

INVESTIGATION OF THE TURBULENT SWIRL FLOWS IN A CONICAL DIFFUSER

by

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Results of the theoretical and experimental investigations of the turbulent mean swirl flows characteristics change along straight conical diffuser of incompressible fluid (air) are presented in this paper. The main swirl flow characteristics review is given. In addition: the specific swirl flow energy, the energy loss, the mean circulation, the swirl flow parameter, the ratio between the swirl and axial flow loss coefficients change along the diffuser are presented. Among other values: the Boussinesq number, outlet Coriolis coefficient and swirl flow loss coefficient dependences on inlet swirl flow parameter are also given. The swirl flow specific energy and outlet Coriolis coefficient calculation procedure are presented in this paper, as well as experimental test bed and measuring procedures. The swirl flow fields were induced by the axial fan impeller. Various swirl parameters were achieved by the impeller openings and rotational speeds.

Key words: *swirl flow, swirl parameters, specific energy, loss coefficient, measurements.*

Introduction

Investigation of the axial fan geometries, their in built and operating characteristics and turbulent swirl flow generated following the axial fan impeller have been occupying researchers attention for years. Though most of the operating characteristics have been cleared out, still fundamentals of the generated swirl fluid phenomena stay undiscovered. Focus of this paper is on this very complex physical phenomenon and recent techniques in modeling modern blade geometries and revealing existing ones.

Swirl turbulent flow of the incompressible fluids in the straight conical diffusers occupies attention of many researches due to its technical presence and specific flow phenomena challenge. Such kind of flow arises at the exit of bulb turbine runners, and also in

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the diffusers after axial pump impellers, as well as in conical diffuser behind the axial fan runners and in many other diffuser passages with internal swirl flow.

Some aspects of swirl flow have been investigated in [1-11], but definite answers of many questions have not been given yet.

One important task is to find good diffuser flow prediction using the recent CFD calculations. In connection with this is the problem of flow energy as well as the value of the Coriolis coefficient at the exit of diffuser, what represents the main object of this paper.

The main reason for performing these measurements is the bulb turbine draft tube flow investigations. The bulb turbine has the draft tube like the straight conical diffuser. Turbine runner induces swirl flow at its inlet cross section and it exists till the draft tube outlet. Draft tube has to recuperate the great amount of inlet kinetic energy with as small as possible losses. Depending on turbine's operating point, swirl flows at the inlet cross sections is less or more significant. In working regimes with small flow rates, when runner blades are more closed, circumferential component of velocity at the exit of the runner becomes more significant in relation to axial component what results in greater losses in draft tube. Swirl at the exit of the draft tube does not disappear in a large domain of turbine operation. Coriolis coefficients are, as a consequence, higher at the exit than in the case for pure axial flow.

All values, such as energy loss and Coriolis, depend on the swirl non-dimensional parameters. There are several swirl non-dimensional parameters which are introduced by various authors. These swirl parameters considerations follows.

Experimental and theoretical investigation of swirl flow characteristics in the straight conical diffuser

The experimental research was performed with the air test bed presented in figure 1. Straight conical diffuser is placed in the reservoir. Swirl flow was produced by the axial fan impeller. The test bed is equipped with flow meter, honey-comb and booster fan.

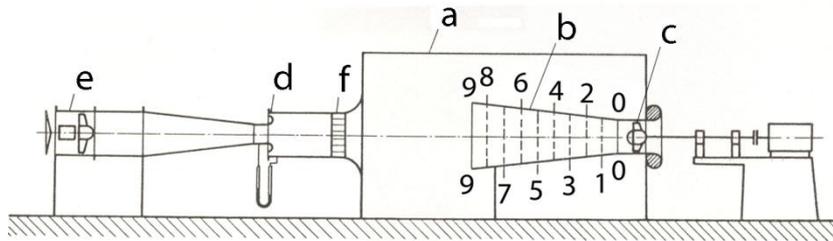


Figure 1. Test bed for experimental diffuser flow research

(a) – reservoir, (b) – diffuser, (c) – axial fan impeller, (d) – flow meter, (e) – booster fan, (f) – honey-comb

The main dimensions of the conical diffusers are given at the figure 2. Velocity and pressure fields were measured at ten cross sections (numbered from 0 to 9) by the combined Prandtl probe [12] and Conrad probe [13, 14]. The following values were measured: c , c_z , c_u , c_r , Δp_t ($\Delta p_t = p_t - p_a$) and Δp_s ($\Delta p_s = p_s - p_a$), where $c_r \ll c_z$. The measurements were performed for twenty two measuring series A, B, C, D, E, F, G, H, I, J, K,

L, M, N, O, P, Q, R, S, T, U, and V, characterized by various swirl parameters Ω_0 or S_0 , and Re numbers.

