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INVESTIGATION OF THE TURBULENT SWIRL FLOW IN PIPE GENERATED BY AXIAL FANS USING PIV AND LDA METHODS

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Abstract. In this paper is presented experimental investigation of the turbulent swirl flow in pipe generated by axial fans. Two various models of industrial axial fans are used. One of these is axial fan W30, model AP 400, Minel, Serbia and has seven blades and outer diameter 0.397 m. Second axial fan SP30 is model TGT/2-400-6, S&P, Spain, has six blades and outer diameter 0.386 m. This results with greater clearance in the second case. Blades were adjusted for both fans at the angle of 30° at the outer diameter. Test rig length is $27.74 \cdot D$, where D is average inner diameter app. 0.4 m. Measurements are performed in two measuring sections downstream the axial fans ($z/D = 3.35$ and $z/D = 26.31$) with one-component laser Doppler anemometry (LDA) system and stereo particle image velocimetry (SPIV). Obtained Reynolds numbers, calculated on the basis of the average axial velocity (U_m) in the first measuring section are for fan SP30 Re = 226757, while for fan W30 Re = 254010. Integral flow parameters are determined such as average circulation and swirl number. Significant downstream axial velocity transformation occurs for both fans, while circumferential velocity is decreased, but non-dimensional velocity profile remains the same. Circumferential velocity distribution for both fans in the central zone corresponds to the solid body, while in $r/R > 0.4$, where $D = 2R$, distribution is more uniform. Radial velocity in the case of fan SP30 has almost zero values in the measuring section $z/D = 3.35$, while its values are significantly increased in the downstream section with the maximum in the vortex core region. On the contrary radial velocity decreases downstream for fan W30 and has also maximum value in the vortex core region for both measuring sections. Level of turbulence, skewness and flatness factors are calculated on the basis of the experimental data. The highest levels of turbulence for circumferential velocity are reached in the vortex core region for both fans. It is shown how statistical moments of the third and fourth order differ from the values for normal Gaussian distribution. In this paper are also analyzed velocity fields by use of SPIV.

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Key words and phrases: turbulence, swirl flow, axial fan, LDA, PIV.

1. Introduction

Turbulent swirl flow in pipe behind two industrial axial fans without guide vanes has been experimentally studied in this paper. Fans are in built after ISO norm, case B - free inlet, ducted outlet. Complex three dimensional turbulent swirl flow has been studied by numerous authors [1–23]. Statistical properties of the turbulent swirl flow in pipes is studied in [1, 9]. Turbulent swirl flow in pipe on the axial fan pressure side is thoroughly studied in [1–3, 10, 15]. Literature overview is given in [1–3, 9, 10, 14, 15]. In [9] are studied statistical characteristics of the Rankine swirl flow in pipes and diffusers. Study of the influence of Reynolds number on the statistical and correlation-spectral properties of the generated turbulent swirl flow is studied in [3, 5, 6]. Investigation of structure and non-gradient turbulent transfer in swirling flows is studied in [4], while high speed stereo particle image velocimetry (HSS PIV) is employed in [3, 7]. Study of the influence of the axial fan blade angle on the turbulent swirl flow characteristics is presented in [8]. In this paper are studied integral and statistical parameters of the turbulent swirl flow behind two industrial fans. Statistical moments of the second and higher order are calculated and analyzed.

2. Experimental Test Rig

Experimental test rig, $27.35 \cdot D$ long, where average inner pipe diameter is $D = 0.4\,\mathrm{m}$, is presented in Figure 1. Fan rotation speed was 1500 rpm and was controlled by a fully automated thyristor bridge with error up to ± 0.5 rpm. Two axial fans were used as swirl generators.

