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Aerodynamics of building structures for flue gas removal

Аэродинамика строительных сооружений для удаления дымовых газов

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Abstract. Natural fuel burning in modern heat power plants with flue gas formation is accompanied with harmful environmental impact and potential opportunity of acid fallout. This can lead to local or even global catastrophe under adverse circumstances. High-rise structures combining a smokestack and a cooling tower are used for ecological natural fuel burning. The most important problem of these structures design is to study gas-dynamic behavior of flue gas mixing with warm ambient air flow during its movement along exhaust duct. Mathematical model and efficient numerical technique for problem solution have been developed in this work. The flowfields and the temperature and concentration distributions are calculated for various inlet conditions. Swirl flow ratio influence on flow nature has been studied. Obtained solutions have been compared with available experimental data and numerical researches. Calculation results can be used in search of optimum building structures.

Аннотация. Сжигание природного топлива в современных тепловых электростанциях с образованием дымовых газов сопровождается вредным воздействием на окружающую среду и потенциальной возможностью выпадения кислотных дождей. При неблагоприятных обстоятельствах это может приводить к локальным или даже к глобальным катастрофам. Для экологически чистого процесса сжигания природного топлива применяются комбинированные высотные сооружения, объединяющие дымовую трубу и мокрую градирню. Важнейшей задачей проектирования таких устройств является изучение газодинамических характеристик процесса смешения дымовых газов с потоком окружающего теплого воздуха при движении по газоотводящему каналу. В данной работе разработана математическая модель и эффективный численный метод решения поставленной задачи. Рассчитаны поля течений, распределения температур и концентраций при различных условиях на входе в канал. Изучено влияние закрутки потока на характер течения. Представлено сравнение полученных решений с известными экспериментальными данными и численными исследованиями. Результаты расчетов могут быть использованы для поиска оптимальной конструкции возводимых сооружений.

1. Introduction

Investigations on combined high-rise structures development for ecological fuel burning have been carried out since the seventies. Such structures have the following principle of operation. At the base of the stack flue gas, from which the sulfur has been removed, is fed into a flow of air heated in a heat exchanger. As it moves through the stack, the gas mixes with the hot air and is carried into the atmosphere by the natural draft. This design has the following advantages. The energy consumption for re-heating of the smoke in this case is reduced. The pollutant concentrations and temperature of the gas at the stack outlet is significantly reduced, because the volume of heated air is much greater than the volume of flue

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gas (ratio 5:1 – 25:1). Combined high-rise structures provide better draft due to the mixing process in comparison with conventional smokestacks. Problems of external aerodynamics of high-rise buildings were investigated in [1–3].

One promising means of enhancing the efficiency of combined high-rise structures is to swirl the flue gas ahead of the stack inlet. Swirling flows are widely used in various technical applications and are observed in natural phenomena. They have been the object of a great deal of theoretical and experimental study. The most important properties of swirling flows are described in [4, 5]. Swirling flows in channels were investigated numerically in [6–8], in an unbounded medium in [9, 10] and experimentally in [11–13].

The problem of the interaction between two axisymmetric swirling flows is topical in the context of the problems of modeling flows in combustion chambers and gas turbines [14, 15] and in vortex chambers and gas curtains [16–18]. An important feature of these flows is the formation of axial recirculation zones when the initial swirl reaches a critical value. The shape and the character of these zones resemble those formed in swirling streams upon the breakdown of vortex flow [19, 20]. The results of experiments on the stability of swirling flows and the structure of the axial recirculation zone are presented in [21–24].

Thus, the object of research of this work is a combined high-rise structure. The subject of the study is a turbulent flow consisting of smoke and heated air. The task of the research is to study the effect of swirling flow on the mixing and heat transfer processes in a combined high-rise structures. The aim of the research is to ensure minimal environmental damage from burning natural fuels.

The purpose of this work is to develop mathematical model and study the gas-dynamic process of turbulent mixing of flue gas and hot air in the structure under consideration. The general formulation of the problem of the mixing of two nonisothermal turbulent flows is based on the complete Reynolds equations. This system closed by a turbulence model is fairly complicated and its solution is laborious. So we will use a simplified model is based on the parabolized Navier-Stokes equations. In this paper, an efficient numerical method for solution of the problem is presented.

