On the Non-Local Turbulent Transport and Non-Gradient Thermal Diffusion Phenomena in HVAC Systems

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The turbulence structure investigation is essential for understanding the physics of flow-thermodynamic processes in Heating, Ventilation and Air conditioning (HVAC) systems. Analysis and calculation of these systems are based on the knowledge of turbulent transfer mechanism and its modeling. In this regard, the paper analyzes the phenomena of non-local momentum transfer and non-local transfer of energy by heat in curved channels, asymmetric jets, wakes and swirling flow. The physics of non-gradient turbulent diffusion and negative production in velocity and temperature fields are analyzed. There was a certain analogy between the turbulent processes in these classes of flow. By means of numerical processing of experimental results, modeling of non-local transport in turbulent swirling flow was conducted.

Keywords: *turbulence, non-gradient thermal diffusion, non-local transport, swirling flow, modeling.*

1. INTRODUCTION

Almost all flows in nature and engineering are turbulent. This is no accident. Although it is one of the most complex flows, there is a tendency of establishing turbulent flow in all devices of the energetic systems. This provides improvement in mass, momentum and energy transport, but problems occur due to increased pressure drop and flow resistance, as well as in the analysis of such devices. Scientific community is still focused on the problem of closing the system of Reynolds equations. There is a need for modeling, i.e. establishing a link between the Reynolds stress tensor and the components of the mean flow field [1].

One of the important places in the turbulence modeling belongs to the so called gradient models [2]. Here we have local connections of both linear and gradient type between the Reynolds stress tensor and the components of the mean flow field, in accordance with the concepts of the theory of transfer based on the ideas of Boussinesq (1877, -97), Taylor (1915, -32, -35), Prandtl (1925, -42) and Karman (1930). However, in certain classes of flows important for technical practice, in some areas of the flow field, there can be non-gradient transport processes [3], like processes of non-local turbulent transport and non-local turbulent diffusion. It is clear that in those areas of the flow field one can not apply gradient model. That is why those non-local processes must be further analyzed if one wishes as closely as possible to access the modelling of turbulent exchange mechanism. In these areas of turbulent flow there is also a negative production phenomenon [4, 5] which implies that the transport of kinetic energy of turbulence is carried out from small to large scale eddies.

The zone of non-gradient turbulent diffusion and negative production in the turbulent mixing layer with an asymmetrical profile of average temperature was investigated in [6]. The existence of non-local turbulent transport was found in asymmetric wake of a heated cylinder [3], and non-gradient turbulent diffusion of heat in the wake of a cylinder is studied in [7].

HVAC systems consist of many complex duct components in which the flow is highly turbulent [8], and because of the geometry there appear non-local transport processes too. The aim of this paper is to analyze the physics of the non-local turbulent transport and negative production phenomena in velocity and temperature fields that are present in the HVAC systems. For this purpose, the flows in a curved channel, in asymmetrical jets and wakes of cylinders are considered. Based on experimental measurements in [9], the paper provides an original contribution to the analysis and modeling of non-local turbulent transport in a turbulent swirling flow in a pipe.

2. GOVERNING EQUATIONS

The equations governing the motion of a fluid in a turbulent flow and the turbulent transport of momentum and transport of energy by heat are the averaged continuity equation for an incompressible flow

$$\mathrm{div}\underline{U} = 0,\ \nabla \cdot \underline{u} = 0\,, \tag{1}$$

averaged Navier-Stokes equation, known as Reynolds equations, in vector form, without body forces

$$\mathrm{div}\left(\underline{U}\,\underline{U}\right) = -\nabla\left(P/\rho\right) + \nu\nabla^2\underline{U} - \nabla\cdot\underline{\underline{\tau}}^R \tag{2}$$

and the advection-diffusion equation for heat

$$\rho c_p \underline{U}\cdot\nabla T = -\nabla\cdot\left(-kT + \rho c_p\langle t\underline{u}\rangle\right). \tag{3}$$

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The dyad $\underline{\underline{\tau}}^R \equiv \langle \underline{u}\underline{u} \rangle \equiv \langle \underline{u} \otimes \underline{u} \rangle$ in (2) is called the Reynolds stress tensor. It appears as a result of the Reynolds decomposition and the Reynolds averaging process applied to the nonlinear advection term. This is a new unknown that represents the transport of momentum caused by turbulent fluctuations. The determination of the components of this tensor $\tau_{ij}^R = \langle u_i u_j \rangle$ is one of the main objectives of turbulent research. The turbulent term $\langle t\underline{u} \rangle$ in (3), which has arisen from averaging the diffusion equation for heat, is clearly analogous to the Reynolds stresses [1,2].