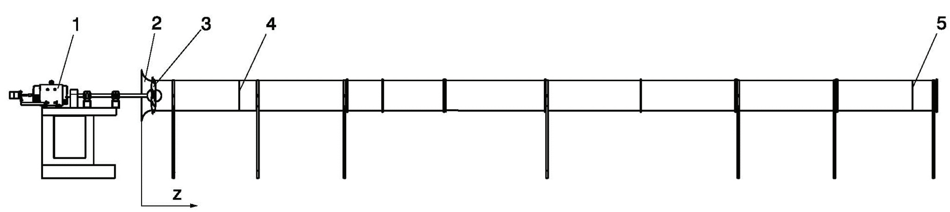

FIGURE 1. Experimental test rig: 1 - DC motor with electrical power 5 kW, 2 - profiled free bell-mouth inlet, 3 - axial fan (swirl generator), 4 - measuring section 1 and 5 - measuring section 3.

Measurements have been performed in two measuring sections $z/D = 3.35$ and $z/D = 26.31$.

Axial fan W30, model AP 400, Minel, Serbia (Figure 2a), has outer diameter 0.397 m and seven blades, while the second model SP30 is TGT/2-400-6, Soler and Palau, Spain (Figure 2b), with outer diameter 0.386 and six blades. Blades were adjusted for both fans at the angle of $\beta_R = 30°$ at the outer diameter.

Ratio of the hub and outer diameter, i.e., non-dimensional radius is for W30 ν=0.434, while for SP30 is $\nu = 0.5$. Fan W30 is positioned inside the test rig on

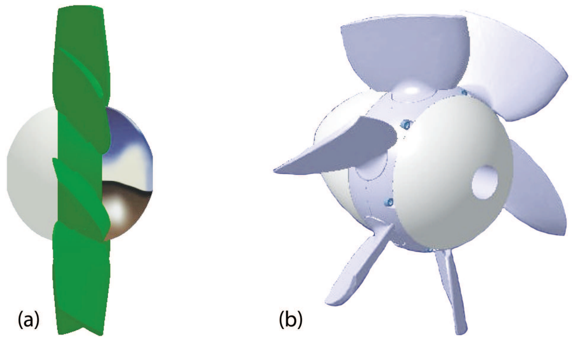

FIGURE 2. Scanned and modeled axial fan impellers: a) W30 and b) SP30.

distance 90 mm measured from the test rig inlet to the top of the suction cap, while SP30 on distance 190 mm.

3. Experimental Techniques

In this research have been employed two laser based measurement techniques, such as laser Doppler anemometry (LDA) and stereo particle image velocimetry (SPIV).

3.1. Laser Doppler Anemometry. One-component LDA measurements have been performed successively for all three velocity components in specified measurement sections (Figure 1) along the vertical diameter on distance 10 mm each. Flow Explorer Mini LDA, Dantec, with BSA F30 signal processor and laser power 35 mW was used. It operates in backscatter with focal length at 285 mm and measurement volume dimensions of app. 0.1 mm $\times$0.1 mm $\times$1 mm. Circumferential velocity component was measured, due to technical limitations, from above and bottom side of the pipe, what corresponds to radii $\varphi = 90°$ and $\varphi = 270°$, respectively. There is overlapping in the core region. LDA measuring volume displacement in cylindrical pipe flow is studied in [3,14,21]. Transit time was used as the weighting factor and recording time of 10 s was set up as the stop criterion for all measurements. The flow was seeded by the Antari Z3000II thermal fog machine with liquid EFOG, Density Fluid, Invision. Seeding was naturally sucked in the test rig by the fan. Data sampling rate varied along the vertical diameter, also depending on the measured velocity component.

3.2. Stereo Particle Image Velocimetry (SPIV). SPIV was employed in both specified measurement cross-sections (Figure 1). Local SPIV coordinate system (X, Y), with origin on the pipe axis, is defined in Figure 3.