2. Methods

We will consider the problem of mixing of hot gases in the axisymmetric pipe, whose lateral surface is specified in the cylindrical coordinate system r, φ, z by the equation $R(z)$. A swirled flow of flue gas is fed into the central part $(0 \le r \le R_1)$ of the inlet cross-section $(z = 0)$ of this pipe. An outer unswirled hot air flow is introduced into the peripheral part $(R_1 \le r \le R_0 = R(0))$. To investigate the gas dynamic processes of turbulent mixing of heated gases, we use the system of conservation equations for mixture mass, momentum, energy, and admixture mass in the form of boundary layer approximation

$$\frac{\partial (r\rho U)}{\partial z} + \frac{\partial (r\rho V)}{\partial r} = 0,$$

$$\frac{\partial [(p+\rho U^2) r]}{\partial z} + \frac{\partial (\rho r U V)}{\partial r} = \frac{\partial}{\partial r}(r\tau) - \rho g r,$$

$$\frac{\partial (r\rho\, UH)}{\partial z} + \frac{\partial (r\rho\, VH)}{\partial r} = \frac{\partial (rq)}{\partial r} + \rho V W^2 + \mu r \left(\frac{\partial W}{\partial r} - \frac{W}{r} \right)^2,$$

$$\frac{\partial (r\rho\, UH)}{\partial z} + \frac{\partial (r\rho\, VH)}{\partial r} = \frac{\partial (rq)}{\partial r}, \tag{1}$$

$$\frac{\partial (r\rho\, UE)}{\partial z} + \frac{\partial (r\rho\, VE)}{\partial r} = \frac{\partial (\mu r \gamma_\alpha)}{\partial r},$$

$$\frac{\partial (r\rho\, UW)}{\partial z} + \frac{\partial (r\rho\, VW)}{\partial r} = \frac{\partial}{\partial r}\left(\mu r \frac{\partial W}{\partial r} \right) - \frac{\rho V W}{r} - \mu \frac{W}{r^2},$$

$$h = c_p T, \quad H = h + \frac{U^2}{2} + gz, \quad q = \frac{1}{\sigma}\mu \frac{\partial}{\partial r}(h + 0.5\sigma U^2), \quad \gamma_\alpha = \frac{1}{\sigma_\alpha}\frac{\partial E}{\partial r}, \quad \sigma = \frac{1}{\lambda}\mu c_p,$$

$$\tau = \mu \frac{\partial U}{\partial r}.$$

Here, the following notation is used: U, V and W are the axial, radial, and azimuthal velocity components, respectively, μ is the dynamic viscosity, g is the gravity acceleration, T is the temperature, c_p is the specific heat, h is the enthalpy, H is the total enthalpy, q is the heat flux, E_i is the admixture concentration, γ_i is the admixture mass flow-rate, σ and σ_α are Prandtl numbers, and τ is the friction force.

We will use Shkadov method of equal flow-rate surfaces [25]. In the cylindrical coordinate system r, φ, z we define smooth lines $r = \delta_n(z)$, $n = 0,1,2,\dots,N$, each of which is a streamline and satisfies the equation

$$U\frac{\partial \delta_n}{\partial z} = V \text{ for } r = \delta_n(z). \tag{2}$$

The grid of lines $\delta_n(z)$ is constructed together with the solution. Obviously, $\delta_0 = 0$ is the symmetry axis and $\delta_N = R(z)$ is the pipe wall. The gas dynamic functions can be calculated on the intermediate lines

$$r = \delta_{n+1/2}(z) = 0.5(\delta_n + \delta_{n+1}),\ n = 0, 1, 2, \dots, N-1.$$

Each equation from the system (1) can be written in the form

$$\frac{\partial(r\rho\, UA)}{\partial z} + \frac{\partial(r\rho\, VA)}{\partial r} = \frac{\partial Q}{\partial r} - \varepsilon_A\, \omega\, r, \tag{3}$$

$$A = \{1, U, H, E, W\},\ Q = \{0, r\tau, rq, r\mu\gamma_\alpha, \mu r\partial W/\partial r\},$$

$$\varepsilon_A = 1,\ \omega = \frac{\partial p}{\partial z} + \rho g z, \text{ for } A = U,$$

$$\varepsilon_A = 1,\ \omega = -\frac{\rho V W^2}{r} - \mu\left(\frac{\partial W}{\partial r} - \frac{W^2}{r}\right), \text{ for } A = H,$$

$$\varepsilon_A = 1,\ \omega = \frac{\rho V W}{r} + \mu\frac{W}{r}, \text{ for } A = W,$$

$$\varepsilon_A = 0 \text{ for } A = 1, E.$$

Integrating equation (3) with respect to r from $r = \delta_n$ to $r = \delta_{n+1}$, taking into account equation (2) and the Leibniz rule

$$\frac{d}{d\lambda}\int\limits_{U(\lambda)}^{V(\lambda)} f(x,\lambda)\,dx = \int\limits_{U(\lambda)}^{V(\lambda)} \frac{\partial}{\partial\lambda}(f(x,\lambda))\,dx + f(V(\lambda),\lambda)\frac{dV}{d\lambda} - f(U(\lambda),\lambda)\frac{dU}{d\lambda},$$

we obtain

$$\frac{d}{dz}\int\limits_{\delta_n}^{\delta_{n+1}}(r\rho UA)\,dr = -Q\Big|_{\delta_n}^{\delta_{n+1}} - \varepsilon_A\,\omega\frac{1}{2}(\delta_{n+1}^2 - \delta_n^2), \qquad \frac{d}{dz}\int\limits_{\delta_n}^{\delta_{n+1}}(r\rho U)\,dr = 0. \tag{4}$$

