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Actual Problems of Hydrodynamics at Internal Not-Isothermal Flows in Fields of Mass Forces

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1. Introduction

1.1 General characteristic of problems in an investigation of complicated conjugated turbulent flows

Almost all flows that represent practical interest are turbulent. Turbulent flows are always complex, three-dimensional, unstable in small and irregular. The main feature of turbulence is concluded in the intensive mixing caused by hydrodynamic pulsations. Turbulent fluctuations bring large contribution in transfer of momentum, heat and mass, and, hence, have defining influence on distributions of velocity, temperature and specific concentrations in all motion fields.

At present in connection with fast rates of computer facilities perfection the interest in methods of turbulent transfer modeling has considerably grown. As turbulence is influenced by many factors it is natural that the simple procedures of calculation including empirical formulas have considerably low chance of the realistic description. They are useful only to very specific, simple problems and give integrated information only, but not the details necessary for practice.

Full representation about turbulence characteristics can be received from multidimensional numerical calculations. However the majority of such calculations can be executed only with attraction of model approximations. There are various possibilities for the turbulence description: direct numerical simulation (DNS), large eddy simulation (LES) and the statistical modeling in terms of turbulence models.

Now because of restrictions in computer performance and memory DNS is possible only for flows with rather low Reynolds numbers. However DNS method is very useful in description of turbulent structure as it is capable to give the full information about the flow pattern and to participate in estimation of turbulent models efficiency. DNS application features can be found in [1, 2].

As a result of decision of problem connected with integration of Navier-Stokes equations by DNS methods, LES method had developed, in which flow scales larger than sizes of cells are calculated directly from the equations, and small-scale are subjected to modeling one way or the other. Papers using this ideology can be found in [3, 4]. This approach is also applied in investigation of practical problems. LES gives detailed enough picture and undoubtedly has good prospects for development in the near future.

At consideration of statistical fields (averaged fields) of required characteristics the momentum approach have recently received a wide distribution, and also a method of application of the approximate empirical relationships and purely heuristic assumptions which reliability has no doubts in some special cases. Unlike LES, statistical models of turbulence cover all spectrums of flow turbulent scales.

With the limits of momentum approach we can mark out 3 main ways of turbulence modeling. Two of them use the concept of eddy viscosity, suggesting turbulent Reynolds stresses $\overline{u_i' u_j'}$ proportional to average velocity gradients with coefficient ν_t (eddy viscosity) that defines turbulent transfer intensity. Third approach is based on direct calculation of Reynolds stresses from differential equations and known as full scheme of closure at second moment level. Models of first two types are zero-, one-, two-parametric ones, third type are models of Reynolds stresses transfer (RANS-models).

Application of eddy viscosity allows finding solutions, suitable only in concrete conditions. Complicated turbulent flow often met in engineering applications (combustion chambers of rocket engines, currents in aircraft engines, chemical lasers etc.), demand to use more generalized methods in modeling.

Practical requirements in studying of shear flows promoted formation of tendency to construct technological models of turbulent transfer containing transport equations for the one-point correlation moments of the second and third orders, and also some equations for the two-point moments. In this way practical requirements have allowed to escape from deeply empirical approaches to generally semi empirical RANS-models. Such models are essentially more reliable at studying phenomena in systems and devices with complex geometry, and also in the processes complicated with flow swirling. Insufficient approbation of these models defines necessity of their wide testing. The greatest contribution in investigation of this question has been brought by B.E. Launder, K. Hanjalic, W. Rodi, R.M.C. So, S. Elghobashi, N. Shima, V.A. Kolovandin, A.F. Kurbatsky, E.P. Volchkov, J.V. Lapin and others. From the viewpoint of reliable numerical techniques creation the majority of models do not look universal. The problem of multiple parameter model design is conjugated with expansion of experimental data bank containing data on turbulent structure which are inconsistent now.

In the present chapter the ideas of noted above authors are developed. All considered problems belong to the case of turbulent flows of inert and reacting gas mixes in channels, and developed mathematical models are based on use of essentially subsonic velocities approach. Within the limits of this approach pulsation of density are rigidly correlated with temperature fluctuations.

1.2 Stages of RANS-models construction

The basis of modern RANS-models has been put 40 years ago in works of J.C. Rotty [5], P.Y. Chou [6] and later B.I. Davidov [7, 8]. These investigations have defined the first stage of

RANS-models formulation, the critical analysis of which became possible only after ten years, with the invention of powerful computers corresponding these purposes. Publications of C.P. Donaldson [9], C.W. Hirt [10], B.J. Daley, F.H. Harlow [11] have defined second, qualitatively new stage in works on closure of Reynolds stresses equations. These investigations have convinced that difficulties of the numerical evaluation of all nonlinear differential transport equations in partial derivatives for turbulent stress tensor components are quite surmountable. And closure of flow governing equations is technically possible. From this time the active investigation on improvement of first RANS-models is in progress. It should finally finish with creation of a universal and reliable basis for calculation of wide spectrum of streams containing, in particular, flow curvature, separation, swirling, recirculated zones etc. This level of closure indeed provides the big flexibility and allows creating models, applicable in wide range of defining parameters variations. During the last years it became possible to predict some bright effects in complicated turbulent shear flows: occurrence of secondary flows in channels created by turbulence [12, 13], sensitivity turbulent near-wall fluxes to streamlines longitudinal curvature [14], etc. However we can meet works (for example, [15]) stating unsatisfactory description of flows with buoyancy forces in terms of RANS-models. Given results show it is necessary to search new approaches in closure methodology. Now some of models already get traits, corresponding to the new stage in carrying out of such works. There are already available results making conclusions about the evolution of Reynolds stresses in a developing shear flow.

The given work is focused on research of so-called complex turbulent flows. These are inert and chemically reacting swirled flows widespread in technique. Till now in such problems (for example, about mixing of internal swirled streams) turbulent models of eddy viscosity type were applied only. The considerable efforts [16–20] directed on overcoming of lacks of scalar viscosity models (the main ones are big inaccuracies of calculated size and intensity of recirculation zones in strongly swirled flows [16, 17, 21] and impossibility of calculation by means of various two-parametric models of the experimentally observed flow generated by a combination of free and forced eddies [16, 17]) have been undertaken. In the variety of two-parametric models $k\varepsilon$ - model of W.P. Jones - B.E. Launder [22] is the most popular, mainly because of its simplicity and small computer expenditures on its implementation. Indeed, many direct flows, particularly boundary layers and streams in channels with chemical reactions have been successfully calculated on the basis of $k\varepsilon$ - models [23]. Inconsistence of $k\varepsilon$-models in case of internal swirled flows is probably specified with defectiveness of assumption about the anisotropic character of turbulent transfer. In due time D.G. Lilley and N.A. Chigier [24] shown that in strongly swirled flows eddy viscosity cannot be considered as a scalar. Modifications of $k\varepsilon$ - models taking into consideration the anisotropy significantly increase calculations accuracy [25, 26], but not being universal. These models cannot be used in calculation of three dimensional flows.

In general it is expedient to pay attention to works on large eddy modeling [29, 30], and also on use of Reynolds stress transfer models [31, 32] because of presence of noted lacks of $k\varepsilon$ - models and models of eddy viscosity. In such models turbulent stresses are found out from the solution of model corresponding balance equations which are the equations in partial derivatives. Meanwhile calculated time essentially increases. It is connected with necessity of additional integration of at least six and more equations. More simple models with algebraic relationships for stresses (RSAM) which describe anisotropy without the above-stated costs, can serve in some cases as an intermediate link between *kε* - models and RANS-models. We will notice that application of RSAM has a success in calculations of the thin shear layers not complicated with strong swirled effects [17, 18]. By this time only a few applications of RANS - models to calculation of the swirled flows are known. Basically they concern streams [31, 32] where their application also has not been done without problems. In connection with stated above it is necessary to estimate perspectives of RANS - models and urgency of development and application of RSAM -models [33-37] for calculation of internal flows with and without swirling.

1.3 Shear flows in mass forces fields and features of its investigation

Two main properties of rotating flows allocate them into a special group of motions of liquid and gas: the *first* is a creation of centrifugal forces field suppressing action of gravity; the *second* one is modification of near-wall flow structure and transfer mechanisms in peripheral areas. These properties are purposefully used in design of swirling-type furnaces, combustion chambers, separators, hydro-cyclones etc. These mechanisms define recirculation, eddy core precession, power- and energy division.

The influence of rotation essentially changes turbulent momentum, heat and mass transfer characteristics. In this way, according to [36], in a rotated flow hydraulic resistance can exceed its direct-flow analogue in 5 times. Bibliographic analysis (in particular, [36-41]) allows to allocate questions of swirled streams stability investigation in separate group. For swirling-type devices using strongly twisted flows both average velocity field structure and turbulence structure appears insufficiently investigate.

The main difficulty in studying of swirled flows is connected with occurrence of spatial vortex structures, capable to change the intensity of exchange processes [37]. The character of swirled influence on a flow depends on the way it is created. A variety of swirled ways (rotating pipe, vane twirlers on channel inlet, tangential gas admission, tape and screw twirlers etc.) complicates the process of experimental data generalization and creates problems in analysis of transfer mechanisms. In this connection in applications it is possible to meet criterial dependences received as result of generalization of given concrete experiments, but excluding some effects found out in experiment with another swirler. In such cases the reference to mathematical model is especially valuable.

Numerous investigations of the swirled flows in internal systems should be divided into two groups depending on whether rotation is created by walls of a pipe or provided with the device located on inlet of a channel. The given classification is convenient both for laminar and turbulent rotating flows which are analyzed in the given chapter.

1.4 Main purposes of investigation

The chapter is devoted to discussion of results of complex physico-mathematical and numerical modelling of hydrodynamics and heat transfer of strongly swirled internal laminarising flows. The purpose is to establish relationships of swirled decay on channel length and reconfiguration of rotating non-isothermal flows in direct-flow in technical devices with any configuration of a wall.

Besides, research objectives are focused on the following problems:

- Possibilities of detailed studying of complex shear flows are shown on the basis of the analysis and generalization of the modern data of theoretical and an experimental research of spatial laminar and turbulent flows in pipes and channels with/without mass centrifugal forces and with attraction of statistical second-order turbulence models (full transport equations for the one-point homogeneous and mixed correlation second-order moments of velocity and scalar field pulsations; algebraic models for Reynolds's stresses and specific turbulent heat fluxes (F. Boysen, E. Erdogan), and also separate two-parametrical models with transport equations for dissipation characteristic times of thermal and dynamic fields (C. Spezial, T.P. Sommer, R.M.C. So), integral scale of energy containing eddies (G. Glushko, S. Kharlamov) turbulence kinetic energy dissipation (B. Launder, B. Sharma) [42-46].
- Develop an effective and universal numerical procedure for calculation of non-isothermal flows of viscous media in channels with complicated wall in conditions of various swirled ways.
- Investigate details of developing swirled and direct-flow non-isothermal flows in pipes with sudden expansion, confuser-diffuser sections with rotating and stationary wall.
- Create a database of exact quantitative distributions of average and pulsating parameters of the specified above channel configurations.

It is necessary to notice that numerical investigations of problems are executed with attraction of the original technique including modern and seldom used in practice of applied researches statistical second-order turbulence models with transport equations for full Reynolds stress tensor components, specific scalar turbulent fluxes, and also some two-parametrical models with differential equations for dissipation characteristic times of thermal and dynamic fields. Ideas of combined SIMPLE algorithm [47] and splitting method on physical processes [48, 49] are the purpose for optimization and decrease of time expenses for convergence of numerical algorithm in calculations of intensive reverse flows. Moreover the last algorithm represents generalization of L.M. Simuni' ideas [50, 51] for the case of swirled flow.

By means of the given technique problems of laminar and turbulent direct and locally swirled at inlet flow and heat transfer in constant and variable (on pipe length) cross-section of pipe rotating around its longitudinal axis are solved.

In the chapter it is reported on calculated results of problem about turbulent flow of liquid and gas and heat transfer in pipes including confuser-diffuser sections with constant and moved wall in order to illustrate the ambiguity and specificity of influence of swirled way on flow structure and to extend conceptions about the application field of favorable properties of rotating flows in technological processes

Let's notice that the choice of given configurations of convective heat transfer is caused by their wide spread in industrial devices. Besides, researches of kinematic and heat- and hydrodynamic characteristics distributions for the specified modes is important from the point of view of operated technological process organization.

1.5 Scientific novelty of the obtained results is following:

- Computing procedure of the direct-flow and swirled laminar and turbulent isothermal and non-isothermal flows of liquids and gases in pipes and channels is developed on the basis of SIMPLE algorithm and the generalized Simuni's method for case of variable in a radial direction longitudinal pressure gradient;

- Numerical modeling of complex shear flows in pipes is carried out with following motion conditions:
- A variable on pipe length cross-section area (sudden expansion, narrowing);
- With account of rotation: a local swirled method in the input field and moved wall (rotation of a pipe around the longitudinal axis);
- Heat carrier through confuser and diffuser sections with stationary and rotating wall.
- Substantiation and introduction in practice of swirled turbulent flow calculations under second-order multiple parameter models with transport equations for dissipation time scales of thermal and dynamic fields, integrated scale of turbulence is executed.

1.6 Practical importance

In this work it is presented scientific and technical information on distributions of temperature and velocity fields and its correlations in basic realization schemes of swirled flows in internal systems which are of great importance at testing and calibration of complicated program complexes for modeling of the spatial flows used for engineering calculations. It is important for creating new technological processes and devices for intensification of flows and heat transfer in power systems and industrial-scale plants.

1.7 Reliability of investigation results

Validity of scientific conclusions and summaries presented in this chapter follows from adequacy of used mathematical models and methods of numerical computation. It is proved by experimental results and theoretical data of other authors and calculations with use of commercial software packages.

2. Complex simulation of swirled turbulent flows in channels at any configuration of wall

One of early studies of swirled laminar flow structure was F. Levi's work [37-41] executed in 1929. Subsequently the data obtained by V.M.Kasyanov [52], V.I. Kravtsov [53], A.White [54], G.Y.Kuo [55] and others, has allowed to establish some general laws of wall influence on flow characteristics. It is found out: a steady rotating near-wall layer; flow non-rotative core; a reverse flow zone about a wall (high rotation velocities of pipe, constant flow rate), elongation of axial velocity profile along the axis and also decrease in thermal and dynamic flow influence on a wall. More complex structure is formed by rotating walls in annular channels - there are specific zones of separation [56, 57] and vortexes sliding on wall.

In process of perfection of experimental base and computing facilities it began possible to perform research of swirled turbulent flows at a qualitatively new level. This level is prepared by efforts of many experts. In Russia these scientists are V.K. Schukin [58, 59], A.A. Khalatov[60], V.E. Nakoryakov [61-63], A.M. Lipanov [64-67], E.P. Volchkov [68-70], S.V. Alekseenko [71-73], P.I. Geshev [74-76], V.V. Salomatov [77], V.M. Fomin [78-80], A.R. Dorokhov [81-84], V.A. Arhipov [85]; in the world - D.G. Lilley [24, 86], A.K. Gupta [37], M.T .Abujelala [86], K. Kikuyama [87-90], B.E. Launder [91] and other. The analysis of bibliographic data on swirled flows (for example, [37, 60, 92, 93]) shows: 1) the special role is played by anisotropic spatial vortex structures of screw structure in transfer processes at presence of swirling; 2) full research of various swirled modes is necessary despite relative progress in understanding of the phenomena in swirled flows (e.g. vortex disintegration, mixture and burning delay etc.); 3) there is no uniform full position concerning influence of buoyancy forces, chemical reactions and the form of walls of channel on mechanisms of turbulent transfer of mass, momentum and heat in swirled flows; 4) works on model elaborations of a turbulent transfer and flexible and economic numerical methods are actual; 5) two-parametric models of kε and κL type, modified on rotation and using of S. Patankar's algorithm are very popular in numerical calculations and technical applications [47, 94]; 6) it is possible to establish and explain distinctive features of swirled flow in short pipes, knowing laws of distribution of average velocity, pressure and pulsating characteristics fields; 7) we can observe obvious deficiency of reliable experimental data containing detailed information on swirled lows. It is explained by imperfection of existing measurement methods and ways of processing of the received results; 8) the good tool for the analysis of swirled flows are models with differential transport equations for Reynolds stress tensor (RANS-models).

