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INTEGRAL AND STATISTICAL CHARACTERISTICS OF THE TURBULENT SWIRL FLOW IN A STRAIGHT CONICAL DIFFUSER

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Abstract. The results of the experimental investigations of the turbulent swirl flow in a straight conical diffuser with inlet diameter 0.4 m and total divergence angle 8.6° are presented in this paper. The incompressible swirl flow field is generated by the axial fan with outer diameter 0.397 m. The measurements were performed in one measuring section downstream the axial fan impeller in the conical diffuser in position ($z/R_0 = 1$) with original classical probes and an one-component laser Doppler anemometry (LDA) system, for four flow regimes. The comparative measurements of axial and circumferential velocities are presented. The Reynolds number, calculated on the basis of the average velocity, ranges from 149857 to 216916. Integral parameters, such as volume flow rate, average circulation and swirl number, are determined. Statistical characteristics, such as level of turbulence, skewness and flatness factors, are calculated. The highest levels of turbulence for axial velocity are reached in region $0.4 < r/R < 0.6$, where $D = 2R$. The highest levels of turbulence for circumferential velocity are reached for the regimes with lower circulation in $r/R \approx 0.4$, i.e., in the vortex core region for the cases with higher circulation.

1. Introduction

An overview of the turbulent flow experimental research in diffusers is presented in papers [1, 2]. Statistical properties of the turbulent swirl flow in diffusers are studied in [3, 4]. The influence of the Reynolds number on integral and statistical properties of the generated turbulent swirl flow is studied in [5, 6]. The results of experimental investigations of the turbulent swirl flow in three straight conical diffusers with various diffuser total angles (8.6°, 10.5° and 12.6°) are presented in [7,8]. The original classical probes were used in the investigation presented in [8].

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The turbulent swirl flow study in one of these diffusers, with the total divergence angle of 8.6°, is the object of the research in this paper. Here are presented the experimental results obtained in this diffuser by use of the one-component LDA system and the original classical probes.

2. Test rig and measuring techniques

The experimental test rig for the turbulent swirl flow research is presented in Figure 1 [2, 7, 8].

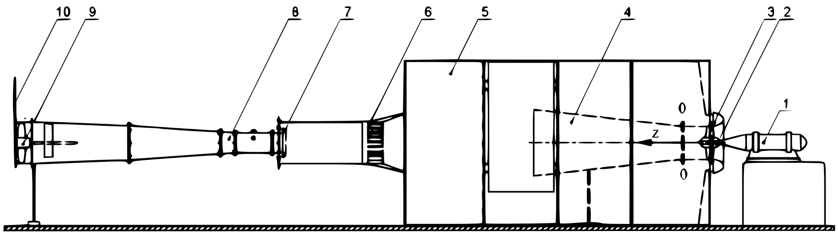

FIGURE 1. Test rig for experimental investigations

The incompressible swirl flow field is generated by the axial fan impeller (2) with a rotational speed-contolled motor (1) (Figure 1). The main geometry characteristics of the axial fan impeller, model AP 400, Minel, Serbia, are provided in [6, 9]. The fan impeller has seven blades adjusted at the angle of 29° at the outer diameter. The axial fan is in-built in the straight pipe section with a profiled inlet nozzle (3). The impeller is followed by the straight conical diffuser (4), which is placed in the chamber (5). The test bed is equipped with the honey-comb (6), flow meter (nozzle) (7), pipe (8), booster fan (9) and flow regulator (10). The diffuser has an inlet diameter $D_0 = 0.4\,\mathrm{m}$, an outlet diameter $D_9 = 0.67\,\mathrm{m}$, length $L = 1.8\,\mathrm{m}$ and an angle $\alpha_{\mathrm{dif}} = 8.6°$. Velocity fields were measured at cross-section number 2 defined in [7, 8] as $z_2 = 0.2\,\mathrm{m}$, or as $z_2/R_0 = 1$ and $z_2/L = 0.22$, along one measuring radius R_2 with 21 measuring points. The measurements were performed for four regimes, with different booster fan rotation speeds, constant AP 400 fan rotation speed ($n = 1000\,\mathrm{min}^{-1}$) and the open flow regulator.