The vector-invariant nature of the equations (1) – (3) is of great importance in practical computations. In particular, for Cartesian coordinates, these equations are written as

$$\partial_j U_j = 0, \quad \partial_j u_j = 0 , \tag{4}$$

$$U_j \partial_j U_i = -\partial_i \left(P/\rho \right) + \partial_j \tau_{ij}^* , \tag{5}$$

$$U_j \partial_j T = \partial_j Q_j^* , \tag{6}$$

where τ_{ij}^* and Q_j^* are mean momentum fluxes and the mean heat flux

$$\tau_{ij}^* = \nu \partial_j U_i - \langle u_i u_j \rangle \tag{7}$$

ANALOGY

$$Q_j^* = \alpha \partial_j T - \langle t u_j \rangle . \tag{8}$$

The analogy between (7) and (8) is "the analytical foundation for the belief that turbulence may transport heat in much the same way as momentum" [1].

Another analogous form of the equations (5) and (6) can be obtained by using (7) and (8)

$$U_j \partial_j U_i = \nu \partial_{jj} U_i - \partial_j \langle u_i u_j \rangle - \rho^{-1} \partial_i P \tag{9}$$

$$U_j \partial_j T = \alpha \partial_{jj} T - \partial_j \langle t u_j \rangle . \tag{10}$$

The mean equations (4), (9) and (10) are not closed, and some terms, principally the Reynolds stresses $\langle u_i u_j \rangle$ and the turbulent heat flux $\langle t u_j \rangle$, need to be modeled.

3. NON – LOCAL AND NON – GRADIENT CHARACTER OF THE TURBULENT TRANSPORT AND THERMAL DIFFUSION MECHANISMS

In many turbulent flows the unknown turbulent fluxes of momentum and heat in (9) and (10) are modeled by the analog local relations of gradient-diffusion, i.e. Boussinesq, type

$$-\langle u_i u_j \rangle = \nu_B^R \left(\partial_j U_i + \partial_i U_j \right) - \frac{1}{3} \langle \underline{u} \cdot \underline{u} \rangle \delta_{ij} , \tag{11}$$

$$-\langle t u_j \rangle = \alpha_B^R \partial_j T \quad \Leftrightarrow \quad -\langle t\underline{u} \rangle = \alpha_B^R \nabla T , \tag{12}$$

where the lower index B indicates that the quantity originates from the Boussinesq concept of turbulence modeling. The basic problem is determining quantities ν_B^R and α_B^R. In more complex turbulent shear flow it is assumed that the eddy viscosity is a second-order tensor $\left(\nu^R\right)_{ik}$ or a fourth-order tensor $\left(\nu^R\right)_{ijkl}$, while the eddy thermal diffusivity is a tensor of the second-order, hence (11) and (12) become [2]

$$-\langle u_i u_j \rangle = \begin{cases} \left(\nu_B^R\right)_{ik} \left(\partial_k U_j + \partial_j U_k \right), \\ \left(\nu_B^R\right)_{ijkl} \left(\partial_l U_k + \partial_k U_l \right), \end{cases} \tag{13}$$

$$-\langle t u_j \rangle = \left(\alpha_B^R\right)_{ji} \partial_i T . \tag{14}$$

Modern research of turbulent momentum transport and energy transport by heat mechanisms show that the physics of the process can not be entirely reduced to a local gradient-diffusion type models, which are described by analytical expressions (11) – (14), as it follows from further physical-mathematical analysis presented in this paper.