Swirled flows are often take place in channels of variable cross-section (e.g. pipeline networks with confuser-diffuser sections, inserts of sudden contraction/expansion, combustion chambers (CC)) for maximization of factor of fuel combustion completeness, stabilization of combustion, intensification of transfer processes of heat, mass and momentum in allocated areas on length of power devices. Necessity of processes intensification leads to necessity of application of swirling various configuration (e.g. with rotary guide blades). Presence of such adaptations frequently complicates modeling process of transfer phenomena. Thus, in [95] author marks formation of two backflow zones at channel axis, one of them is in immediate proximity from the swirler, and the other - at some removal. Considering small size of the first backflow zone and insignificance of axial velocity component between zones it has been noticed that such flow picture can be defined only by the swirler design [96] which is widely used in modern CC. In [97] it is also shown that swirler's blades' curvature considerably influences the sizes of recirculation zones. The sizes and location of backflow zones define CC qualitative characteristics. It is well-known the basic part of a combustible mixture burns down in these zones. When fuel particles have not time to burn down in backflow zones, we can obtain redistribution of high temperatures in CC. It is necessary to investigate features of the swirled flow in details in order to learn how to operate correctly work of such devices. That's why the mathematical modeling is more widely used at recent times at studying of flows in CC [37, 98].

However, flows in real CC are three-dimensional and multiphase, chemical reactions accompanied by radiation. It is difficult to model all these processes in complex consequently simplified models [99]. The factor raising requirements to modeling of turbulent momentum flux in CC is correct calculation of recirculation areas. These areas are characterized by a strong flow curvature, presence of complicated vortex structures, high intensity of turbulence caused by existence of internal shear layers. Complexity of flow inside and near to recirculation area opposes experimental investigations - it is indicated by absence of the wide and full measurement results in literature. The majority of works available now [100] contains data on the measured integral parameters, such, as length of recirculation zone [101] or heat-transfer coefficient along considered section [102]. It is necessary to notice that near-wall flow in recirculation zone differs from classical turbulent flux in boundary layer in many aspects: pulsating velocity profiles has no maximum in boundary area [103-105]; in profiles of average velocity there is no logarithmic layer where the usual parity between average velocity, distance to wall and dynamic velocity (so-called law of wall [103, 105-108] would take place); values of Reynolds shear stresses are small near to a wall [106, 109]; generation and transport of turbulence kinetic energy in near-wall area are insignificant [107].

2.1 Some general summaries on hydrodynamic investigation of complicated shear conjugated and swirled flows

1. Axisymmetric swirled liquid flow experiences both stabilising and destabilising action caused by swirling. Let's explain this statement. Stabilization effect is connected with occurrence of additional turbulence destruction, destabilizing action is caused by curvature of average flow characteristics' profiles under swirling influence. A characteristic example of interaction between zones with stabilizing and destabilizing effects is flow in axially rotating channel. Thus, in inlet area, because of small thickness of boundary layer, rotation of liquid quickly decreases from the maximal values at the wall of rotating pipe to zero out of boundary layer. Near the wall because of high values of average tangent shear additional turbulence generation (destabilizing effect of rotation) takes place. Down flow formation of completely developed flow mode with constant inclination of a full velocity vector to flow axis leads turbulence generation by tangential velocity component equals zero (effective area of stabilizing effect). Between the areas specified above there is the transformation zone which size depends on a number of parameters, among them are ones characterizing the entering flow, and Reynolds number. The similar facts are resulted in [45, 87-90] where it is also noticed that in rotating channel flows because of discrepancy of average stress and shear surfaces nonzero distributions of turbulent shear stress are formed.

Investigation of full friction coefficient $\left|\tau_w\right| = (\tau_{xr}^2 + \tau_{r\varphi}^2)^{0,5}$ behavior shows that the role of tangential frictional component $\tau_{r\varphi} = \mu r \left.\frac{\partial (W/r)}{\partial r}\right|_{r=R}$ becomes appreciable at swirling parameter Ro>0.5, increase in friction with Ro growth can be significant (up to 4-5 times) already beginning from Ro>0.5 under moderate Re ($Re \geq 5 \cdot 10^4$).

2. The basic distinctions in qualitative and quantitative estimations of swirled flow parameters, executed till recent times, have been connected with unbalanced modeling. In many models effects of rotation were considered by means of updating relations defining mixing length, and no references to pulsating structure analysis have been done. However, only average momentum equations are not enough of the description of rotation effects. That's why application of RANS-models is reasonable.
3. At superposition of rotation on axial flow the stream becomes essentially anisotropic (diagonal elements of Reynolds stress tensor significantly differ and transversal turbulent momentum transfer begin to quickly disproportionally grow in comparison with transfer in other directions).
4. Strong flow rotation leads to reduction of turbulence intensity in a flow core in comparison with direct-flow, its simultaneous intensification in near-wall areas takes place.

5. Flow rotation changes condition of initially isotropic turbulence.

In summary it seems suitable to make notice concerning prospects of turbulent swirled flows modeling which is shared by many experts both in Russia and abroad. Thus, according to C.G. Spezial [110], no any of known closure models of second order can truly predict nature of turbulent developing flow with strong rotation (Ro>> 1). Authors of some latest works (for example, [111]) are not so categorical in estimations of the given approach, though as a whole they confirm necessity of updating known versions of the complicated RANS-models. Our point of view is that full universality from RANS-models certainly cannot be demanded, however, works on the further universality of these models are necessary as they are the unique tool for studying complex shear flows. But experimental analysis of these complicated flows is complicated or impossible.

2.2 Heat transfer in swirled flows and its estimation in technical applications

Early studies of heat transfer in swirled flows, carried out more than seventy years ago, have shown possibility of its essential intensification. The large quantity of works on heat transfer in single-phase swirled flows is executed to the present time. Detailed bibliography representing foreign publications, is given in [112], Russian- in [113-120]. A number of successful criterial dependencies for heat transfer calculation in single-phase media can be found in [113-120]. Note worthily that heat transfer problems in laminar swirled flows are presented not so widely, as in turbulent ones. Publications of last years on heat transfer intensification in laminar mode in internal systems show [121-123] that in particular cases increase in heat exchange reaches 200–400 % (a wire spiral section [122], screw rolling on [123] etc.) in comparison with smooth tube, and the effect of intensification amplifies with reduction of step and height growth of rolling-on and wire helix. Presence of such features on the internal surface is capable to form laminar mode with macro eddies and cause intensification up to 700 %.

The insufficient number of criterial dependencies used for the estimation of heat transfer in laminar flow, and its discrepancy [121], leads to actualization of construction of universal relation of following kind:

$$\mathrm{Nu}=f(\mathrm{Re}, \mathrm{Pr}, \mathrm{Gr}, l/R, \mathrm{Ro}, \mathrm{K}_{\text{ц}}), \quad (1)$$

where $\mathrm{Re}=U_0D/\nu$, $\mathrm{Pr}=\nu/a$, $\mathrm{Gr}=g\beta\Delta Tl^3/\nu^2$, $\mathrm{Ro}=W_0/U_0$, $\mathrm{K}_{\text{ц}}=\Omega W/g$ ($\mathrm{K}_{\text{ц}}$ considers influence of centrifugal forces field on liquid flow nature caused by its density variability).

Results of experimental investigations of flows in rotating pipe [124] have shown that increase in heat exchange caused by rotation is well characterized by dependency:

$$\mathrm{Ko}=\mathrm{Nu}/[\mathrm{Pr}^{0,43}\,\mathrm{Gr}^{0,1}(\mathrm{Pr}_l/\mathrm{Pr}_w)^{0,25}\varepsilon_l], \quad (2)$$

where ε_l – correction, depending on relation between longitudinal $(\frac{UD}{\nu})$ and rotational $(\frac{\Omega R^2}{\nu})$ Reynolds numbers, indices «l», «w» in Prandtl criteria correspond to liquid and wall respectively.

For a viscous-gravitational mode it was possible to generalize experimental data and to find Ko, entering in (5) in the form $Ko/Ko_0 = f(Ro, K_{П})$ which, despite its proximity, works with success in heat transfer analysis of electric machines with flow cooling:

$$Ko/Ko_0 = 1{,}75 \cdot K_{ц}^{\;0,18} \cdot Ro^{0,33}, \tag{3}$$

where index "o" corresponds to absence of rotation.

From (3) follows [124] that influence of rotation effects, connected with Rossby criterion Ro, on heat exchange is stronger, than effects of centrifugal displacement.

Special role of centrifugal forces in intensification of convective heat exchange of swirled turbulent flow was marked also in [125, 126]. Analysis of experimental data [126] shows that turbulent self-similar flow in swirled conditions appears at much smaller Re values, than at direct-flow liquid motion in cylindrical pipe.

Heat transfer in damped turbulent flow in pipes with a twisting insert of constant step, investigated in [120], needs construction of criterial dependencies, uniform for direct-flow and swirled streams. In such parities we use Reynolds's effective number

$$Re^{*} = Re \cdot [1 + (W/U)^2]^{0,5} = Re \cdot (1 + tg^2\alpha)^{0,5}, \tag{4}$$

where U – bulk velocity, W – tangential velocity.

In conditions of $Pr \approx 1$ and when assumptions about energy dissipation neglection are fair, i.e. similarity of velocity and temperature fields of swirled flow takes place, heat transfer is defined by boundary layer condition. Therefore, it is expedient to search for correlation of Nusselt number Nu and friction factor with Re^* that according to [120] look like

$$Nu = 0{,}021 \cdot (Re^{*})^{0,8} \cdot Pr_f^{0,45} \cdot \left(\frac{Pr_w}{Pr_f}\right)^{0,25}; \quad \varsigma = 0{,}316 \cdot Re^{*-0,25} \tag{5}$$

These dependences are good enough correlate with experimental data [127]. Influence of additional turbulization is considered in the mentioned work. Measurements are performed on water and liquid metal at $Re=10^4 \div 5 \cdot 10^4$, rolling-on step S=50÷238 mm, and are carefully described by following relation (M.A.Mikheyev's transformed formula with additive ε_l):

$$Nu = 0{,}021 \cdot Re^{0,8} \cdot Pr_f^{0,43} \cdot \left(\frac{Pr_w}{Pr_f}\right)^{0,25} \cdot \varepsilon_l, \tag{6}$$

$$\varepsilon_l = 1 + A \cdot \left(\frac{D}{S}\right)^n / Re^m. \tag{7}$$

where A, m, n are constants ($A=1.13 \cdot 10^5$, m=1.2, n=1).

Throughout experimental researches of strongly swirled decay turbulent flows in [118] for air heat transfer in a cylindrical pipe with swirl chamber on inlet the following formula is offered

$$\mathrm{St} = 0{,}047 \cdot \mathrm{Re}_x^{-0,2} \cdot \mathrm{Pr}^{-0,6} \cdot (\cos\varphi_0)^{-0,6}, \tag{8}$$

where St= $\alpha_x / (\rho c_p U_{av})$ – Stanton number, U_{av} – averaged gas velocity, φ_0 – twist angle. Underline that (11) is quite satisfactory in range: $\mathrm{Re_x}=10^5 \div 10^6$.

The works noted in this paragraph in the majority are experimental. Theoretical results can be found in [119, 128, 129]. Thus, in [128] heat transfer characteristics of turbulent decay swirled flow are analytically investigated. Swirling is carried out by means of short profiled plates placed on workspace inlet. On the basis of solution in the form of series of swirled flow equations obtained from the Navier-Stokes equations with application of asymptotic analysis, the following dependencies for heat transfer characteristics are defined:

$$\alpha_x = \frac{\lambda}{D}[0{,}023(c_\alpha \mathrm{Re})^{0,8} \cdot \mathrm{Pr}^{0,4} + 0{,}114 \cdot (2 \cdot W_w^2 \cdot \mathrm{Re}^2 \cdot c_\beta \Delta T \cdot \mathrm{Pr})^{0,5}] \cdot (\frac{T_w}{T_{av}})^{-0,5}, \tag{9}$$

where α_x – heat transfer coefficient; λ – heat conductivity coefficient; D – channel diameter; Re, Pr – Reynolds and Prandtl number; ΔT и T_w / T_{av} – temperature drop and temperature factor respectively, $c_\alpha = (U^2 + W^2)^{0,5} / U$ (U, W – dimensionless local axial and circumferential velocities), c_β - volumetric thermal-expansion coefficient, W_w – dimensionless local tangential velocity on the wall, obtained by extrapolation of W values on the wall through the viscous sublayer, T_{av} – average gas temperature.

Heat transfer in short rotating channel under $\mathrm{Re}_T^{**} = idem$, according to [130], can be successfully forecasted with relation:

$$\mathrm{St}/\mathrm{St}_0 = \Psi_T \Psi_\varphi \tag{10}$$

where St_0 – Stanton number for non-gradient isothermal flow, St – Stanton number under current conditions, ψ_T, ψ_φ - non-isothermal and rotational indicators.

Noteworthy that the law (10) generalized for inlet part of rotating pipe transforms into dependency:

$$\mathrm{St} = \frac{0{,}012(1 - 0{,}715 \mathrm{Re}_\varphi / \mathrm{Re}_{in})}{\mathrm{Re}_T^{**0,25} \, \mathrm{Pr} \, \psi_W^{0,5}}, \tag{11}$$

where Re_φ – Reynolds number calculated with use of pipe rotation velocity, Re_{in} – with use of averaged bulk velocity, Re_T^{**} – with use of energy thickness of boundary layer, $\Psi_W = T_w/T_0$ – temperature factor. Under $\Psi_W = 1 \div 3$, $\mathrm{Re}_\varphi/\mathrm{Re}_{вх} = 0 \div 1$ in first approximation we obtain

$$\Psi_\phi = 1 - 0{,}715 \frac{\mathrm{Re}_\varphi}{\mathrm{Re}_{in}}, \Psi_T \approx \frac{2}{\Psi_W + 1}. \tag{12}$$

Calculations of $\mathrm{St}/\mathrm{St}_0$ according to the suggested relations show that in range $\mathrm{Re}_\varphi/\mathrm{Re}_{вх} = 0 \div 0{,}8$, there is small nonlinear dependency of the complex from $\Psi_\varphi \approx f(\frac{\mathrm{Re}_\varphi}{\mathrm{Re}_{вx}})$. Agreement between calculated and experimental data is satisfactory.

In conclusion of the short bibliographic analysis of the problem let's notice that relaminarization effects in rotating technical systems and its behavior at extreme operating conditions have not received sufficient illumination in the class of prediction problems of flows complicated by swirling. Last three decades are noted by interest growth in research of "fine" structure of decay rotating and direct-flow streams in devices with complex boundary. As well as in construction of adequate mathematical models of continuous media dynamic behavior, in creation of new effective detection and calculation procedures of nonlinear effects in technological processes complicated by swirling and changes of working substance structure.

3. Laminar direct and swirled flow and heat transfer investigation in pipes and channels with complicated boundary

3.1 General physical and mathematical problem definition

There are investigated non-isothermal flows of an incompressible liquid and weakly compressible gas in pipes with variable cross-section under the influence of mass forces caused by both local swirling of a stream in inlet and swirling caused by pipe rotation around its longitudinal axis. The following equations representing conservation laws of mass (1), momentum (2) - (4) and energy (5) which in axisymmetric statement and cylindrical coordinate system is presented for modeling of such flows and heat transfer:

$$\frac{\partial U}{\partial x}+\frac{1}{r}\frac{\partial (rV)}{\partial r}=0; \tag{1}$$

$$\frac{\partial}{\partial x}\left[\rho UU-\mu\frac{\partial U}{\partial x}\right]+\frac{1}{r}\frac{\partial}{\partial r}\left[r\left(\rho VU-\mu\frac{\partial U}{\partial r}\right)\right]=-\frac{\partial p}{\partial x}; \tag{2}$$

$$\frac{\partial}{\partial x}\left[\rho UV-\mu\frac{\partial V}{\partial x}\right]+\frac{1}{r}\frac{\partial}{\partial r}\left[r\left(\rho VV-\mu\frac{\partial V}{\partial r}\right)\right]=-\frac{\partial p}{\partial r}+\left\{\rho\frac{W^2}{r}-\mu\frac{V}{r^2}\right\}; \tag{3}$$

$$\frac{\partial}{\partial x}\left[\rho UW-\mu\frac{\partial W}{\partial x}\right]+\frac{1}{r}\frac{\partial}{\partial r}\left[r\left(\rho VW-\mu\frac{\partial W}{\partial r}\right)\right]=\left\{-\rho\frac{VW}{r}-\mu\frac{W}{r^2}\right\}; \tag{4}$$

$$\frac{\partial}{\partial x}\left[\rho UT-a\frac{\partial T}{\partial x}\right]+\frac{1}{r}\frac{\partial}{\partial r}\left[r\left(\rho VT-a\frac{\partial T}{\partial r}\right)\right]=S_T; \tag{5}$$

Designations are standard in notation of the equations (1) - (5).