The one-component LDA measurements have been performed successively for both velocity components in the measurement section along the horizontal radius at a distance of 10.9 mm ($0.05R_2$) each. LDA systems (Dantec, laser power 35 mW), signal processor (BSA F30) and thermal fog machine for seeding (Antari Z3000II, liquid EFOG) were employed in this research [5–7, 9]. Seeding was naturally sucked in the test rig by the axial fan AP 400. The cross-shaped slots were cut along the diffuser axis, so axial and circumferential velocities were measured in the same point. Transparent foils were glued over these slots on the inner side of the diffuser wall (Figure 2).

Velocity and pressure fields were measured with classical probes at cross-section number 2. The measurements were performed with original, home-made, combined Prandtl and angular probes [10, 11].

Figure 2. Laser Doppler anemometer measurements in a diffuser

Figure 3. Measurements with a classical probe in a diffuser

2.1. Integral and statistical flow characteristics. The volume flow rate is calculated as follows:

$$Q = 2\pi \int_0^{R_2} rU\, dr, \tag{2.1}$$

where r is a radius coordinate and U is a time averaged axial velocity.

The average circulation is given as:

$$\Gamma = \frac{4\pi^2}{Q} \int_0^{R_2} r^2 WU\, dr, \tag{2.2}$$

where W is a time averaged circumferential velocity.

The swirl flow parameter [2] is defined as follows:

$$\Omega = \frac{Q}{R_2 \Gamma}. \tag{2.3}$$

The average velocity is defined as:

$$U_m = \frac{Q}{\pi R_2^2}. \tag{2.4}$$

The Reynolds number is defined as follows:

$$Re = \frac{U_m D_2}{\nu}, \tag{2.5}$$

where ν is a fluid kinematic viscosity.

The Reynolds normal stresses and levels of turbulence for axial and circumferential velocities are calculated as follows [5,9]:

$$\overline{u_i^2} = \sum_{j=0}^{N-1} \eta_j (u_i^2)_j, \quad \text{where} \quad \eta_j = \frac{t_j}{\sum_{k=0}^{N-1} t_k} \quad \text{and} \quad \frac{\sigma_i}{U_m} = \frac{\sqrt{\overline{u_i^2}}}{U_m}. \tag{2.6}$$

Here η_j is a weighing factor, t_j is transit time of the j-th particle crossing the measuring volume and $u_i = u$ and w are fluctuating velocities in axial (x) and circumferential (φ) directions respectively. Normalized central moments for axial and circumferential velocity components of the third S_i (skewness), and the fourth order F_i (flatness) are calculated in the following way:

$$S_i = \overline{u_i^3}/\sigma_i^3, \quad F_i = \overline{u_i^4}/\sigma_i^4. \tag{2.7}$$

3. Results and discussion

The integral flow parameters in measuring section s2, such as volume flow rate, average circulation, swirl flow parameter, average velocity and Reynolds number, are calculated on the basis of equations (2.1)–(2.5) and presented in Table 1.

Table 1. Calculated integral flow parameters in measuring section 2

Regime	$Q[m^3/s]$	$\Gamma\,[m^2/s]$	$\Omega\,[-]$	$U_m\,[m/s]$	$Re\,[-]$	Booster
J	0.720	4.27	0.78	4.87	149857	off
D	0.899	3.10	1.33	6.02	185201	on
E	0.995	1.84	2.47	6.66	204932	on
F	1.050	1.41	3.43	7.05	216916	on

The comparison of the measurements results (velocity distribution for axial and circumferential velocity) obtained with classical probes (CP) and Laser Doppler anemometry (LDA), in section 2, for series J, D, E and F, is presented in Figs. 4–7.