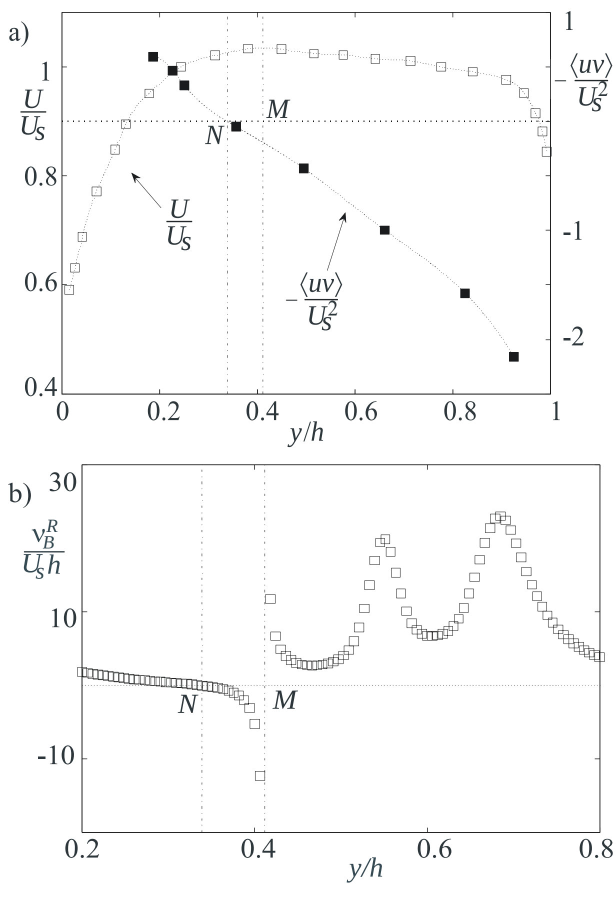

Figure 1. Non-gradient turbulent transport in a fully developed turbulent flow in a curved channel: a) experimental distributions of mean axial velocity U and Reynolds stress $-\langle uv \rangle$; b) calculated distribution of eddy viscosity ν_B^R in accordance with the Boussinesq model. Other signs: MN – the displacement zone of turbulent transport; y – distance from the inner wall of the channel; h – channel width; U_S – average (by area) velocity.

By analyzing the experimental results presented in [4] is shown, for example, that in one-dimensional developed turbulent flow in a curved channel, in a certain area of the channel, occurs the non-gradient turbulent transfer phenomenon. Namely, in Figure 1a is observable characteristic domain MN of the channel cross section which is determined by the relations

$$\partial_y U\big|_M = 0,\ \langle uv\rangle\big|_N = 0\,, \tag{15}$$

in which the turbulent stress $-\langle uv\rangle$ and mean velocity gradient are of the opposite sign. In this case (11) simplifies considerably, so that by use of (15) the following values for the eddy viscosity ν_B^R are obtained:

$$\begin{gathered} -\langle uv\rangle = \nu_B^R \partial_y U \\ \Downarrow \\ \overbrace{\lim_{M\to M^\pm} \nu_B^R = \pm\infty,\ \nu_B^R\big|_{MN} < 0,\ \nu_B^R\big|_N = 0.} \end{gathered} \tag{16}$$

The functional dependence $\nu_B^R(y)$, as calculated via (15) and (16), is shown graphically in Figure 1b. Physically unacceptable values of the eddy viscosity ν_B^R in the MN zone, including its boundaries, are indicators of the non-local turbulent transport of momentum and the non-gradient turbulent diffusion phenomena. In the MN domain of the cross-sectional area of the curved channel gradient model must be generalized, as will be demonstrated later in this paper.

Analogous mechanisms in the processes of turbulent momentum transport and transport of energy by heat are observed also in non-local turbulent transport. The asymmetric mean velocity profile in Figure 1 is analogous to the asymmetric profile of the mean temperature in Figure 2, which is determined experimentally in asymmetrically heated wake of a cylinder [3]. With points $M\left(\partial_y T = 0\right)$ and $N\left(\langle tv\rangle = 0\right)$ thin area of non-local energy transport by heat is confined. In that area the turbulent heat flux and the mean temperature gradient have opposite signs. In accordance with (12), the turbulent thermal diffusivity in this case is negative. In fact, from (12) in the zone of non-gradient transport MN, the so called displacement zone, one can apply expressions analogous to (16), in which, according to the equation $-\langle tv\rangle = \alpha_B^R \partial_y T$, should instead u, ν_B^R and U, include t, α_B^R and T respectively. Non-gradient turbulent diffusion is shown as a curve in the system $\left(\partial_y T, -\langle tv\rangle\right)$ in Figure 2b. That curve, in case of a gradient transport, would be reduced to a curve that passes through the origin, and this would, in the case of a constant diffusivity be reduced to a straight line.

Transport phenomena in a wake of a cylinder are of great interest in thermal engineering, technology and fundamental research. In the flow around a heated cylinder temperature rise does not cause a change of density and flow dynamics. The paper shows that in this class of flow there is a non-local turbulent thermal diffusion.