Solution of governing equation system (1) - (5) is carried out with attraction of numerical technique based on combined SIMPLE algorithm and method of simultaneous finding of longitudinal pressure gradient with a velocity field, originally offered by L.M. Simuni [50] and generalized on a case of its variability in radial direction [45, 51] for research of spatial deformed flows caused by swirling and/or expansion/narrowing of cross-section section. In the given chapter problems of laminar direct-flow and swirled flow and heat transfer with walls in pipes and channels with any configuration of boundary wall are considered.

The matter of technique is following. Calculated workspace is covered by finite-difference spaced grid. Functions T, U, V, W and pressure correction are calculated according to standard SIMPLE procedure with implementation of upwind scheme and TDMA method.

Discrete analogs are calculated by variable direction method which uses TDMA method on each step for the solution of system of linear algebraic equations.

Complicated pipe geometry definition is made on a uniform grid by switched off control volume approach so that the remained operating control volumes made considered irregular area.

The way of blocking of unnecessary control volumes consists in defining of great values for source components in discrete analog. Thus it is probably to assign known value (e.g. for velocity value a zero or for temperature T_w) in the switched off control volumes.

In conditions of combined algorithm we accept that numerical integration of governing equation system and closure equations (for turbulent flow) is performed on the basis of economic implicit finite-difference schemes of second order accuracy for axial and radial coordinate steps, splitting schemes both for independent variables and physical processes and TDMA method. In a radial direction we use grid concentration under the logarithmic law that provides high resolution of the grid in near-wall areas. The features of given algorithm consist in the following. For cases of small swirled intensity, small heights of the ledge (when there is no reverse flows) the marched method is used. Further this algorithm is generalized on modes with high intensity swirling, but its essence, still, consists in allocation of marched variables and in simultaneous calculation of velocity field and pressure gradient. As a result the algorithm generalizing ideas of L.M. Simuni does not concede in calculated speed to algorithms of the numerical solution of two-dimensional boundary layer problems.

The idea of sharing of SIMPLE algorithm with generalized algorithm of L.M. Simuni is defined by necessity of optimization and decrease of time expenses on numerical decision convergence at intensive reverse flows in channels with high values of swirl intensity (Ro), flow velocity (Re), ledge heights (h/d). So, in the areas where there are features caused by reverse flows, calculation is carried out with SIMPLE algorithm, in other areas - with L.M. Simuni's algorithm. Calculations show that this combined method demands less time in comparison with original SIMPLE algorithm when obtaining steady solution of intensively swirled non-isothermal flows in pipes and channels with complicated boundary.

Possibilities of numerical algorithm are illustrated with some test examples, each of them serves for correct estimation of flow calculation under the influence of one of the factors – flow swirling at the inlet and in rotating pipe, as well presence of separated flows caused by channel irregular geometry. We notice that the offered numerical algorithm is tested on numerous flows.

3.2 Results of flow and heat transfer calculation in cylindrical pipe locally swirled in flow inlet region

Boundary conditions for governing equations integration are following:

At the inlet into the pipe the uniform profile of velocity axial component is set, flow swirled is carried out under the law of solid body. The temperature of entering stream is constant and equals T_0:

$$U|_{x=0} = U_0;\ V|_{x=0} = 0;\ W|_{x=0} = W_0 \cdot \frac{r}{R}\left(1-\left(\frac{r}{R}\right)^m\right);\ T|_{x=0} = T_0; \tag{6}$$

Here values of U_0 и W_0 are defined from dimensionless parameters of Reynolds ($Re=U_0{\cdot}D/\nu$) and swirling intensity ($Ro=\Omega{\cdot}R/U_0=W_0/U_0$). Value of exponent *m=const*.

At the wall - equality of velocity vector components to zero. The temperature on a wall is accepted constant and equal T_w. *On an exit* - "soft" boundary conditions (equality to zero of derivative all sizes in an axial direction) are set.

At the axis - symmetry conditions: equality of axial velocity and temperature derivative in radial direction to zero; equality of radial and tangential components of velocity vector to zero.

In this part results are presented for wide range of flow parameters: Re=10-1000 and Ro=0-20. It is shown that local entrance swirling gives central recirculated zones (fig.5). Zones of returnable flows are characterised by swirling parameters and Reynolds number (fig.1).

There are big losses of pressure in comparison with a direct-flow flow at increasing of coefficient friction on a pipe wall (fig.2), caused by additional shear stress in the swirled flow. Distributions of Nusselt number (fig.3) and temperature fields (fig.4) show heat transfer intensification on an initial site of a pipe with increase of flow swirling.

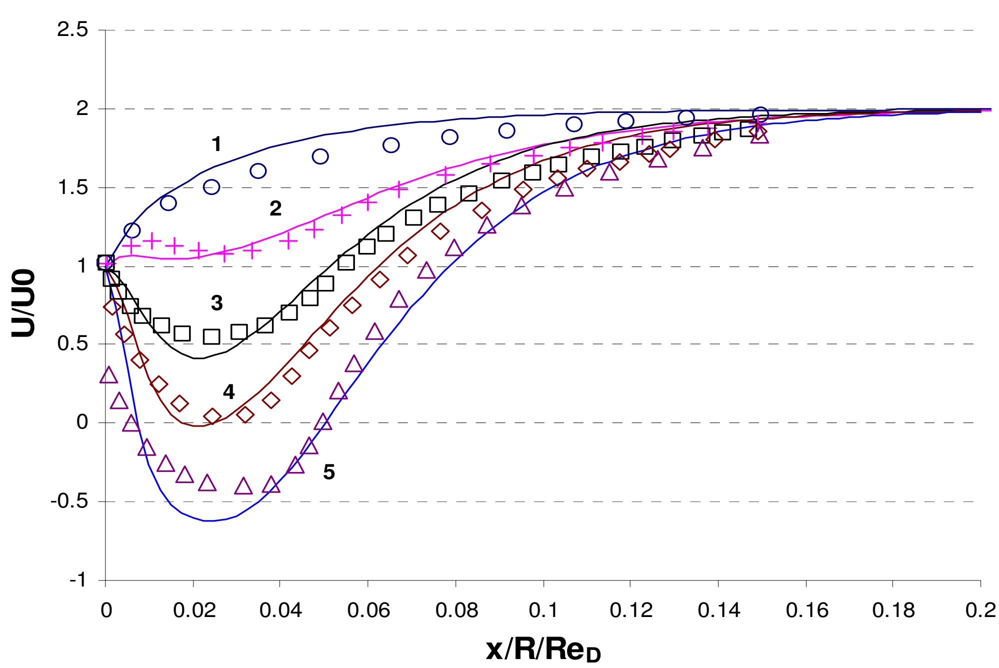

Fig. 1. Distribution of relative axial velocity U/U_0 versus normalized length ($x/R/Re_D$) at various values of swirling parameter $Ro = \Omega\ R/U_0$. Lines are calculation, symbols are Shnajderman M. F and Ershov's A.I data [131]: 1-Ro=0; 2-2; 3-3; 4-4; 5-6.

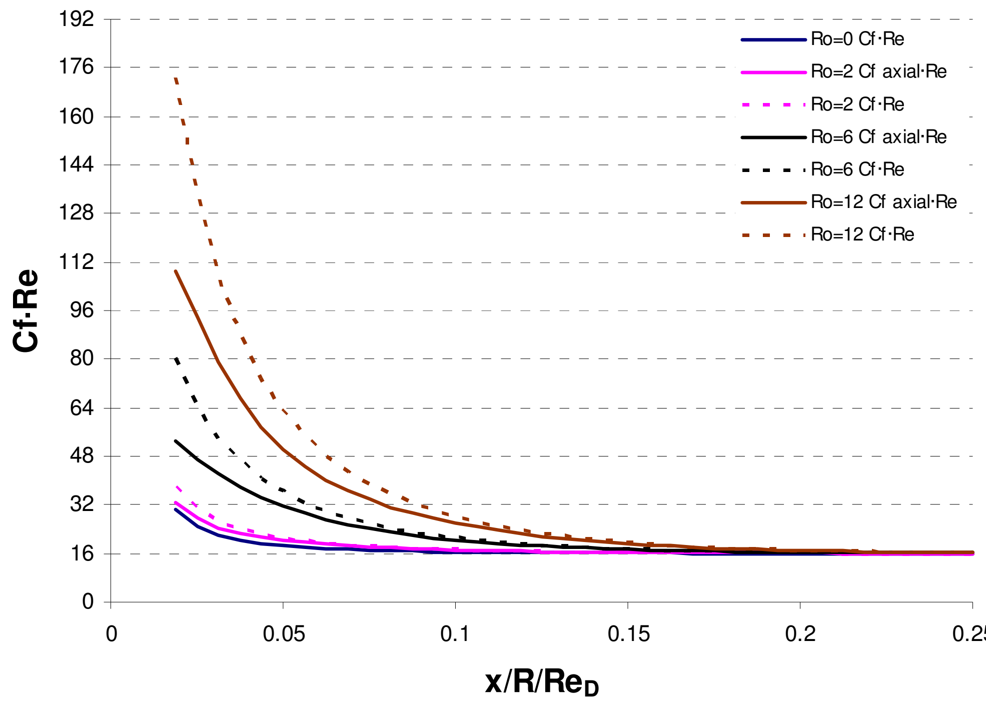

Fig. 2. Distribution of full coefficient friction (dotted lines) and coefficient friction with the account only axial component of velocity (solid line) versus the normalized length of the channel ($x/R/Re_D$) at various swirling. (This is local swirling on an input).

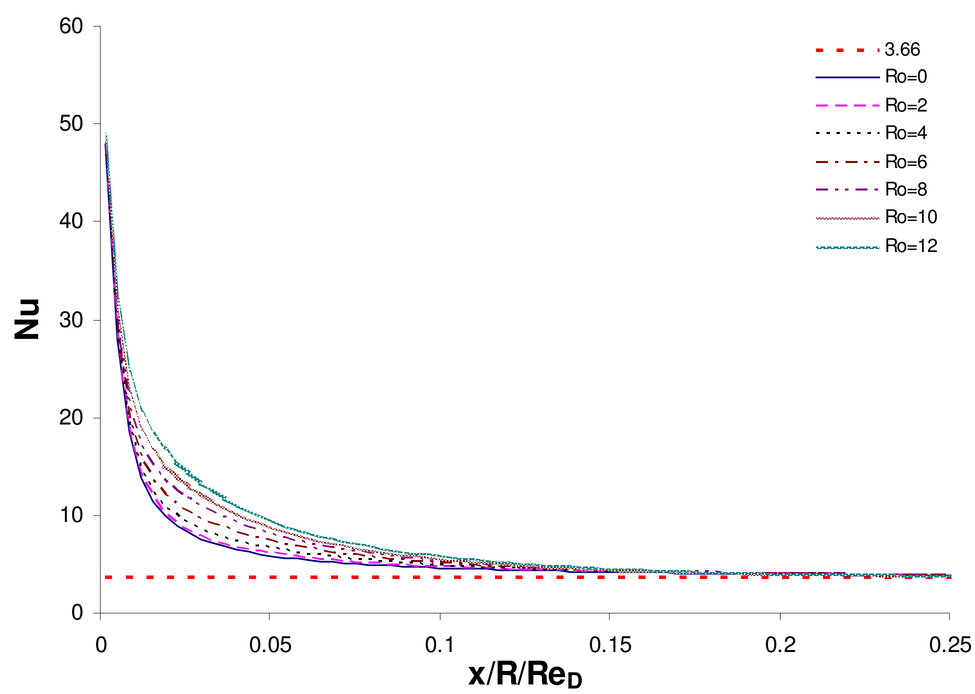

Fig. 3. Distribution of Nusselt number versus swirled parameter and normalized length of the channel ($x/R/Re_D$). (Data is local swirling on an input).

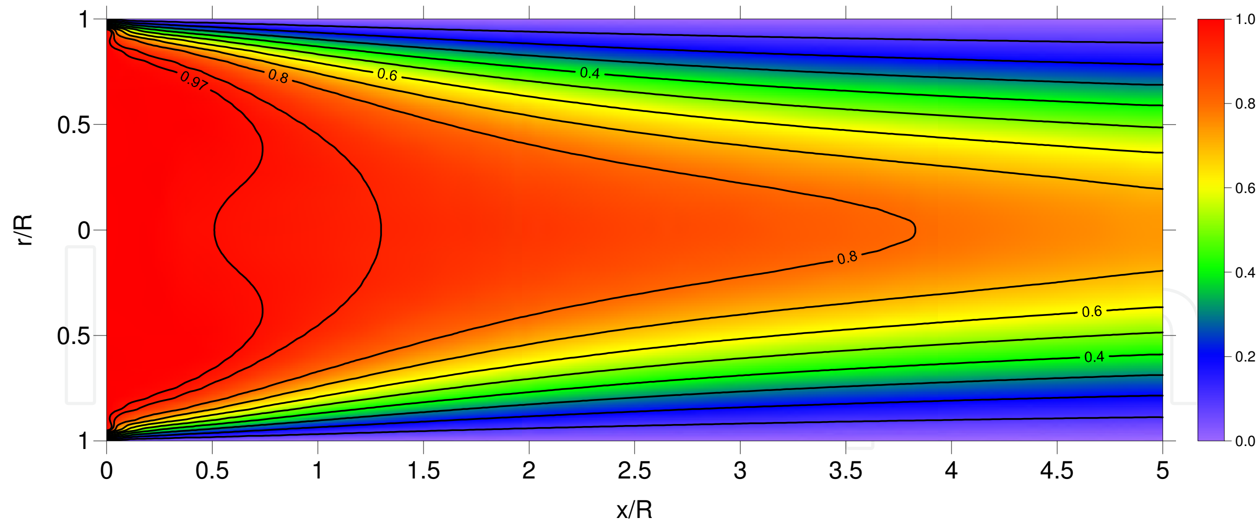

Fig. 4. Isolines and a field of temperature values $(T-T_w) / (T_0-T_w)$ at Re=20 and Ro=10

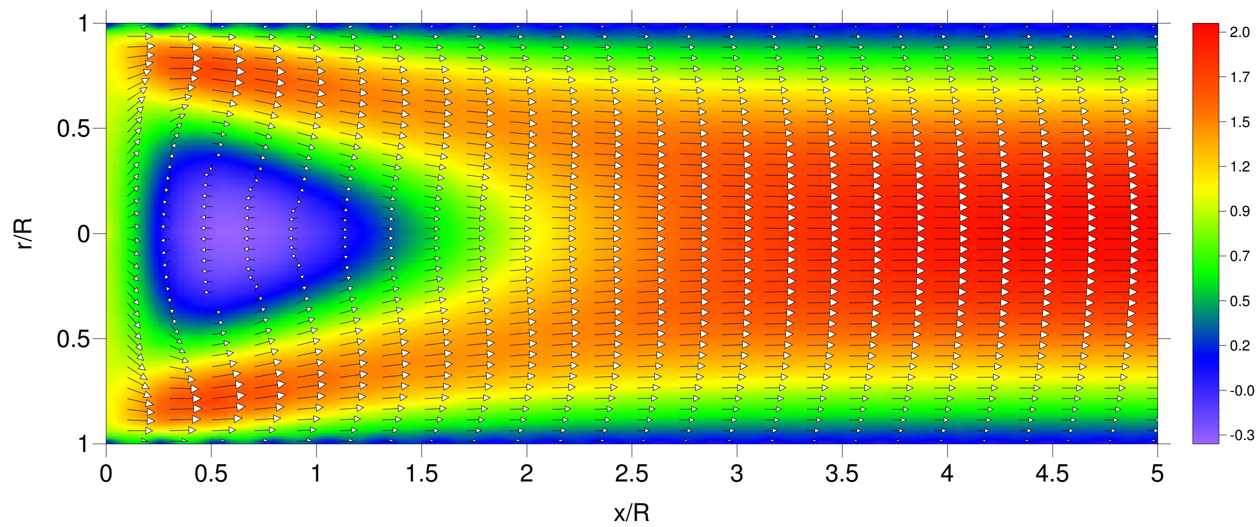

Fig. 5. A field of values of axial components of velocity U/U_0 (colour) and a vector field of a flow (arrows) in the channel with local swirling on an input (Re=20 and Ro=10).

3.3 Research of flows in rotating pipes

Let's notice, that data about influence of swirling on hydrodynamics in the conditions of complex shear flow are small and inconsistent. Nevertheless, it is possible to establish some general properties of flows in pipes with a rotating wall round the longitudinal axis. Interest to similar flows is caused by organisation of laminarizing flows under the influence of rotating effects and keeping of heat transfer extensification mode on lengthy sites.

For the purpose of explanation of details of such process problems about a laminar flow and heat transfer in pipes were originally solved.