The experimental results show that in the sound flow region, repeatability and compatibility of CP and LDA measurements are excellent, while they are weaker in the vortex core region. A solid body profile is obtained for all flow regimes.

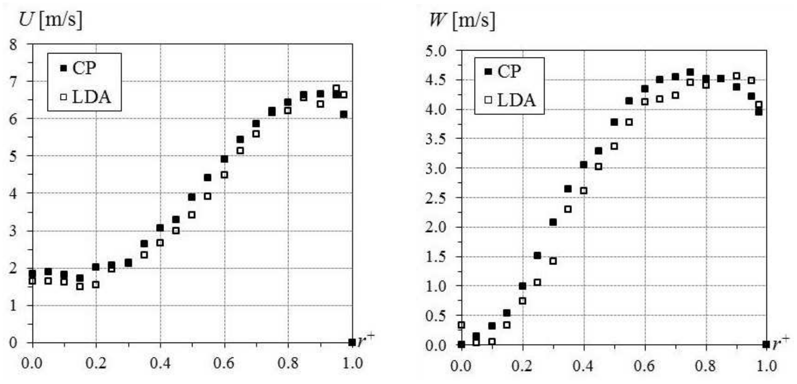

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FIGURE 4. Distributions of a) axial and b) circumferential velocities in measuring section 2 for regime J

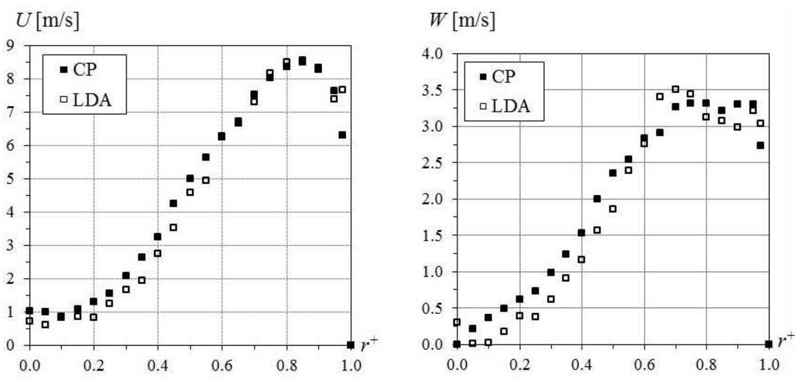

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FIGURE 5. Distributions of a) axial and b) circumferential velocities in measuring section 2 for regime D

The experimentally obtained time averaged dimensionless axial and circumferential velocities, measured with LDA systems, are presented in Figure 8.

The non-dimensional axial velocity profiles are similar (Figure 8a). Circumferential velocity distributions have a forced vortex distribution in the central flow region for all regimes, i.e., mainly uniform distribution for $r^+ = r/R_2 > 0.65$. The highest circumferential velocity is achieved for case J, without a booster fan (Figure 8b).

The distributions of the turbulence level, skewness (S_w) and flatness (F_w) factors for both velocities in measuring section 2 are presented in Figures 9–11. These statistical values are calculated on the basis of relations (2.6)–(2.7).

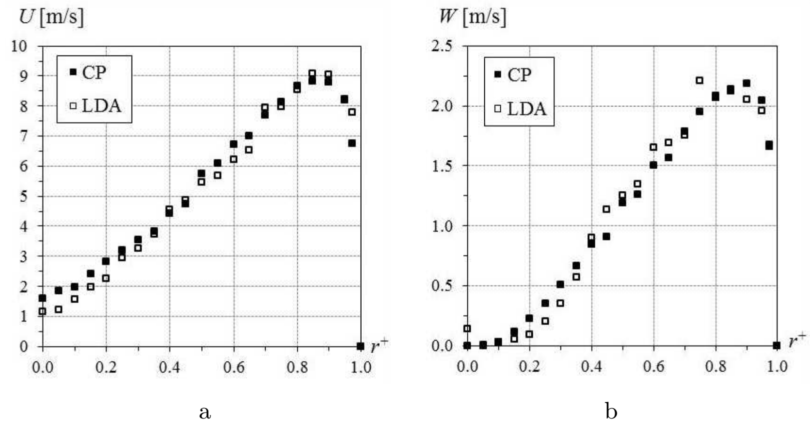

FIGURE 6. Distributions of a) axial and b) circumferential velocities in measuring section 2 for regime E