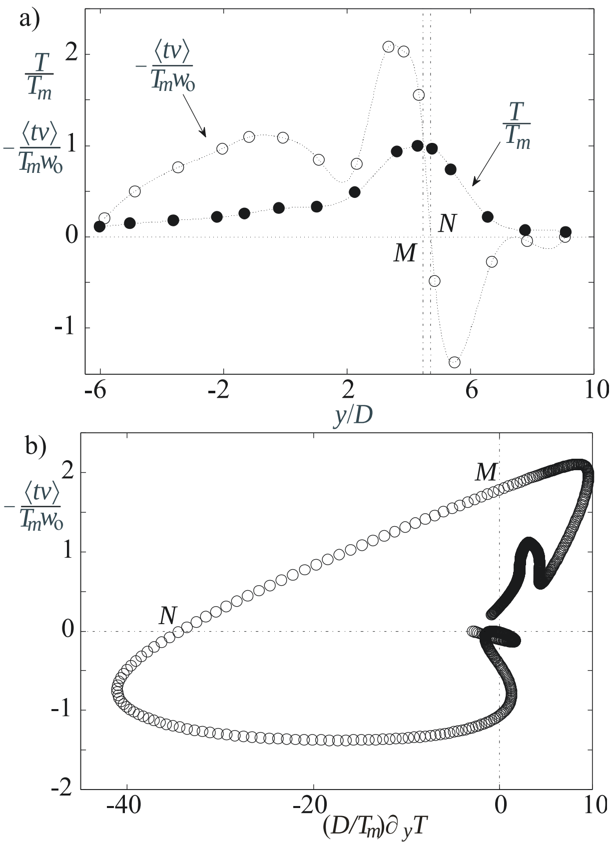

Figure 2. Non-gradient turbulent heat flux in an asymmetrically heated wake: a) distributions of mean temperature T and turbulent heat flux $-\langle tv\rangle$ across the wake (flow width); b) the variation of $-\langle tv\rangle$ with mean temperature gradient $\partial_y T$. Other signs: T_m – maximum temperature rise above the ambient; w_0 – wake defect velocity; y – coordinate axes in the lateral direction of the flow; D – cylinder diameter.

Based on experimental data from [7], the mean square temperature fluctuations $\langle t^2\rangle$ and lateral transport of the square of temperature fluctuations $-\langle t^2 v\rangle$ are shown in Figure 3a. In the equation of temperature-fluctuation variance correlations of third-order $\langle t^2 v\rangle$ describe turbulent diffusion of the quantity $\langle t^2\rangle$. By applying numerical calculations on the measurement results from [7] and with use of the gradient-diffusion type model (12) and (14) is obtained

$$\begin{gathered} -\langle t^2 v\rangle = \alpha_{t^2}^R \partial_y \langle t^2\rangle \\ \Downarrow \\ \overbrace{\alpha_{t^2}^R \begin{cases} = \pm\infty \text{ in } M_1;\ \partial_y\langle t^2\rangle\big|_{M_1} = 0 \\ = 0 \text{ in } N;\ \langle t^2 v\rangle\big|_N = 0 \\ < 0 \text{ in } NM_2 \text{ zone} \\ = \pm\infty \text{ in } M_2 \text{ and } M_3;\ \partial_y\langle t^2\rangle\big|_{M_3,M_2} = 0, \end{cases}} \end{gathered} \tag{17}$$

where $\alpha^R_{t^2} \equiv \left(\alpha^R_B\right)_{t^2}$. Numerical results are graphically shown in Figure 3b. Calculated values of the eddy thermal diffusion show its considerable changes in the lateral direction, as well as physically unacceptable, i.e. negative values in the displacement zone NM_2, and an infinite ones near the vertical asymptotes in the points M_1, M_2 and M_3, where $\partial_y \langle t^2 \rangle = 0$. In these parts of the flow field the turbulent transport is counter gradient and can not be described by a gradient model (17).