The formulation of boundary conditions in such problem is reduced to the following. *At the input*: there are the developed profile of axial component of velocity vector and absence (equality to zero) of radial and tangential components of velocity. T_0 is flowing stream uniform temperature.

$$U\big|_{x=0} = 2 \cdot U_0 \left(1 - \left(\frac{r}{R}\right)^2\right); \;\; V\big|_{x=0} = 0; \;\; W\big|_{x=0} = 0; \;\; T\big|_{x=0} = T_0; \qquad (7)$$

At the pipe wall we have conditions of absence of axial and radial components of velocity vector at $r=R$. Tangential velocity component on a wall is equal to pipe velocity rotation W_0. *At the exit* there are "soft" boundary conditions, *at the axis* - symmetry conditions.

Calculation procedure included actions with consecutive working off of blocks: the decision of a problem on isothermal and not-isothermal flows with constants and variables thermo physical properties in a range of defining parameters- Re=10-1000, Ro=0-12.

Comparisons with available calculated data (fig.6 and fig.7) and their analysis allow doing following conclusions:

- flow in a rotating pipe is characterised by occurrence of zones of returnable stream near the wall on an initial pipe site and profile elongation of axial components of velocity vector in comparison with Poiseuille profile. Flow intensity and recirculated zone size in near-wall flow essentially depend on pipe rotation velocity and Reynolds number;

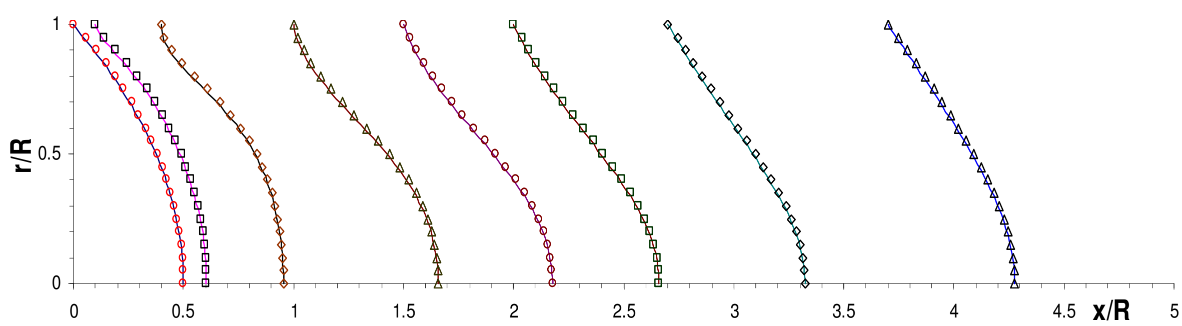

Fig. 6. Development of axial component of velocity vector U/U_0 on channel length (Reynolds number - Re=20; swirled intensity - Ro=5.22; this is case of rotating pipe wall. Lines - calculation, symbols - data [132]).

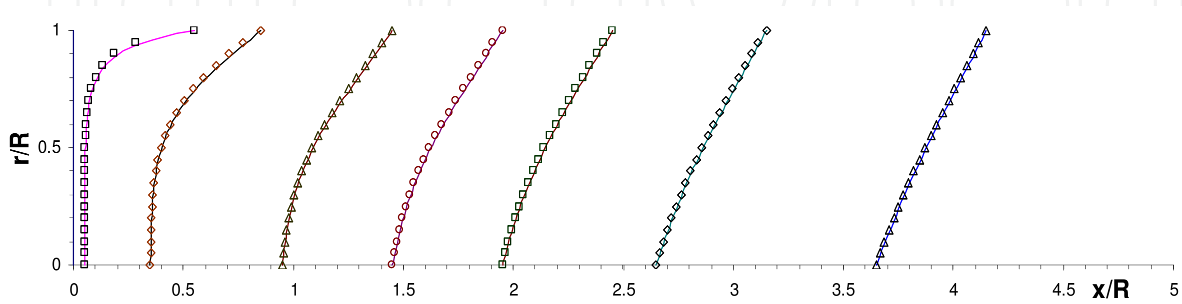

Fig. 7. Development of velocity tangential profile W/U_0 on channel length (Reynolds number - Re=20; swirlied intensity - Ro=5.22; this is case of rotated pipe. Lines - calculation, symbols - data [132]).

- shear stress caused by rotation ($\tau_{\varphi\ r}$), completely prevails in value of coefficient friction on a wall of rotating pipe; the full coefficient friction (fig.8) also increases with increasing of swirling parameter;
- distributions of Nusselt number (fig.9) and temperature fields show extensification of heat transfer processes in rotating pipe flow. And since some distance from an input the temperature profile is arranged under change of a velocity profile in the near wall fields. Also it is observed smaller fullness of temperature profile at the wall in comparison with a direct-flow stream. Some calculated results illustrating this process, are presented below.

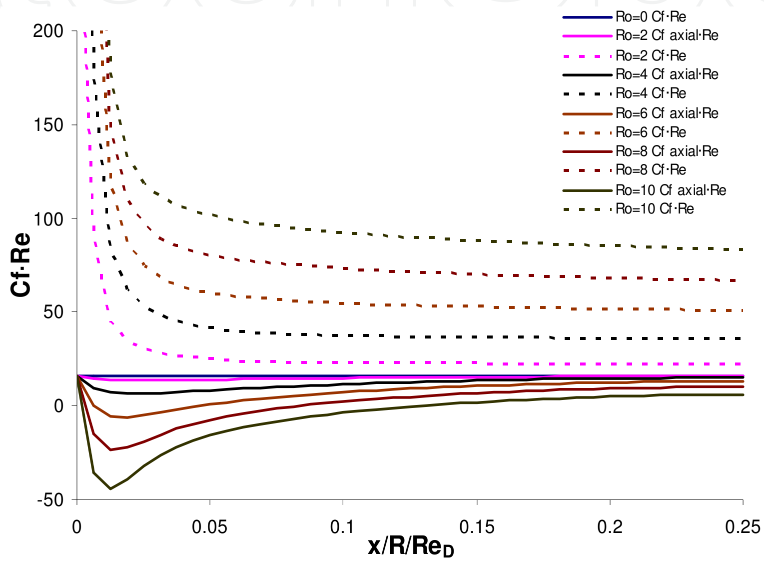

Fig. 8. Distribution of full coefficient friction (dotted lines) and coefficient friction with the account only axial component of velocity vector (solid lines) versus normalized channel length ($x/(RRe_D)$) at various swirling parameters (rotating pipe).

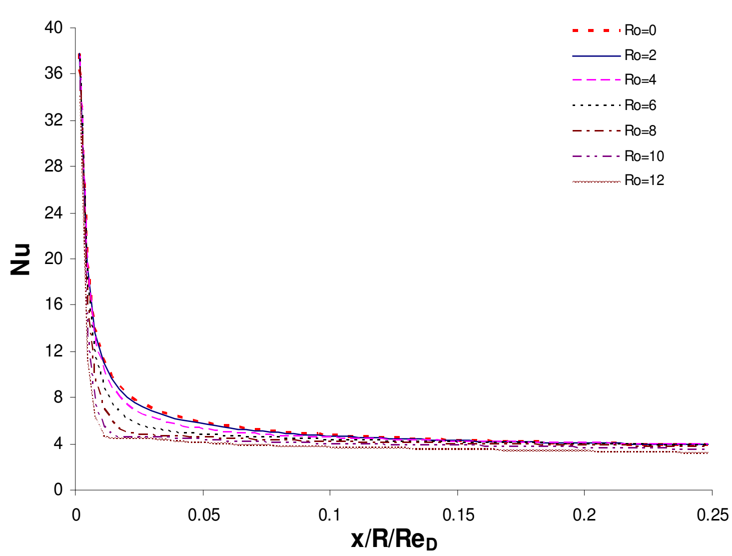

Fig. 9. Distribution of Nusselt number versus swirling parameter and nornalized channel length ($x/(RRe_D)$). (rotating pipe).

3.4 Investigations of hydrodynamics and heat transfer for a flows in channels with complex geometry

Not-isothermal subsonic fluid flow in pipes of variable cross-section section is analysed. It is supposed, that generally the flow at the input is considered completely developed. The stream flows into a pipe with uniform temperature T_0. T_w is temperature at the wall; components of velocity vector are accepted equal to zero (no-slipping conditions). At the axis - symmetry conditions, at the exit - "soft" boundary conditions.

Here, presented calculation of channel configurations shows that modelling of flows in internal systems with irregular geometry will quite well be co-ordinated with results of calculations and experiments of other authors [133]. Calculations of flows in pipes with sudden expansion at the input h/R=0.5 show presence of stream separation and formation of eddies at once behind a ledge in that kind in which it has been presented in experimental papers and numerical researches of other authors.

Calculated results of some flows illustrating possibilities of algorithm in a prediction of direct-flow and swirled streams in the conditions of irregular pipe geometry are more low given.

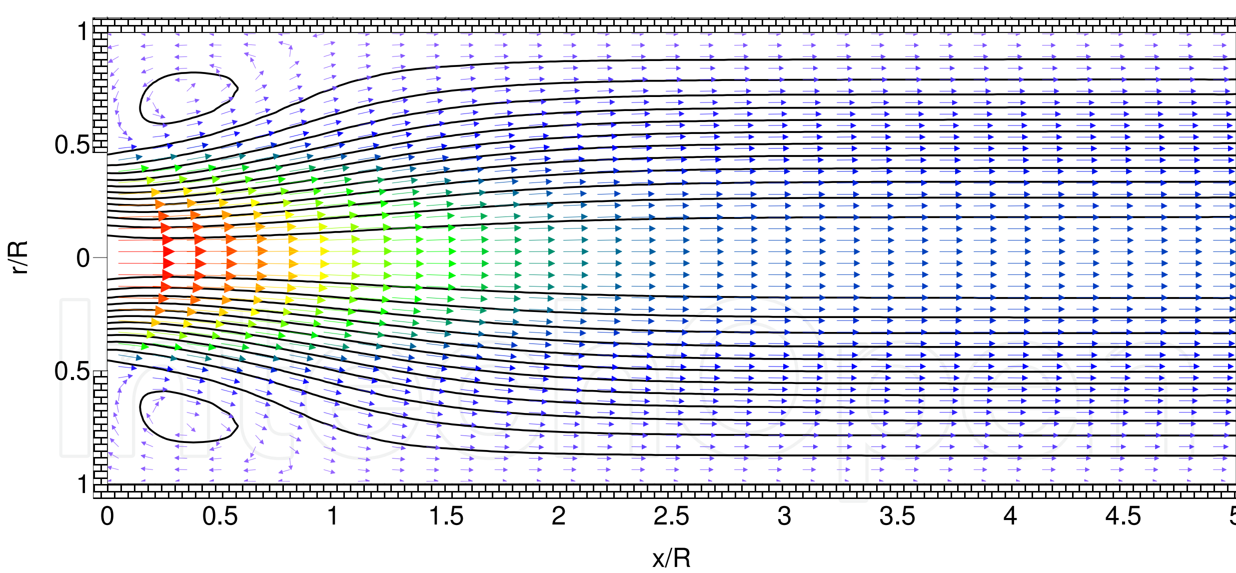

Fig. 10. Streamlines and vector field at a flow in the channel with sudden expansion. Calculation is executed at Re=20 and h/R=0.

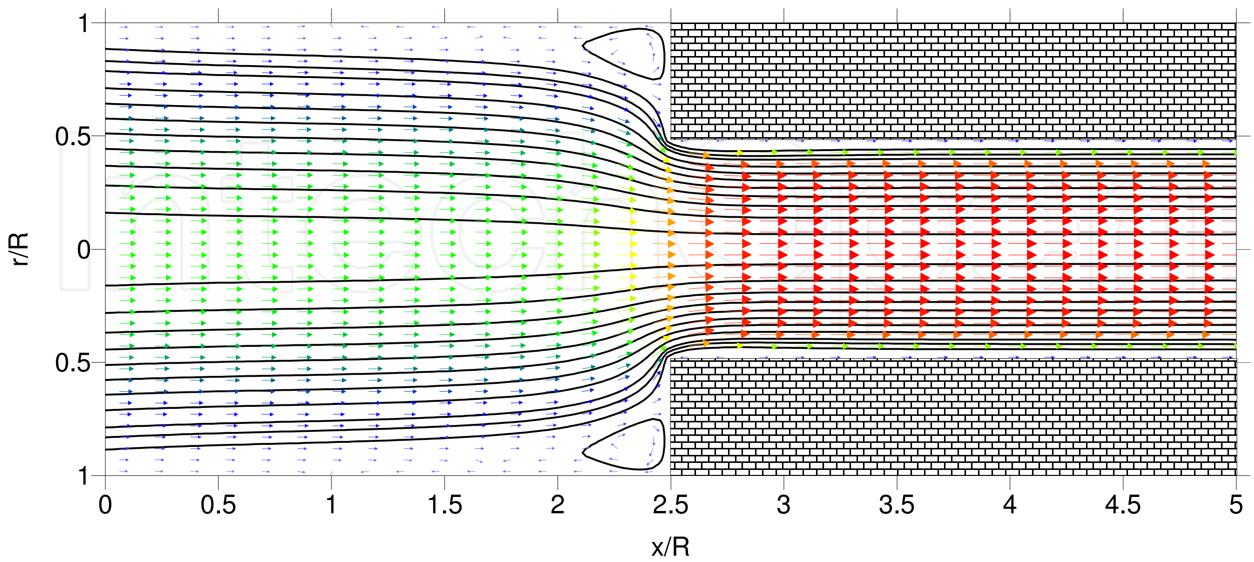

Fig. 11. Streamlines and vector field at channel flow with sudden narrowing (Re=1600 and h/R=0.5).

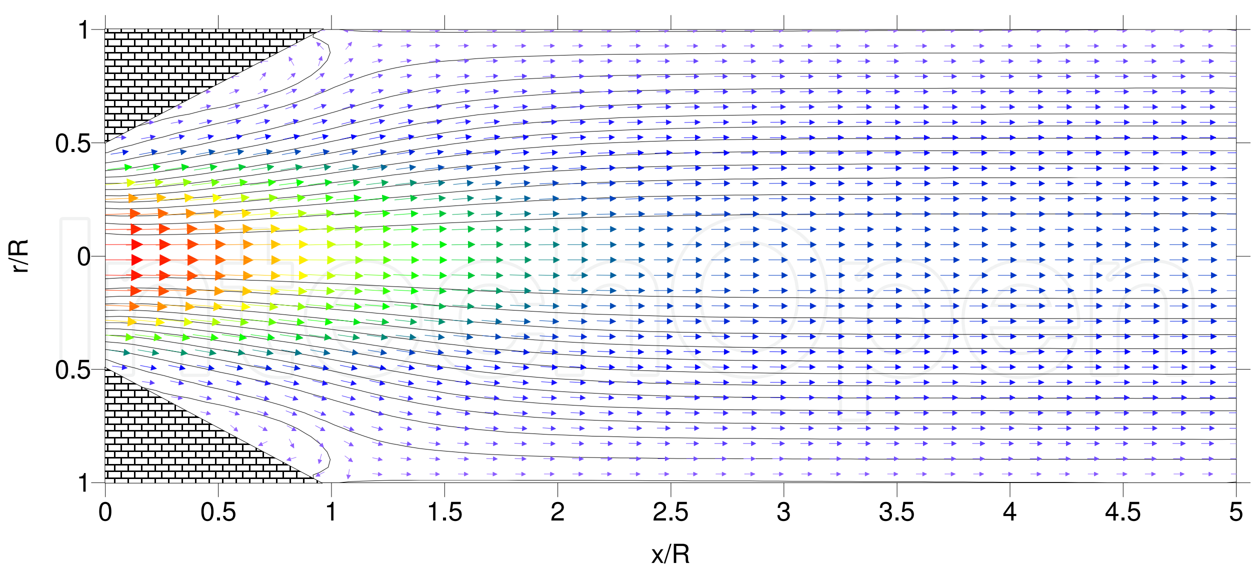

Fig. 12. Streamlines and a vector field at a channel flow with gradual expansion (Re=20, h/R=0.5, α =30°

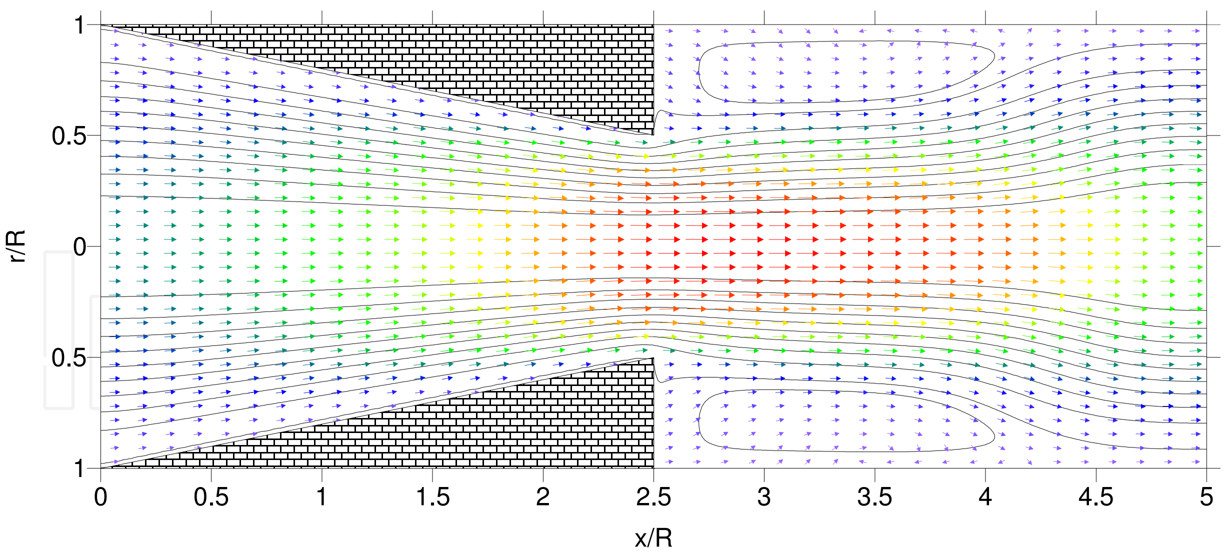

Fig. 13. Streamlines and a vector field in the channel flow with gradual narrowing to the channel middle (Re=20, $h_R/R=0.5$, $h_x/L=0.5$).