Integrals are approximated by finite-difference expressions

$$\int\limits_{\delta_n}^{\delta_{n+1}}(r\rho UA)\,dr = 0.5(\delta_{n+1}^2 - \delta_n^2)\,(\rho UA)_{n+1/2}.$$

Considering as unknown functions

$$f_{n+1/2} = 0.5(\delta_{n+1}^2 - \delta_n^2), \; n = 0, 1, 2, ..., N-1,$$

we obtain expressions for $\delta_n(z)$

$$\delta_1^2 = 2 f_{1/2}, \quad \delta_2^2 = 2(f_{1/2} + f_{3/2}), \quad ..., \quad \delta_N^2 = 2\sum_{n=1}^{N} f_{n-1/2}.$$

Taking this into account we deduce from (4) the system of ordinary differential equations on each line $r = \delta_{n+1/2}(z)$

$$U\dot{U} = \frac{1}{\rho f} R_u - (1 - \frac{1}{\gamma})\pi_T \frac{1}{\rho}\dot{p} - \pi_g,$$

$$U\dot{T} = \frac{1}{\rho f} R_T - (1 - \frac{1}{\gamma}) U \frac{1}{\rho}\dot{p} + \frac{1}{\rho}\frac{\pi_w^2}{\pi_T} G_T,$$

$$U\dot{E} = \frac{1}{\rho f} R_E, \tag{5}$$

$$U\dot{W} = \frac{1}{\rho f} R_w + \frac{1}{\rho} G_w,$$

$$\frac{\dot{f}}{f} = -\frac{\dot{p}}{p} + \frac{\dot{T}}{T} - \frac{\dot{U}}{U}.$$

Here a dot denotes differentiation with respect to z. The system of equations (5) is written in the dimensionless form. The quantities U, T, ρ, E, p and W are scaled by their maximum values U_1, T_1, ρ_1, E_1, p_1 and W_1 in the inner jet at the pipe inlet and f is scaled by R_0^2. The three dimensionless parameters in (5) $\pi_g = R_0 g / U_1^2$, $\pi_w = W_1 / U_1$, $\pi_T = c_p T_1 / U_1^2$ are the Froude number, the swirl parameter and the analog of the Mach number M.

For flows without swirl, equation for the pressure is written as

$$\frac{\dot{p}}{p}\left[-\frac{1}{2\gamma}R^2 + \left(1 - \frac{1}{\gamma}\right)\pi_T p \sum_{n=0}^{N-1}\frac{f_{n+1/2}}{\rho U^2}\right] = R\dot{R} - \sum_{n=0}^{N-1}\left(\pi_g \frac{f_{n+1/2}}{U^2} + \frac{R_T}{\rho U T} - \frac{R_u}{\rho U^2}\right). \tag{6}$$

For swirling flows, the pressure is determined by the equation

$$\frac{\partial p}{\partial r} = \frac{\gamma}{\gamma - 1}\frac{\pi_w^2}{\pi_T}\rho\frac{W^2}{r}$$

which can, after integration, be written in the form:

$$p(z,r) = p^w(z,r) + p_0(z), \quad p^w(z,r) = \frac{\gamma}{\gamma - 1}\frac{\pi_w^2}{\pi_T}\int_0^r \rho \frac{W^2}{r} dr.$$

In order to find $p(z,r)$, we calculate $p^w(z,r)$ from the mean value theorem and $\dot{p}^w(z,r)$ from the recurrence relations

$$\dot{p}_1^w = \alpha_{1/2} f_{1/2}, \quad \dot{p}_{n+1}^w = \dot{p}_n^w + \alpha_{n+1/2} f_{n+1/2}, \quad n = 1, 2, \ldots, N-1,$$

$$\dot{p}_{n+1/2}^w = 0.5(\dot{p}_n^w + \dot{p}_{n+1}^w), \quad n = 0, 1, 2, \ldots, N-1,$$

$$\alpha_{n+1/2}=\frac{\gamma}{\gamma-1}\frac{\pi_w^2}{\pi_T}\frac{\rho f}{r^2}\left(2W\dot{W}-W^2\frac{\dot{U}}{U}\right)\Bigg|_{\delta_{n+1/2}},$$

and determine $p_0(z)$ by integrating the equation

$$\dot{p}_0\sum_{n=0}^{N-1}g_{n+1/2}+\sum_{n=0}^{N-1}\dot{p}^w g_{n+1/2}=R\dot{R}-\sum_{n=0}^{N-1}\left(\pi_g\frac{f_{n+1/2}}{U^2}+\frac{R_T}{\rho UT}+\frac{f_{n+1/2}}{\rho UT}\pi_w^2\frac{G_T}{\pi_T}-\frac{R_u}{\rho U^2}\right),\quad (7)$$

$$g_{n+1/2}=-\frac{f_{n+1/2}}{\gamma(p^w+p_0)}+\left(1-\frac{1}{\gamma}\right)\pi_T f_{n+1/2}\frac{1}{\rho U^2}.$$

