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.

1. 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 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

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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, depends on the swirl non-dimensional parameters. There are several swirl non-dimensional parameters which are introduced by various authors. These swirl parameters considerations follows.

2. 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 fig. 1. Straight conical diffuser (2) is placed in the reservoir (1). Swirl flow was produced by the axial fan impeller (3). The test bed is equipped with flow meter (4), honey-comb (6) and booster fan (5).

![Figure 1. Test bed for experimental diffuser flow research.](image)

The main dimensions of the conical diffusers are given at the fig. 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: \( c, c_{w}, \Delta p_{r} (\Delta p_{r} = p_{r} - p_{s}) \) and \( \Delta p_{c} (\Delta p_{c} = p_{c} - p_{s}) \), where \( c_r \ll c_c \). 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 \( \Omega_{0} \) or \( S_{0} \) and Re numbers.

![Figure 2. The main dimensions of the conical diffuser.](image)

On the basis of the measuring results (\( \Delta p_{c}, \Delta p_{r}, c_{w} \) and \( c_r \)) 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 \( \Delta p_{c} \) 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 (\( i=0,1,2,...,9 \)) of the conical diffuser are:
- Flow discharge
  \[ Q_i = 2\pi \int_0^{\frac{R_i}{r}} r_c \, dr, \quad \text{in} = \rho Q_i, \]  
  (1)

- Mean circulation
  \[ \bar{\Gamma}_i = 4\pi^2 \frac{R_i}{Q_i} \int_0^{\frac{R_i}{r}} r^2 c_r c_i \, dr, \]  
  (2)

- Specific energy of the rotational flow
  \[ e_{ci} = \frac{1}{m_i} \int_A \frac{c_i^2 \, d\theta}{2} = \frac{1}{R_i^2 c_m} \frac{R_i}{c_i} \int_0^{R_i} c_i^2 c_r \, dr, \]  
  (3)

- Specific energy of the axial flow
  \[ e_{cij} = \frac{1}{m_i} \int_A \frac{c_i^2 \, d\theta}{2} = \frac{1}{R_i^2 c_m} \int_0^{R_i} c_i^2 r \, dr, \]  
  (4)

- Mean axial velocity
  \[ c_{zmi} = \frac{Q_i}{\pi R_i^2}, \]  
  (5)

- Moment of momentum for tangential flow
  \[ M_{cij} = \int_A r_c \, d\theta = 2\pi \frac{R_i}{c_m} \int_0^{R_i} c_r c_i r^2 \, dr = \frac{m_i \bar{\Gamma}_i}{2\pi}, \]  
  (6)

- Moment of axial flow
  \[ \dot{K}_{cij} = \int c_i \, d\theta = 2\pi \frac{R_i}{c_m} \int_0^{R_i} c_i^2 r \, dr = \beta_i \dot{K}_{zmi}, \]  
  (7)

- Moment of mean axial velocity
  \[ \dot{K}_{zmi} = \pi \rho c^2 R_i^2, \]  
  (8)

- Boussinesq number [15]
  \[ \beta_i = \frac{K_{cij}}{K_{zmi}}, \]  
  (9)

- Swirl flow intensity
  \[ \theta_i = \frac{e_{ci}}{e_{cij}} = \frac{\int_0^{R_i} r_c c_r c_i \, dr}{\int_0^{R_i} r_c c_i \, dr}, \]  
  (10)

- Swirl flow parameter [16]
  \[ \Omega_i = \frac{Q_i}{R_i \bar{\Gamma}_i} = \left( \frac{R_i}{\int_0^{R_i} r_c \, dr} \right)^2, \]  
  (11)
Swirl intensity \[17\]

\[\Omega^*_i = \frac{M_{z\omega_i}}{R_{c,c_{zm_i}} c_{zm_i}} = \frac{\frac{R_i c_{z_i} r_i^2 dr}{R_{c,c_{zm_i}}}}{\frac{R_i c_{z_i} r_i^2 dr}{R_{c,c_{zm_i}}}}, \quad (12)\]

Swirl number \[18\]

\[S_i = \frac{M_{z\omega_i}}{R_i K_{z\omega_i}} = \frac{\frac{R_i c_{z_i} r_i^2 dr}{R_{i} c_{z_i} r_i^2 dr}}{R_i c_{z_i} r_i^2 dr} = \frac{2 \int_0^R c_z c_i r_i^2 dr}{\beta_i R_i c_{zm_i}^2}, \quad (13)\]

