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CONTEMPORARY PROBLEMS IN TURBULENT SWIRLING FLOWS

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Abstract. *The aim of this paper is to investigate on the turbulence structure and on the statistical properties of vortex shear layer in swirling flow in pipes and in a diffuser. Accordingly, for the experimental measuring of statistical properties, hot-wire anemometry has been applied with the use of three-sensor probe, and with digital data processing and statistical analysis of measured data [1].*

1. INTRODUCTION

Theoretical and experimental investigations on turbulent swirling flows are of great scientific and technical importance. Namely, the turbulent transfer processes of mass, momentum and energy in various fields of energy systems, thermal systems, metallurgy, process technic, magneto-hydrodynamics and in other energetic-technologic systems, are governed by the swirl flow characteristic patterns. However, investigation on the structure and mechanics of turbulet transport processes is difficult as the turbulent swirling flows are three-dimensional, inhomogeneous and anisotropic flows with shear, incorporating significant changes of all statistical properties in radial as well as in axial direction. These are the reasons for an incomplete understanding on the structure of turbulence and on the mechanics of turbulent interchange in internal swirling flows.

The aim of this paper is to investigate on the turbulence structure and on the statistical properties of vortex shear layer in swirling flow in pipes and in a diffuser. Accordingly, for the experimental measuring of statistical properties, hot-wire anemometry has been applied with the use of three-sensor probe, and with digital data processing and statistical analysis of measured data [1].

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2. DISTRIBUTIONS OF MEAN VELOCITIES AND INTEGRAL CHARACTERISTICS OF TURBULENT INTERCHANGE PROCESSES

The flow field of turbulent swirling flow may be roughly divided into four regions each characterized by the structural and statistical properties. All four regions, namely vortex core, shear vortex layer, main flow, and flow region near the wall, are distinctively shown of Figures 1 and 2. In cylindrical coordinate system (x, r, φ) quantities $\overline{U}$, $\overline{V}$, $\overline{W}$, and $u_1 = u$, $u_2 = v$, $u_3 = w$, , denote time-averaged and fluctuating velocity components in radial, axial and circumferential direction. Mean velocity and Reynolds number of experiments are given by $U_m = \dot{V}/(R^2\pi) = 31{,}41\,\mathrm{ms}$ and $\mathrm{Re} = U_m \cdot 2R/\nu = 2{,}835 \cdot 10^5$ respectively. Intensity of the swirl is defined by $\theta = \int_0^R r\overline{W}^2\overline{U}dr \Big/ \int_0^R r\overline{U}^3 dr$, where the radius of the pipe is $R = D/2 = 100$ mm.

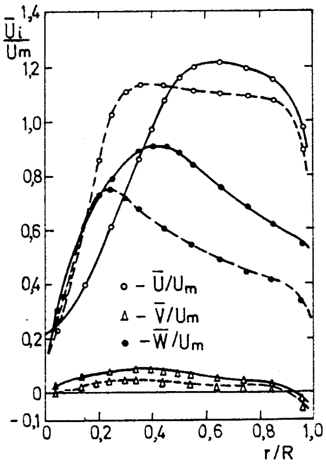

Figure 1. Distributions of dimensionless time averaged velocities in the inlet cross-section of the pipe ($x/R = 0$) for two swirl intensities (dashed line θ_1=0,229, full line θ_2=0,429).

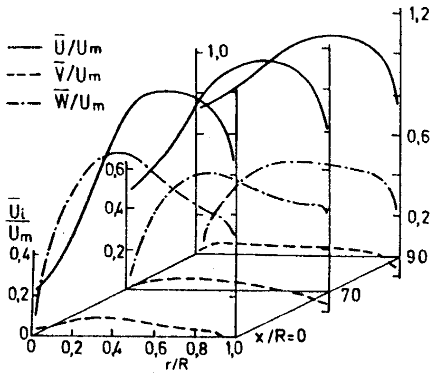

Figure 2. Transformation of mean swirling flow velocity field in the pipe in radial and axial direction for swirl intensity θ_2=0,429 in cross-section $x/R = 0$.

The influence of swirl intensity on the velocity field in a pipe is shown on Figure 1. Namely, for a greater swirl intensity, region of vortex core gets wider and a shear layer (where circumferential velocity $\overline{W}$ reaches its maximum) moves towards the pipe wall. Accordingly, the region of main flow, with approximately constant value of axial velocity, gets smaller. Transformation of the velocity field (Figure 2) is the consequence of great interchange between time-averaged and fluctuating velocity field. For defined swirl intensities recirculating flow structure does not occur. The development of turbulet swirling flow in a diffuser is analogous, as it is shown in [1] for a diffuser with central angle of diffusing $v = 12^0$. However, it may be observed that this transformation is more rapid for a diffuser.

