The study of gas flow in the industrial smoke pipe

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Abstract. To describe the flow of flue gases in the working space of the exhaust shaft of an industrial chimney, a three-dimensional mathematical model based on the Favre-averaged complete Navier-Stokes equations closed by $k-\varepsilon$ – a turbulence model using improved wall functions is proposed. Thus, it is possible to draw up a detailed physical picture of the process under study, to establish the presence of a significant part of the internal volume of the barrel of intensive secondary flows, vortex zones, which have a significant effect on the kinematic structure of the entire flow, on the nature of the velocity distribution in its various cross sections, as well as on friction, heat transfer and mass transfer in the parietal regions. The calculations showed that a swirling gas flow, which reduces the corrosion resistance of its walls appears in the root of the chimney. This undesirable phenomenon noticeably weakens in case of installation of special ramps or partitions at the inlet of the outlet trunk.

Keywords: mathematical modeling, gas stream, smoke gases, smoke pipe, sulfur corrosion, destruction of the smoke pipe.

1 Introduction

Scientific and technological progress encourages the development and improvement of various industries in the industrial complex, including energy-intensive ones. The development of new mineral deposits and the expansion of production at existing sites requires the formation of appropriate infrastructure to ensure the life of personnel, which eventually leads to the construction of new or expanding the area of existing settlements. Thus, it requires considerable amounts of electrical and thermal energy. This explains not only the introduction of new capacities in the country's energy complex, but also the modernization of existing units and the improvement of technological processes.

One of the current trends in the heat-producing industry is energy resource saving during the operation of technological equipment.

A thermal power station (TPS) is formed by a complex of equipment and devices, the main of which are a boiler plant that produces steam of high parameters, a turbine or steam turbine plant that converts the heat of steam into mechanical energy of the turbine unit's rotor, and electrical devices (electric generator, transformer, etc.) that provide electricity generation (figure 1).

The main element in a boiler plant that produces steam is a boiler. The boiler looks like an arched structure with the ducts of rectangular cross section. The left part, called the furnace, is fed with gas mixed with heated air. The air is heated by recirculating the smoke gases leaving the boiler. The air in the regenerative air heater (RAH) is heated with smoke gases. Partially cooled smoke gases [2-6] are fed into the smoke pipe by the smoke pump. Through the smoke pipe [7-11] the products of combustion (smoke gases) are pushed into the upper layers of the atmosphere and disperse.
Smoke pipes are complex special engineering structures of the tower type designed to remove smoke gases from thermal power plants and disperse them in the atmosphere and are an integral part of thermal power plants. The reliability, efficiency and durability of smoke pipes [12-16] depend not only on the smooth operation of the power equipment connected to them in normal mode, but also on the environmental condition of the environment. At the same time, the indicators of these structures themselves are largely determined by the nature of the rather complex aerodynamic and heat and mass transfer processes [17-22] that take place in them. To date, these processes have remained little studied due to the lack of practical feasibility of conducting more in-depth field experimental studies using such modern diagnostic tools on such objects. In this situation, an acceptable alternative to a detailed physical field experiment is a mathematical experiment based on the use of modern methods of computational gas dynamics and computer technologies.

2 Materials and methods

2.1 Mathematical statement of the problem

The stream of a non-isothermal gas flow, including its acceleration, was studied in [23-26]. It is well known that in the case of channel narrowing, a negative longitudinal pressure gradient appears. Under its influence the velocity profile becomes more filled, the relative friction coefficient increases in magnitude, and the gas flow rate increases as well. Non-isothermcity in the heat flow directed from the more heated smoke gases to the walls of the gas-air path also contributes to a greater filling of the velocity profile, an increase in the relative coefficient of friction and the smoke gas flow rate.

In the turbulent stream mode of the working medium, the fields of actual values of velocities, pressures, and temperatures in the flow are a complex structure. The reason for this structure is the irregularity or randomness of the nature of changes in these parameters in space and time. Therefore, in the mathematical description of turbulent flows, all approaches, including the direct modeling of turbulence, the direct modeling of large-scale structures and the so-called Reynolds moment approach, are based on non-stationary three-dimensional equations of viscous gas dynamics - the Navier-Stokes system of equations, as well as on statistical averaging operations performance, which is implemented at one of the stages of the problem statement or in its solution. When direct turbulence modeling is performed based on three-dimensional non-stationary Navier-Stokes equations, statistical averaging is
performed after integrating these equations. Averaging has the main goal of making the traditional form of practical analysis more convenient.