Expression (7) is obtained by summing equations (5) for all grid points with the account of equality

$$\sum_{n=0}^{N-1}f_{n+1/2}=\frac{1}{2}R^2(z).$$

Density on each line is calculated by the formula

$$\rho(z,\delta_{n+1/2})=\frac{p(z,\delta_{n+1/2})}{T(z,\delta_{n+1/2})}.\quad (8)$$

Equations (5)–(7) contain the dissipative terms

$$R_u=[r\mu\frac{\partial U}{\partial r}],\quad R_w=[r\mu\frac{\partial W}{\partial r}],\quad R_E=\frac{1}{\sigma_\alpha}[r\mu\frac{\partial E}{\partial r}],$$

$$R_T=\frac{1}{\sigma}[r\mu\frac{\partial T}{\partial r}]+\frac{1}{\pi_T}\left([r\mu U\frac{\partial U}{\partial r}]-U[r\mu\frac{\partial U}{\partial r}]\right),\quad (9)$$

$$G_T=\mu\left(\frac{\partial W}{\partial r}-\frac{W}{r}\right)^2+\frac{\rho VW^2}{r},\quad G_w=-\frac{\rho VW}{r}-\mu\frac{W}{r^2}.$$

where the quantity in brackets means $[Q]=Q_{n+1}-Q_n$.

The boundary conditions on the flow axis for the unknown quantities $A=\{U,T,E,W\}$ of system (5) follow from the symmetry conditions. In the wall region we assume that the boundary layer is thin and the uniform flow zone extends to the wall. Therefore, we have

$$\frac{\partial A}{\partial r}=0 \text{ for } \delta=0,\ \delta=R(z).\quad (10)$$

To determine the derivatives with respect to r in expressions (10), we use the following algorithm. We will assume that the unknown functions $A'=\partial A/\partial r$, where $A=\{U,\ W,T,E\}$, on the segments $\Delta_n=\delta_n-\delta_{n-1}$ have the form

$$A'=a_n+b_n\eta_n,\quad \eta_n=\frac{r-\delta_{n-1}}{\delta_n-\delta_{n-1}},\quad r\in[\delta_{n-1},\delta_n],\quad \eta_n\in[0,1].\quad (11)$$

Obviously, $a_n=A'_{n-1}$, $a_n+b_n=A'_n$, $b_n=A'_n-A'_{n-1}$. After integration, the expression (11) takes the form

$$A(\eta_n)=A_{n-1}+\Delta_n(a_n\eta_n+\frac{b_n\eta_n^2}{2}),\quad \eta_n\in[0,1],\quad n=1,2,\ldots,N.\quad (12)$$

Substituting in (12) the values $\eta_n=1$ and $\eta_n=0.5$, we obtain

$$A_n = A_{n-1} + \frac{1}{2}\Delta_n (A'_{n-1} + A'_n), \quad n = 0, 1, 2, \dots, N \text{ ,}$$

$$A_{n-1/2} = A_{n-1} + \frac{1}{8}\Delta_n (3A'_{n-1} + A'_n), \quad n = 1, 2, \dots, N \text{ .}$$

Excluding unknowns in integer nodes, we obtain a system of three-point equations with respect to unknowns A'_n:

$$\Delta_n A'_{n-1} + 3(\Delta_n + \Delta_{n+1})A'_n + \Delta_{n+1}A'_{n+1} = 8(A_{n+1/2} - A_{n-1/2}), \quad n = 1, 2, \dots, N-1. \qquad (13)$$

The values A'_0 и A'_N for the flow in a channel, in accordance with expression (10), are assumed to be zero. The system of equations (13) is effectively solved by the sweep method.

The system of equations (5)–(9) must be closed by specifying a turbulence model. We will use an algebraic model based on the Prandtl mixing length l_i which for swirling flows is linked with the turbulent viscosity ν_{ti} as follows:

$$l_i^2 = \nu_{ti} \left\{ \left(\frac{\partial V_z}{\partial r} \right)^2 + \left[r \frac{\partial}{\partial r} \left(\frac{V_\varphi}{r} \right) \right]^2 \right\}^{-1/2}, \qquad (14)$$

where the subscript i has the values z for the axial and φ for the azimuthal direction. The dimensionless empirical constants were taken to be equal to $l_z / R_0 = 0.068$, $l_\varphi / R_0 = 0.034$. These values were obtained experimentally [16] for swirling flows of the gas-curtain type. Investigations presented in [16] showed that the numerical results based on these values of l_z and l_φ are in good agreement with the experimental data.