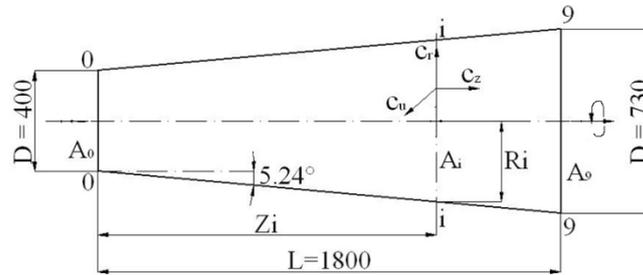


Figure 2. The main dimensions of the conical diffuser

On the basis of the measuring results (Δp_s , Δp_t , c_u , and c_z) obtained at every diffuser cross section (0 to 9) along their diameters for all measuring series (A to V) the next conclusions can be stated. The rapid change of stream and total pressure as well as velocity components is evident along the diffuser. The profile of total pressure (energy) becomes more uniform. Total pressure is almost constant in the diffuser outlet. Stream pressure is the highest on the wall, while it is the lowest in the vortex core, where the value of Δp_s can be negative. Axial velocity components have small values in the vortex core and, also, in some cases reverse flow occurred [12]. The “diffuser effect” influences on the flow uniformity. Circumferential velocity components change their profile along the diffuser cross section with tendency to form “solid body” profile on the diffuser outlet.

The bulk swirl flow characteristics in the cross sections ($i = 0, 1, 2, \dots, 9$) of the conical diffuser are:

- Flow discharge:

$$Q_i = 2\pi \int_0^{R_i} r c_z dr, \quad \dot{m}_i = \rho Q_i \quad (1)$$

- Mean circulation:

$$\bar{\Gamma}_i = \frac{4\pi^2}{Q_i} \int_0^{R_i} r^2 c_u c_z dr \quad (2)$$

- Specific energy of the rotational flow:

$$e_{c_{ui}} = \frac{1}{\dot{m}_i} \int_{A_i} \frac{c_u^2}{2} d\dot{m} = \frac{1}{R_i^2 c_{zmi}} \int_0^{R_i} c_u^2 c_z r dr \quad (3)$$

- Specific energy of the axial flow:

$$e_{c_{zi}} = \frac{1}{\dot{m}_i} \int_{A_i} \frac{c_z^2}{2} d\dot{m} = \frac{1}{R_i^2 c_{zm_i}} \int_0^{R_i} c_z^3 r dr \quad (4)$$

- Mean axial velocity:

$$c_{zm_i} = \frac{Q_i}{\pi R_i^2} \quad (5)$$

- Moment of momentum for tangential flow:

$$\dot{M}_{c_{ui}} = \int_{A_i} r c_u d\dot{m} = 2\pi\rho \int_0^{R_i} c_u c_z r^2 dr = \frac{\dot{m}_i \bar{\Gamma}_i}{2\pi} \quad (6)$$

- Moment of axial flow:

$$\dot{K}_{c_{zi}} = \int_{A_i} c_z d\dot{m} = 2\pi\rho \int_0^{R_i} c_z^2 r dr = \beta_i \dot{K}_{c_{zm_i}} \quad (7)$$

- Moment of mean axial velocity:

$$\dot{K}_{c_{zm_i}} = \pi\rho c_{zm_i}^2 R_i^2 \quad (8)$$

- Boussinesq number [15]:

$$\beta_i = \frac{\dot{K}_{c_{zi}}}{\dot{K}_{c_{zm_i}}} \quad (9)$$

- Swirl flow intensity:

$$\theta_i = \frac{e_{c_{ui}}}{e_{c_{zi}}} = \frac{\int_0^{R_i} r c_u^2 c_z dr}{\int_0^{R_i} r c_z^2 dr} \quad (10)$$

- Swirl flow parameter [16]:

$$\Omega_i = \frac{Q_i}{R_i \bar{\Gamma}_i} = \frac{\left(\int_0^{R_i} r c_z dr \right)^2}{R_i \int_0^{R_i} r^2 c_u c_z dr} \quad (11)$$

- Swirl intensity [17]:

$$\Omega_i^* = \frac{\dot{M}_{c_{u_i}}}{R_i c_{z m_i} \dot{m}_i} = \frac{2 \int_0^{R_i} c_u c_z r^2 dr}{R_i^3 c_{z m_i}^2} \quad (12)$$

- Swirl number [18]:

$$S_i = \frac{\dot{M}_{c_{u_i}}}{R_i \dot{K}_{c_{z_i}}} = \frac{\int_0^{R_i} c_z c_u r^2 dr}{R_i \int_0^{R_i} c_z^2 r dr} = \frac{2 \int_0^{R_i} c_z c_u r^2 dr}{\beta_i R_i^3 c_{z m_i}^2} \quad (13)$$