Swirl intensity \[19\]

\[I = \frac{M_{z\omega_i}}{K_{c,c_{zm_i}} D_i} = \int_0^R c_z c_i r_i^2 dr = \int_0^R c_z c_i r_i^2 dr = \frac{R_i c_{z_i} r_i^2 dr}{R_{c,c_{zm_i}}^2}, \quad (14)\]

Following relations for \(\Omega, \Omega^*, S, I\) and \(i\) exist:

\[\Omega^*_i = \frac{1}{2\Omega}, \quad I = \frac{1}{4\Omega} = \frac{1}{2} \Omega^*, \quad (15)\]

\[\Omega_i \cdot S_i = \frac{1}{2\beta_i} \quad S_i = \Omega^*_i = \frac{2i}{\beta_i}, \quad (16)\]

For Rankin swirl flow, where \(r_{c,c} = \text{const}\) and \(c_i = \text{const}\), 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

\[\text{Re}_i = \frac{c_{zm_i} \cdot 2R_i}{\nu}. \quad (19)\]

For \(z = 0\):

\[\text{Re}_0 = \frac{c_{zm_0} \cdot 2R_0}{\nu}. \quad (20)\]

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

It is decided, here, to use parameter \(\Omega\) 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

\[-e_0 = \frac{2 \pi}{\rho Q} \int_0^R r \Delta P c_i dr \quad (21)\]

for \(i = 0, 1, 2, ..., 9\).

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

\[\Delta e_i = e_0 - e_i. \quad (22)\]
Next expression follows for the conical diffuser flow using the influenced values

\[ f_1(\Delta \bar{c}_0, R_0, c_{\text{in}}, \Delta, \rho, \nu, \bar{F}_0, \alpha, n_i) = 0, \quad (23) \]

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

\[ \Delta \bar{c}_0 = f_2(\delta, Re_0, \Omega_0, \alpha, n_i) \cdot \frac{c_{\text{in}}^2}{2} = \zeta_{Si} \cdot \frac{c_{\text{in}}^2}{2}, \quad (24) \]

where \( \delta = \Delta / 2R_0 \), \( \Omega_0 \) - diffuser inlet swirl flow parameter \( \Omega_0 = Q_0 / R_0 \bar{F}_0 \) and \( \zeta_{Si} \) - diffuser swirl flow energy loss coefficient.

Loss coefficient \( \zeta_{Si} \) can be represented as

\[ \zeta_{Si} = f_2(\delta, Re_0, \Omega_0, \alpha, n_i) \cdot f(\Omega_0). \quad (25) \]

For pure axial diffuser flow specific energy loss \( [20] \) is

\[ \Delta \bar{c}_{Ai} = \zeta_{Ai} \cdot \frac{c_{\text{in}}^2}{2} = f_1(\delta, Re_0, \alpha, n_i) \cdot \frac{c_{\text{in}}^2}{2}, \quad (26) \]

where \( \zeta_{Ai} \) is the axial flow coefficient of the diffuser axial flow specific energy \( [18] \)

\[ \zeta_{Ai} = f_1(\delta, Re_0, \alpha, n_i). \quad (27) \]

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

\[ \frac{\zeta_{Si}}{\zeta_{Ai}} = f(\Omega_0). \quad (28) \]

As swirl flow parameter at the diffuser inlet is constant for one measuring series it means that value \( \zeta_{Si}/\zeta_{Ai} \) is also constant along the given diffuser.

Coriolis coefficient at the diffuser outlet is

\[ \alpha_{\text{so}} = \frac{1}{R_0^2 \rho c_{\text{in}}^2} \int c_{\text{c}}^2 c_{\text{so}} \, dA_0 = \frac{2}{R_0^2 c_{\text{in}}^2} \int_{0}^{n_0} r c_{\text{c}}^2 c_{\text{so}} \, dr. \quad (29) \]

All relations which depend on the swirl flow parameter \( \Omega_0 \) can be presented as the function of Boussinesq number \( \beta_0 \) and swirl number \( S_0 \) using the dependence (16).

3. Some experimental results of the swirl flow in conical diffuser

Numerous measuring series were performed on the test bed (fig. 1) in the diffuser (fig. 2). Measurements are marked by the A, B, ... and V. Each series is characterized by the parameters \( \Omega_0, S_0, Re_0 \) and \( \beta_0 \). These values are specified in the table 1.