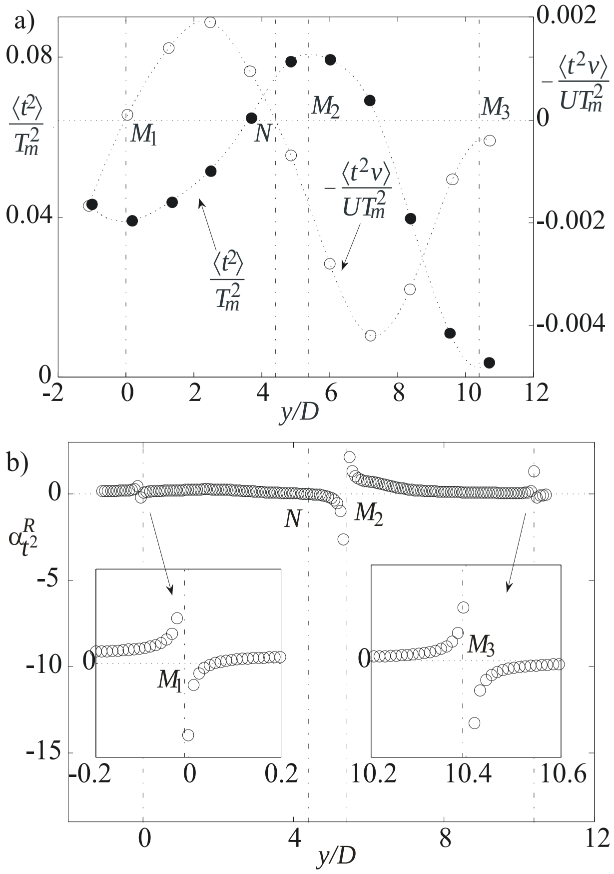

Figure 3. Non-gradient thermal diffusion in a turbulent wake flow of a mildly heated cylinder: a) Profile of temperature fluctuations and lateral transport of t^2 with the displacement zone NM_2 ; b) Lateral distribution of turbulent thermal diffusivity. Other signs: T_m – maximum wake temperature overheat; U – free stream velocity; y – lateral coordinate; D – cylinder diameter.

Research shows that in areas where non-local turbulent momentum transport, non-local transport of energy by heat and non-gradient turbulent diffusion occur there also appear the phenomenon of negative production of velocity and temperature fluctuations intensities. This is confirmed in flows in a curved channel and wakes that were analyzed in this paper. Since turbulent jets are of great importance for the HVAC systems, the phenomenon of negative production is observed in one of these flows. For this purpose here are analyzed the experimental results obtained from [6]. Mildly heated plane jet is discharged in a peaceful environment and in a homogeneous flow. The temperature differences were small, so that the buoyancy effects were neglected. In such homogenous turbulent flow with asymmetric mean profiles of velocity U and temperature T, along with counter gradient transport in the displacement zone NM (Fig. 4), there also appears a negative production of temperature fluctuations intensities. By means of numerical analysis of experimental data from [6] the distribution of eddy thermal diffusivity $\alpha^R_B = -\langle tv \rangle / \partial_y T$ is obtained, and it is shown in Fig. 4.

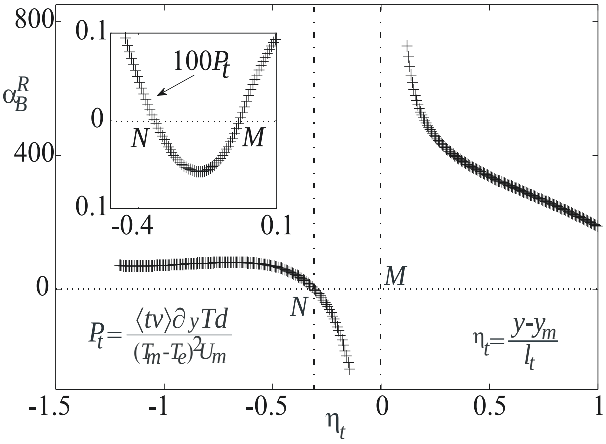

Figure 4. Negative production of temperature fluctuations intensity in the displacement zone NM $(P_t < 0)$ and distribution of eddy thermal diffusivity α^R_B in a mixing layer. Other signs: l_t – scale for the thermal field; U_m – velocity on the lower side of the jet; T_m – maximum temperature of the jet fluid; T_e – ambient temperature; d – discharge slot width; y_m – location of the maximum temperature difference $T_m - T_e$ in the lateral direction of the flow.

It may be observed, analogous to (17), that α^R_B is negative in NM zone and infinitely large near the temperature maximum $\partial_y T\big|_M = 0$. Quantity α^R_B is equal to zero at the point $N\left(\langle tv \rangle = 0\right)$, which represents the second confining point of the displacement zone MN. Using the measurement results and the expression $\mathcal{P}_t = -\langle tv \rangle \partial_y T$, the production of temperature fluctuations is calculated and its distribution in dimensionless form is shown in Figure 4 as a function of dimensionless lateral coordinate $\eta_t = \left(y - y_m\right)/\ell_t$. The dimensionless production P_t is negative in the displacement zone MN, the later being a result of a displacement between the points in witch quantities $\partial_y T$ and $\langle tv \rangle$ are equal to zero. Physically this means that the direction of heat diffusion is opposite to the mean gradient diffusion. The negative production is a consequence of the eddy flow structure dynamics. There are a lot of papers in which modeling of non-local turbulent transport and negative production is based on a computer program for $k - \varepsilon$ model, like for example [10]. In this paper, however, the assumption of Townsend [11] on the bimodal structure of the turbulent transport mechanism, i.e. that the turbulent flux of momentum, heat etc. can be represented in the form of transport by small scale eddies and by large scale eddies, is used. This physical idea made it possible the modeling of non-local turbulent transport of momentum in turbulent swirling pipe flow, which is conducted in next section.