The main practice interest in calculations of similar configurations and corresponding estimations of algorithm possibilities in prediction of transfer mechanisms of momentum, heat and mass are connected with problems of peripheral recirculated zones definition in fields behind the obstacles representing of confuser and diffuser sections. Calculations show that the size of recirculated zones will well be co-ordinated with experiments. This circumstance allows hoping for the correct description of complex flows with similar geometry in the conditions of influence of mass inertial forces.

3.5 Detailed analysis of spatial swirled flows in channels of complex form

In this work it is established that joint influence on flow of swirling and features of pipe geometry conducts to combination of these effects accompanying each type of a flow separately. So, in channel stream swirled locally at input and including section of sudden expansion the occurrence of central recirculated zones (CRZ) causes reduction of peripheral recirculated zones (PRZ) and shifts reattachment more close to an input (Fig. 14).

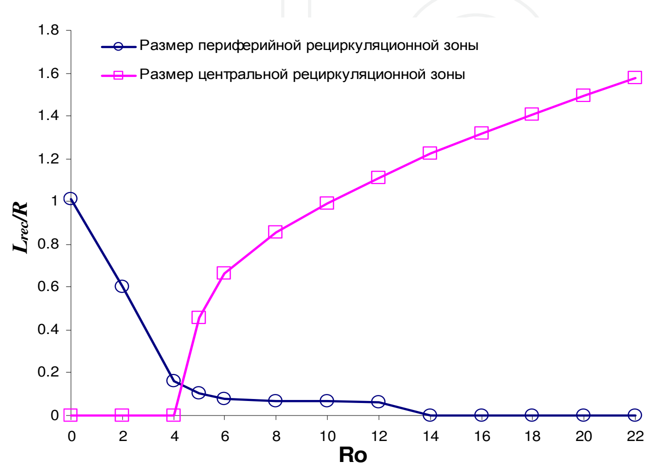

Fig. 14. Comparison of peripheral recirculated zones and central recirculated zones at combined effects of local swirling at the input and channel sudden expansion (h/R=0.5).

Some results illustrating reorganisation of vector velocity field in channels of the complex form are presented in fig. 15.

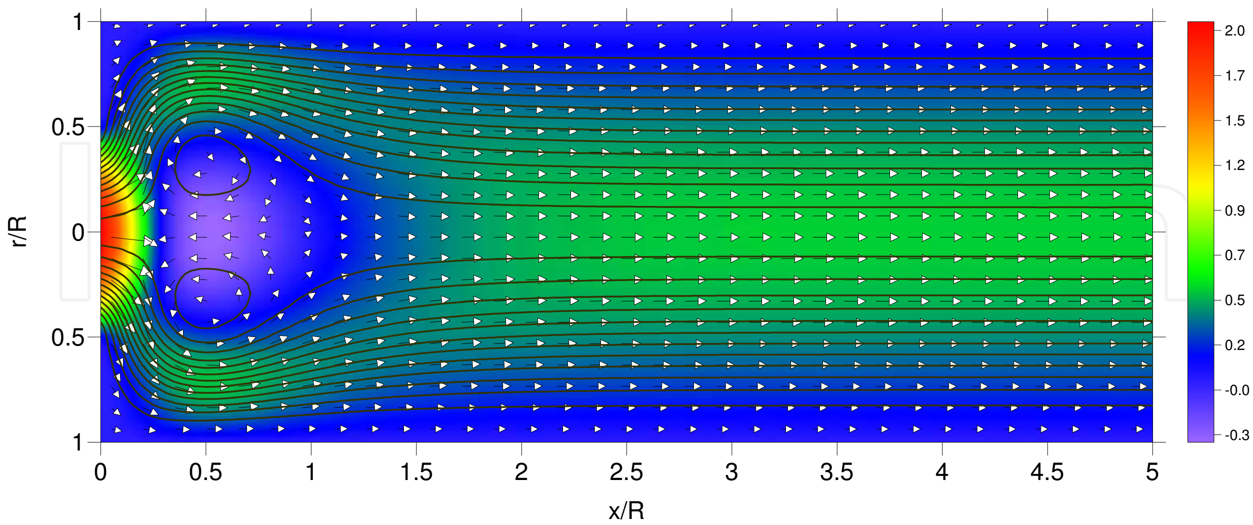

Fig. 15. Streamlines and a vector field of swirled flow at the input in conditions of suddenly extending pipe (Re=20, h/R=0.5, Ro=6).

4. Detailed modelling of structure of turbulent swirled stream

Researches of the turbulent flows complicated of non-isothermarlity, swirling, variability of properties of the heat-carrier, any wall configuration, combustion are multifaceted and multi-aspect. Publications in this direction are numerous. However, among authors of significant publications (and they mentioned above in paragraphs 2,3) concerning swirled flows at action of centrifugal mass forces and their applications in technics it is necessary to allocate some last results of the Russian scientists. So, considering the big contribution of Russian school of mechanical engineers to problems of the turbulence description, it is necessary to notice that results of last decades are reflected by successes in use of momentum approach (MA), large eddy simulation (LES), direct numerical simulation (DNS) with use of full Navier-Stokes equations, and also on the basis of the approach with application of the generalised hydrodynamic equations (GHE).

Among the specified directions actively developed last years, papers executed by B.V.Alekseev [134-141], A.M. Lipanov [142], O.M. Belotserkovskiy [143], J.V. Lapin, M.H.Strelets [144-146], A.F. Kurbatsky [147-150], B.P. Golovnay [151] are rather appreciable.

B.V.Alekseev's papers representing the elaboration of Boltzmann' ideas give the beginning of the original approach of turbulence analysis from kinetic positions. In classical understanding turbulence is described by Navier-Stokes model with characteristic for it irregularity of changing of thermo-dynamic parameters and wide range of scales of pulsing sizes. Lacks of such model of flow are connected with the absence in these equations of Kolmagorov' fluctuations. Hence, defining equations is problematic to consider as the equations which have been written down concerning actual magnitudes. In this sense on the basis of Boltzmann' equation the generalised hydrodynamic equations (GHE) received by B.V.Alekseev are more perfect and universal. These equations take into account the total spectrum of Kolmagorov' pulsations and allow to model the vortical flows in a wide range of Reynolds numbers, including regimes of laminar and turbulent transitions. Some possibilities of the numerical description of vortical flows by means of GHE, containing physical viscosity are shown for example in [137]. It is noticed, that in comparison with the data received on difference schemes for Navier-Stokes equations, GHEquations look more preferable. In [138] the prospects are outlined for development of the kinetic and hydrodynamic theory of liquids taking into account change of functions of distribution on characteristic flow scales of an order of time of fluctuation of particles. In [139] the generalised Boltzmann kinetic theory is applied to a conclusion and research of the dispersive equations of plasma in absence of a magnetic field. In [136] the full system of the hydrodynamic equations is resulted at the level of Chapman-Enskog generalised equations (GECE). Small-scale turbulent fluctuations within the limits of model (GECE) are given in tables to [134]. In [140, 141] some problems are solved about distribution of sound speed and attenuation, shock wave structure. Despite appeal and novelty of ideas of the description of turbulence by B.V.Alekseev's equations (GHE), these equations are still poorly studied and while there is no confidence of possibilities of application of the given approach for the decision of practical problems. As any new theory it rejects already settled representations that Navier-Stokes equations are theoretical base for the turbulence description. However, as always happens in such cases, after long disputes in this occasion obviously there will be a heavy question of using of GHEquations and Navier-Stokes equations.

In direct numerical simulation (DNS) on the basis of full Navier-Stokes equations considerable successes are reached by A.M. Lipanov [142], O.M. Belotserkovskiy [143]. Calculations are executed at big Reynolds numbers (to 10^5) for the three-dimensional channel with jump of the area of cross-section section at the input with use of rather small steps on space and time, and also schemes of a high order of accuracy.

Within the given direction O.M. Belotserkovsky investigated a wide class of problems about free turbulent flows in jets, traces with effects of a separation, laminar and turbulent transition, and the transition phenomena to chaos.

Recently momentum approach actively develops in turbulent mechanics. To this approach a lot of attention is given in groups, which are managed by J.V. Lapin [144-146], A.F. Kurbatsky [147-150], B.P. Golovnya [151] etc. Efforts of these groups define successes of Low-Reynolds modelling, and also achievement in working out of practical versions of turbulent models in various complex cases.

In [144] Yu.V. Lapin has shown possibilities of following models: algebraic – T.Cebeci-S.Smit; semidifferential - John-King, Horton; differential - A.N. Sekundov, Spalart-Allmaras; B.Launder-B.Sharma, C.Chien (k ε); Menter (k ω) [for a class of problems about flows on flat or axisymmetric surfaces with sign-variable (sign-constant) gradients of pressure within the limits of a return method of the decision of the equations of turbulent boundary layer]. It is established, that in flows with a favourable (negative) gradient of pressure the greatest divergence between models and experience is observed in a prediction of longitudinal change of coefficient friction. Here, the best data are available for models of T.Cebeci-S.Smit, A.N.Sekundov-G.S.Glushko-S.N.Kharlamov, Menter.

At an adverse (positive) gradient of pressure models of Horton, A.N.Sekundov and Menter are allocated. (k-ε) models are unsuitable in calculation of flows of the given class. Menter's model gives good characteristics in calculation of effects of deceleration and a separation in comparison with analyzed models.

All models are reproduced only qualitatively accelerated or slowed down flows. The chosen models do not provide the exact description in the analysis of non-equilibrium boundary layers with a sign-variable pressure gradient.

In [145] the new algebraic model of turbulence is offered. In that paper results of model testing on a class of flows with adverse gradients of pressure are presented. These data show that the offered model does not concede to differential two-parametrical kε–, kω– turbulent models.

In [146] the Reynolds Stresses Algebraic Model (RSAM) of Vallin-Johansson with kε-base of Chen and kω of Wilcox in the conditions of flow with sign-constant pressure gradient is analysed. In comparison with classical models of Chen, Wilcox at work with RSAM-models their high sensitivity to the task of initial data, a choice of basic base is found out. It is underlined, that advantages of RSAM-models concern first of all calculation of pulsated parameters though accuracy of a prediction of components of kinetic energy of turbulence leaves much to be desired.

In [147, 148] Kurbatsky A.F. presents RANS-, RSAM-models and a numerical method to calculation of structure of a turbulent flow with an obstacle in the form of a ledge on a flat wall. In order to determine special zones (a separation, attachment, etc.) the models are involved, capable to reproduce anisotropic character of turbulence, behaviour of full tensor of Reynolds stresses in the fields near wall. Calculations show that quantitative divergences are considerable because of anisotropy of flow and proximity of used expressions for eddy viscosity. The correct description of fine structure can be received on the base of RANS-models.

Papers [149, 150] present calculated results of statistic characteristics of scalar turbulent field in channels in the conditions of the direct-flow and swirled stream. In these papers features of the description of transport heat and momentum processes at a wall with inclusion of data about time scales of thermal and dynamic turbulence are analyzed and also problems of construction of the balance equations for the given scales.

In [151] B.P.Golovnya offers original ($\overline{t'^2}, \varepsilon_t, k, \varepsilon$)-model to calculation near-wall turbulence. The model considers viscous effects, damping of walls in turbulent interactions. The model is tested on flows of type of boundary layer and is quite correct to forecast of complex flow.

Now the scientific direction connected with use of moment approach and theory of interpenetrating media in the decision of practically important problems about modelling of transfer processes and heat- and masstransfer in two-phased multicomponent systems "particle-gas" fruitfully enough develops. Here interesting results are received by M.A. Pakhomov, S.N. Kharlamov [152, 153]. So, in [152] the character of particle interaction and channel wall is analyzed in detail in frameworks of continuous model of gas-dispersed media. The assumption is entered about division of particles on falling and reflected fractions. Turbulent processes are described by L.V. Kondratiev model which is generalised on a case of presence several particle fractions. The model allows receiving the correct description of flow on dynamic and thermal characteristics.

In [152, 153] within the limits of Euler-Lagrange approach the mathematical model for a turbulent flow of multicomponent homogeneous and heterogeneous mixes in channels is formulated and compared with numerous experiment data. Problems of detailed modelling of turbulent structure of the carrying media in the near-wall fields on the basis of popular two-parametrical turbulent models are investigated. On the basis of developed continuous models are studied the effects connected with influence of gravitational forces on parameters of not-isothermal turbulent gas suspension flow in the vertical channel in flow regimes of lifting and lowering. Intensification mechanisms of heat transfer are in details investigated at lowering of a disperse mix.

In the theoretical description of turbulence the main problems are the choice of models, methods of realisation of numerical algorithms, creation of steady numerical schemes of integration of the multidimensional transport equations, construction of approaching difference grids and so on. On these questions authors [45, 51, 146, 149,152, 153] receive new results. In particular, original multiple parameter dynamic and thermal turbulent models turbulence with $(\mathrm{k},\mathrm{L}, \tau,\omega,\nu_t,\overline{t'^2},\varepsilon_{\overline{t'^2}})$ - parameters are developed. These models are included the multiscale factor of dissipation of scalar and dynamic fluctuated fields [153], and also a method oriented pseudo-convection [45, 51]. Advantages of this method are connected with simplicity of calculation of the developed and non-stationary spatial flows with high Reynolds numbers at the expense of original representation of convective transfer by finite-difference approximation of the second order of accuracy. The offered way of introduction of pseudo-convection allows to by pass problems with numerical diffusion. The constructed iterative process provides stability of the decision at pseudo-additive disappearance (at convergence of iterations) and allows to connect advantages of finite-difference approximations of convective terms by the scheme against a stream, having the first order accuracy, to approximation by the scheme with the central differences of the second order of accuracy.

4.1 Remarks and conclusions to modelling of structure of turbulence in complex shear flows

Two-parametric *kL-, kε-, k*ω- turbulent models of B.E. Launder, B.I. Sharma [46], M.V. Rubezin [154], G.S. Glushko [44,155] certainly are worthy from the point of view of maintenance of high accuracy of calculations and moderate expenses of an estimated time. However, these compromise models have considerable lacks. First, calculated time of these models is much more calculated time of simple one-parametrical models. Secondly, there is no satisfactory consent in the description of essentially anisotropic movement. Besides, in order to combine the theory and experiment the permanent investigations on updating of such models is conducted.

Possibilities of two-parametrical models are rather limited, but they provide the successful description concerning simple flows. Thus, it is necessary to notice that use of constant values c_μ does not provide true predictions in shear layers. Corrections are required on a case of small values of Reynolds number at the analysis of near-wall flows. Also those or other model modifications are required for the exact description of flows within boundary layers on the curved surfaces. Models of this class can work in the analysis of two-dimensional flows with a separation, rotation, curvature at corresponding selection of dependence $c_\mu \approx f\left(P, \varepsilon, gradU, \overline{u_i'u_j'}\right)$. The modified versions are comprehensible in not swirled recirculated flows (except reattachment of a flow), in swirled flows without separation. There are good results in a prediction of flow behaviour in external area of strongly swirled stream at the account by turbulent model of eddy anisotropic properties. In spite of utility of existing models at designing of technical devices, essential improvements of numerical techniques and models of physical process are necessary in order to predict correctly of the complex shear flow behaviour existing in real conditions. Thus, it is required to improve accuracy of the description of transport turbulent processes of averaged characteristics of scalar quantities, in particular, concentration of reacting mixes, interactions of turbulence and chemical reactions.