The system (5), (7) from $5N+1$ differential equations is solved numerically by the Runge-Kutta method. In most calculations we used $N = 50$.

3. Results and Discussion

This method of calculating for unswirled flows was tested using numerical solutions [26] obtained on the basis of the complete Navier-Stokes equations and the differential $k-\varepsilon$ turbulence model. The velocity distribution over the inlet cross-section $z = 0$ was specified as follows:

$$U = U_1 = 1, \quad 0 \le r \le r_1; \qquad U = U_2 = 0.1, \quad r_1 < r \le 1, \qquad (15)$$

where $r_1 = 0.12$. The velocity profiles obtained from a numerical solution of problem (5), (7)–(10) with conditions (15) are presented in Figure 1,a. The velocity distributions are only slightly different from the results of [26].

For swirled flows, this method was tested using experimental data [27] on the mixing of two coaxial isothermal flows in the absence of admixtures. The flow in an annular channel $(0.5 \le r \le 1)$, which the inner flow entered pre-swirled and the outer flow unswirled, was considered. At $z = 0$, the velocity distribution was specified as follows:

$$U = 1.2, \ W = 1, \ 0.5 \le r \le 0.75; \quad U = 0.8568, \ W = 0, \ 0.75 \le r \le 1 \text{ .} \qquad (16)$$

Here, U is divided by the mean-flow velocity and W by the maximum azimuthal velocity at the channel inlet. In this case, the inner to outer mass flow-rate ratio was equal to unity and the swirl parameter $\pi_w = 0.833$.

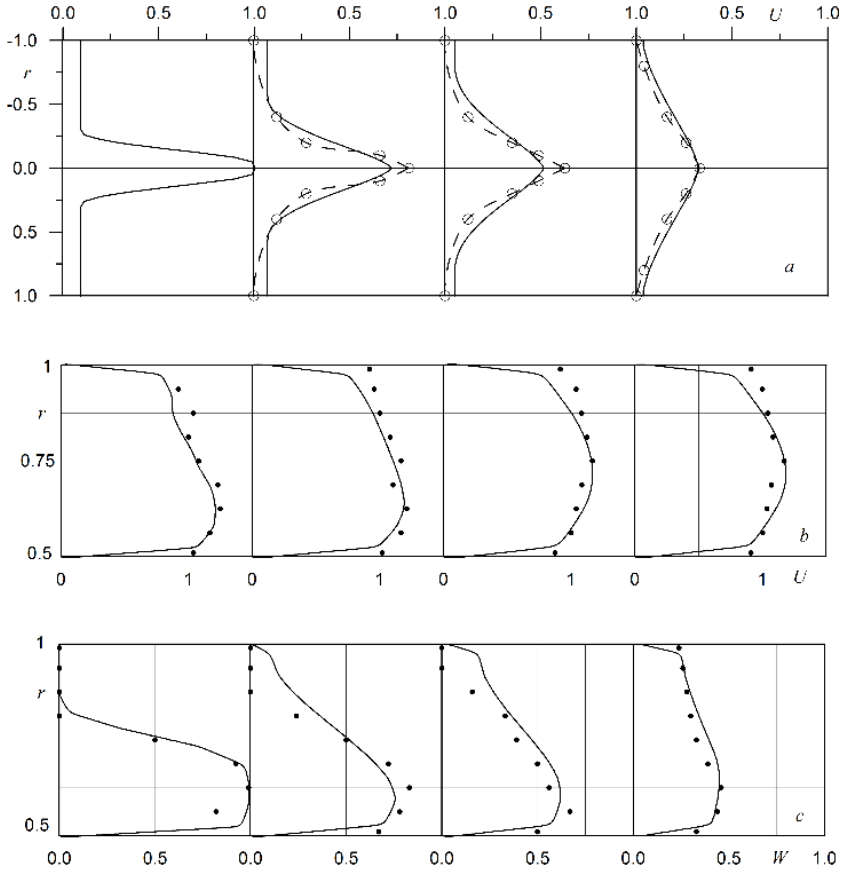

Figure 1. Comparison of the calculated profiles (solid lines) for unswirled flows with the data of [26] (dashed lines) for $z = 0.1,\ 2,\ 3,\ 4$ (a) and for swirled flows with experiments [27] for $z = 0.06,\ 1.56,\ 3.06,\ 4.56$ (b)

The profiles of the axial and azimuthal velocities found from the numerical solution of problem (5), (7)–(10) with conditions (16) are presented in Figure 1,b. The data of experiments [27] are indicated by the points. A comparison shows fairly good agreement between theory and experiment and confirms the possibility of using the mathematical model to describe the process of mixing of two turbulent flows in the presence of swirling.