- Swirl intensity [19]:

$$I = \frac{\dot{M}_{c_{u_i}}}{\dot{K}_{c_{z m_i}} D_i} = \frac{2 \pi \rho \int_0^{R_i} c_u c_z r^2 dr}{D_i \pi \rho c_{z m_i}^2 R_i^2} = \frac{\int_0^{R_i} c_u c_z r^2 dr}{R_i^3 c_{z m_i}^2} \quad (14)$$

Following relations for Ω_i , Ω_i^* , S_i and I exist:

$$\Omega_i^* = \frac{1}{2\Omega_i}, \quad I = \frac{1}{4\Omega_i} = \frac{1}{2}\Omega_i^* \quad (15)$$

$$\Omega_i \cdot S_i = \frac{1}{2\beta_i}, \quad S_i = \frac{\Omega_i^*}{\beta_i} = \frac{2I}{\beta_i} \quad (16)$$

For Rankin swirl flow, where $rc_u = \text{const}$ and $c_z = \text{const}$, next relations exist:

$$\Omega_i \cdot S_i = \frac{1}{2}, \quad S_i = \Omega_i^* \quad (17)$$

$$I = \frac{\Omega_i^*}{2} = \frac{\Omega_i}{4} \quad (18)$$

- Reynolds number:

$$\text{Re}_i = \frac{c_{z m_i} \cdot 2R_i}{\nu} \quad (19)$$

For $z = 0$:

$$\text{Re}_0 = \frac{c_{z m_0} \cdot 2R_0}{\nu} \quad (20)$$

Above mentioned considerations offer various forms for swirl parameter definition and relations between them.

It is decided, here, to use parameter Ω as the most convenient one for calculation in turbomachinery. It can be easily determined on the runner (impeller) outlet, *i. e.* at diffuser (draft tube) inlet, knowing the flow discharge and specific flow energy of machine. Definition of parameter S_0 demands determined axial velocity profile at the diffuser inlet, what is Boussinesq number. It is, in this way, more complicated.

Specific swirl flow energy in each diffuser cross section is:

$$\bar{e}_{s_i} = \frac{2\pi}{\rho Q_i} \int_0^{R_i} r \Delta p_t c_z dr \quad (21)$$

for $i=0,1,2,\dots,9$.

Specific energy swirl flow losses along the straight conical diffuser from 0 to i -th cross sections are:

$$\Delta \bar{e}_{s_i} = \bar{e}_{s_0} - \bar{e}_{s_i} \quad (22)$$

Next expression follows for the conical diffuser flow using the influenced values

$$f_1(\Delta \bar{e}_{s_i}, R_0, c_{zm_0}, \Delta, \rho, \nu, \bar{\Gamma}_0, \alpha, n_i) = 0 \quad (23)$$

where area ratio is defined as $n_i = A_i/A_0$.

On the basis of dimensional analysis the formula for specific swirl flow can be expressed as:

$$\Delta \bar{e}_{s_i} = f_2(\delta, Re_0, \Omega_0, \alpha, n_i) \cdot \frac{c_{zm_0}^2}{2} = \zeta_{s_i} \frac{c_{zm_0}^2}{2} \quad (24)$$

where $\delta = \Delta/2R_0$, Ω_0 – diffuser inlet swirl flow parameter $\Omega_0 = Q_0/R_0\bar{\Gamma}_0$ and ζ_{s_i} – diffuser swirl flow energy loss coefficient.

Loss coefficient ζ_{s_i} can be represented as:

$$\zeta_{s_i} = f_2(\delta, Re_0, \Omega_0, \alpha, n_i) = f_3(\delta, Re_0, \alpha, n_i) \cdot f(\Omega_0) \quad (25)$$

For pure axial diffuser flow specific energy loss [20] is:

$$\Delta \bar{e}_{A_i} = \zeta_{A_i} \frac{c_{zm_0}^2}{2} = f_3(\delta, Re_0, \alpha, n_i) \cdot \frac{c_{zm_0}^2}{2} \quad (26)$$

where ζ_{A_i} is the axial flow coefficient of the diffuser axial flow specific energy [18]:

$$\zeta_{A_i} = f_3(\delta, Re_0, \alpha, n_i) \quad (27)$$

From eq. (25) and (27) follows next relation:

$$\frac{\zeta_{S_i}}{\zeta_{A_i}} = f(\Omega_0) \quad (28)$$

As swirl flow parameter at the diffuser inlet is constant for one measuring series it means that value $\zeta_{S_i} / \zeta_{A_i}$ is also constant along the given diffuser.