Characteristic distributions of time-averaged velocities of swirling flows in a pipe and in a diffuser, for different values of Reynolds number Re, initial circulations $\overline{\Gamma}_0$, swirl parameters Ω_{0R} and similitude parameters Φ, are shown in papers [1,2], and some of them are given on Fig. 3-(a), (b). On the basis of theoretical considerations and numerous experimental data analyses [2], it is shown that the dependence between turbulent transfer parameters and swirling flow integral characteristics has the form:

$$-2b^2(v + v_{r\varphi})/v\overline{U}^*\mathrm{Re} = c\Omega_{0R}^{\alpha}\Phi^{\gamma}, \tag{1}$$

where $v_{r\varphi}$ designates component of kinematic, turbulent viscosity tensor.

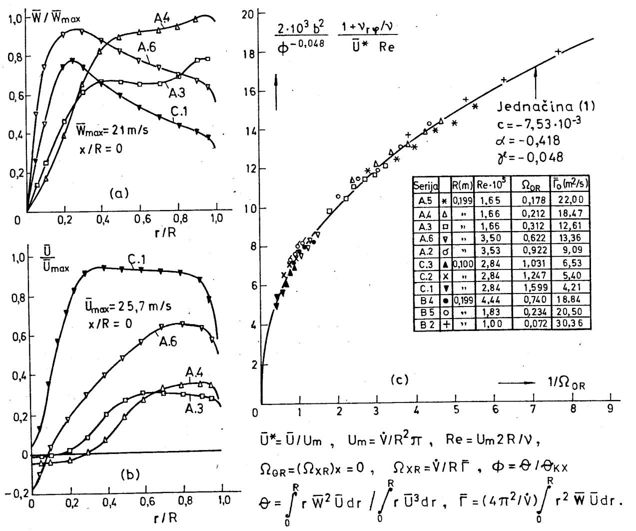

Figure 3. Distributions of time-averaged circumferential (tangential) $\overline{W}$ (a) and axial $\overline{U}$ (b) velocities in initial pipe section ($x/R = 0$) for various measuring series and dependencies among local and integral characteristics of turbulent transfer (c). Other signs and definitions: Ω_{xR}- swirl parameter, Φ- similitude parameter, Θ- swirl intensity, $\overline{\Gamma}$ - mean circulation, $\Theta_{kx} = (4\Omega_{xR}^2)^{-1}(1 - r_0^{*2})\ln(1/r_0^*)^2$ - intensity of the swirl of constant circulation, $r_0^* = r_0 / R$ - nondimensional radius of "dead water", $U_m = \dot{V}/R^2\pi$ - mean (bulk) velocity, $\dot{V}$ - volume flow-rate, R- pipe radius, v- kinematic viscosity, and x, r, φ - cylindrical coordinates.

Distributions of swirling flow integral quantities Ω, Θ and $\overline{\Gamma}$ have been calculated applying numerical integration on measured values for a pipe and a diffuser, and are shown on Fig. 4. Downstream transformation of mean circulation $\overline{\Gamma}$ is defined with expression:

$$\overline{\Gamma} = \overline{\Gamma}_0 \cdot \exp\{[-2b^2(1+v_{r\varphi}/v)/\overline{U}^* \,\mathrm{Re}](x/R)\}\,, \tag{2}$$

which, together with (1), shows that left-hand-side of equation (1) is determined experimentally. Applying the leastsquares method, for all measuring series constants $c = -7{,}53\cdot 10^{-3}$, $\alpha = -0{,}418$ and $\gamma = -0{,}048$, in expression (1), were calculated, and the result is shown on Fig. 3-(c). It is concluded that the obtained analytical dependence (1) fits experimental data very good. Using generalized Prandtl hypothesis

$$v_{r\varphi} = l_{r\varphi}^2\{(\partial_r\overline{U})^2 + [r\partial_r(\overline{W}/r)]^2\}^{1/2}\,,\ \overline{W}(x=const, r) = \overline{W}_{\max}\left(\frac{r_{\max}}{r}\right)^n, \tag{3}$$

and expression (1), the dependence between mixing length $l_{r\varphi}$ and similitude parameter Φ, i.e swirl intensity Θ is gained. Index max stands for maximal value.

