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Numerical study of the thermo-hydraulic characteristics in a circular tube with ball turbulators. Part 1: PIV experiments and a pressure drop

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ABSTRACT

In the paper, being the first part out of two (the second one is focused on processes of heat transfer), results of the computer simulations of the flow in a circular pipe with a ball inserts turbulising the flow are presented. An influence of the diameter of balls and their longitudinal distance on a pressure drop in the turbulent flow as a function of the Reynolds number (for Re = 10,000 ÷ 300,000) was analyzed. The investigations were carried out for different diameters of the balls (Db = 7, 10, 13, 16 and 19 mm) and different distances between them (L = 20, 24, 28, 32, 36, 40, 48, 60 and 85 mm) at a constant inner diameter of the tube (Dp = 26 mm). The results indicate that for the whole tested range of ball diameters and their longitudinal arrangements, there is an analytical dependency which allows for expressing a friction factor by the relationship: $f = A \cdot Re^B$. The constants A and B were functions of two variables: a dimensionless diameter of the ball ($X = Db/Dp$) and a dimensionless longitudinal distance between balls ($Y = L/Dp$). These two constants are closely related. They can be calculated analytically for the entire range of X and Y using a formula of the fourth order surface polynomial (15 coefficients of that polynomial are presented in the paper).

The paper presents also experimental investigations carried out using a PIV (Particle Image Velocimetry) apparatus. A comparative analysis of selected inserts and numerical calculations was the goal. The obtained results show a good correlation between the experiment and computer modelling.

1. Introduction

Processes of heat transfer intensification are now widely used in heat exchangers. The improvement of heat transfer between the tube wall and the fluid involves an application of different ways of flow turbulization, aimed at reducing the laminar boundary layer thickness in the immediate vicinity of the tube wall. One of the most commonly used methods of heat transfer enhancing is flow turbulization. This effect can be achieved, e.g., by placing special turbulising elements into the channel. Another way for "breaking the boundary layer" is to place various types of spikes or ribs on the wall [1–3]. A common feature of such flow turbulators, aside from their shapes, is a strong influence of certain geometric parameters on the flow-heat characteristics (e.g., an inclination angle of ribs, their height or thickness) [4–6]. However, every turbulising device, apart from a local increase in the heat transfer intensity, will also increase the flow resistance (this involves the obvious enlargement of power on pumping).

For testing, inserts with a ball geometry were selected due to their simplicity of design as well as availability and a wide range of materials they can be made of. Due to the passive character of mechanism of the heat transfer intensification in channels with inserts, there is no need to supply energy in a different form for this effect to occur. An additional advantage of such inserts is a possibility of applications, e.g., in quick modernization of already operating heat exchangers. While presenting the analytical dependences in the form of $f(Re,X,Y)$ and $Nu(Re,X,Y)$, one has a possibility to choose precisely economical design parameters of an insert in the tubular channel under consideration.

As has been mentioned previously, the effectiveness of turbulising inserts strongly depends on their geometry. Focusing only on channels with spaced, axially fixed elements turbulising the flow, it can be said that most often these are investigations of one or several types of insert geometries. Thus, Promvonge and Eiamsa-ard [7] presented the experimental investigations of conical-nozzle turbulators where the variable parameter was the longitudinal spacing of the nozzles in the range of Re = 8000 ÷ 17,000 for the flow in both directions. In [8], they considered a similar geometry but with a helical type insert. Durums [9] shows an effect of the

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Nomenclature

$a_1 \ldots a_{15}$	polynomial coefficients	*Re*	Reynolds number
A	constant in Eq. $f = \mathrm{A} \cdot Re^{\mathrm{B}}$	*u*	average velocity (m/s)
B	constant in Eq. $f = \mathrm{A} \cdot Re^{\mathrm{B}}$	V_D	volume of the domain (m^3)
dp/*dx*	pressure gradient (Pa/m)	V_f	volume flow rate (m^3/s)
Dp	pipe diameter (m)	*X*	diameter ratio (*Db*/*Dp*)
Db	ball diameter (m)	*Y*	longitudinal distance ratio (*L*/*Dp*)
f	friction factor	δ	relative error
L	longitudinal distance between balls (m)	ρ	density (kg/m^3)
n	number of grid nodes	Δp	pressure drop (Pa)
Nu	Nusselt number		

angle of this conical nozzle on a pressure drop and heat transfer intensity. The presented results show that with an increase in the turbulator nozzle angle, also the Nusselt number and the friction factor increase nonlinearly. Another example of the turbulator is a circular ring mounted on the pipe wall. Kongkaitpaiboon et al. [10] investigated experimentally flow parameters for three diameters of these rings and for three longitudinal distances, in a narrow range of the Reynolds number (4000 ÷ 20,000). These studies have shown that the highest pressure drop, but also the best heat transfer, is for the smallest inner diameter of the rings and the smallest longitudinal spacing between them.