In view of unsatisfactory speed and an insufficient memory size of modern computers, at numerical modelling of turbulence have important values of achievement in the field of producing capacity of computers. However, possibilities of computer calculated speed-up have a limit on each of concrete stages of computer engineering development. Therefore we can expect reception of the detailed and important information about complex shear flows interesting to appendices, from introduction of RANS - RSAM-models in calculated schemes. Thus, it is necessary to notice that for the present there are problems with realisation of RANS-, RSAM-models (low processing speed for calculation of the big data level) that limits their wide application.

RSAM-turbulent models have been developed for the purpose of expenses reduction by the decision of the differential equations in RANS-models. In special cases RANS-models are reduced to algebraic relationships for stresses through introduction of simplifying assumptions for convective and diffusive terms in the transport equations for Reynolds stresses. RSAM-models are used together with $k\varepsilon$ -, kL - or $k\ \omega$ -equations in the form expanding two-parametrical model. Additional effects (curvature of streamlines, rotation, buoyancy etc.) are considered in these relationships through sourced terms.

Averaged parameters of flow field, calculated on the RSAM-models, are close to data on two-parametrical models.

In simple flows all components of Reynolds stresses calculate precisely enough on the base of these models. In the analysis of near-wall shear layers the model corrections are required for registration of little turbulent Reynolds numbers at a wall. Various model modifications are required for calculation of complex flows (camber, concavity, complex surface).

Generally, the decision of system of the algebraic equations for stresses represents not trivial problem. From here there are many numerical techniques on using of RSAM-models in practice of engineering calculations. However, the transport equations for Reynolds stresses can be solved effectively with increasing of computer efficiency and development of calculated methods. Then RSAM-models will lose urgency.

Last twenty years considerable progress in turbulence modelling is connected with possibility of the detailed analysis of complex flows on the base of RANS-models. RANS-models application is interfaced to difficulties especially concerning modelling of unknown terms (redistribution, diffusion, dissipation) though the advantages of these models caused by their ability precisely to predict not only averaged characteristics, but also fine structure. Modern experience shows that application of RANS-models with $k\varepsilon$ - or kL-base almost invariably conducts to good results in the description of complex shear flows. The low-

Reynolds and high-Reynolds versions of RANS-models distinguish depending on applicability to concrete conditions of a flow. The high-Reynolds turbulent models use out of viscous sublayer and buffer zone $\left(y^{+} > 50\right)$. Such models do not describe effects of molecular viscosity. Therefore, they often unite with the wall law.

Until recently in the majority of practical appendices calculations on $k\varepsilon$ - and RANS-models did not cover of near-wall area, because of problems of the definition of high gradients in this zone and bad validity of these models which are not using of damping relationships. It is necessary to notice, that unlike of High-Reynolds model versions, the low-Reynolds closing is studied poorly enough, especially for complex flows. And it is a subject of intensive researches on turbulent modelling.

Most likely, now the version of RANS-model offered by B.E. Launder, K. Hanjalic [156-158], M.M. Gibson [154, 159-161], D. Najot [162, 163] is considered as most developed one. And near-wall influence on correlation between pressure pulsations and deformation velocity tensor pulsation occurs in this version

These RANS- ε -models have good proved from the point of view of enough exact description of many features of a flow (velocity fields of the basic and secondary flows, shear components of Reynolds stresses full tensor). However, almost all versions of RANS-models with base in the form of ε -equation are not satisfactory in a prediction of the big maximum of autocorrelations of pulsations of axial velocity component $\overline{u'^2}$ and concerning of positive value of normal pressure at a wall. The analysis of having papers shows, that considerable efforts on improvement of models, construction of effective procedures of anisotropic near-wall field flow are necessary to receive a universal variant of turbulent equations closing at level of the second moments. Introduction of the complicated forms for a term representing correlation of pressure-deformations considerably strengthen a realizability of RANS-models and define correct behaviour of turbulence about near the wall. In [164] B.E. Launder underlines, that preservation of terms to the third order in a fast part of a redistributing term appears sufficient for modelling of near-wall behaviour of turbulence. Besides, a series of researches on diffusive modelling for $\overline{u_i'u_j'}$ -equations shows possibility of use of more simple form of gradient type for D_{ij} without accuracy loss in comparison with the complex form of diffusion approximation. We will notice that theoretically more proved RANS-models still are not used in practical calculations, despite their obvious advantages. Therefore the further wide testing of these models for the purpose of their reasonable use in engineering practice is necessary.

Thus, the decision of averaged Reynolds equations together with turbulent model is represented to more economic, rather than calculations on LES modelling. Nevertheless, for challenges (chemically reacting systems, aerodynamic effects of the big speeds etc.) the estimated time can be lasting many hours on modern computers.

4.2 Physical and mathematical models of flow and heat transfer

In this part developed turbulent gas flow and heat transfer in cylindrical pipes and channels with constant and weak-changeable cross-section section is considered. It is supposed, that the stream is one-component chemically inert media. Movement is axisymmetrical and carried out in absence of external forces, gravity and volume sources of heat. Temperature drops can be considerable so, that it is necessary to consider variability of thermo physic characteristics of a working fluid from temperature.

The system of the equations defining a flow and heat transfer includes the equation of continuity, movement (Reynolds full equations), energy and a condition and looks like, which is presented in tensor form:

$$\frac{\partial(\rho U_j)}{\partial x_j} = 0; \tag{1}$$

$$\frac{\partial(\rho U_i U_j)}{\partial x_j} = -\frac{\partial p_1}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\mu\frac{\partial U_i}{\partial x_j} - \rho\overline{u_i' u_j'}\right) + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial U_j}{\partial x_i} - \frac{2}{3}\frac{\partial U_i}{\partial x_i}\delta_{ij}\right)\right]; \tag{2}$$

$$c_p\frac{\partial(\rho U_i T)}{\partial x_i} = \frac{\partial}{\partial x_i}\left(\lambda\frac{\partial T}{\partial x_i} - \rho c_p\overline{u_i' t'}\right) + \mu\left(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}\right)\frac{\partial U_i}{\partial x_j} + \mu\left(\overline{\frac{\partial u_i'}{\partial x_j}\frac{\partial u_i'}{\partial x_j}} + \overline{\frac{\partial u_j'}{\partial x_i}\frac{\partial u_i'}{\partial x_j}}\right); \tag{3}$$

$$p_0 = \rho R_0 T; \tag{4}$$

The used designations in these equations (1) - (4) are standard, all values are averaged ones (Reynolds averaging). For closing of the defining equations the model of turbulence with the equations of balance of the one-point correlation moments of the second order of pulsations of velocity field ($\overline{u_i' u_j'}$) and temperatures ($\overline{u_i' t'}$) is involved.

4.3 Formulation of the low-Reynolds versions of transfer model for Reynolds stresses in incompressible media

Transfer equations for turbulent stresses in a stationary incompressible flow have following form [165]:

$$U_k\frac{\partial\overline{u_i' u_j'}}{\partial x_k} = \frac{\partial}{\partial x_k}\left(\nu\frac{\partial\overline{u_i' u_j'}}{\partial x_k}\right) - \overline{u_i' u_k'}\frac{\partial U_j}{\partial x_k} - \overline{u_j' u_k'}\frac{\partial U_i}{\partial x_k} + D_{ij} + R_{ij} - \varepsilon_{ij} \quad (i,j=\overline{1,3}), \tag{5}$$

where D_{ij}, R_{ij}, ε_{ij}, – accordingly turbulent diffusion, redistribution and dissipation, line over terms is Reynolds averaging.

On principle questions of term modelling of the higher orders (diffusion, redistribution, dissipation) we have no discrepancies with Y.G. Lai, R.M.K. So's approach [166]. Moreover, we practically remain system of coefficients of RANS-models. However, in representation of diffusive term we have entered a damping analogically by M. Prudhomme, S. Elgobashi [167]. Despite the made remark of the general character, the structure of modelled terms will be lower shown.

Turbulent diffusion is modelled with use of representation of K. Hanjalic [157] modified on near-wall field by using of damping function $f_\mu(\mathrm{Re}_t)$, taken on $k\varepsilon$ –model B.E. Launder- B.I. Sharma [46]:

$$D_{ij} = \frac{\partial}{\partial x_k}[c_s f_\mu(\mathrm{Re}_t)\frac{k}{\varepsilon}(\overline{u'_i u'_m}\frac{\partial \overline{u'_j u'_k}}{\partial x_m} + \overline{u'_j u'_m}\frac{\partial \overline{u'_k u'_i}}{\partial x_m} + \overline{u'_k u'_m}\frac{\partial \overline{u'_i u'_j}}{\partial x_m})], \tag{6}$$

where $c_s = 0{,}15$; $f_\mu(\mathrm{Re}_t)=\exp[-3{,}4/(1+\mathrm{Re}'_t/50)^2]$, $\mathrm{Re}'_t=k^2/(\nu\varepsilon)$.

Y.G. Lai, R.M.C. So accept for redistributing term [166]:

$$R_{ij} = \overline{\frac{p'}{\rho}(\frac{\partial u'_i}{\partial x_j} + \frac{\partial u'_j}{\partial x_i})} = R_{ij,1} + R_{ij,2} + R_{ij,w} \tag{7}$$

where it is used according to the of J.C. Rotta's approach [5]

$$R_{ij,1} = -\alpha_0^* \varepsilon a_{ij},\ a_{ij} \equiv (\frac{\overline{u'_i u'_j}}{k} - \frac{2}{3}\delta_{ij}),\ \alpha_0^* = 1{,}17; \tag{8}$$

and it is accepted according to B.E. Launder [137, 145]

$$R_{ij,2} = \alpha(P_{ij} - \frac{2}{3}\delta_{ij}P) + \beta(Q_{ij} - \frac{2}{3}\delta_{ij}P) + \gamma k S_{ij}; \tag{9}$$

$$\alpha = -\frac{(c_{R2}+8)}{11}, \beta = -\frac{(8c_{R2}-2)}{11}, \gamma = -\frac{2(30c_{R2}-2)}{55}, c_{R2} = 0{,}3;$$

$$P_{ij} = -\overline{u'_i u'_k}\frac{\partial U_j}{\partial x_k} - \overline{u'_j u'_k}\frac{\partial U_i}{\partial x_k};$$

$$P \equiv \frac{1}{2}P_{kk}, Q_{ij} = -(\overline{u'_i u'_k}\frac{\partial U_k}{\partial x_j} + \overline{u'_j u'_k}\frac{\partial U_k}{\partial x_i}), S_{ij} = \frac{1}{2}(\frac{\partial U_i}{\partial x_j} + \frac{\partial U_j}{\partial x_i}).$$

Effects of "near-wall an echo" are entered on the basis of Y.G. Lai, R.M.C. So, B.E. Launder's structural relationship [156,166]:

$$R_{ij,w} = f_w [\alpha_0^* \varepsilon a_{ij} + \alpha^*(P_{ij} - (2/3)\delta_{ij} P) - \frac{\varepsilon}{k}(\overline{u'_i u'_j} n_k n_j + \overline{u'_j u'_k} n_k n_i)]],\ \alpha^* = 0{,}45, \tag{10}$$

where we use V.I. Kvon's damping function in form:

$$f_w(\mathrm{Re}_t) = 1 - \exp(-\sigma_2 \mathrm{Re}_t^2) + \sigma_3 \mathrm{Re}_t^{1.5}\exp(-\sigma_1 \mathrm{Re}_t^2),\ \mathrm{Re}_t = k^{0,5}L/\nu, \tag{11}$$

$$\sigma_1 = 4\cdot 10^{-4},\ \sigma_2 = 2{,}1\cdot 10^{-4},\ \sigma_3 = 2\cdot 10^{-2}.$$

According to Y.G. Lai, R.M.C. So [166], as model of dissipative term can be accepted:

$$\varepsilon_{ij} = \frac{2}{3}\varepsilon(1-f_{w,1})\delta_{ij} + f_{w,1}\frac{\varepsilon}{k}[\overline{u'_i u'_j} + \overline{u'_i u'_k} n_k n_j + \overline{u'_j u'_k} n_k n_i + n_i n_j \overline{u'_k u'_l} n_k n_l] / [1 + 3\overline{u'_k u'_l} n_k n_l / 2k],\quad f_{w,1} = \exp[-(\mathrm{Re}'_t/150)^2]. \tag{12}$$

Relationships (12) are designed in such a manner that their use does not impose restrictions on value of an isotropic component of dissipation ε and basically for it any model can be used. As such model the transport equation for ε is used in all published papers. If to mean of the low-Reynolds number closure the decision of the equation for ε is connected with the known difficulties expressed in instability of computing process. The last is defined first of all by that of near-wall extremum in distribution ε is too close at a surface: $y^+_{max}\approx 5$ (in auto modelling internal currents). Such complexity is absent in models of the high-Reynolds number closure. As in this case the zone containing an extremum is out of calculated field. It is known also, that the turbulence scale changes monotonously at approach to a wall. Therefore the calculated algorithm of near-wall flows leaning against use of the equations for turbulence scale differs computing stability. Further we will use such equation as basic one to transport models of Reynolds stresses.

Proceeding from physical reasons the dissipation of an isotropic part of turbulence should be function of only scalar characteristics of fluctuated values and also viscosity:

$$\varepsilon=\varepsilon(\nu, k, L, l_D, \dots), \tag{13}$$

where ν is kinematic viscosity, k is kinetic energy of turbulence, L is integrated scale of turbulence, l_D is dissipative scale.

We should write down following expression for the dissipation of turbulent kinetic energy generalising experience of calculations of near-wall flows:

$$\frac{\varepsilon}{k} = c_{\varepsilon 1} f_{1\varepsilon}(\mathrm{Re}_t)\frac{\nu}{L^2} + c_{\varepsilon 2} f_{2\varepsilon}(\mathrm{Re}_t)\frac{\sqrt{k}}{L} \tag{14}$$

where $c_{\varepsilon 1}$, $c_{\varepsilon 2}$ are constants; $f_{1\varepsilon}$, $f_{2\varepsilon}$ are some individual functions:

$$f_{1\varepsilon}(\mathrm{Re}_t),\quad f_{2\varepsilon}(\mathrm{Re}_t)\in[0,1];\quad \mathrm{Re}_t \in[0,\infty) .$$

The relationship (14) can be considered as "the condition equation" of two time scales for an isotropic part of turbulence.

If $f_{1\varepsilon}$ to take for identical unit, and $f_{2\varepsilon}$ is V.I.Kvon's damping function (11):

$$f_{1\varepsilon}(\mathrm{Re}_t) = 1,\quad f_{2\varepsilon}(\mathrm{Re}_t) \equiv f_w(\mathrm{Re}_t) \tag{15}$$

And to accept $c_{\varepsilon 1}$=3,93; $c_{\varepsilon 2}$ =0,31 that relationship (14) will describe wide enough class of internal near-wall flows. Let's use further relationships (14), (15), and for L we will be received transport equation.

4.4 Equation for turbulent scale

Spatial distribution of linear integrated scale of turbulence L we will find from a following equation:

$$U_j \frac{\partial L}{\partial x_j} = \frac{\partial}{\partial x_j}(\nu \frac{\partial L}{\partial x_j}) + D_L + P_L - \varepsilon_L . \tag{16}$$

At construction of modelling relationship for turbulent diffusion D_L (in this equation for L) the B.J. Daly, F.H. Harlow's modified gradient forms are used [11, 156]. They are presented taking into account influence of a wall by means of introduction of damping function $f_\mu(\mathrm{Re}'_t)$ and new value of a constant c_{sL}:

$$D_L = \frac{\partial}{\partial x_j}(c_{sL} f_\mu \overline{u'_i u'_j} \frac{L}{\sqrt{k}} \frac{\partial L}{\partial x_i})\text{; } c_{sL} = 1{,}1; \tag{17}$$

Generation P_L is represented a combination of terms from Reynolds normal and tangential stresses:

$$P_L = c'_{1L} \frac{L}{k} P_n - c''_{1L} \frac{L}{k} P_\tau \tag{18}$$

where $P_\tau = -\sum_{i \neq j} \overline{u'_i u'_j} \frac{\partial U_i}{\partial x_j}$; $P_n = P_k - P_\tau$, $P_k = -\overline{u'_i u'_j} \frac{\partial U_i}{\partial x_j}$ is generation of turbulent kinetic energy, c'_{L1} =20; c''_{L1} =0,7.