Flow was illuminated with dual head Nd:Yag laser (max power: 30 mJ/pulse, wavelength 532 nm, 15 Hz). Two 12-bit CCD cameras with the resolution of 1660 $\times$ 1200 pixels and 32 fps were in Scheimpflug and backscatter setup. Software INSIGHT 3G TSI was used for data acquisition and processing. Image processing

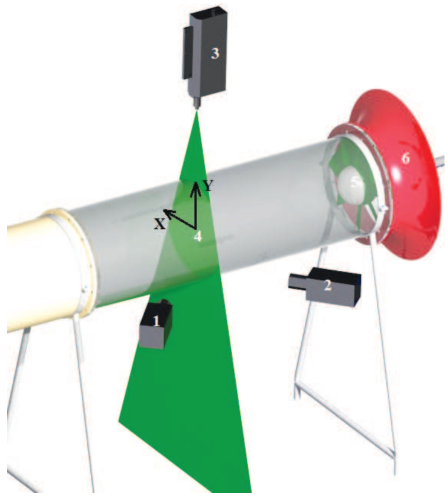

FIGURE 3. SPIV measuring arrangement in the measuring section: 1-left camera, 2-right camera, 3-Nd:Yag laser, 4-illuminated pipe cross-section, 5-swirl generator and 6-profiled inlet nozzle.

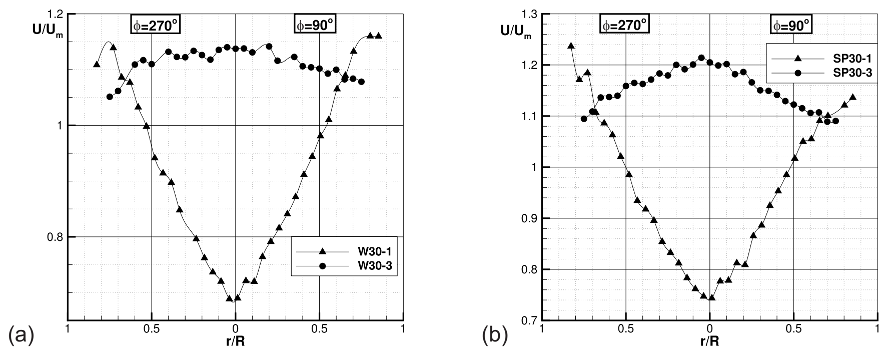

FIGURE 4. Dimensionless axial velocities in measuring sections 1 and 3 for fans: a) W30 and b) SP30 ("270°" denotes measurements in the pipe lower part, i.e., for angle $\varphi = 270°$).

was performed using the central difference image correction (CDIC) and deformation algorithm combined with the FFT correlator [3, 11, 24]. In this case 400 pictures are obtained with laser frequency of 2 Hz and afterwards averaged.

4. Experimental Results

4.1. Velocity profiles and integral parameters. Experimentally obtained time averaged dimensionless axial (U) velocity for both fans and measuring sections are presented in Figure 4. Similarity in downstream profile transformation is obvious. All profiles are axisymmetrical and reverse flow doesn't exist. Extremely non-uniform distribution in section 1 is transformed in almost uniform in the downstream section for both fans. This is the consequence of fluid acceleration in domain $0 \leqslant r/R \leqslant 0.7$ for fan SP30 (Figure 4b) and in the zone $0 \leqslant r/R \leqslant 0.65$ for fan W30 (Figure 4a) [3].

Non-dimensional circumferential velocity distributions for both fans and measuring sections are presented in Figure 5. Axial fans have opposite direction of rotation.

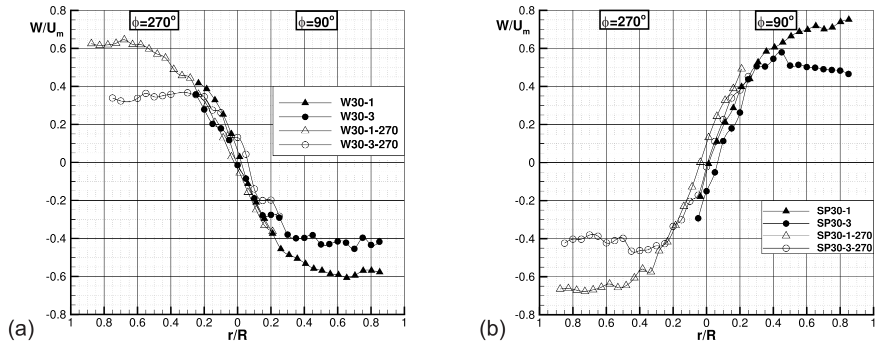

FIGURE 5. Circumferential velocity distributions in measuring sections 1 and 3 for fans: a) W30 and b) SP30

Circumferential velocity (W) decreases downstream in all points of the measuring section. Circumferential velocity distributions for both fans are similar to the axial velocity distributions, because in the central flow region forced vortex distribution is obvious, while mainly uniform distribution for $r/R > 0.4$.