Coriolis coefficient at the diffuser outlet is:

$$\alpha_{S_0} = \frac{1}{R_0^2 \pi c_{z_0}^3} \int c_{\theta_0}^2 c_{z_0} dA_0 = \frac{2}{R_0^2 c_{z_0}^3} \int_0^{R_0} r c^2 c_z dr \quad (29)$$

All relations which depend on the swirl flow parameter Ω_0 can be presented as the function of Boussinesq number β_0 and swirl number S_0 using the dependence (16).

Some experimental results of the swirl flow in conical diffuser

Numerous measuring series were performed on the test bed (figure 1) in the diffuser (figure 2). Measurements are marked by the A, B,..., and V. Each series is characterized by the parameters Ω_0 , S_0 , Re_0 and β_0 . These values are specified in the table 1.

Table 1. Characteristic diffuser swirl flow values

Series	Ω_0	$Re_0 \cdot 10^{-5}$	α	S_0	β_0	ζ_S / ζ_A
A	1,22	3,30	2,20	0,356	1,15	3,36
B	1,19	4,70	2,30	0,367	1,14	3,03
C	1,00	3,70	2,85	0,431	1,16	4,95
D	1,04	5,40	2,55	0,416	1,16	4,28
E	1,16	2,90	2,70	0,373	1,15	3,27
F	1,08	3,60	2,50	0,401	1,16	4,56
G	0,25	1,30	12,40	1,455	1,38	60,37
H	0,09	0,60	34,00	1,587	3,50	284,84
I	2,25	4,13	2,45	0,193	1,15	2,10
J	1,57	3,58	1,99	0,278	1,14	2,87
K	3,98	3,13	1,31	0,114	1,10	1,30
L	0,85	2,97	2,50	0,512	1,15	6,30
M	0,17	1,51	18,80	1,590	1,85	113,70
N	0,23	1,13	13,50	1,550	1,40	50,29
O	0,25	1,61	11,15	1,538	1,30	76,60
P	0,67	3,00	3,99	0,635	1,17	8,75
Q	0,47	2,35	6,50	0,905	1,18	14,02
R	0,21	1,16	15,15	1,536	1,55	59,00
S	0,19	1,23	17,10	1,548	1,70	109,00

Table 1. Continuation

T	0,34	3,20	9,50	1,176	1,25	29,14
U	0,37	2,64	8,10	1,126	1,20	24,60
V	1,96	4,60	1,56	0,221	1,15	2,10

Coriolis coefficient values at the diffuser outlet α_{S_9} and ratio ζ_{S_9}/ζ_{A_9} are presented. Many important values of the swirl flow are determined on the basis of the measured values Δp_s , Δp_t , c , c_u and c_z in the numerous points of diffuser cross sections (0, 1, 2 ...9). In the next figures some characteristic values of swirl flow in diffuser are presented.

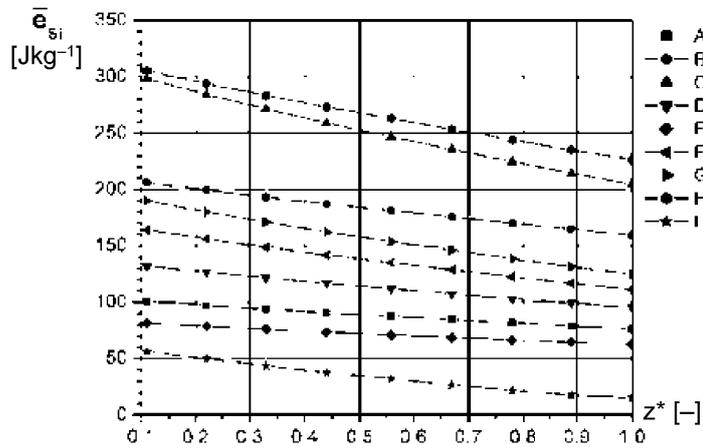


Figure 3. Swirl flow specific energy e_{s_i} along the diffuser ($z^* = z/L$) for the measuring series: A to I.

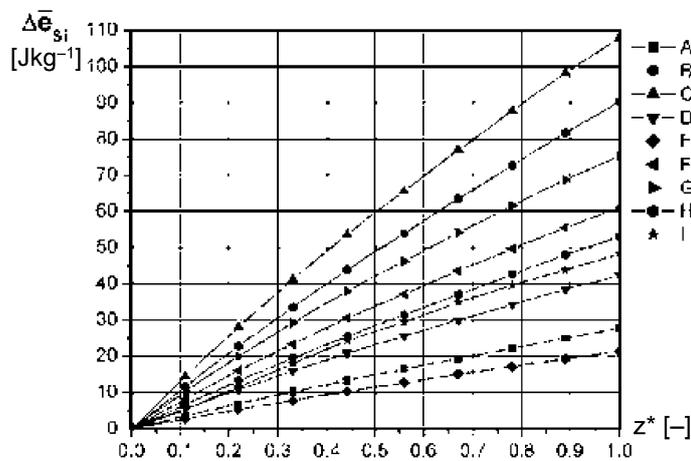


Figure 4. Swirl flow specific energy loss Δe_{s_i} along the diffuser ($z^* = z/L$) for the measuring series: A to I.