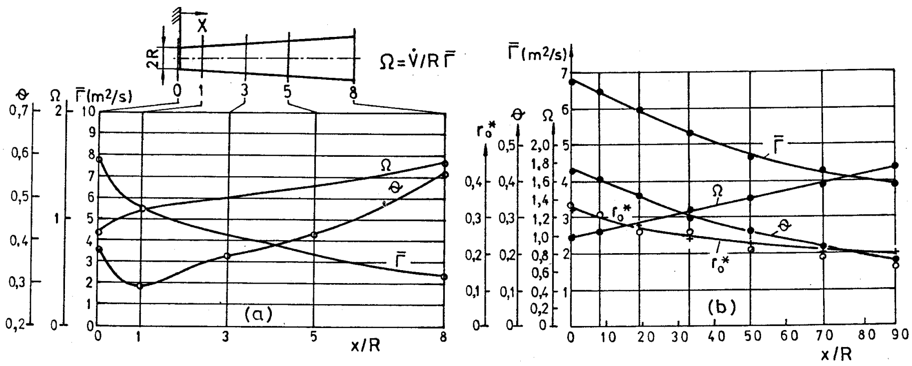

Figure 4. Downstream transformations of integral energy characteristics of turbulent interchange for a swirling flow in a diffuser of angle $\theta = 12^0$ (a) and in a pipe (b) ($\Theta = 0{,}429$) for $x/R = 0$ measuring series C.3 from Fig. 3-(c). Quantity $\Omega = \dot{V}/R\overline{\Gamma} \equiv \Omega_{xR}$ is a swirling flow parameter.

3. Problems of Turbulent Transfer Modelling

Exact, non-closed system of differential equations for statistical momentums of turbulent flow field up to the third order, may be written as:

$$D_t\overline{U}_\alpha = -\rho^{-1}\partial_\alpha\overline{p} + v\partial_{kk}\overline{U}_\alpha - \partial_k Q_{\alpha k}\,, \tag{4}$$

$$\partial_k\overline{U}_k = 0 \tag{5}$$

$$D_t Q_{\alpha\beta} = P_{\alpha\beta} + T_{\alpha\beta}^{(R)} + D_{\alpha\beta}^{(p)} + D_{\alpha\beta}^{(v)} + \pi_{\alpha\beta} - \varepsilon_{\alpha\beta}\,, \tag{6}$$

$$D_t Q_{ijk} = P_{ijk} + T_{ijk}^{(S)} + D_{ijk}^{(v)} - \pi_{ijk} - \varepsilon_{ijk} \,, \tag{7}$$

where: $\overline{U_i}$ and u_i - time averaged and fluctuating velocities in direction i; ρ and ν- density and kinematic viscosity of a fluid; $D_t f \equiv \partial f/\partial t + \overline{U}_l/\partial x_l \equiv \partial_t f + \overline{U}_l \partial_l f$, $\partial f/\partial x_1 \equiv \partial_l f$, $\partial^2 f/\partial x_l^2 \equiv \partial_u f$; $Q_{\alpha\beta} = \overline{u_\alpha u_\beta}$ - statistical momentums of the second order; $Q_{\alpha\beta} = \overline{u_\alpha u_\beta}$ - third order correlation tensor of fluctuating velocities u_i; $\alpha, \beta, i, j, k = 1,2,3$. The physical meaning of different terms in equations (1)-(4) is [3]: $P_{\alpha\beta}$, P_{ijk}, - production; $T_{\alpha\beta}^{(R)}$, $T_{ijk}^{(S)}$- turbulent diffusion; $D_{\alpha\beta}^{(p)}$- pressure diffusion; $D_{\alpha\beta}^{(p)}$, $D_{ijk}^{(v)}$- viscous (molecular) diffusion; $\pi_{\alpha\beta}$ and π_{ijk}- mechanisms of interchange: correlation between pressure and fluctuating velocity gradient, and correlation between pressure gradient and fluctuating velocity field, and $\varepsilon_{\alpha\beta}$, ε_{ijk} - viscous dissipation.

Equations (4) and (5) represent Reynolds equations and equation of continuity, whilst equations for tensor components of turbulent stresses - $-\rho Q_{\alpha\beta}$, and for velocity correlations of the third order Q_{ijk}, which describe processes of turbulent diffusion, are given with relations (6) and (7). Second order correlations $Q_{\alpha\beta}$, (components of turbulent transfer of impulse, mass, heat, etc.) and third order correlations Q_{ijk}, (turbulent diffusion processes of impulse, heat, turbulent kinetic energy, etc.) have clear physical meaning, and they significantly characterize structure and mechanisms of turbulent transfer. Functions in expression (6) are defined with following relations:

$$P_{\alpha\beta} = -Q_{\alpha k}\partial_k \overline{U}_\beta - Q_{\beta k}\partial_k \overline{U}_\alpha \,,\; T_{\alpha\beta}^{(R)} = -\partial_k Q_{\alpha\beta k} \,,\; D_{\alpha\beta}^{(p)} = -\rho^{-1}(\partial_\beta \overline{pu_\alpha} + \partial_\alpha \overline{pu_\beta}) \,, \tag{8}$$