Volume flow rate (Q), average circulation (Γ), swirl number (Ω), averaged axial velocity (U_m) and Reynolds number (Re$=U_m D/\nu$), where ν is kinematic viscosity) are calculated on the basis of axial and circumferential velocities distributions in both measuring sections and relations reported in [3]. Obtained results for both measuring sections are presented in Table 1. Higher volume flow rate, for the same fan rotation number (n=1500 rpm), is gained by the fan W30.

Obtained relative difference between calculated volume flow rates for the same fan in both measuring sections is 1.98% for fan SP30, while less than 1.01% for fan W30. Average circulation has downstream decrease, what is expected. Circulation

TABLE 1. Calculated integral flow parameters.

Fan	Section	Q [m^3/s]	U_m [m/s]	Re	Γ [m^2/s]	Ω
SP30	1	1.06	8.23	226757	4.72	1.11
	3	1.039	8.26	225923	3.05	1.7
W30	1	1.178	9.14	254010	4.12	1.41
	3	1.19	9.47	255558	3.03	1.97

decays to almost the same value. It is also shown that swirl number (Ω), where $\Omega = Q/(R \cdot \Gamma)$, increases downstream for both fans.

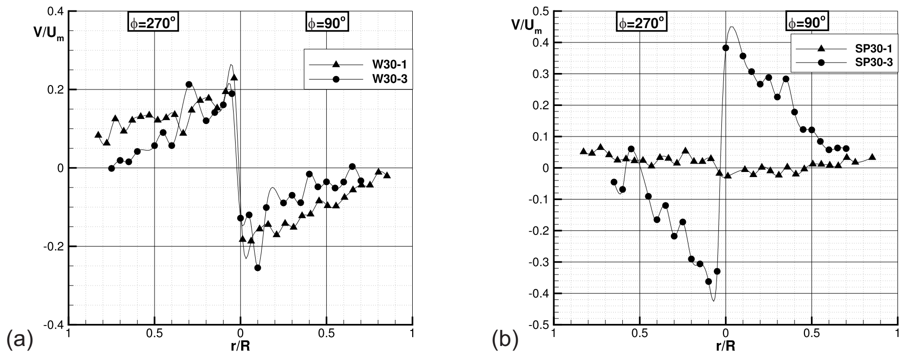

FIGURE 6. Radial velocity in measuring sections 1 and 3 for fans: a) W30 and b)SP30.