4. TURBULENCE MODEL FOR NON – LOCAL TRANSPORT IN SWIRLING FLOW

In the HVAC and other energetic systems turbulent swirling flows are inevitable. Research of the flow-thermodynamic processes in such flow is considerably difficult, because it is a three-dimensional inhomogeneous anisotropic turbulent flow. The influence of the swirl, which is formed by different distributions of circumferential velocity, is expressed in a complex structure of turbulence and complicated mechanism of turbulent transport processes. The existence of the vortex core, shearing layer, the wall area, and even the recirculation flow makes physical-mathematical modeling of such flow very complicated. Research shows that in different areas of swirling flow there is a non-local turbulent momentum transport, non-local transport of energy by heat, as well as the counter gradient turbulent diffusion.

Using own measurement results from [9] the analysis of the non-local turbulent transport in a swirling pipe flow is conducted. In Figure 5a are graphically shown measured values of axial velocity U and the Reynolds stresses $-\langle uv\rangle$ and $-\langle v^2\rangle$. It is observed that the normal turbulent stress in the radial direction $-\langle v^2\rangle$ reaches its highest value in the shearing layer and vortex layer, which include coaxial region $0 \le r/R \le 0.4$. Especially characteristic of the swirling flow is the change of sign of the shear stress $-\langle uv\rangle$ at the point N. This correlation moment reaches its greatest value in the shearing layer, and then decreases towards the axis and the main flow. The physical meaning and the sign of the mixed correlation moment $\langle uv\rangle$ show that the transport of the axial momentum is radial from the shearing layer towards the pipe axes, so that the axial velocity profile of the vortex core downstream becomes more even. Axial velocity reaches a maximum at the point M, where $\partial_r U = 0$.

By applying numerical calculations on the experimental results, on the basis of expressions (13) for anisotropic viscosity field, the following relations for the radial flux of momentum and the corresponding component of the eddy viscosity tensor are obtained

$$-\langle uv\rangle = \left(\nu_B^R\right)_{rx} \partial_r U$$
$$\Downarrow$$
$$\left(\nu_B^R\right)_{rx} \begin{cases} < 0 \text{ in } MN \text{ zone} \\ = 0 \text{ in } N;\ \langle uv\rangle\big|_N = 0 \\ \to \pm\infty \text{ for } M \to M^{\pm} \left(\partial_r U\big|_{M^{\pm}} = 0\right). \end{cases} \quad (18)$$

These relations are analogous to expressions (16) and (17), indicating that in the MN zone there can be a transformation of fluctuating flow energy into the mean flow energy, which leads to negative production of kinetic energy of turbulence. This means that a complex interaction between the mean and fluctuating fields is not strictly local, which, according to the Boussinesq model, suits the transport by the small scale turbulent eddies. The phenomena of non-local transport, non-gradient diffusion and negative production are due to the presence of large-scale eddies, which introduce the anisotropy and memory effects. Based on this bimodal model [11], the generalized gradient model [6] is formed, which is adapted in this paper to the non-local turbulent transport in turbulent swirling flow as follows

$$-\langle uv\rangle = \nu_{rx}^R \partial_r U + \frac{1}{\sqrt{2\pi}} \frac{\left(\nu_{rx}^R\right)^3}{\left(\langle v^2\rangle\right)^{3/2}} \partial_r \left(\langle v^2\rangle\right)^{1/2} \partial_{rr}^2 U \quad (19)$$