The main part of the calculations was performed for the following distributions over the inlet cross-section $z = 0$:

$$\begin{aligned} &U(r) = U_1 = 1,\ W(r) = W_1(r),\ T(r) = T_1 = 1,\ E(r) = E_1 = 1,\ 0 \le r \le r_1, \\ &U(r) = U_2, \quad W(r) = W_2, \quad T(r) = T_2, \quad E(r) = E_2, \quad r_1 < r \le 1, \end{aligned} \tag{17}$$

where $r_1 = R_1 / R_0$. The solution domain was determined by the length $z_0 = 2.2 R_0$ and the lateral surface was either assumed to be cylindrical $R_0 = 1$ or specified by the equation $R(z) = 1 - 0.15 z$.

For high-rise structures of the kind described, typical values of the parameters are as follows: base diameter 90 m, height 100 m, flow-rate of the flue gases in the inner flow 300 m^3/s at a gas temperature of 120^{0}C, and air flow-rate in the outer flow 5000 m^3/s at a gas temperature of 70^{0}C. Therefore, in the calculations the values of the dimensionless quantities were taken to be equal to

$$U_2 = 0.05 - 0.4,\ T_2 = 0.5 - 0.9,\ E_2 = 0 - 1,$$

$$\sigma = 0.72,\ \pi_g = 6.45,\ \pi_T = 5754,\ \pi_w = 0 - 1.35.$$

In investigating the process of mixing of two hot gases, our attention was focused on the effect of the inner jet swirl on the flow parameters. In the axial velocity distribution (Figure 2) an important effect can be detected: swirling of the inner jet leads to a deceleration of the flow. When the swirl $\pi_w > 1.35$, we were unable to carry out further calculations on the basis of the parabolized equations, and the complete Navier-Stokes equations had to be used.

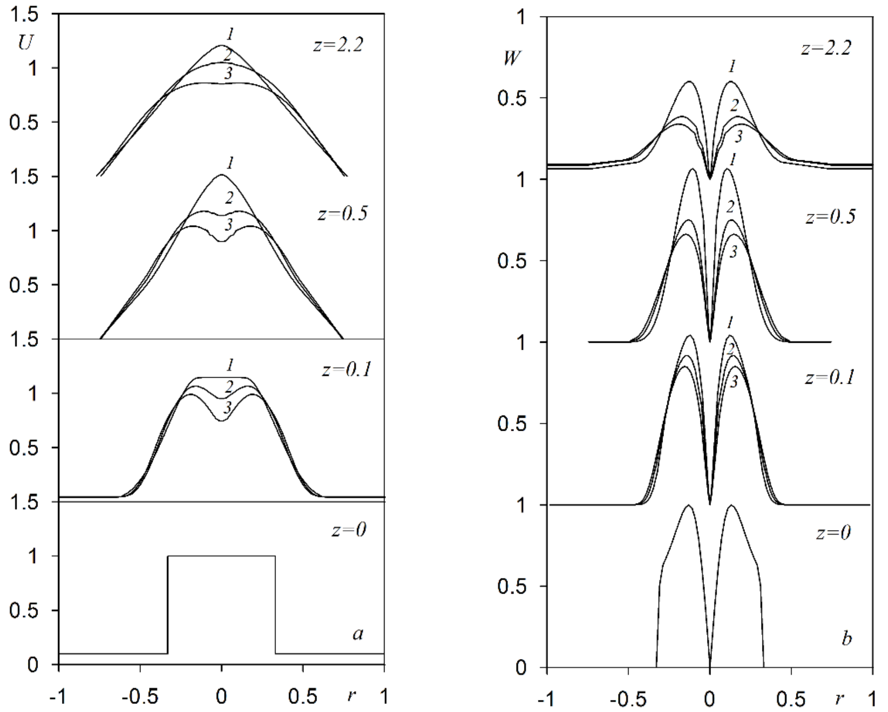

Figure 2. Axial and azimuthal velocities profiles for $\pi_w = 0,\ 1,\ 1.3$ (a), $\pi_w = 0.2,\ 1,\ 1.3$ (b) (curves 1-3) in sections z=const

Another effect discernible in the axial velocity distribution is that associated with jet acceleration under the action of a lift force (Figure 3,a). In the distribution of the azimuthal velocity the most important property is as follows. For a weak swirl $\pi_W = 0.2$, under the action of the lift force produced by the temperature difference the flow rotation velocity increases The effects of flow acceleration and increase in the rotation velocity on an initial segment of the channel are manifested even more clearly with increase in the inner gas jet to outer air flow temperature ratio T_1 / T_2 (Figure 3,b).