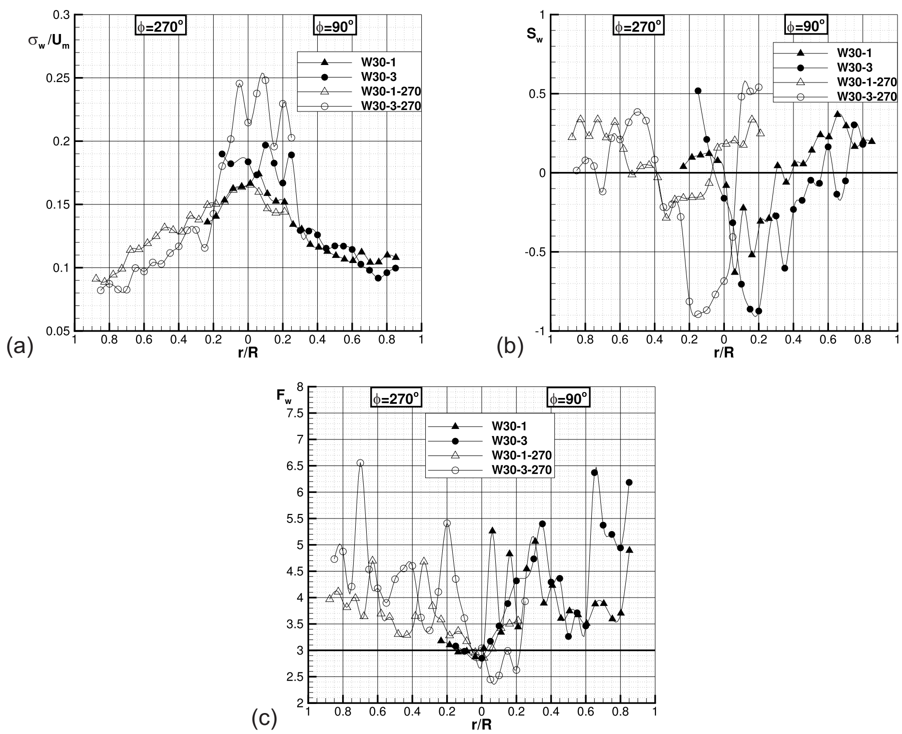

FIGURE 7. Statistical moments for fan W30 in measuring sections 1 and 3: a) turbulence level, b) skewness and c) flatness factors for circumferential velocity.

The greatest difference between turbulent swirl flows generated by these both fans is for radial velocity. Fan SP30 (Figure 6b) has almost neglected radial velocity in the measuring section 1, while very high and extremely non-uniformly distributed in the downstream section. On the contrary, radial velocity generated by the fan W30, has similar distributions in both measuring sections (Figure 6a). It is decreased downstream.

4.2. Influence of the fan type on the evolution of the statistical moments of circumferential fluctuating velocity. Circumferential velocity always had the greatest sampling rates, so it is chosen for this turbulence statistics analysis. Distributions of the statistical values: turbulence level (σ_{w}/U_m), skewness (S_{w}) and flatness (F_{w}) factors for both fans and both measuring sections are presented in Figures 7 and 8. Turbulence level, skewness and flatness factors for circumferential velocity are calculated as follows, respectively:

$$\sigma_{\mathrm{w}}/U_m = \sqrt{\overline{\mathrm{w}^2}}, \quad S_{\mathrm{w}} = \overline{\mathrm{w}^3}/\sigma_{\mathrm{w}}^3, \quad F_{\mathrm{w}} = \overline{\mathrm{w}^4}/\sigma_{\mathrm{w}}^4,$$

where w is fluctuating velocity in circumferential direction [3, 5–8].

Turbulence level for fan W30 has higher values in the core region in the downstream section 3, while lower in the sound flow region (Figure 7a). Distribution of

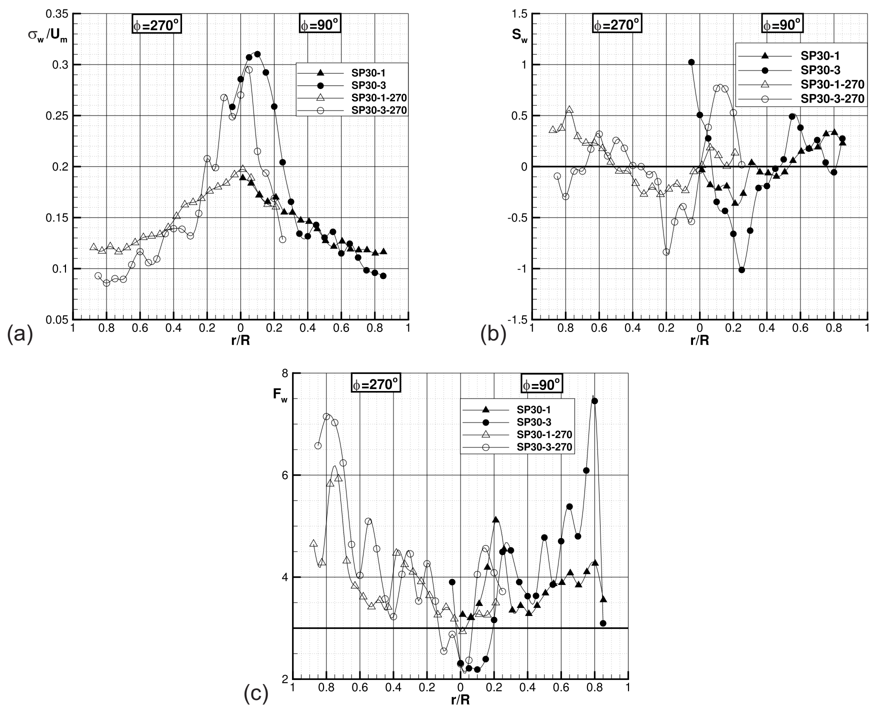

FIGURE 8. Statistical moments for fan SP30 in measuring sections 1 and 3: a) turbulence level, b) skewness and c) flatness factors for circumferential velocity.

