal internal energy per unit volume and time ($\omega=\varepsilon/k$). The use of *k-ω* model enable a very precise near-wall simulation of the fluid flow and it is commonly used in computations off free shear and transitional flows with complex boundary layer.
- *k-ω* SST (Shear Stress Transport) – a combination of *k-ω* and *k-ε* models, that offers the same benefits as *k-ω*, however applicable in broader range of flow types with an increased accuracy of numerical calculations.
- The most important solver settings (*Fluent 15*) used for calculations were presented in the Tab. 2.

Results and disussion

Mesh selection based on Grid Convergence Index (GCI)

The first obligatory step that enables obtaining reliable simulation results is a proper mesh selection consisting of an optimal computational cells number. To that end, there is a necessity of performing the grid density tests based on *Grid Convergence Index* (GCI) computed from Eq. (1)

Tab. 2. Fluent solver settings

CFD Software	*ANSYS FLUENT 15*
Main model	RANS
Viscous models	Realizable *k-ε* *k-ω* *k-ω* SST
Near-wall treatment	*k-ε* – enhanced wall treatment *k-ω* – default *k-ω* SST – default
Fluid properties	Temperature t = 20°C Density ρ = 998,2 kg/m^3 Viscosity η = 10,0008·10^{-4} Pa·s
Boundary conditions	Inlet: mass-flow-inlet Outlet: pressure-outlet Wall: stationary wall, no slip condition
Solution methods	SIMPLE, second order upwind
Under relaxation factors	Default
Residuals	Residuals < 10^{-5}

The testing parameter used for calculations was an averaged (flows from the range F = 40÷200 l/h) pressure drop in the Koflo® static mixer (calculated as a difference between the inlet and outlet pressure). Values of GCI, counted for all of the considered turbulence models were listed in the Tab. 3.

Tab. 3. Comparison of GCI values for different viscous models

Model	GCI [%]				
	Mesh 454K	*Mesh 491K*	*Mesh 616K*	*Mesh 874K*	*Mesh 1,7M*
k-ω	18,1	10,9	4,5	3,9	1,2
k-ω SST	65	23	3,57	2,5	1,2
k-ε	11,1	7,2	1,5	1,0	0,9

where: *K* – thousands of mesh elements; *M* – millions of mesh elements

As seen from the Tab. 3, the numerical simulation sensitivity decreases with an increase of computational cells number and this trend is observed for each of the examined models. Therefore, the best option would be the use of grid with the highest density. Nevertheless, because of long calculation duration as well as huge computation requirements and large memory consumption it was decided about the use of 874 k elements mesh which also gives small values of GCI.

Turbulence model selection. Numerical model validation

The selection of a turbulence model and also the validation of the performed numerical Koflo static mixer model were made on a basis of the comparison between the pressure drops values obtained from both: CFD simulations (for chosen mesh with 874 *k* elements) and the manufacturer correlation, presented in Eq.2 [*Koflo® Corporation, 2015*]. It should be mentioned that the form of presented empirical equation:

$$\Delta p = \frac{2Q^2 S k^{'}}{A}[PSI]/12\,el. \tag{2}$$

make it impossible to be converted into SI units and that is why it was written in its original form;
where: Q – volumetric flow rate [gal/min]; S – specific gravity [-];
$k^{'}$ – viscosity correction factor for turbulent flow [cP] defined as:

$$k^{'} = \eta^{0,6} \tag{3}$$

η – fluid dynamic viscosity [cP]; Δp – pressure drop [PSI]; A – constant depending on the inner mixer diameter [-] [*Koflo® Corporation, 2015*]

On the basis of Eq. (2) pressure drops across the Koflo® static mixer were calculated. Considered flow rates ranged in (40÷200) l/h. Achieved results were presented in Fig. 4 together with numerical

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data. The design and computational points were fitted using a power function

$$\Delta p \propto \mathrm{Re}^{C} \tag{4}$$

The comparison of the estimated exponent values C were presented in the Tab. 4.