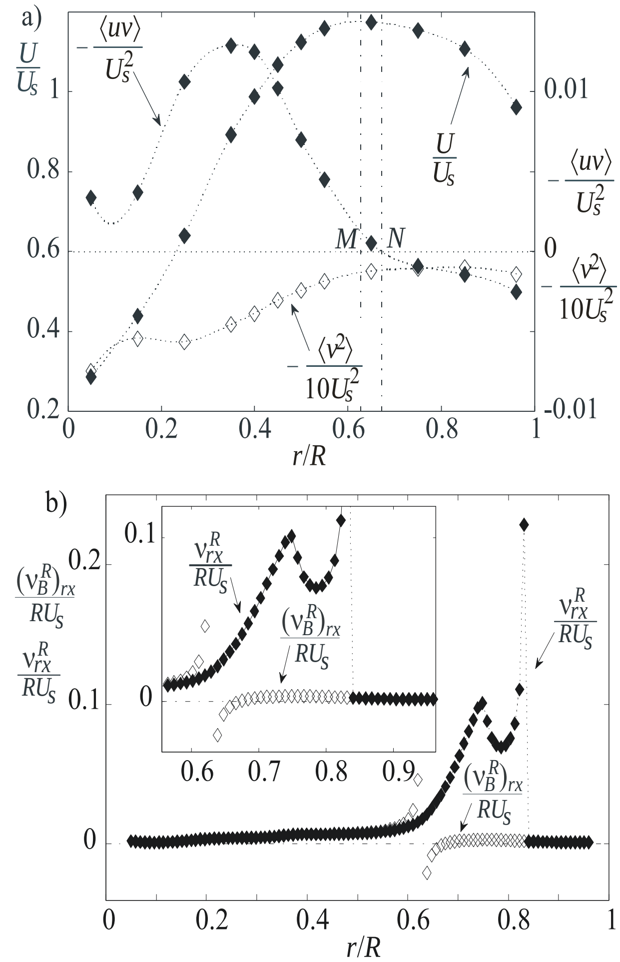

Figure 5. Non-local turbulent transport of a momentum in a swirling pipe flow: a) Radial distributions of measured values for axial velocity U, radial transport of axial momentum $\langle uv\rangle$ and double the value of kinetic energy of radial velocity fluctuations intensity $\langle v^2\rangle$; b) Modeling of non-local transport – calculated distributions of eddy viscosity; $\left(\nu_B^R\right)_{rx}$ – Boussinesq model, $\left(\nu^R\right)_{rx} = \nu_{rx}^R$ – non-local model. Other signs: U_S – average (by area) velocity, R – pipe diameter.

The second member on the right side of non-local model (19) describes the non-local turbulent transport of convective type induced by the large scale eddies flow, which has a contribution to the turbulent stress due to convective diffusion.

By numerical analysis of measurement results, using the models (18) and (19), the distributions of eddy viscosities $\left(\nu_B^R\right)_{rx}$ and $\left(\nu^R\right)_{rx} = \nu_{rx}^R$ are calculated and they are graphically shown in Figure 5b. It is observed that the turbulent bimodal model (19) all physically unacceptable values (18) for $\left(\nu_B^R\right)_{rx}$ translates into the final and positive valuesof eddy viscosity ν_{rx}^R. Based on this research it can be concluded that the turbulence model (19) describes well the non-local turbulent transport in a turbulent swirling pipe flow.

5. CONCLUSION

The mechanism of turbulent mass, momentum and energy transport in physical-chemical processes of HVAC systems is very complex. This paper discusses the physics of flow-thermodynamic processes in such systems, using analytical and numerical analysis of own experimental results as well as the experimental data of other authors. Meaningfully, flow in a curved channel, asymmetric jets, wakes of cylinders and swirling flows were analized. In these classes of flow an asymmetric profiles of mean velocity and mean temperature, non-local turbulent transport and non-gradient turbulent diffusion arise. In this paper, these phenomena are analyzed using a variety of characteristics that define them.

By means of numerical processing of experimental results, the distribution of eddy viscosity is obtained and this quantity defines the displacement zone in the flow in a curved channel and swirling flow. Non-gradient heat flux in the wake of a cylinder is analyzed using the diffusion curve, which is obtained by numerical analysis of experimental data. The lateral distribution of eddy thermal diffusivity is physically analyzed and non-gradient turbulent diffusion in the wake of a mildly heated cylinder is proven.

By numerical processing of experimental results for the flow in the mixing layer a non-local turbulent transport was observed, on the basis of negative production of temperature fluctuations intensities, on one hand, and on the basis of non-gradient distribution of eddy thermal diffusivity, on the other.

The paper discusses turbulent swirling flow in pipe lines of HVAC systems. Numerical analysis of experimental data showed that in this complex flow there are non-local turbulent transport and non-gradient turbulent diffusion. Based on certain physical assumptions specific to bimodal model, a mathematical model that describes the non-local turbulent transport of momentum in the displacement zone of swirling flow is developed.

By analyzing the given classes of flow important analogies of these phenomena in velocity and temperature fields are noted. It is shown, namely, that the negative production of temperature fluctuation intensities is analogous to the negative production of turbulent velocity in the dynamic case. This applies to the character of the diffusion process in velocity and temperature distributions also.

It can be concluded that the mechanisms of non-local turbulent transfer and non-gradient turbulent diffusion points to a complex interactions between fluctuating and mean flow fields. In order to obtain a more profound physical-mathematical model of these phenomena in velocity and temperature fields, further research and closer insight into the structure of turbulence and non-local turbulent transfer physics is necessary.

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REFERENCES

[1] Tennekes, H. and Lumley, J. L.: *A First Course in Turbulence*, MIT Press, Cambridge, 1978.

[2] Hinze, J. O.: *Turbulence*, McGraw-Hill, New York, 1975.