the skewness factor is very complex in both sections (Figure 7b). It is not equal to Gaussian probability distribution value ($S_w = 0$), as well that negative and positive values occur. Probability distribution asymmetry in the side of the negative circumferential fluctuations with its high probability of small fluctuations exist in the core region. This turbulence structure is obvious in point $r/R \approx 0.2$ where $S_w \approx -1$ and $F_w \approx 5.5$. It is also shown that significantly higher values of F_w occur in region r/R>0.6 in downstream section (Figure 7c). Flatness factor values differ from value for normal, i.e., Gaussian probability distribution ($F_w = 3$) in almost all regions and in both measuring sections. Distributions of the statistical moments for circumferential velocity and for fan SP30 are presented in Figure 8. Distribution of the turbulence level is very similar to those for fan W30 (Figure 8a). Significantly higher negative and positive skewness factors occur downstream (Figure 8b).

Flatness factor has higher values in downstream section and values less than 3 in the core region (Figure 8c).

4.3. Stereo PIV Results. Total velocity (c) vectors for both fans and in both measuring sections are presented in Figure 9. Opposite direction of rotation is obvious.

Almost the same cross-section area is captured in all cases. Velocity intensities and distributions correspond to the presented in Figures 4 to 6. Axisymmetry occur for both fans in the measuring section 1, while the vortex core center is not on the pipe axis in the downstream measurement section. Vortex core is visible in all cases. Maxima are achieved in approximately $r/R \approx 0.4$. Velocity intensity redistribution occurs downstream for both fans.

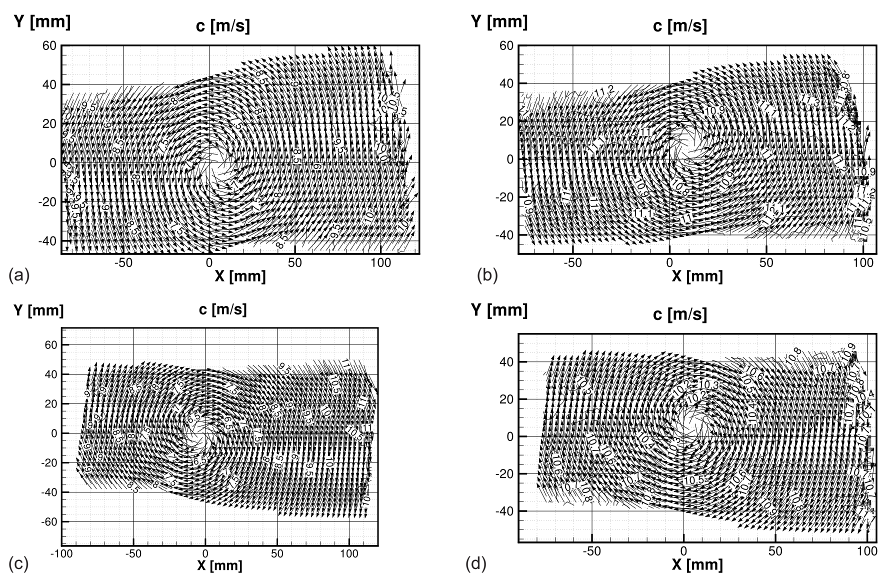

Figure 9. Total velocity vectors for fans and cross-measurement sections 1 and 3: a) W30-1, b) W30-3, c) SP30-1 and d) SP30-3.