$$D_{\alpha\beta}^{(v)} = \nu \partial_{ll} Q_{\alpha\beta} \,,\; \pi_{\alpha\beta} = \rho^{-1}\overline{p(\partial_\beta u_\alpha + \partial_\alpha u_\beta)} \,,\; \varepsilon_{\alpha\beta} = 2\nu \overline{\partial_l u_\alpha + \partial_l u_\beta} \,, \tag{9}$$

while quantities in eq. (7) are determined with expressions

$$P_{ijk} = -Q_{ijl}\partial_l \overline{U}_k - Q_{jkl}\partial_l \overline{U}_i - Q_{kil}\partial_l \overline{U}_j + Q_{ij}\partial_l Q_{kl} + Q_{jk}\partial_l Q_{il} + Q_{ki}\partial_l Q_{jl} \,, \tag{10}$$

$$T_{ijk}^{(S)} = -\partial_l Q_{ijkl} \,,\; D_{ijk}^{(v)} = \nu \partial_{ll} Q_{ijk} \,,\; \pi_{ijk} = \rho^{-1}(\overline{u_i u_j \partial_k p} + \overline{u_j u_k \partial_i p} + \overline{u_k u_i \partial_j p}) \,, \tag{11}$$

$$\varepsilon_{ijk} = 2\nu(\overline{u_i \partial_l u_j \partial_l u_k} + \overline{u_j \partial_l u_k \partial_l u_i} + \overline{u_k \partial_l u_i \partial_l u_j}) \,, \tag{12}$$

where $Q_{ijkl} \equiv \overline{u_i u_j u_k u_l}$ represents fourth order correlation momentum.

System of differential equations for central momentums (4)÷(7) is non-closed due to the existence of functions $T_{\alpha\beta}^{(R)}$, $T_{\alpha\beta}^{(R)}$, $\pi_{\alpha\beta}$, $\varepsilon_{\alpha\beta}$, P_{ijk}, $T_{ijk}^{(S)}$, π_{ijk} and ε_{ijk}. Certain mathematical modelling of quantities which appear in expressions (9) and (12) are given in [3, 4]. However, many problems of modelling non-local turbulent transfer, which exists in numerous turbulent shear flows, cannot be solved using models of gradient type [5, 6]. Non-gradient turbulent diffusion must be determined using system of equations (4) ÷(7), i.e. accounting for third order statistical momentums obtained from differential equations of turbulent transfer.

4. DISTRIBUTIONS OF TURBULENT KINETIC ENERGY, ITS PRODUCTION, TURBULENT VISCOSITY AND STRUCTURAL PARAMETERS

The experimentally found distributions of velocity field and correlation moments of the second order allow some modelling of turbulent flows.

Namely, on the basis of these results, numerical methods were used to determine distributions of turbulent kinetic energy production P_k in radial and axial direction (Figure 5). Adopting Boussinesq`s concept of turbulent viscosity μ_t, spatial distributions of this quantity were calculated, and they show extremely complex structure of swirling turbulent field. The influence of swirl is strong and significant in regions near the wall and shear layer, which corresponds to the interaction of mean flow gradients and distributions of the second order moments.

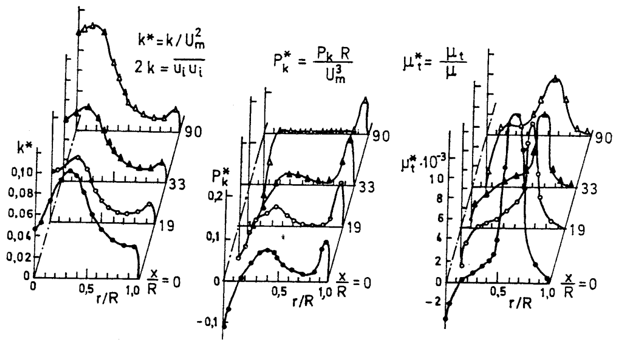

Figure 5. Radial and axial distribution of dimensionless turbulent kinetic energy $k^* = k/U_m^2 = q^2/(2U_m^2)$ its dimensionless production $P_k^* = P_k R/U_m^3$ and dimensionless turbulent viscosity $\mu_t^* = \mu_t/\mu$ in a pipe for swirl intensity θ_2 = 0,429 in inlet cross-section x/R = 0.