The most similar geometrically turbulator to the one presented in this paper was examined by Charun [11]. His experimental investigations were conducted on a vertical tube with a fixed ball insert in the axis, where the balls were adjacent to each other to form a cascade. He examined four types of inserts with different diameters of the balls, in the range of *Re* = 3000 ÷ 30,000. A correlation for the friction factor and the *Nu* number for these inserts was performed on the basis of the data for one geometrical parameter only – the diameter of the balls.

Most experimental investigations of turbulising inserts are performed on test stands, where the main measured parameters are: pressure drop, wall temperature, fluid temperature or heat/cooling power. However, a measurement method of the velocity field, using the PIV technique, is the most useful to compare to the numerical simulations. It allows one to measure the local velocity field in the test tube, and, on this basis, to define basic flow parameters (especially in turbulence regions). The majority of authors using a PIV apparatus in their investigations note that the main problem in the image recording are optical distortions, especially for tubular channels, which, however, may be minimized by using methods appropriate to the nature of experiments [12–15].

2. Test stand and a measurement procedure

The main part of the test stand is a transparent tube (made of Plexiglas) with an inner diameter of 26 mm and wall thickness of 2 mm. It has a turbulising insert, consisting of several dozens of balls threaded on a thin steel cable and located on it at equal distances. The cable was coming out from the measuring tube by a packing gland and was fixed on the support structure of the test stand (Fig. 1). In every fourth ball, there were thin plastic rods mounted, spaced at 120° on the circumference, which kept the entire insert in the axial position (Fig. 2). The measurement area of the velocity field with a PIV apparatus comprised: (I) vertically – the bottom plane between the pipe wall and the cable (in the axis of the channel), and (II) horizontally – 2 or 3 segments of the insert (Fig. 1 – detail 10).

The measuring section of the tube was immersed in water contained in a specially mounted, transparent tank, fixed outside the tube (Fig. 3b). Surrounding the circular, transparent tube with water is one of the most frequently used methods aimed at eliminating, or significantly reducing, the reflections of light emerging from the laser beam (which passes through the tube wall [13]). Other disturbing reflections of the laser beam were eliminated by painting the insert at the measuring section with black matte paint and by gluing a tape on the unnecessary camera view field [15].

The total length of the tube with an insert was 4 m (to ensure a fully developed flow). A pressure drop was measured at the central section of the pipe (at the distance of 2.1 m, which allows to keep high accuracy of the measurement). The measurements of a pressure drop and velocity fields using the PIV method were carried out under thermally fixed conditions at water temperature of 30 °C, which was stabilized by a cooling system.

In the experiment carried out, two turbulising inserts with the same ball diameter of *Db* = 16 mm, the longitudinal arrangement of *L* = 40 mm and *L* = 48 mm (Fig. 2) and the range of *Re* = 12,000 ÷ 55,000 were investigated.

In Fig. 3 a test stand and a relative position of the laser and the camera of the PIV system are shown. The laser beam illuminated the test area of the tube from the bottom and the camera was mounted perpendicularly to the plane of the highlighted image. The measurements were made with a PIV apparatus of Dantec Dynamics Digital Company equipped with the Flow Manager software. PSP-50 (Polyamide Seeding Particles) powder with a diameter of grains of 50 μm was used as seeding. The great advantage of this type of seeding is its density, which is very close to water density −1.03 g/cm^3, due to which there is no phenomenon of gravitational sedimentation of particles at low flow velocities. The most important parameters of the data acquisition system are presented in Fig. 4, which shows a report window from the Flow Manager software (in this figure, the laser parameters visible in other program windows were also added).

The mathematical processing of the measurement data was carried out with the Flow Manager software. To calculate displacement vectors, a cross-correlation technique which allows one to determine a rough velocity field for each pair of images was used. The size of the interrogation window used for the PIV processing was 32 × 32 pixels with a 50% overlap. The next step was filtering and averaging of the vector field from 100 photos. The resulting data were exported in a tabular form to an external program in order to compare with the numerical calculations.

3. Comparison of the experimental and numerical results

3.1. Measurement of the velocity field

In Figs. 5–7, results of the measurements obtained with the PIV method and results of the numerical calculations for one (repeatable and periodical) section of the insert are shown. For