Figure 5. Mean circulation $\bar{\Gamma}_i$ along the diffuser ($z^* = z/L$) for the measuring series: A to I

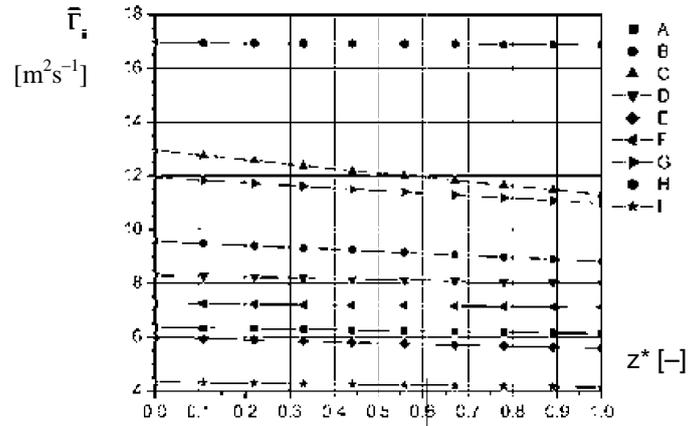


Figure 6. Swirl flow parameter Ω_i along the diffuser ($z^* = z/L$) for the measuring series: A to I

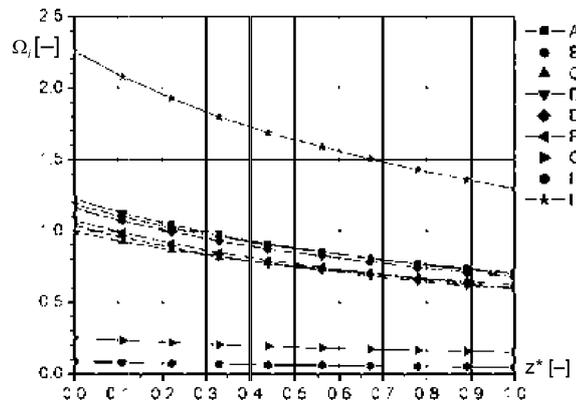
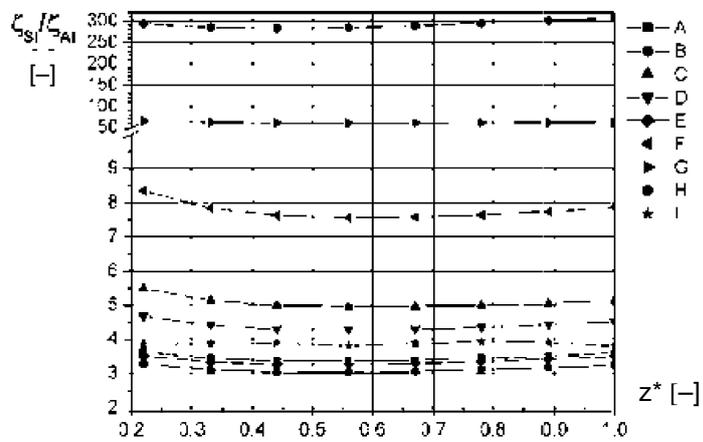


Figure 7. Ratio $\zeta_{S_i} / \zeta_{A_i}$ along the diffuser ($z^* = z/L$) for the measuring series: A to I



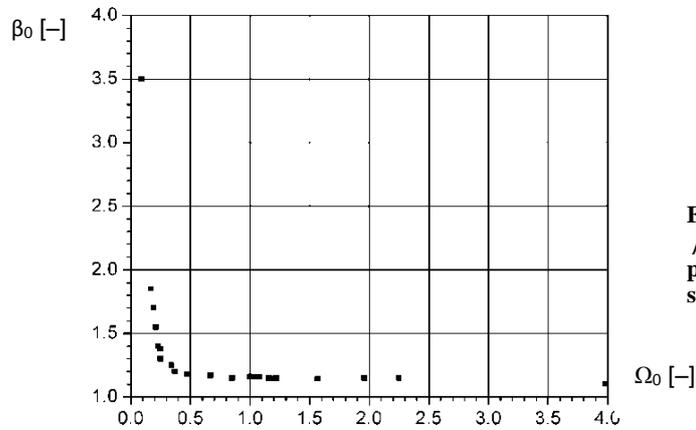


Figure 8. Boussinesq number β_0 dependence on swirl flow parameter Ω_0 for measuring series: A to V