The structure of dissipative term ε_L is similar to a form offered by A.N. Sekundov [168]. However, here we enter the correction on the account of influence of curvature of streamlines:

$$\varepsilon_L = -c_{Lf} c^*_{2L} k^{0,5} \left(1 - \frac{L^2}{x_n^2}\right). \tag{19}$$

where c_{Lf}=c_{3L}+c_{4L}/Re_t; c_{3L}=0,3; c_{4L}=1,75; $c^*_{2L} = \max(0{,}3; c_{2L} f_s)$; c_{2L}=0,29; f_s=(1+a_1·Ri)·[1-$a_2$exp(-Re_t^2/2)]; a_1·=0,74; a_2 =0,2; Ri= $\frac{(W/r)\partial W/\partial r}{[(\partial U/\partial r)^2 + (\partial W/\partial r)^2]}$.

Values of presented constants a_1, a_2 are found for developing swirled flows in pipes as result of optimum conformity of the given calculations and D.R. Veske's to measurements [169].

In practice instead of direct use of six equations (5) it is more convenient to work with three equations for Reynolds shear stresses, the equation for autocorrelation of a pulsation of axial velocity $\overline{u'^2}$, and also the transport equation for quantity $z = \overline{v'^2} - \overline{w'^2}$ and the equation for $k = (\overline{u'^2} + \overline{v'^2} + \overline{w'^2})/2$, finding after their integration $\overline{v'^2} = k + (z - \overline{u'^2})/2$ and $\overline{w'^2} = \overline{v'^2} - z$.

More low in 4.5 the transport model of turbulent fluxes of momentum and heat also will be formulated. This model includes as basic base of two-parametrical turbulent dynamic and thermal models with parameters: kinetic energy of turbulence (k), characteristic time of velocity pulsations (τ), intensity of temperature pulsations and its dissipation. These two-parameter models together with version of RANS-model will make the expanded version of "RANS-FLUXES"-model used in the present paper for the analysis of internal flows and heat- and mass transfer in the conditions of the direct-flow and swirled flows.

4.5 RANS-turbulent model with dynamic kτ-base

We will use tensor view for the purpose of simplicity of representation of the model equations and its closing parities. Approximated relationships for the description of the higher order terms (turbulent diffusion, redistribution, viscous dissipation) are used in a kind, offered by A.F. Kurbatsky's [150], J. Potta [5], B. Kolovandin [170], B. Launder [171], B. Petukhov [172], and generalised by us on base from kτ-equations. Taking into account remarks, the model has following view (values of constants are received as a result of numerical optimisation of calculations).

$$\frac{D\overline{u_i'u_j'}}{Dt}=\frac{\partial}{\partial x_\alpha}\left[(\nu+c_{\mu1}f_\mu\overline{u_i'u_j'}\tau)\frac{\partial\overline{u_i'u_j'}}{\partial x_\alpha}\right]-\frac{d_2}{\tau}\left(\overline{u_i'u_j'}-\frac{2}{3}k\delta_{ij}\right)-$$
$$-d_3\nu\frac{\overline{u_i'u_j'}}{\tau^2k}-\frac{2}{3}d_4\frac{k}{\tau}\delta_{ij}+P_{ij}-\frac{\partial\nu}{\partial x_\alpha}\frac{\partial\overline{u_i'u_j'}}{\partial x_\alpha}; \tag{20}$$

$$\frac{D\overline{u_i't'}}{Dt}=\frac{\partial}{\partial x_\alpha}\left[\left(\nu+\frac{(a-\nu)}{(n_i+2)}+c_{\mu\theta}f_{\mu\theta}\overline{u_i'u_j'}\tau\right)\frac{\partial\overline{u_i't'}}{\partial x_\alpha}\right]-c_2\frac{1}{\tau}\overline{u_i't'}-$$
$$-c_3(\nu+a)\frac{\overline{u_i't'}}{l^2_{\overline{u_i't'}}}-\overline{u_i'u_\alpha'}\frac{\partial T}{\partial x_\alpha}-\overline{u_\alpha't'}\frac{\partial U_i}{\partial x_\alpha}-\frac{\partial\nu}{\partial x_\alpha}\frac{\partial\overline{u_i't'}}{\partial x_\alpha}; \tag{21}$$

$$\frac{Dk}{Dt}=\frac{\partial}{\partial x_i}\left[\left(\nu+c_{\mu2}f_\mu\overline{u_i'u_j'}\tau\right)\frac{\partial k}{\partial x_i}\right]-c_{k1}\overline{u_i'u_j'}\frac{\partial U_i}{\partial x_j}-\frac{k}{\tau}; \tag{22}$$

$$\frac{D\tau}{Dt}=\frac{\partial}{\partial x_i}\left[\left(\nu+c_{\mu2}f_\mu\overline{u'_iu'_j}\tau\right)\frac{\partial\tau}{\partial x_i}\right]-\frac{2}{\tau}\left(\nu+c_{\mu2}f_\mu\overline{u'_iu'_j}\tau\right)\frac{\partial\tau}{\partial x_i}\frac{\partial\tau}{\partial x_i}+$$
$$+\left(c_{\varepsilon2}f_2-1\right)-\left(1-c_{\varepsilon1}\right)\frac{\tau}{k}\overline{u'_iu'_j}\frac{\partial U_i}{\partial x_j}+\frac{2}{k}\left(\nu+c_{\mu2}f_\mu\overline{u'_iu'_j}\tau\right)\frac{\partial k}{\partial x_i}\frac{\partial\tau}{\partial x_i}. \tag{23}$$

Here it is designated:

$$\frac{D}{Dt}=U\frac{\partial}{\partial x}+V\frac{\partial}{\partial r};\quad a=\frac{\nu}{\mathrm{Pr}};\quad P_{ij}=-\overline{u_i'u_\alpha'}\frac{\partial U_j}{\partial x_\alpha}-\overline{u_j'u_\alpha'}\frac{\partial U_i}{\partial x_\alpha}; \tag{24}$$

$$f_\mu=(1+3.45/\sqrt{\mathrm{Re}_t})\left[1-\exp\left(-y^+/85\right)\right];\quad f_{\mu\theta}=f_\mu f(\mathrm{Pr});\quad f(\mathrm{Pr})=0.5\cdot\left(1+0.871/\sqrt{\mathrm{Pr}}\right); \tag{25}$$

$$f_2=\left[1-\exp\left(\frac{-y^+}{4.9}\right)\right]^2;\quad \mathrm{Re}_t=k\tau/\nu\quad l_{\overline{u_i't'}}=f(\mathrm{Pr})\tau\sqrt{k}; \tag{26}$$

$$c_{k1}=0.9;\ c_{d1}=1.853;\ c_{d2}=0.83;\ c_{d3}=1.7;\ c_{d4}=1.44; d_2=1.4;\ d_3=140;\ d_4=0.7;$$
$$c_{\mu\theta}=0.15;\ c_\mu=0.09;\ c_{\mu1}=0.225;\ c_{\mu2}=0.066; \tag{27}$$
$$c_{\varepsilon1}=1.44;\ c_{\varepsilon2}=1.7;$$

The defining equations (1) - (27) are integrated under following boundary conditions. At the input (*X=0*) - homogeneous profiles of averaged and fluctuated values, at the exit ($X=X_K$) - so-called "soft" boundary conditions for all required parameters are set. At the wall (*r=R*) - absence of flow for hydrodynamic values and thermal stability for averaged temperatures ($T=T_w$ or q_w=*const*), the turbulent heat flux is too small. At the axis (*r=0*) - a condition of symmetry for all values, except shear stresses and a radial heat flux.

The decision of the defining equations is based on use of implicit finite-difference schemes, splitting schemes on physical processes with the subsequent application of TDMA-methods and an establishment method on march variable t (time). For this purpose of the equation (1) - (27) are represented in a non-stationary form. Iterative process proceeds until at carrying out of iterations the convergence on a friction and heat transfer with accuracy in 0.1 % will not be reached. The decision is under construction on non-uniform grids with a condensation of mesh nodes at a wall and an axis. Approximation of derivatives is carried out with the second order of accuracy concerning steps to radial and axial directions.

4.6 Results and their discussion

In this part of paper the calculated data of local velocities U, V, W, Reynolds stresses $\overline{u'^2}, \overline{v'^2}, \overline{w'^2}, \overline{u'v'}, \overline{u'w'}, \overline{v'w'}$, and also kinetic energy k, integrated scale of turbulent pulsations L, characteristic time of pulsations of velocity τ, integrated parameters of the swirled flow were analyzed: tg $\varphi_w = \tau_{\varphi w} / \tau_{xw}$, Φ=M / (R·F), where $\tau\varphi_w$, τ_{xw} are shear stresses at the wall in azimuthal and axial directions accordingly.

Second parameter entered by N. Khiger and D. Bar [173] expresses the swirled flow intensity in any section. Now this parameter is widely used in the characteristic of rotary and axial impulses. Validation of the presented mathematical model is executed with attraction of experimental data [169, 174-176]. The main geometrical and flow dynamic characteristics were defined by following parameters: Re=5000÷100000; D=2R=0.01÷0.5m; x_k = (20÷500) D; Ro = (Ω R)/U_0=0.1÷5, Tu = (0.01÷01) %; L_0 = (0.02÷0.1) ·R. Working media is natural gas, air, water, oil. Here x_k is the co-ordinate defining length of the pipeline, the channel, Ro - dimensionless swirled parameter (Rossby number), Ω is angular velocity of rotation of a flow/wall of a pipe, Tu is intensity of turbulence ($\frac{\sqrt{\frac{1}{3}\sum_{i=1}^{3}\overline{u_i'^2}}}{U_0}$), "0" are noted by an index of size on an input in the channel.

The given researches *of moderately swirled* turbulent flow, feature of changes of its fine structure are presented on fig. 1, 2. Calculated distributions of axial velocity U/U_0 (fig. 1), normal a component of Reynolds stresses $\sqrt{\overline{u'^2}}/U_0, \sqrt{\overline{v'^2}}/U_0, \sqrt{\overline{w'^2}}/U_0$ (fig. 2) depending on dimensionless cross-section co-ordinate (y/R) in the allocated section of a pipe x/D=4 at various values of Rossby number Ro (line 1 is Ro=0, 2-0, 3-1) are compared to experiments [174, 175] (Re=50000, D=0.0762m). It is visible, that the theory and experiment consent quite satisfactory. The swirling intensifies of turbulent transfer at a wall, causing big fullness of profile U (a line 3), connected with sharper radial gradient. The intensity of swirling is considerable in a vicinity of an input. Therefore here the swirled flow effect is brightly shown. It is expressed that at a channel surface the axial flow velocity exceeds averaged flow rate velocity. In the field of an axis we observe a zone of less moving flows ("failure" on a profile of axial velocity), which is transformed in a zone of returnable flows at higher Ro. In near-wall field the mass velocity decreases with removal from an input at swirling decay, and in axial zone, on the contrary, increases. The direct-flow stream is observed in the end of a hydrodynamic initial site x ≈ (80÷100) D.

Results show that radial velocity V is practically zero at Ro=0. By the way it increases with increase of Rossby number Ro though still the order of its value at chosen Ro is less a than order of axial and tangential velocities. In all cases velocity is directed to an axis, and its maximum decreases with growth x/D, being displaced in a flow core. It is seen that mode of quasi-solid rotation remains with almost linear distribution of tangential velocity in the field 0.05≤y/R≤1 at channel length x/D≈4. These data can be use for the approached estimations of a thickness of a buffer layer. Calculations show that W/U0 profile deformation well predicts by experiment [175] for near-wall zone with growth Ro. The location of maximum value of tangential velocity is displaced to a pipe wall with increase Ro, and the maximum converges to an axis at swirling decay conditions. Swirling influence on components of Reynolds stresses is well visible from fig. 2. Turbulent generation of tangential velocity takes place on all section of the channel.

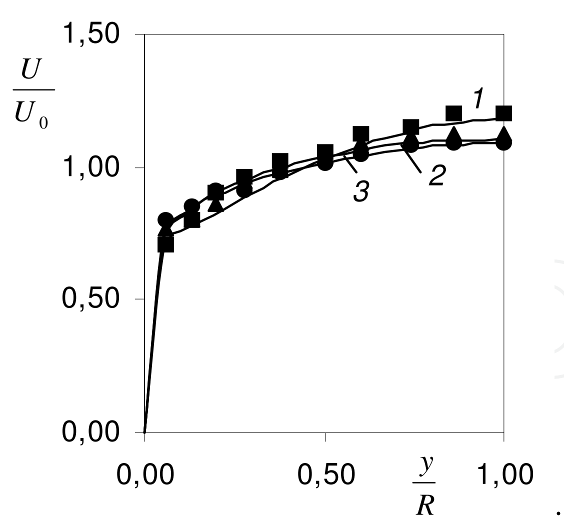

Fig. 1. Radial distribution of U/U_0 axial velocity in section x/D =4 at various swirling parameter Ro. Calculation is line, symbols are experiment [174, 175]: Ro = 0 (1, ■), 0.5 - (2, ▲), 1 - (3, ●).

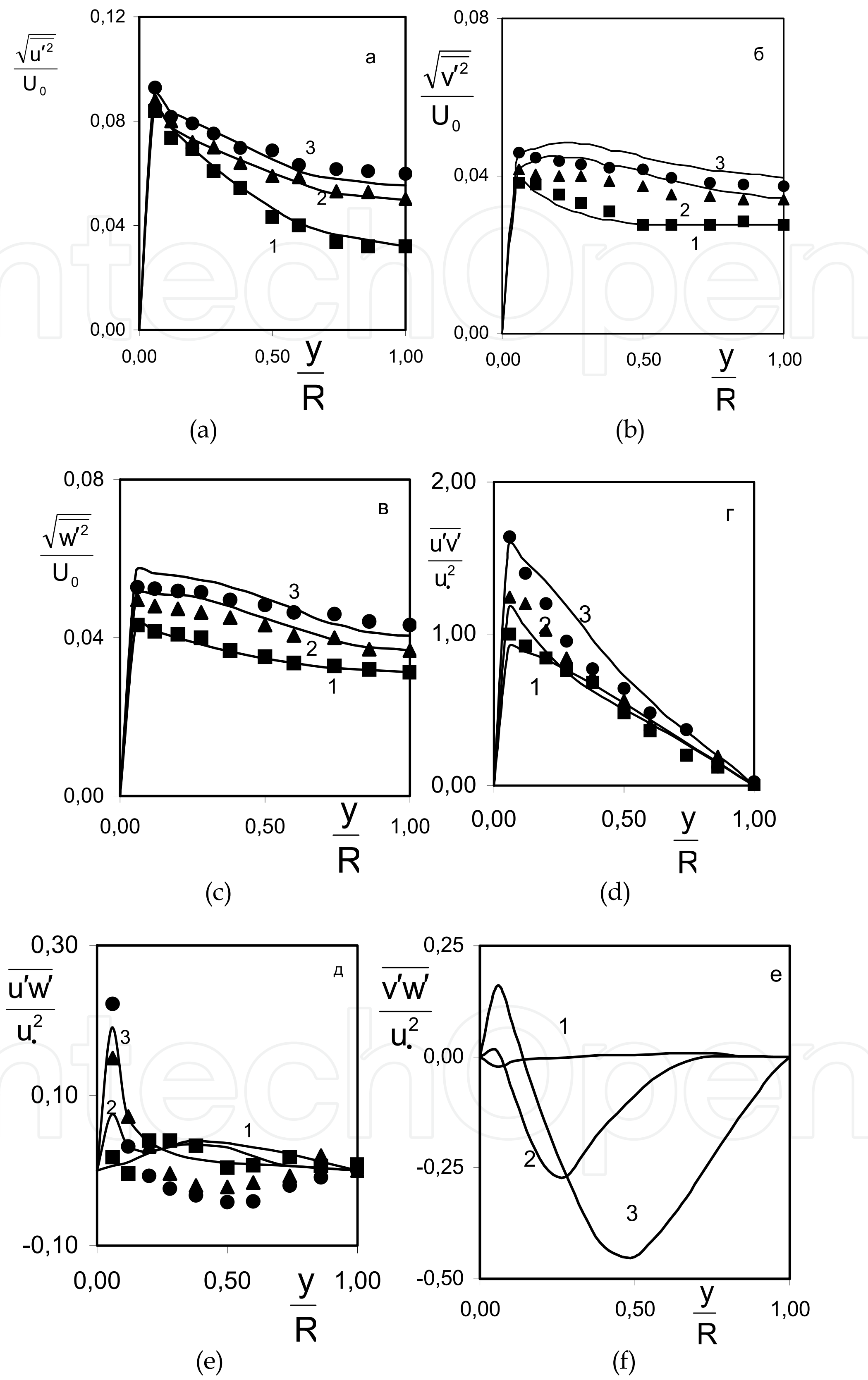

Fig. 2. Radial distributions of correlations of velocity pulsations $\overline{u_i' u_j'}$ in channel section x/D=4 at various parameters Ro. Designations are analogically to fig. 1.