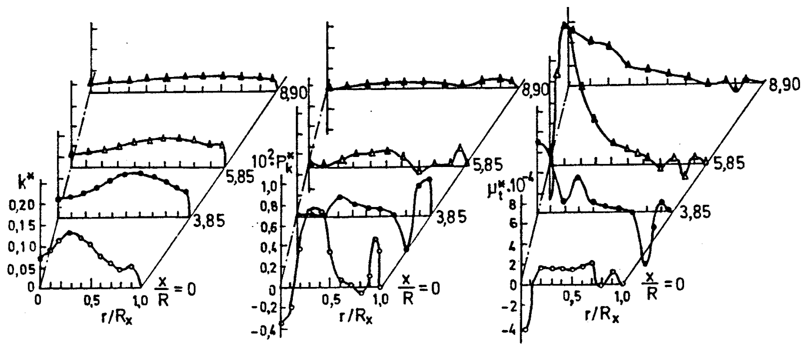

Figure 6. Distributions of turbulent kinetic energy k^*, production of turbulent energy P_k^* and dynamic turbulent viscosity μ_t^* in axial and radial direction in a diffuser for swirl intensity θ_2 = 0,429 in inlet cross-section x/R = 0.

The consequence of this is a negative production of turbulent kinetic energy in a vortex core. Negative values of turbulent viscosity and its significant changes in a flow field expose the validation of k - ε turbulence mathematical model, putting in question its physical fundamentals, as well as Boussinesq`s assumption. Figure 6 shows distributions of mentioned quantities for the case of swirling flow in a diffuser, thus supporting the same conclusions as for the swirling flow in a pipe.

Clear physical meaning of correlation statistical momentums of the second $\overline{u_i u_j}$ and third $\overline{u_i u_j}$ order, which describe turbulent transfer and diffusion processes of mass, energy and impulse, allows for determination of essential structural characteristics on the basis of experimental investigations. For example, large positive values of parameter K_1 point to the intensive turbulent interchange processes in radial direction (Fig. 7). Parameter K_1 decays downstream and tends to the negative values across the whole section as in the case of a fully developed non-swirling flow. Parameter K_2 decreases from wall to the axis of a pipe or a diffuser, whereby the region in which K_2 increases, or remains approximately constant, denotes stream zone of rapid deformations in the process of intensive flow development and evolution to a fully developed one. With weakening of swirl in downstream sections, K_2 tends to the positive values, so its negative values are to be prescribed to a swirl existence and influence. Distributions of K_1 and K_2 relate to all three turbulent intensities and indicate on non-isotropic character of turbulet transfer [1].

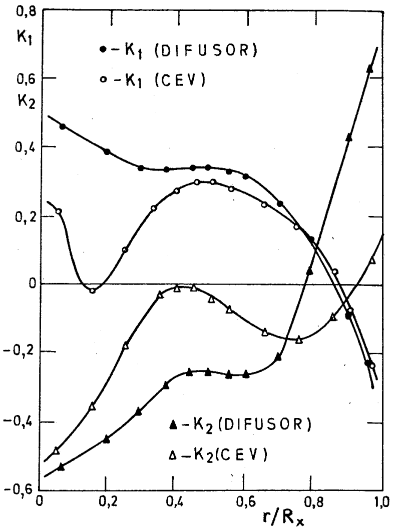

Figure 7. Distributions of structural parameters $K_1 = (\overline{v^2} - \overline{w^2})/(\overline{v^2} + \overline{w^2})$ and $K_2 = 3\overline{u^2}/\overline{q^2}$ in a pipe ($R_x = R = 100$mm, $x/R = 0$) and in a diffuser pipe (R_x=131mm, $x/R = 3{,}85$) with swirl intensity Θ=0,429 in section $x/R = 0$, where R_x is the radius of diffuser on longitudinal length x from initial section.

5. Theoretical considerations on non-gradient turbulent diffusion

Reynolds tensor $R_{ij} = \overline{u_i u_j}$ for non-isotropic turbulence may be written in the following form

$$-R_{ij} = \beta_0 \delta_{ij} + \beta_1 \overline{D}_{ij} + \beta_2 \overline{D}_{ik} \overline{D}_{kj}\,, \quad \overline{D}_{ij} = (\partial_j \overline{U}_i + \partial_i \overline{U}_j)/2\,, \tag{13}$$

where $u_i = U_i - \overline{U}_i$ is fluctuating velocity in *i*- direction, and β_k is the function of main invariants from $\overline{D}_{ij}$ and $\partial_j f \equiv \partial f / \partial x_j$. Although non-linear equation (13), which is analog with constitutive equation of Stokes and Reiner-Rivlin, and which for $\beta_2 = 0$ follows into the augmented Boussinesq equation, fully describes the local turbulent action, it doesn`t account for turbulent decaying effect (*Gedächtniseffekte*). In order to model turbulent flows in which various phenomena of non-local action and non-gradient diffusion occur, higher order terms of timeaveraged velocities $\overline{U_i}$ must be considered.