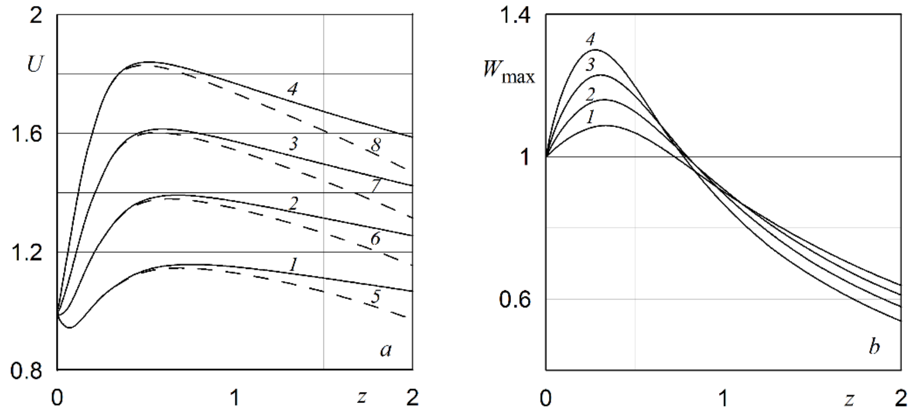

Figure 3. Distributions of the axial velocity over the axis $r = 0$ for $\pi_w = 1$ (a) and the maximum azimuthal velocity (b) for $\pi_w = 0.2,\ T_2 = 0.8,\ 0.7,\ 0.6,\ 0.5$ (curves1–4), $R(z) = 1 - 0.15z$ (curves 5–8)

A favorable effect can be detected in the variation of the admixture concentration along the flow axis, which is almost halved at the channel outlet as compared with its initial value. With increase in the swirl, due to efficient mixing of the flows, the admixture concentration falls closer to the inlet cross-section. At the stack mouth the concentration depends only slightly on the initial swirl of the inner jet. In all cases, the temperature decreases with increase in z (Figure 4).

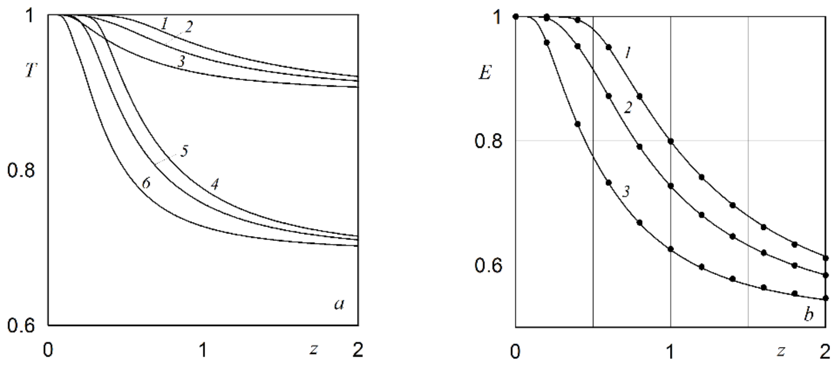

Figure 4. Distributions of the temperature (a) and the concentration (b) over the axis $r=0$ $\pi_w=0.2,\ 0.5,\ 1.3$, $T_2=0.8$ (curves1–3) and $T_2=0.5$ (curves1–4)

A graphic representation of the flow pattern inside the ventilation pipe can be seen in Figure 5. The streamlines converge fairly rapidly toward the center with increase in the distance z. This information can be used in profiling the stack walls in order to reduce the dimensions of the structure, cut costs, and make the structure more stable.