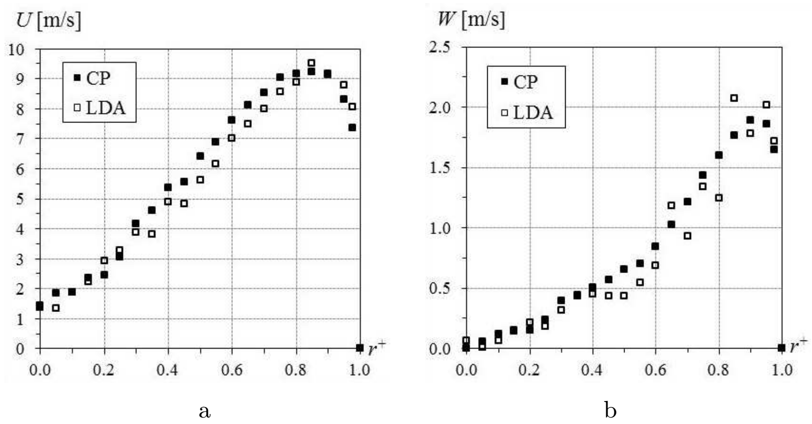

FIGURE 7. Distributions of a) axial and b) circumferential velocities in measuring section 2 for regime F

The highest levels of turbulence for axial velocity are reached in region $0.4 < r/R_2 < 0.6$ for all regimes (Figure 9a). The highest levels of turbulence for circumferential velocity are reached in the region around $r/R_2 \approx 0.4$ for regimes E and F with higher values of Re and Q, and lower values of circulation, i.e., in the core region $0 < r^+ < 0.3$ for regimes D and J with lower values of Re and Q, and higher values of circulation (Figure 9b). The distribution of the skewness factor is nonuniform for all regimes (Figure 10). The skewness factor is not equal to zero, which corresponds to the Gaussian probability distribution. It changes sign along the radius.

The skewness factor for axial fluctuating velocity has maxima in the center of the diffuser (central flow region) for all flow regimes, except J, without the

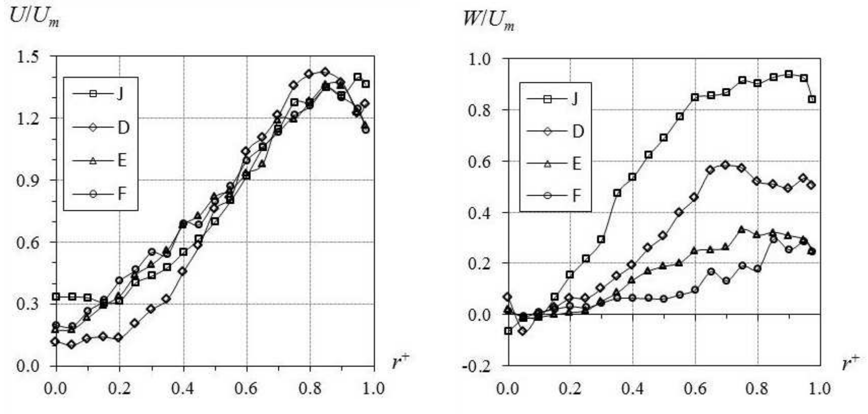

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FIGURE 8. Dimensionless a) axial and b) circumferential velocities in measuring section 2 in a diffuser, for regimes J, D, E and F