[3] Sreenivasan, K. R., Tavoularis, S. and Corrsin, S.: A Test of Gradient Transport and Its Generalizations, in *Turbulent Shear Flow 3*, (ed. L. J. S. Bradbury, F. Durst, B. E. Launder, F. W. Schmidt and J. H. Whitelaw), Springer, pp. 96-112, 1982.

[4] Eskinazi, S. and Erian, F. F.: Energy Reversal in Turbulent Flows, Physics of Fluids, Vol. 12, No. 10, pp. 1988-1998, 1969.

[5] Burattini, P., Leonardi, S., Orlandi, P. and Antonia, R. A.: Comparison between experiments and direct numerical simulations in a channel flow with roughness on one wall, J. Fluid Mech, Vol. 600, pp. 403-426, 2008.

[6] Beguier, C., Fulachier, L. and Keffer, J.: The Turbulent Mixing Layer with an Asymmetrical Distribution of Temperature, J. Fluid Mech, Vol. 89, Par. 3, pp. 561-587, 1978.

[7] Fabris, G.: Turbulent temperature and thermal flux characteristics in the wake of a cylinder. in *Turbulent Shear Flows 1* (ed. F. Durst, B. E. Launder, F. W. Schmidt and J. H. Whitelaw), Springer, pp. 55-70, 1979.

[8] Suga, K., Nishiguchi, S., Asano, H. and Kitada, M.: Application of the combination of an analytical wall-function and a realizable two component limit second moment closure to HVAC related complex turbulent flows, CMFF'09, The 14th International Conference of Fluid Flow Technologies, Budapest, Hungary, September 9-12, 2009.

[9] Čantrak, S.: Experimental Investigation of Statistical Properties of Turbulent Swirling Flows in Pipes and Diffusers, Fluid Mechanics and Turbomachines, 31, pp. 23-66, Karlsruhe, 1982 (in German)

[10] Gretler, W. and Baltl, M.: Numerical calculation of fully developed turbulent flow in curved channels: An extended algebraic Reynolds-stress model, Forschung im Ingenieurwesen, pp. 138-146, Springer-Verlag, 2000.

[11] Townsend, A. A.: *The Structure of Turbulent Shear Flow*, Cambridge University Press, London, 1976.

NOMENCLATURE

$\underline{U}$	mean velocity vector
$\underline{u}$	fluctuating velocity vector
P	mean static pressure
T	mean temperature
t	fluctuating temperature
U_i, u_i	mean and fluctuating velocities in the x_i direction ($i = 1,2,3$)
(x, y, z)	Cartesian coordinates
(x, r, φ)	cylindrical coordinates
U, V, W	mean velocities in axial (x), radial (r) and circumferential (φ) directions
u, v, w	fluctuating velocities in axial (x), radial (r) and circumferential (φ) directions
c_p	specific heat
k	thermal conductivity
$\langle \ldots \rangle$	time-average of …
$\underline{(\ )}$	vector
$\underline{\underline{(\ )}}$	second-order tensor

$\partial_i f = \partial f / \partial x_i$, $\partial_{ii}^2 f = \partial^2 f / \partial x_i^2$

Greek symbols

$\underline{\underline{\tau}}^R$	Reynolds stress tensor
τ_{ij}^R	Reynolds stresses
δ_{ij}	Kronecker delta
α	thermal diffusivity, $\alpha = k/(\rho c_p)$
α^R	eddy thermal diffusivity
ν	kinematic viscosity
ν^R	eddy viscosity
ρ	fluid density
∇	gradient operator
∇^2	Laplacian operator

Subscripts

B	Boussinesq model

ФЕНОМЕНИ НЕЛОКАЛНОГ ТУРБУЛЕНТНОГ ПРЕНОСА И НЕГРАДИЈЕНТНЕ ТОПЛОТНЕ ДИФУЗИЈЕ У КГХ СИСТЕМИМА

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Истраживање структуре турбуленције је неопходно за разумевање физике струјно-термодинамичких процеса у КГХ системима. Анализа и прорачун ових система засновани су на познавању турбулентног преноса и његовом моделирању. С тим у вези, у раду се анализирају феномени нелокалног преноса импулса и нелокалног преноса енергије топлотом у закривљеним каналима, асиметричним млазевима, вртложним траговима и вихорном струјању. Разматра се физика неградијентне турбулентне дифузије и негативне продукције у брзинским и температурским пољима. Утврђена је извесна аналогија између турбулентних процеса у овим класама струјања. Помоћу нумеричке обраде сопствених експерименталних резултата извршено је моделирање нелокалног турбулентног преноса у вихорном струјању.