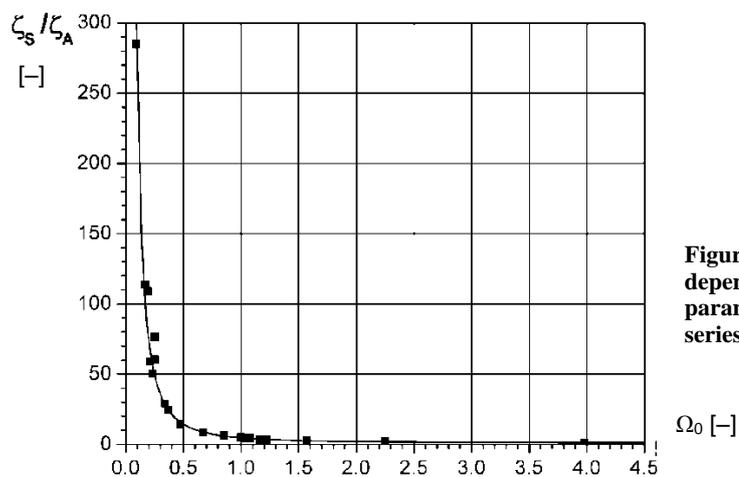


Figure 9. Ratio ζ_S / ζ_A dependence on swirl flow parameter Ω_0 for measuring series: A to V

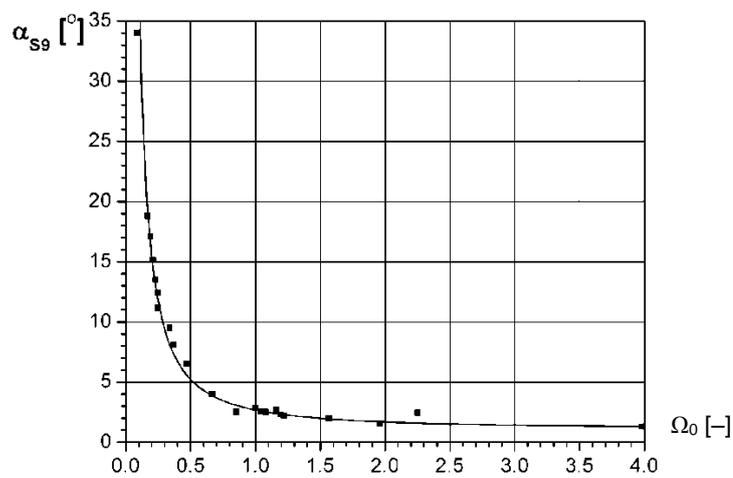


Figure 10. Outlet Coriolis coefficient α_{S9} dependence on swirl flow parameter Ω_0 for measuring series: A to V

On the basis of the obtained results (figures 3,4,5,6,7,8,9 and 10) following conclusions can be obtained:

- Total specific energy of swirl flow \bar{e}_{s_i} change (figure 3) along the diffuser has decreasing exponential character in the form $\bar{e}_{s_i} = \bar{e}_{s_0} \cdot \exp(-\omega z^*)$ for all series (\bar{e}_{s_0} – specific energy for $z^* = 0$, ω – damping coefficient which depends on Ω_0 , Re_0 and δ),
- Specific energy loss $\Delta \bar{e}_{s_i}$ change along the diffuser (figure 4) has increasing character and depends on Ω_0 , Re_0 and δ ;
- Mean circulation $\bar{\Gamma}_i$ distribution (figure 5) along the diffuser has decreasing linear character in the form $\bar{\Gamma}_i = \bar{\Gamma}_0 - \gamma z^* = \bar{\Gamma}_0(1 - (\gamma/\bar{\Gamma}_0)z^*) = \bar{\Gamma}_0(1 - az^*)$ for measuring series A to I ($\bar{\Gamma}_0$ – mean circulation for $z^* = 0$, γ – damping coefficient which depends on Ω_0 , Re_0 and δ);
- Swirl flow parameter Ω_i change (figure 6) along the diffuser has decreasing character in the form $\Omega_i = \Omega_0 \cdot \exp(1 + c_1 z^* + c_2 z^{*2})$ for measuring series A to I (Ω_0 – swirl flow parameter for $z^* = 0$, $c_1 = \text{Ltg} \alpha / R_0 - a = \text{const}$, $c_2 = a \text{Ltg} \alpha / R_0 = ac_1 + a^2 = \text{const}$, $a = \gamma / \bar{\Gamma}_0$, L and α , figure 2);
- Ratio $\zeta_{S_i} / \zeta_{A_i}$ along the diffuser is constant for any measuring series that is for constant swirl flow parameter Ω_0 (figure 7). This experimental results confirms relation (28);
- Boussinesq number dependence on swirl flow parameter Ω_0 (eg. 16) shows that there are rapid change in the region $\Omega_0 < 0,5$, but slowly tends toward $\beta = 1,02$ in the region $\Omega_0 \geq 0,5$. It means that for the strong swirls at the diffuser inlet, when Ω_0 is small and S_0 is great, Boussinesq parameter is great and difference between these two parameters is also great. For the weak swirl the production is $\Omega_0 \times S_0 = 2\beta = 2,04$;
- On the basis of the results shown on figure 7 and above mentioned facts the figure 9 is drawn. It means that ratio ζ_S / ζ_A depends only on Ω_0 . Applying method of least squares on experimental gained points the next relation can be derived:

$$\frac{\zeta_S}{\zeta_A} = 1 + \frac{k}{\Omega_0^n} \quad (30)$$

where $k = 3,708$ and $n = 1,839$;