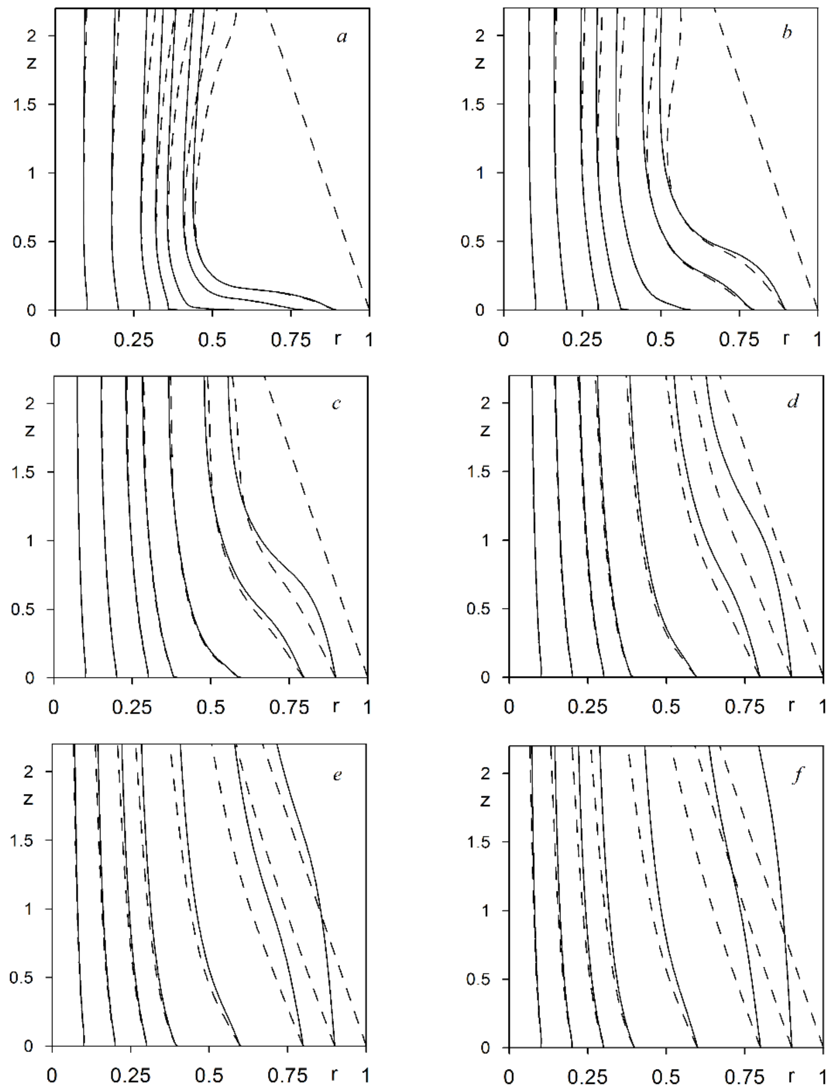

Figure 5. Streamlines for $\pi_w=1$, $r_1=0.33$, $T_2=0.8$, $U_2=0.1,\ 0.2,\ 0.3,\ 0.4,\ 0.5,\ 0.6$ (a-e), $R(z)=1$ – solid lines, $R(z)=1-0.15z$ – dashed lines

Obtained critical swirl flow ratio $\pi_W = 1.35$ can be compared with calculation results based on complete Navier-Stokes equations system. Let us define two characteristic values: r_* – vortex core radius over the inlet cross-section $z = 0$ (distance from the axis, at which azimuthal velocity W has maximum value), and U_* – flow axial velocity at $r = r_*$, $z = 0$. Then we introduce dimensionless parameters that determine viscous swirling flow

$$\mathrm{Re} = \frac{U_* r_*}{\nu}, \qquad \mathrm{Ro} = \frac{U_*}{r_* \omega}. \tag{18}$$

where ω is flow angular velocity at $r \to 0$. Rossby number Ro is inversely proportional to swirl parameter. Critical Rossby number value dependence from Reynolds number, which results in axial recirculation zone formation in a flow, is represented in Figure 6. Solid line corresponds to swirling flow calculation results in cylindrical channel with impermeable walls, obtained on the basis of complete Navier-Stokes equations system solution [10]. Data of works [28], [29], recalculated by formula (18), are marked with circles and rhombs. Critical swirl ratio $\pi_W = 1.35$, obtained by means of parabolized Navier-Stokes equations (5), is represented in Figure 6 by dashed line and corresponds to $\mathrm{Ro} = 0.43$.

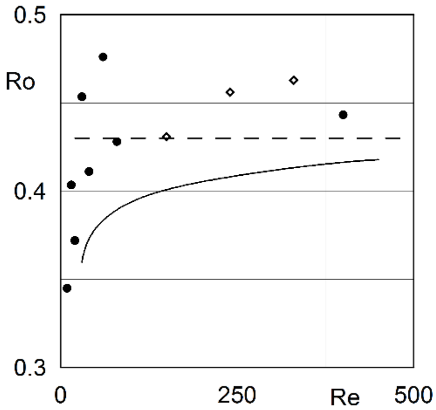

Figure 6. Critical values of Rossby numbers

4. Conclusions

1. Mathematical model is developed and boundary value problem is formulated for studying the process of turbulent mixing of flue gas and heated air in combined high-rise structure.

2. An efficient method of solving the parabolized Navier-Stokes equations, which reduces the initial system to ordinary differential equations written on the streamlines, is proposed.

3. Algorithm and computer calculation program have been developed. Verification of the program was carried out.

4. All fundamental flow characteristics have been calculated: velocity profiles, temperature distribution and harmful impurities concentration distribution for different flow cross-sections. The results of calculations showed the following important features of the flows. Initial inner swirl flow serves to mixing process intensification. Weak and moderate swirling of the inner flue gas, which causes additional rotation in flow, is of special interest for stack flue stream. Strong swirl results in abrupt flow deceleration and possible formation of an axial reverse-flow zone. This effect is undesirable.

5. The positive effect discernible in the axial velocity distribution is that associated with jet acceleration under the action of a lift force. The flow swirl promotes a more rapid temperature equalization over the channel length. In the cases considered, the admixture concentration at the channel outlet decreases by a factor of 2-4.

6. Streamline flow patterns have been obtained. These patterns can be used for smokestack wall profiling to shorten structure dimensions and reduce construction costs. The results of this work allow us to seek the optimal flow regimes in high-rise structures for ejecting pollutant-containing smokes and gases into the atmosphere with a view to minimizing environmental damage.

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