In order to describe the non-local turbulent interchange process of impulse $R_{ij} = \overline{u_i u_j} = T^{-1}\int_0^T U_i(t_L)u_j(t_L)dt_L$, expression of Hinze [5] for the fluctuating velocity $u_i = U_i(t_L;\tau) - (\overline{U}_i)_L$ must be used, in order to gain:

$$-\overline{u_i u_j} = \int_0^\tau \{[\overline{u_j(t_L)u_k(t_L - t)} - \frac{1}{2}\overline{u_j(t_L)u_k(t_L - t)\varsigma_l(t_L;t)}\partial_l + \\ + \frac{1}{6}\overline{u_j(t_L)u_k(t_L - t)\varsigma_l\varsigma_m(t_L;t)}\partial_{lm} + \ldots]\partial_k\overline{U}_i\}dt \quad , \tag{14}$$

where $\varsigma_k(t_L;\tau) = \int_0^\tau u_k(t_L - t)dt$ is the distance of fluid particles for all from time instance τ until T_L, i.e. for all $\tau \leq T_L$. On the basis of statistical theory of turbulence, for the case of second approximation of eq. (14), it follows

$$-\overline{u_i u_j} = -\overline{u_k u_k}\delta_{ij} + v_{jk}(\tau)\partial_k\overline{U}_i - (1/2)v_{jk}^0(\tau)L_l(\tau)\partial_{lk}\overline{U}_i \, , \tag{15}$$

where v_{jk}\ - are components of viscosity tensor, L_l- characteristic length $\overline{u_j(t_L)u_k(t_L - \tau)}$- Lagrange autocorrelation function and $\partial_{lk}\overline{U}_i \equiv \partial^2\overline{U}_i / \partial x_l \partial x_k$.

Using certain assumptions [5,7], expression (15) yields to

$$-\overline{u_1 u_2} \equiv (-\overline{u_1 u_2})_B + (-\overline{u_1 u_2})^* = v_{12}\partial_2\overline{U}_1 + \left[(2\pi)^{-1/2} v_{12}^3 \left(\overline{u_2^2}\right)^{-3/2} \partial_2 \left(\overline{u_2^2}\right)^{1/2} + \ldots\right]\partial_{22}\overline{U}_1 \, , \tag{16}$$

with which non-local turbulent impulse-transfer $\overline{u_1 u_2}$ may be determined.

6. NON-LOCAL TURBULENT TRANSFER IN INTERNAL SWIRLING FLOWS

Non-local turbulent transfer and non-gradient turbulent diffusion are significant characteristics of turbulent swirling flows. Physical-mathematical modelling of contra-gradient transfer processes is very difficult and requires research on fundamental physics of these processes. Fig. 8 shows the MN-region of contra-gradient turbulent impulse transfer in diffuser cross-section $x/R = 3{,}85$. In the region MN, Reynolds stress $-\overline{uv}$ and velocity gradient $\partial_r\overline{U}$ have opposite sign, while $\partial_r\overline{U}\,|_M = 0$ and $\overline{uv}\,|_N = 0$.

The character of non-gradient transfer may be seen also on Fig. 9. Presented curve does not pass through coordinate origin, and shows sign change of correlation momentum $\overline{uv}$ in radial direction at the place where derivative $\partial_r\overline{U}$ has a negative value. Picture of contra-gradient transfer zone extent (width) is fulfilled with the number of data points in quadrants with the same sign of quantities $\overline{uv}$ and $\partial_r \overline{U}$ in respect to the total number of points. Application of conventional gradient model ($\nu_{rx} = \nu_{rx,B}$) yields to physically unacceptable values of turbulent viscosity tensor component $\nu_{rx,B}$:

$$-\overline{uv} = \nu_{rx,B} \cdot \partial_r \overline{U} \Rightarrow \lim_{M \to M^-} \nu_{rx,B} = \infty, \ \lim_{M \to M^+} \nu_{rx,B} = -\infty, \ \nu_{rx,B} \,|_{MN} < 0, \ \nu_{rx,B} \,|_N = 0 \quad (17)$$

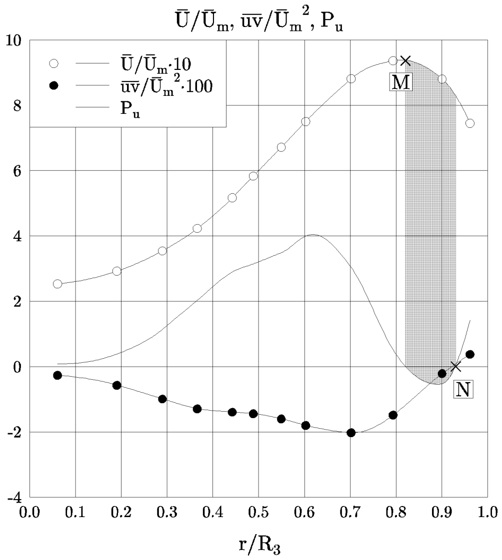

Figure 8. Distributions of $\overline{U}$, $\overline{uv}$ and P_u in turbulent swirling flow in a diffuse in cross-section x/R = 3,85 (R = 100mm, R$_3$ = 100mm, $\overline{U}_m$ = 21.41m/s).