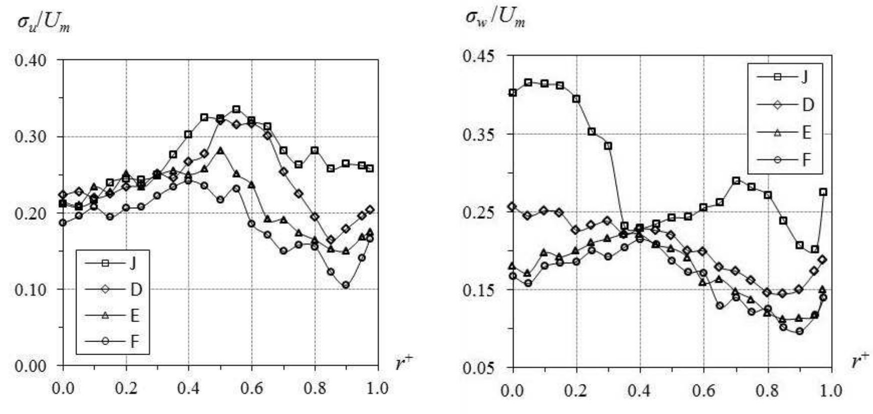

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FIGURE 9. Turbulence level in a diffuser (measuring section 2) for four regimes: a) axial and b) circumferential fluctuating velocities

booster fan. A similar trend occurs for flow regimes D, E and F. It has minimum in $r^+ = 0.65$ for regime J, without a booster fan (Figure 10a). The skewness factor for circumferential fluctuating velocities for regimes with a booster fan has values close to 0 in the center of the diffuser and oscillates around it till $r^+ = 0.3$. It, again, behaves in a different way for flow regime J (Figure 10b). The flatness factor for axial fluctuating velocity differs from value 3 for all regimes. The highest values are reached for regime J in the vortex core, i.e., in $r^+ = 0.8$ for regime D and in $r^+ = 0.9$ for regime F (Figure 11a). The distribution of the flatness factor for circumferential fluctuating velocity is similar for all regimes with the booster fan on. Flatness factor F_w has values close to the value for normal, i.e., Gaussian probability distribution

($F_w = 3$) till $r^+ = 0.4$, for all regimes, and increases afterwards till $r^+ = 0.85$ for regime D, i.e. till $r^+ = 0.9$ for regimes E, F and J (Figure 11b).

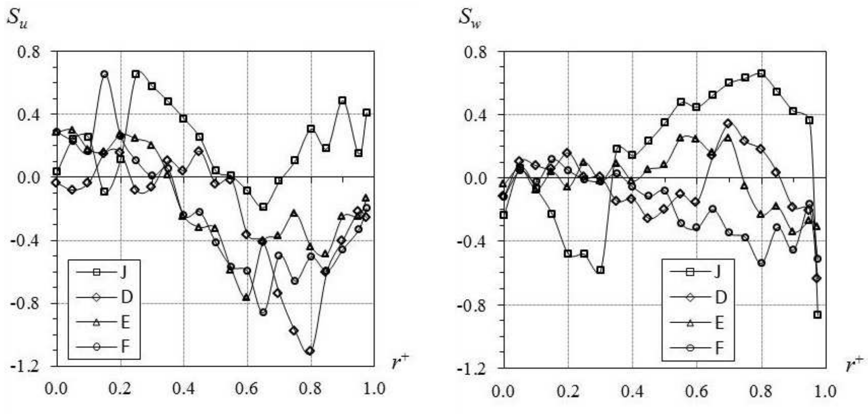

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FIGURE 10. Skewness factors in a diffuser (measuring section 2) for four regimes: a) axial and b) circumferential fluctuating velocities