- Total specific energy loss $\Delta \bar{e}_{s_i}$ of swirl flow in conical diffuser can be now calculated on the basis of relations (24) and (30) as:

$$\Delta \bar{e}_{s_i} = \zeta_{S_i} \frac{c_{zm_0}^2}{2} = \zeta_{A_i} \left(1 + \frac{k}{\Omega_0^n}\right) \frac{c_{zm_0}^2}{2} \quad (31)$$

- Total specific energy at any cross section can be calculated by the next relation:

$$\bar{e}_{s_i} = \bar{e}_{s_0} - \Delta \bar{e}_{s_i} \quad (32)$$

- Coriolis coefficient (figure 10) has a great value when the swirl flow parameter Ω_0 is small. It means that the inlet mean circulation is strong and discharge is small. In the case of great swirl parameter values Ω_0 when the circulation is weak and discharge is greater the Coriolis coefficient decreases and tends to $\alpha_A = 1,058$;
- Coriolis coefficient at the diffuser outlet is presented in the figure 10. Applying the method of the last squares on experimentally gained points the next relation was obtained:

$$\frac{\alpha_{S_9}}{\zeta_A} = 1 + \frac{A}{\Omega_0^m} \quad (33)$$

where $A = 1,534$ and $m = 1,353$, and

- Coriolis coefficient for swirl flow at the diffuser outlet α_{S_9} is very important for determination of the real swirl flow specific kinetic energy loss at the diffuser outlet. The value of the real specific kinetic energy loss $\Delta \bar{e}_{s_9}$ is:

$$\Delta \bar{e}_{s_9} = \alpha_{S_9} \frac{c_{zm_0}^{-2}}{2} = \alpha_A \left(1 + \frac{A}{\Omega_0^m}\right) \frac{c_{zm_0}^{-2}}{2} \quad (34)$$

where \bar{c}_{zm_0} is the mean velocity axial component $\bar{c}_{zm_0} = Q / A_9$.

Conclusions

On the basis of investigations, presented in this paper in short, following claims can be given:

- All experimental investigations were performed on one diffuser geometry, which is adapted geometry of the draft tube of one bulb turbine,
- Several parameters for swirl flow definition are introduced by various authors. In this paper are given relations between them. For the practical use the most convenient is bulk swirl flow parameter Ω_0 behind the runner, which can be simply calculated knowing the specific hydraulic energy of turbomachine,
- The measurements of velocity and pressure profiles in various cross sections along the diffuser show the rapid change. Exit profiles of energy, axial velocity and stream pressure become nearly uniform by the activity of friction and “diffuser effect”,
- Many swirl flow measurement series, characterized by swirl flow parameters Ω_0 , Reynolds number Re_0 and, also, for various forms of velocity components and pressure profiles were measured. These series were chosen to cover a wide range of diffuser operation points,
- The change of main circulation $\bar{\Gamma}_i$ along the diffuser has a decreasing linear character,

- Ratios ζ_S / ζ_A along the diffuser cross sections stay constant for the constant entrance swirl parameter Ω_0 . It depends only on swirl parameter Ω_0 . The influence of Re_0 number on total energy swirl flow loss coefficient ζ_S is taken into account by the coefficient pure axial flow loss coefficient ζ_A which depends only on Re_0 number and δ for given diffuser geometry. Dependence $\zeta_S / \zeta_A = f(\Omega_0)$ is proved by numerous measuring results,
- Changes of the total specific energy loss $\Delta \bar{e}_{s_i}$ and the total specific energy \bar{e}_{s_i} along the diffuser can be determined by knowing the relations for ζ_S ,
- Carioles coefficient α_{S_0} at the exit of diffuser depends only on swirl flow parameter Ω_0 . Knowing the value α_{S_0} gives the possibility for determine the real kinetic loss of flow at the diffuser outlet.