Profile of turbulent viscosity coefficient $\nu_{rx,B}$ is shown on Fig. 10 together with the MN-region of non-local turbulent transfer, in which generation of axial velocity fluctuations kinetic energy is negative:

$$P_u = -2(\tilde{u}^2 \partial_x \overline{U} + \overline{uv} \partial_r \overline{U}) \approx -2\overline{uv} \partial_r \overline{U} \quad \Rightarrow \quad P_u \,|_{MN} < 0 \,. \quad (18)$$

Distribution of production P_u is shown on Fig. 8. By application of general gradient model based on bimodal structure of process

$$-\overline{uv} = \nu_{rx} \partial_r \overline{U} + (-\overline{uv})^* = \nu_{rx} \partial_r \overline{U} + (2\pi)^{-1/2} (\nu_{rx} / \tilde{v})^3 \partial_r \tilde{v} \partial_{rr} \overline{U} \,, \quad (19)$$

it was possible to calculate non-local turbulent transfer in MN-region and to gain distribution of turbulent viscosity ν_{rx} that is shown on Fig. 10, whereby

$$-\overline{uv} \,|_M = (-\overline{uv})^* \qquad \text{and} \qquad \nu_{rx} \partial_r \overline{U} \,|_N = (\overline{uv})^* \quad (20)$$

because of $\partial_r \overline{U} \,|_M = 0$ and $\overline{uv} \,|_N = 0$. Thus, by application of model (19), it was possible to obtain positive and finite values for turbulent viscosity ν_{rx} in the MN-region of non-local turbulent transfer in a swirling flow.

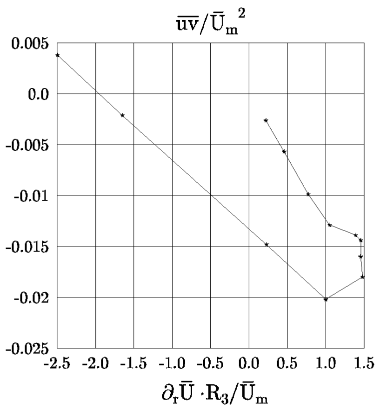

Figure 9. Non-gradient turbulent transfer in swirlingflows

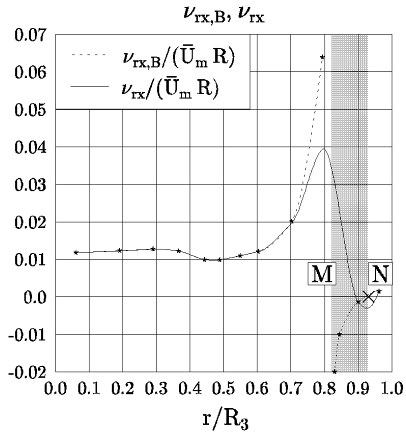

Figure 10. Distribution of turbulent viscosity (Data Fig. 8).
$\nu_{rx,B}$- Boussinesq-model,
ν_{rx} - non-local model (eq. (19)).

7. Central momentums of higher order and autocorrelation function

High values of skewness factor S_i and flatness factor F_i, as well as the opposite sign of moments S_u and S_v, in the regions of vortex core and shear layer may be correlated to the intermittent structure of flow. Described properties of S_u, F_u and S_v distributions serve as an existence indicator of coherent structures in vortex core and shear layer (Fig. 11).

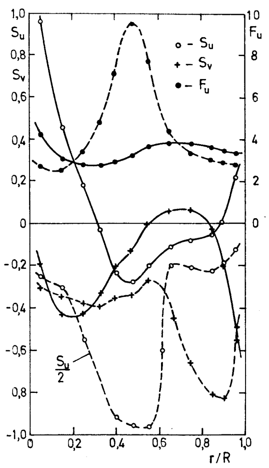

Figure 11. Distribution of $S_u = \overline{u^3}/\tilde{u}^3$, $S_v = \overline{v^3}/\tilde{v}^3$ and $F_u = \overline{u^4}/\tilde{u}^4$ in pipe sections: full line $x/R = 0$, dashed line x/R90, for inlet swirl intensity $\theta_2 = 0{,}429$.