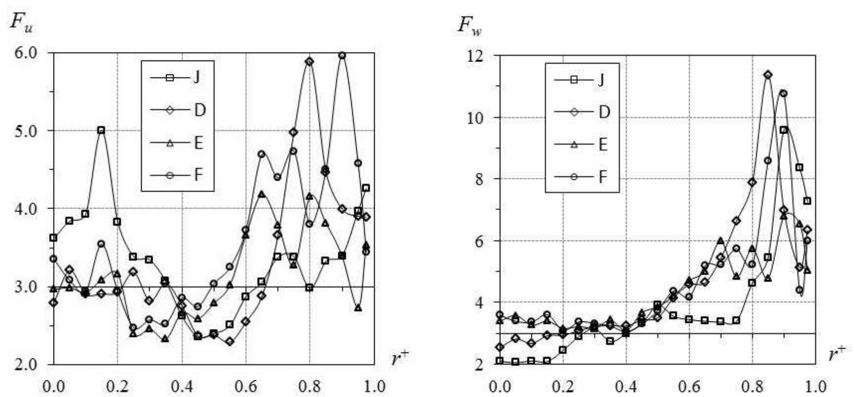

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FIGURE 11. Flatness factors in a diffuser (measuring section 2) for four regimes: a) axial and b) circumferential fluctuating velocities

4. Conclusions

An experimental investigation of the turbulent swirl flow in a straight conical diffuser behind the axial fan is presented in this paper. The measurements are performed with classical probes and a one-component LDA system. Similar axial velocity distributions are achieved. Solid body circumferential velocity profiles are generated for all regimes. The Reynolds number is in the range from 149857 to

216916 (Table 1). A comparison of the obtained experimental results for axial and circumferential velocities with two measurement methods, classical probes and the LDA system, reveals a significant agreement. It is even more obvious for the axial velocity component. The overlapping of the circumferential velocity distributions, obtained by use of both measuring techniques is better in the vortex core region, while it is not so clear in the sound flow region, especially for regimes with a lower Reynolds number (J and D). Statistical moments up to the fourth order are calculated. High values of statistical moments and significant deviation from normal, i.e., Gaussian distribution in measuring section for all regimes, are determined on the basis of the experimental results. The influence of the Reynolds number on all statistical characteristics is obvious [12]. It is shown (Figure 9) that the lowest turbulence levels, for both velocities, are reached for regime F with the highest Reynolds number and vice versa for regime J, without a booster fan. This could be also correlated to the values of the average circulation (Table 1). The distributions of turbulence levels for axial velocity are more similar than for circumferential fluctuating velocities, where regime J has a completely different character. These experiments, as well as those in the pipe [6], reveal an intermittent character of the observed turbulent flow, as well as the existence of the coherent structure in the vortex core region and shear layer.

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ИНТЕГРАЛНЕ И СТАТИСТИЧКЕ КАРАКТЕРИСТИКЕ ТУРБУЛЕНТНОГ ВИХОРНОГ СТРУЈАЊА У ПРАВОМ КОНУСНОМ ДИФУЗОРУ

Резиме. У раду су представљени резултати експерименталних истраживања турбулентног вихорног струјања у правом конусном дифузору улазног пречника 0.4 m и укупног угла ширења 8.6°. Некомпресибилно вихорно струјање генерисано је помоћу аксијалног вентилатора са спољним пречником 0.397 m. Мерења су обављена иза радног кола аксијалног вентилатора у једном мерном попречном пресеку конусног дифузора у позицији $(z/R_0 = 1)$ са оригиналним класичним сондама и једнокомпонентним ласер Доплер анемометарским (ЛДА) системом за четири режима струјања. Приказана су упоредна мерења аксијалних и обимских брзина. На основу средњих брзина израчунати су Рејнолдсови бројеви, при чему је најмања вредност 149857, док је највећа постигнута 216916. Одређени су интегрални параметри попут запреминског протока, средње циркулације и вихорног броја, као и статистичке карактеристике, као што су ниво турбуленције и статистички моменти трећег и четвртог реда. Највиши нивои турбуленције за аксијалну брзину су достигнути у области од $0,4 < r/R < 0,6$, где је $D = 2R$. Највиши нивои турбуленције за обимску брзину су достигнути у $r/R \approx 0,4$ за режиме са мањом циркулацијом, односно у региону вихорног језгра за режиме са већом циркулацијом.

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