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Nomenclature

c	– local velocity, [ms ⁻¹]
c_r	– radial velocity component, [ms ⁻¹]
c_u	– circumferential velocity component, [ms ⁻¹]
c_z	– axial velocity component, [ms ⁻¹]
L	– diffuser length, [m]
p_a	– ambient pressure, [Pa]
R	– diffuser radius, [m]
z	– distance from diffuser inlet to specified diffuser cross section, [m]
z^*	– relative distance from diffuser inlet to specified diffuser cross section, [–]

Greek letters

α	– diffuser angle, [°]
Δ	– roughness, [m]
Δp_t	– relative total pressure, [Pa]
Δp_s	– relative stream pressure, [Pa]
δ	– relative roughness, [–]
ν	– kinematic viscosity, [m ² s ⁻¹]
ρ	– fluid density, [kgm ⁻³]

References

- [1] Beiler, M. G., Carolus, T. H., Computation and Measurement of the Flow in Axial Flow Fans with Skewed Blades, *ASME J. of Turbomachinery*, 121 (1999), 1, pp. 59-66
- [2] Azad, R. S., Hummel, R. H., Measurement of the Intermittency Factor in Diffuser-Flow, *Canadian J. of Physics*, 49 (1971), 23, pp. 2917-2930
- [3] Čantrak, S., Experimental Investigation of the Statistical Properties of Swirl Flows in Pipes and Diffusers (in German), Ph. D. thesis, Karlsruhe, Germany, 1981
- [4] Čantrak, S., *et al.*, Anisotropic Turbulence and Non-Local Diffusion in Swirl Shear Flow (in German), *PAMM*, 2 (2003), pp. 346-347
- [5] Čantrak, S., Felsch, K. O., Jungbluth, H., Turbulence Structure and Mechanism of the Transport Process in Diffusor Swirl Flow (in German), *ZAMM*, 65 (1985), 4, pp. T 189-T 191

- [6] Neve, R. S., Wirasinghe, N.E.A., Changes in Conical Diffuser Performance by Swirl Addition, *Aeronautical Quarterly*, 29 (1978), 3, pp. 131-143
- [7] Okwuobi, P. A. C., Azad, R. S., Turbulence in a Conical Diffuser with Fully Developed Flow at Entry, *J. Fluid. Mech.*, 57 (1973), 3, pp. 603-622
- [8] Senoo, Y., Kawaguchi, N., Nagata, T., Swirl Flow in Conical Diffusers, *Bulletin JSME*, 21 (1978), 151, pp. 112-119
- [9] So, K. L., Vortex Phenomena in a Conical Diffuser, *AIAA Journal*, 5 (1967), 6, pp. 1072-1078
- [10] Weske, J. R., Sturov, G.E., Experimental Investigation of Turbulent Swirl Flow in a Cylindrical Tube, *Proc. Siberian Siv. Acad. Sci., USSR*, 13 (1972), 3, pp. 3-7
- [11] Wiggins, E. G., Measurement and Correlation of Reynolds Stresses in a Conical Diffuser, Ph. D. thesis, Purdue Univ., Lafayette, Ind., 1976
- [12] Benišek, M., Investigation of the Swirl Flow in Long Lined Circular Pipes (in Serbian), Ph. D. thesis, Faculty of Mech. Eng., Belgrade, 1979
- [13] Benišek, M., Čantrak, S., Nedeljković, M., Universal Calibration Characteristics Conrad Probe for Measures 3-D Velocity, Pressure and Total Pressure of Stationary Inviscid Fluid Flow, *Proc. of Metrological, Proceedings on CD*, Yug. Cong., Novi Sad, Serbia, 2000
- [14] Benišek, M. H., *et al.*, Application of New Classical Probes in Swirl Fluid Flow Measurements, *Experimental Techniques*, 34 (2010), 3, pp. 74-81
- [15] Čantrak, S., Hydrodynamics – Selected Chapters (in Serbian), Faculty of Mechanical Engineering, Belgrade, 1998
- [16] Strscheletzky, M., Equilibrium Forms of the Axisymmetric Flows with Constant Swirl in Straight, Cylindrical Rotation Geometries (in German), *Voith Forschung und Konstruktion*, 5 (1959), 1
- [17] Kitoh, O., Experimental Study of Turbulent Swirl Flow in a Straight Pipe, *J. Fluid Mech.*, 225 (1991), Apr, pp. 445-479
- [18] Mahmud, T., Truelove, J.S., Wall, T.F., Flow Characterizations of Swirl Coaxial Jets from Diverging Nozzels, *J. Fluid Eng.*, 109 (1987), 3, pp. 275-281
- [19] Baker, W., Sayre, C. L., Decay of Swirl Flow of Incompressible Fluids in Long Pipes, *Flow: its Meas. and Control in Sci. And Ind., Proc. Symp.*, VI. (1971) Pt. 1, Pittsburgh, pp. 301-312
- [20] Povh, I. L., Aerodynamic Experiments in Mechanical Engineering (in Russian), Moscow, Leningrad, 1974

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