5. Conclusions

Experimental investigation of the turbulent swirl flow in pipe behind the industrial axial fans, without guide vanes, what is a common technical practice, is presented in this paper. Laser based measurement techniques, such as LDA and SPIV have been employed. Similar axial and circumferential velocity distributions are achieved despite completely different geometries. Both fans have the same angle at the outlet diameter and rotation number. Solid body circumferential velocity profiles are generated by both fans. Radial velocity has shown various behaving in the upstream measuring section (1). It was shown that average circulation decreases downstream to approximately the same value for both fans. Initial average circulation is bigger for fan SP30. Fan W30 has higher swirl number values in both measuring sections, due to the higher volume flow rate. Statistical moments up to the fourth order are calculated. High values of statistical moments and significant deviation from normal, i.e., Gaussian distribution in both measuring sections, are determined on the basis of the experimental results. These results point out the intermittent character of the generated turbulent flow, as well, the existence of the coherent structure in the vortex core and shear layer. Obtained SPIV results correspond to those measured by the LDA. They revealed axisymmetry in the upstream measuring section, what is not case in the downstream measuring section. Velocity intensity redistribution is observed downstream for both fans.

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ИСТРАЖИВАЊЕ ТУРБУЛЕНТНОГ ВИХОРНОГ СТРУЈАЊА У ПРАВОЈ ЦЕВИ ИЗА ОБРТНИХ КОЛА АКСИЈАЛНИХ ВЕНТИЛАТОРА ПРИМЕНОМ PIV И LDA МЕРНИХ ТЕХНИКА

Резиме. У овом раду је приказано експериментално истраживање турбулентног вихорног струјања у правој цеви иза обртних обртних кола аксијалних вентилатора. Коришћена су два различита модела индустријских аксијалних вентилатора. Први је аксијални вентилатор W30, модел AP 400, произвођача Минел, Србија, са седам лопатица и спољашњим пречником 0,397 m. Други аксијални вентилатор је SP30, модел TGT/2-400-6, произвођача S&P, Шпанија, са шест лопатица и спољашњим пречником 0,386 m, што резултује већим процепом у другом случају. Лопатице оба вентилатора су подешене тако да је излазни угао на пречнику уз кућиште 30°. Дужина целе инсталације је 27,74 D, где је D средњи унутрашњи пречник од око 0,4 m. Мерења са једнокомпонентним LDA (ласер Доплер анемометром) системом и стерео PIV (Particle image velocimetry) системом су обављена у два мерна пресека иза кола аксијалних вентилатора ($z/D = 3,35$ и $z/D = 26,31$). Добијене су вредности Рејнолдсовог броја, израчунате на основу средње брзине (U_m) у првом мерном пресеку, и то за вентилатор SP30 $Re = 226757$, док је за вентилатор W30 $Re = 254010$. На основу експерименталних резултата су израчунати и циркулација и вихорни број. Приметна је значајна трансформација профила статистички осредњене аксијалне брзине између два мерна пресека у случају оба вентилатора, док се статистички осредњена обимска брзина смањује, али њен бездимензиони профил остаје исти. Расподела обимске брзине у централној зони, у случају оба вентилатора, је по закону крутог тела, док је у области $r/R > 0,4$, где је $D = 2R$, расподела униформнија. Статистички осредњена радијална брзина у случају вентилатора SP30 је веома мала у мерном пресеку $z/D = 3,35$, али има значајан пораст у другом пресеку са максималним вредностима у области језгра. У случају вентилатора W30 радијална брзина опада (посматрајући брзине у апсолутном износу) низводно и достиже максималне вредности у вртложном језгру за оба мерна пресека. Нивои турбуленције, нормиране вредности момената трећег и четвртог реда за флуктуације брзине у обимском правцу су израчунати на основу експерименталних података. Највећи нивои турбуленције за обимску брзину се постижу у вртложном језгру за оба вентилатора. Показано је како се вредности коефицијената асиметрије и спљоштености густине расподеле вероватноће обимске флуктуационе брзине разликују од одговарајућих вредности за нормалну, тј. Гаусову расподелу вероватноће. У овом раду такође су анализирана брзинска поља експериментално добијена помоћу стерео PIV мерне технике.

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