<table>
<thead>
<tr>
<th>Series</th>
<th>( \Omega_0 )</th>
<th>( Re_0 \times 10^{3} )</th>
<th>( \alpha )</th>
<th>( S_0 )</th>
<th>( \beta_0 )</th>
<th>( \zeta_{Si}/\zeta_{Ai} )</th>
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<tbody>
<tr>
<td>A</td>
<td>1.22</td>
<td>3.30</td>
<td>2.20</td>
<td>0.356</td>
<td>1.15</td>
<td>3.36</td>
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<td>1.19</td>
<td>4.70</td>
<td>2.30</td>
<td>0.367</td>
<td>1.14</td>
<td>3.03</td>
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<td>2.85</td>
<td>0.431</td>
<td>1.16</td>
<td>4.95</td>
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<td>D</td>
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<td>5.40</td>
<td>2.55</td>
<td>0.416</td>
<td>1.16</td>
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<td>1.16</td>
<td>2.90</td>
<td>2.70</td>
<td>0.373</td>
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<td>3.27</td>
</tr>
<tr>
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<td>1.08</td>
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<td>2.50</td>
<td>0.401</td>
<td>1.16</td>
<td>4.56</td>
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<tr>
<td>G</td>
<td>0.25</td>
<td>1.30</td>
<td>12.40</td>
<td>1.455</td>
<td>1.38</td>
<td>60.37</td>
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</table>
Coriolis coefficient values at the diffuser outlet $\alpha_{S9}$ and ratio $(\zeta_{S9}/\zeta_{S})$ are presented.

Many important values of the swirl flow are determined on the basis of the measured values $\Delta p_{1}, \Delta p_{1}, c_{y}, c_{x}$ 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.

<table>
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<tr>
<th></th>
<th>H</th>
<th>0.09</th>
<th>0.60</th>
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<th>1.587</th>
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<td>4.13</td>
<td>2.45</td>
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<td>1.15</td>
<td>2.10</td>
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<tr>
<td>J</td>
<td>1.57</td>
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<td>0.278</td>
<td>1.14</td>
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<td>K</td>
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<td>1.31</td>
<td>0.114</td>
<td>1.10</td>
<td>1.30</td>
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<tr>
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<td>2.97</td>
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<td>0.512</td>
<td>1.15</td>
<td>6.30</td>
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<td>1.85</td>
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<td>1.536</td>
<td>1.55</td>
<td>59.00</td>
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</tr>
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<td>1.548</td>
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<td>9.50</td>
<td>1.176</td>
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<td>1.126</td>
<td>1.20</td>
<td>24.60</td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>1.96</td>
<td>4.60</td>
<td>1.56</td>
<td>0.221</td>
<td>1.15</td>
<td>2.10</td>
<td></td>
</tr>
</tbody>
</table>

Figure 3. Swirl flow specific energy $\bar{c}_{S9}$ along the diffuser ($z^* = z/L$) for the measuring series: A to I.
Figure 4. Swirl flow specific energy loss $\Delta \tilde{c}_{\eta, i}$ along the diffuser ($z^* = z/L$) for the measuring series: A to I.

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

Figure 6. Swirl flow parameter $\Omega_{i, i}$ along the diffuser ($z^* = z/L$) for the measuring series: A to I.
Figure 7. Ratio $\frac{\zeta_{30}}{\zeta_{30}^*}$ along the diffuser ($z^* = z/L$) for the measuring series: A to I.

Figure 8. Boussinesq number $\beta_0$ dependence on swirl flow parameter $\Omega_0$ for measuring series: A to V.

Figure 9. Ratio $\frac{\zeta_{30}}{\zeta_{30}^*}$ dependence on swirl flow parameter $\Omega_0$ for measuring series: A to V.
On the basis of the obtained results (fig. 3 to fig. 10) following conclusions can be obtained:

- Total specific energy of swirl flow $\bar{\varepsilon}_{S_i}$ change (fig. 3) along the diffuser has decreasing exponential character in the form
  \[ \bar{\varepsilon}_{S_i} = \varepsilon_{S_0} \exp(-\omega z') \]
  for all series ($\varepsilon_{S_0}$ - specific energy for $z'=0$, $\omega$ - damping coefficient which depends on $\Omega_0$, $Re_0$ and $\delta$),

- Specific energy loss $\Delta\bar{\varepsilon}_{S_i}$ change along the diffuser (fig. 4) has increasing character and depends on $\Omega_0$, $Re_0$ and $\delta$,