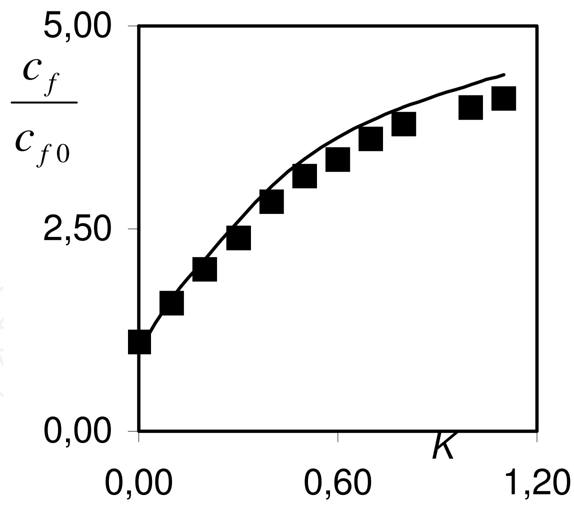

Fig. 3. Relative values of coefficient friction c_f/c_{f0} versus swirled parameter Ro in section x/D=4. Symbols are data [175], lines are calculation.

Calculations have shown, that the swirling is found the strongest influence on axial and radial component of Reynolds stresses $\overline{u'^2}, \overline{v'^2}$. These parameters essentially increase in an average part of the channel (lines 2, 3, fig. 2 (a)). At the direct-flow and swirled flows the theory will well be co-ordinated for component $\overline{u'^2}, \overline{w'^2}$. Increasing of Rossby number (Ro) conducts to formation of more homogeneous profiles of normal Reynolds stresses in comparison with case Ro=0 (a line 1). Such behaviour is caused by presence of generation of turbulent energy, connected with tangential averaged velocity which relative contribution grows in process of movement from a wall to a channel axis. Growth of velocity autocorrelations with increase Ro, and, hence, values of pulsations of these components leads to increase in values of mixed correlation $\overline{u'v'}$ on all section of the channel. Such intensification will quantitatively be co-ordinated with measurements [175]. In a direct-flow stream of correlation $\overline{u'w'}, \overline{v'w'}$ are practically equal to zero. Therefore the neglect is admissible by these components in majority channel parts. However, raised values $\overline{u'w'}$ are observed directly at a wall. Swirling causes essential growth of correlation $\overline{u'w'}$ directly at a wall, i.e. within a thickness of a buffer zone. In the given field $\overline{u'v'}, \overline{u'w'}$ correlations can be commensurable at big number Ro. Our data show that $\overline{v'w'}$ on a site x/D≤4 already at Ro=1 becomes commensurable for $\overline{u'v'}$. Such behaviour testifies to essential influence of swirling on turbulent structure of a flow. On fig. 3 relative change of coefficient friction c_f/c_{f0} in the allocated section of the channel (x/D) with growth of Ro (line is calculation, $c_f = 2\tau_{xw}/(\rho U_0^2), c_{f0}$ is a friction in a direct-flow stream, symbol is experiment [175]). It is visible that flow swirling is capable to intensify essentially dynamic processes (to 4 times on friction at Ro=1). Similar picture is noted in [58, 29, 176].

So, the turbulent scale has lengthier formative channel zone in comparison with a case of axial movement (approximately on 15÷20 %). Pressure distribution in a flow corresponds to complex character of reorganisation of axial and tangential velocities on pipe section: in near-wall field movement is carried out with a negative longitudinal gradient of pressure, at the axis - with positive, and at a surface the module of a longitudinal gradient is less, than on an axis. With swirling degeneration the distribution of pressure more and more corresponds to a direct-flow stream on a hydrodynamic initial site.

On a channel site $x/D \approx 2 \div 4$ distributions U, W component of velocity, statistical pressure are defined by swirling intensity in considered section (parameters - Φ, $\tau\varphi_w$, τ_{xw}) and does not depend on the swirling law at the input. It will qualitatively be co-ordinated with data [58, 169, 176]. Identity of profiles of axial and tangential velocities takes place at uniform parameters Φ in pipes of various diameters in the specified zone (flow of air, water, natural gas). It allows speaking about Higir's parameter, as about criterion of hydrodynamic similarity of the swirled flows. Stream rotation influences turbulent structure mainly through additional generation of velocity pulsations and growth all of them correlations. The gradient of tangential velocity component and character of its change at a wall lend to revealing of local zones of active and passive action of centrifugal forces on fluctuated flow. It is confirmed also with data [58, 29, 177, 169].

Data of calculations of strongly twirled currents. It is known [58, 37, 178, 177, 169] that there is an intensive zone of returnable currents in such movement in a flow core. Existence of such zone is caused by attenuation of rotary movement and pressure increase on a pipe axis at removal from entrance area. Dynamics of strongly swirled stream was investigated earlier in pipes of constant and variable sections (for example, [177, 179]). Similar experimental papers can serve as a material for model validations. At the same time mathematical models allow to study in details physics of the swirled flow in the conditions complicating statement of experience: a short site of oil- and gas pipelines, intensive swirling, non-isothermality and so on.

In the present paper the estimation of working capacity of RANS-L-turbulent model is spent by comparison of calculated results with data [169, 176, 179]. Experiments are selected for flows at high values of Ro (Ro=3÷7). Calculations are executed at following values of parameters: $Re = (2 \div 5) \cdot 10^4$, D=0.03-0.4m, $x_k = (10 \div 300)$ D.

So, on fig. 4 distributions of normal components of Reynolds stresses ($\overline{u'^2}, \overline{v'^2}, \overline{w'^2}$) on cross-section co-ordinate y/R in various sections on length of a pipe are presented at Ro=3 in comparison with data [169]. Symbols are experiment, line is calculation. It is necessary to notice, that the given mode answers a flow with the expressed tendency to formation of a zone of return currents. So, at x/D=0.35 in the field of a flow axis we have value $U_s/U_0 = 0.25$. close to experiment. The analysis of averaged velocity field shows that radial gradient of pressure gives the basic influence on formation of dynamic structure at Ro≈3. From fig. 4 it is visible, that the swirling intensity decays and values of autocorrelations $\overline{u'^2}, \overline{v'^2}, \overline{w'^2}$ decrease in process of stream advancement on length of channel. And, as well as in case of moderated swirling, the influence of rotation is more essential to correlations $\overline{u'^2}, \overline{v'^2}$ (fig. 4 a, b). Autocorrelation $\overline{v'^2}$ in the field of $0.35 \le x/D \le 5.1$ falls almost in 2 times. To section x/D≈50 the reorganisation of swirled flow in direct-flow is observed (lines 4, 5). Shear stresses tend to distributions of completely developed turbulent flow which is established in sections x/D=100÷150 (profile $\overline{u'v'}$ becomes linear). There is a satisfactory consent under statistical characteristics of turbulence with experimental data for all field of a flow. However, the divergence of near-wall values $\overline{u'w'}$ (approximately in 2 times) is observed in a zone 0.3≤x/D≤5, which is levelled on the channel length. It is connected with influence of a real swirled way not considered in mathematical model. Distributions of W/U_0 depending on radial co-ordinate y/R for an experimental mode [179] (Re≈20000, Ro=6) are represented on fig. 5 for the purpose of an illustration of features of swirling decay on length of the channel. Such strongly swirled flow forms the expressed zone of return stream which according to calculations has the size (18÷20) D. The features of a flow connected with vortex, in input section (x/D=2) were modelled by the task of experimental distributions of velocity and pressure as initial parameters (line is 1, symbol is ■). From fig. 5 follows the consent of theory (calculation) and experiment is satisfactory on sites (x/D≤7). In distal channel fields the intensity of tangential flow at a wall lower, than according to experiments (fig. 5, lines 6-8). Thus, quality of effect of swirling influence on velocity component W remains. Such position in structure of strongly swirled stream will qualitatively be co-ordinated with data of papers [177, 169, 176, 179].

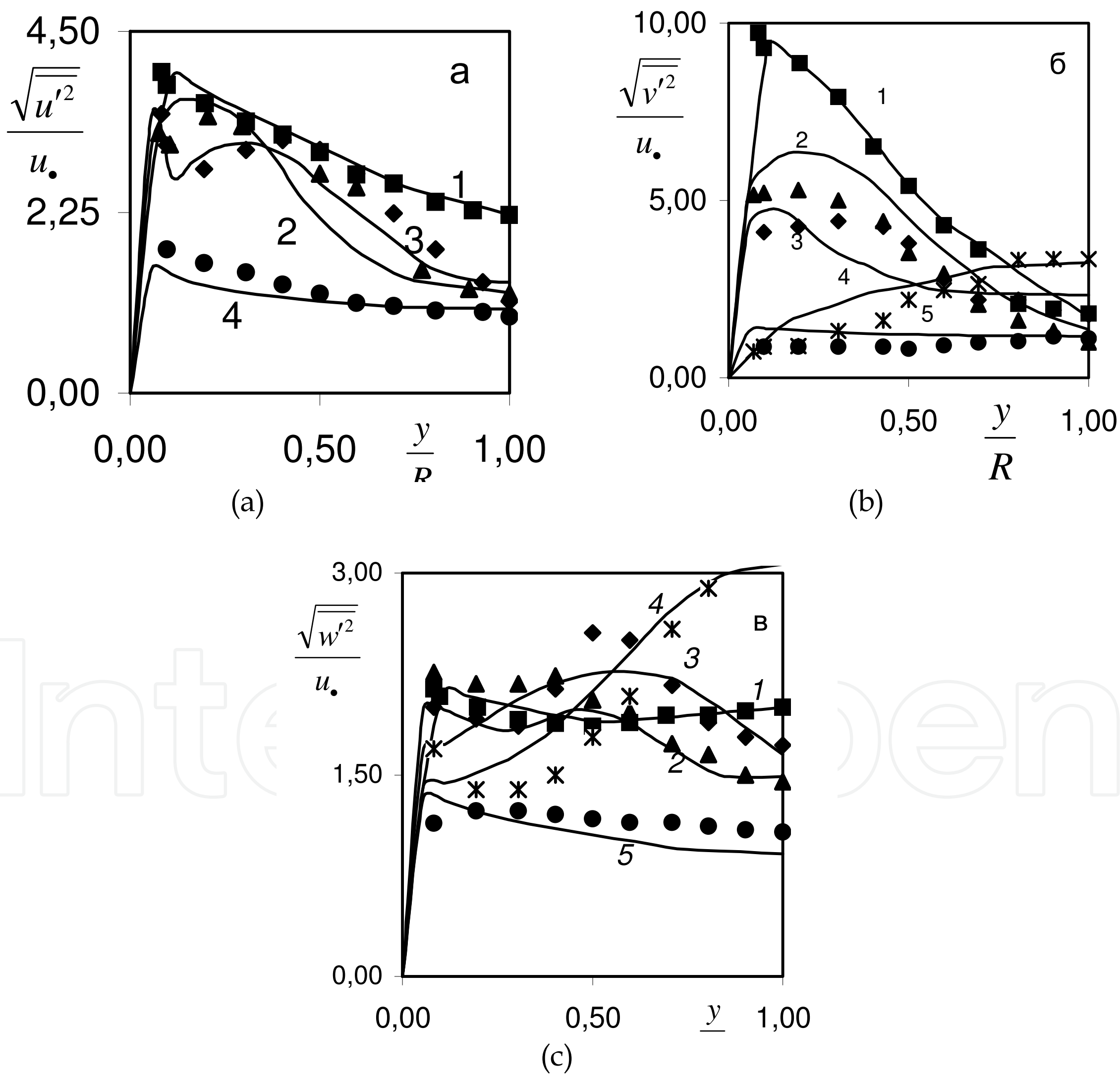

Fig. 4. Radial distributions of pulsated intensity of normal velocity components (axial – a, radial – b, tangential - c) at Ro=3 in an entrance site. Here, line - calculation, symbols - data [169]: ■ - x/D=0.35, ▲ - 5.1, ♦ - 10, * - 50, ● - 100.

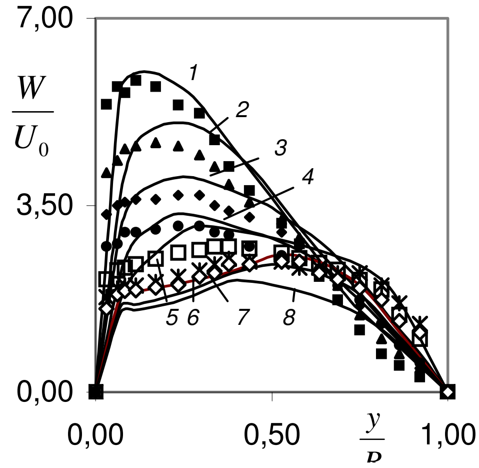

Fig. 5. Radial profiles of relative tangential velocity in an entrance site at K=6. Here, line - calculation, symbols - data [179: 1] - x/D=0 (■), 2-2 (▲), 3 - 4.5 (♦), 4 - 7.05 (●), 5 - 10.6 (○), 6 - 14.1 (*), 7 - 16.1 (□), 8 - 18.1.

As a whole, calculations show that rotation of media essentially rises turbulent mixing in a flow core. And active growth of hydrodynamic pulsations is observed in sections close to an input in a viscous sublayer and a buffer zone. Then, in process of movement, the intensification zone of pulsated flows moves in axial field. There is a liquidation of zones to a return flow in process of swirled decay. And it is established inflow of liquid mass to a core from a wall, caused by boundary layer increase. Changes in turbulent structure, in the sizes of zones of returnable flows are well predicted by RANS-L-turbulent model. Realized comparisons of calculations and experiments about the direct-flow and swirled flows on short and lengthy sites of pipelines speak about reliability of a numerical method, profitability and efficiency of RANS-L-turbulent model in the analysis of complex shear flows.

5. Conclusion

The number of important configurations of convective heat transfer in technical devices is consistently studied with use of methods of mathematical and numerical modelling of complex shear internal flows. In given chapter the development and a substantiation of complex multiple parameter turbulent models of the second order for a component of full tensor of Reynolds stresses and specific scalar fluxes with original basic bases from the transport equations for scales of dissipative dynamic and thermal times is presented for calculations of turbulent convective swirled and direct-flow streams.

By results of the presented research it is possible to do following conclusions.

1. Results of calculation of Navier-Stokes and Reynolds full equations with reference to areas of complex wall configuration (sudden expansion, narrowing, confuser-diffuser sections) with the account of heat transfer, turbulence, presence of mass inertial forces (swirling is carried out by a method of local swirling in the field of an input and method of a rotating wall of a pipe round the longitudinal axis). Calculations are executed for within the limits of models of stationary laminar and turbulent subsonic, chemically inert, not isothermal axisymmetric flows and on base of finite-difference calculated

technique - joined algorithms of SIMPLE and L.M. Simuni's approach. It is noted this approach is generalised on a case variable on radius of a longitudinal gradient of pressure.

2. The technique is characterised by working off of modules with consequence use of SIMPLE algorithm in calculations of the strong swirled laminar and turbulent flows (Ro> 4, h/d=0.5 - flows in pipes with local swirling in the field of an input; Ro> 2, h/d=0.5 - a rotating wall) and L.M.Simuni's generalised algorithm (other cases).
3. Big series of comparative test calculations is executed for cases isothermal and not isothermal, laminar and turbulent axisymmetrical flows in cylindrical pipes with complex surface (confuser-diffuser sections, sections of expansion - narrowing). It is established, that results of calculation are in the satisfactory consent with known data of other authors.
4. Calculations are carried out for swirled isothermal and not isothermal turbulent flows with attraction of modern closing schemes of the second order. These schemes include the transport equations for a component of full tensor of Reynolds stresses, specific turbulent thermal fluxes and basic bases from two-parametrical kL, $k\tau$ dynamic and thermal models with the equations for dissipative times of scalar and dynamic fields, integrated scale of turbulence.
5. Hydrodynamics and heat transfer is in details analysed by a rotating wall in conditions of flow laminarisation in pipes. Conclusion is presented about perspectives of using of the second order closures in calculations of local anisotropic turbulence on RANS-, RSAM- models.
6. The obtained data have the important applied significance about development of turbulent structure of incompressible liquid and weak-compressed gas in the conditions of action of mass inertial forces. The received results make *a databank* for construction of the general theory of rotating turbulent flows and universal statistical models for turbulent momentum and heat transfer in internal systems.

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