The changes of axial (u) and radial (v) velocity fluctuations and of correlation moment (uv) during time t are shown on Figure 12. It is noticed that the significant negative uv - fluctuations are the consequence of high positive axial and low negative radial fluctuations interaction. In these injective phases ($u < 0$ and $v > 0$) in respect to the core, i.e. pipe axis (denoted with arrows on Figure 12), large turbulent vortexes are intermittently injected into the core from the regions where turbulence is generated. Ejective phases ($u < 0$ and $v > 0$) then come to replace, and intermittently overlap injective phases, which is in close correlation with turbulence structure near the wall and vortex shear layer. One of the methods of intermittence investigation is the application of conditional sampling. High curvature and distinctive change of autocorrelation function $R_{uu}(t)$ in the neighborhood of point $\tau = 0$ shows that wide frequency - energy spectrum of axial fluctuations exists in the core, and that turbulent vortexes of various sizes are present. In this region, the time integral turbulence scale $T_u = \int_0^\infty R_{uu}(\tau)d\tau$ reaches its maximal, and a flatness factor F_u its minimal value. Visualizations of these flows point out the existence of complex coherent structures, which are needed to be investigated further using the methods applied for instance in papers.

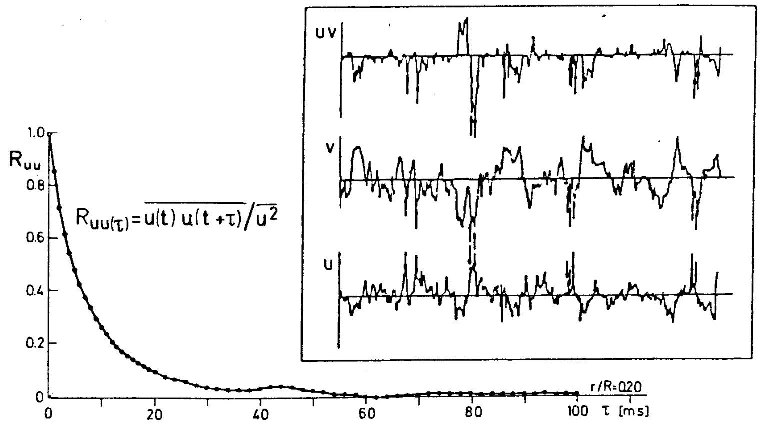

Figure 12. Autocorrelation coefficient $R_{uu}(\tau) = \overline{u(t)u(t+\tau)}/\overline{u^2}$ of axial velocity fluctuations and time change of u- and v-fluctuations and correlation moment $uv(t)$ in the core at point $r/R = 0{,}20$ of pipe cross-section $r/R = 0$ for $\theta_2 = 0{,}429$.

8. Conclusions

Experimental and theoretical investigations of turbulent swirling flows reveal the significant influence of swirl onto the turbulence structure and turbulent transfer processes. The obtained distributions of structural parameters characterize the four essentially different swirling flow regions. Paper proves that the presence of swirl has the consequence of non-local turbulent transfer and that it should be modelled adequately. One approach to modelling has been given in the paper, with the final statement that further investigation should be directed to more exact and complete model development which would express the physical essence of the processes involved in swirling flow non-local turbulent transfer.

Complex experimental investigations on turbulent swirling flow in pipes and in a diffuser have been conducted in order to determine important statistical properties of the flow field, as well as the influence of swirl onto the turbulence structure. Distributions of correlation coefficients, structural parameters, statistical moments of higher order and probability density show significant characteristics of internal swirling flows. So, for instance, the correlation coefficient R_{uv} change of sign occurs at the place where central moment $\overline{u^2}$ reaches its minimal value. Skewness factor S_u changes its sign at the place where $\overline{u^2}$ reaches its maximal, and flatness factor F_u its minimal value. Thus, the structure of vortex shear layer and the tendency of turbulent diffusion are characterized by the properties of flow close to the wall. Anisotropy is greater in the vortex core than in the main flow. Turbulent viscosity distributions shown in the paper expose certain maltreatments in some physical-mathematical turbulence models. By the spatial distribution of circumferential velocity, additional intensive impulse interchange in radial in axial direction is characteriyed Values and characters of change in distributions of statistical parameters show the possible existence of injective and ejective phases which, through turbulence, intermittently replace one another and overlap. The results of investigations confirm on the intermittent incidence and on the existence of organiyed coherent structures in turbulent swirling flows. Further investigations in this field should give more detailed answers.

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Cilj ovog rada je da se istraži struktura turbulencije i statističke osobine vrtložnog smičućeg sloja u vihornim strujanjima u cevima i u difuzoru. Shodno tome, za eksperimentalna merenja statističkih veličina korišćena je anemometrija sa vrelom žicom korišćenjem trosenzorskih sondi, sa digitalnom obradom podataka i statističkom analizom izmerenih podataka.