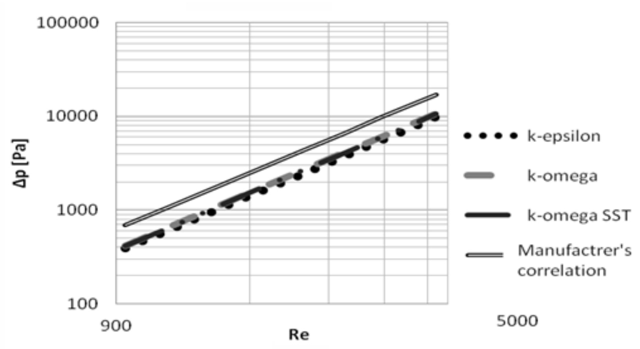

Fig. 4. Pressure drop as a function of *Reynolds* number – comparison of numerical data obtained by use of different turbulence models and values calculated on the basis of Eq. 2

Tab. 4. Values of C exponent from Eq. 4

C value			
Manufacturer's correlation	*k-ε*	*k-ω*	*k-ω SST*
2,0	1,998	2,016	2,025

It can be seen from the above (Fig. 4) that all viscous models give a comparable results of predicted pressure drops across a static mixer and, what is the most important, the calculated values are in good agreement with those calculated from vendor's correlation. However, if the effect of *Reynolds* number on the pressure drop in the Koflo® mixer will be taken under consideration (Tab. 4), it turns out that *k-ε* model most closely corresponds to values calculated on the basis of Eq. 2 (the smallest difference between the exponents is observed). Moreover, the analysis of values collected in Tab. 2 leads to the conclusion that use of *k-ε* model results in obtaining the lowest GCI. Therefore, the k-ε model was chosen as the most suitable and the closest to real terms.

To sum up, it can be concluded that the pressure drop relating to the considered Koflo® static mixer during the turbulent flow is proportional to the square of *Reynolds* number. This effect is significant but in comparison to other commercially available static mixers (in example commonly used Kenics type) it is at average level. Hence, use of Koflo® mixer can be an interesting alternative to another static mixers geometries.

CONCLUSIONS

In the presented study the CFD model of Koflo® static mixer was developed to predict the pressure drops during the one-phase turbulent flow (Re = 1000÷5000). For this purpose, the review of available computational methods used for turbulent flow description was made and in order to guidelines given by the ANSYS software producer as so as the computational efforts of possessed machines it was a decision about RANS method selection as the most appropriate for considered case. What is more, as part of numerical simulations the accessible viscous models (*k-ε, k-ω, k-ω* SST) were also examined and in the base of performed analysis, k-ε model was chosen as the most suitable.

The validation of presented computational method was performed in addition to correlation given by the manufacturer (Eq. 2).

As a result of the accomplished study it was observed that the pressure drop strongly depends on *Reynolds* number. That enhancement obtained from CFD simulations and calculations based on Eq. (4) is proportional to the squared *Reynolds* number ($\Delta p \propto Re^2$). Admittedly, when the values calculated on the basis of vendor's correlation (Eq. 2) were taken under considerations, some slight discrepancies were seen in comparison to the computational values. However, they stayed within the limits of acceptability and were related to the commonly occurring measurements errors. It can be concluded, that the presented paper showed a good agreement between the numerical (CFD) computations and pressure drops calculated from Eq. (2). This demonstrates the applicability of use CFD methods as adequate to determine the pressure drop in the Koflo® static mixer during the turbulent flow.

In practice, to perform numerical computations of pressure drops during the flow through Koflo® static mixer and allow for reliable results obtain, the key role played:

- generation of computational domain, that was:
  - proper mesh selection – hybrid mesh,
  - the choice of adequate grid density – 874 K,
- selection of appropriate modelling method – RANS with use of suitable turbulence model – *k-ε* and other *Fluent*-solver settings.

Due to extensiveness of concerned problem as well as lack of literature reports related to considered Koflo® static mixer construction, presented subject will be extended by experimental data and new analysis connected to flows in laminar regime, also with the recognition of multiphase flows in liquid-solid systems.

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