- Mean circulation $\bar{\Gamma}_i$ distribution (fig. 5) along the diffuser has decreasing linear character in the form
  \[ \bar{\Gamma}_i = \bar{\Gamma}_0 - \bar{\gamma}z' = \bar{\Gamma}_0 (1 - (\bar{\gamma}/\bar{\Gamma}_0)z') = \bar{\Gamma}_0 (1 - a \cdot z') \]
  for measuring series A to I ($\bar{\Gamma}_0$ - mean circulation for $z'=0$, $\bar{\gamma}$ - damping coefficient which depends on $\Omega_0$, $Re_0$ and $\delta$),

- Swirl flow parameter $\Omega_i$ change (fig. 6) along the diffuser has decreasing character in the form
  \[ \Omega_i = \Omega_0 \cdot \exp(1 + c_1z + c_2z^2) \]
  for measuring series A to I ($\Omega_0$ - swirl flow parameter for $z'=0$, $c_1 = a \tan \alpha / R_0 - a = \text{const}$, $c_2 = a \tan \alpha / R_0 = ac_1 + a^2 = \text{const}$, $a = \gamma / \bar{\Gamma}_0$, $L$ and $\alpha$, fig. 2),

- Ratio $\zeta_S/\zeta_{A_i}$ along the diffuser is constant for any measuring series that is for constant swirl flow parameter $\Omega_0$ (fig. 7). This experimental results confirms relation (28),

- Boussinesq number dependence on swirl flow parameter $\Omega_0$ (eq. 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 $\Omega_0$ 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 fig. 7 and above mentioned facts the fig. 9 is drawn. It means that ratio $\zeta_S/\zeta_{A_i}$ depends only on $\Omega_0$. Applying method of least squares on experimental gained points the next relation can be derived
  \[ \frac{\zeta_S}{\zeta_{A_i}} = 1 + \frac{k}{\Omega_0^2} \]
  where $k=3.708$ and $n=1.839$,

- Total specific energy loss $\Delta\bar{\varepsilon}_{S_i}$ of swirl flow in conical diffuser can be now calculated on the basis of relations (24) and (30) as
  \[ \Delta\bar{\varepsilon}_{S_i} = \varepsilon_{S_0} \cdot \frac{\varepsilon_{S0}^2}{2} \cdot \frac{\zeta_{A_i}}{\zeta_S} \left( 1 + \frac{k}{\Omega_0^2} \right) \]

- Coriolis coefficient (fig. 10) has a great value when the swirl flow parameter $\Omega_0$ is small. It means that the inlet mean circulation is strong and discharge is small. In the case of great swirl parameter values $\Omega_0$ when the circulation is weak and discharge is greater the Coriolis coefficient decreases and tends to $a_A = 1.058$. 

Coriolis coefficient at the diffuser outlet is presented in the fig. 10. Applying the method of the last squares on experimentally gained points the next relation was obtained:

$$\frac{a_{S9}}{a_A} = 1 + \frac{A}{\Omega_0^m},$$

where $A=1.534$ and $m=1.353$.

Coriolis coefficient for swirl flow at the diffuser outlet $a_{S9}$ is very important for determination of the real swirl flow specific kinetic energy loss at the diffusor outlet. The value of the real specific kinetic energy loss $\Delta \tilde{e}_{K9}$ is

$$\Delta \tilde{e}_{K9} = a_{S9} \frac{e_{z9g}^2}{2} = a_A \left(1 + \frac{A}{\Omega_0^m}\right) \frac{e_{z9g}^2}{2},$$

where $e_{z9g}$ is the mean velocity axial component $e_{z9g} = Q/A_9$.

4. Conclusion

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 $0\Omega$ 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 $0\Omega$, Reynolds number $0Re$ 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 $\Gamma$ along the diffuser has a decreasing linear character,
- Ratios $\zeta_5/\zeta_A$ along the diffuser cross sections stay constant for the constant entrance swirl parameter $0\Omega$. It depends only on swirl parameter $0\Omega$. The influence of $Re_0$ number on total energy swirl flow loss coefficient $\zeta_5$ is taken into account by the coefficient pure axial flow loss coefficient $\zeta_A$ which depends only on $Re_0$ number and $0\Omega$ for given diffuser geometry. Dependence $\zeta_5/\zeta_A = f(0\Omega)$ is proved by numerous measuring results,
- Changes of the total specific energy loss $\Delta \tilde{e}$ and the total specific energy $\tilde{e}$ along the diffuser can be determined by knowing the relations for $\zeta_5$,
- Coriolis coefficient $a_{S9}$ at the exit of diffuser depends only on swirl flow parameter $0\Omega$. Knowing the value $a_{S9}$ gives the possibility for determining the real kinetic loss of flow at the diffuser outlet.

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Nomenclature
References

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