When the Reynolds moment approach is used, the statistical averaging operation is performed at the initial stage of the problem statement. Then, first, the equations of viscous gas dynamics are statistically averaged. Then a preliminary semi-empirical closure is performed and then the integration is performed. The averaging operation is performed on all scales simultaneously. Therefore, universality is lost here. These methods remain in demand when analyzing a narrow range of hydrodynamic processes.

When direct modeling is performed, statistical averaging of the equations is performed at the stage of setting the problem. However, not all scales are covered, since semi-empirical turbulence modeling must be performed only on sub-grid scales, i.e. on scales of phenomena that are smaller than the size of a statistical cell. Thus, in all cases, we obtain a system of Navier-Stokes equations averaged by Reynolds. This means that any gas-dynamic value in a turbulent flow is represented as the sum of averaged and pulsating components. Moreover, when determining the average values, averaging is performed over a certain time interval, i.e., temporary averaging. In addition to this averaging, there are other methods – statistical averaging by volume (spatial averaging), statistical averaging by ensemble.

The classical approach of statistical averaging over a certain time interval (according to Reynolds) is mainly used in solving equations that describe the flow of a working body with a constant density-incompressible liquids. When it comes to describing the turbulent flows of a compressible gas, a combined averaging method is more often used. Here, the pressure and density of the gas are averaged over time (by Reynolds), and other flow parameters are entered using the so-called weighted average values. This method of averaging is called the weighted average method or Favre averaging. Its main advantage is that the system of equations of turbulent motion is more compact compared to other approaches.

In the description of turbulent stream gas flow, in particular, and in the smoke pipe thermal power plants, the system of equations includes equations of momentum, continuity equation, energy equation and equation $k$-$\varepsilon$ turbulence model, i.e. when three-dimensional formulation in Cartesian coordinate system are:

- continuity equation:
  \[ \frac{\partial p}{\partial x} + \frac{\partial p}{\partial y} + \frac{\partial p}{\partial z} = 0. \]  \(1\)

Equation of the amount of motion in the projection on the $X$ axis:
  \[ \frac{\partial p}{\partial t} + \frac{\partial (p u)}{\partial x} + \frac{\partial (p v)}{\partial y} + \frac{\partial (p w)}{\partial z} = -\frac{\partial}{\partial x} \left( \frac{\mu}{\rho} \frac{\partial u}{\partial x} \right) - \frac{\partial}{\partial y} \left( \frac{\mu}{\rho} \frac{\partial v}{\partial y} \right) - \frac{\partial}{\partial z} \left( \frac{\mu}{\rho} \frac{\partial w}{\partial z} \right) + \frac{\partial p}{\partial x} = 0. \]  \(2\)

Equation of the amount of motion in the projection on the $Y$ axis:
  \[ \frac{\partial p}{\partial t} + \frac{\partial (p u)}{\partial x} + \frac{\partial (p v)}{\partial y} + \frac{\partial (p w)}{\partial z} = -\frac{\partial}{\partial y} \left( \frac{\mu}{\rho} \frac{\partial u}{\partial y} \right) - \frac{\partial}{\partial x} \left( \frac{\mu}{\rho} \frac{\partial v}{\partial x} \right) - \frac{\partial}{\partial z} \left( \frac{\mu}{\rho} \frac{\partial w}{\partial z} \right) + \frac{\partial p}{\partial y} = 0. \]  \(3\)

Equation of the amount of motion in the projection on the $Z$ axis:
  \[ \frac{\partial p}{\partial t} + \frac{\partial (p u)}{\partial x} + \frac{\partial (p v)}{\partial y} + \frac{\partial (p w)}{\partial z} = -\frac{\partial}{\partial z} \left( \frac{\mu}{\rho} \frac{\partial u}{\partial z} \right) - \frac{\partial}{\partial x} \left( \frac{\mu}{\rho} \frac{\partial v}{\partial x} \right) - \frac{\partial}{\partial y} \left( \frac{\mu}{\rho} \frac{\partial w}{\partial y} \right) + \frac{\partial p}{\partial z} = 0. \]  \(4\)

Where, $x, y, z$ – are Cartesian coordinates, $t$ – is time, $u, v, w$ – are projections of the velocity vector on the $x, y, z$ axis respectively, $p$ – is pressure, $\mu$ – is the effective viscosity coefficient, $\rho$ – is the density of the working medium.

Energy equation:
  \[ \frac{\partial (\rho h)}{\partial t} + \frac{\partial (\rho hu)}{\partial x} + \frac{\partial (\rho hv)}{\partial y} + \frac{\partial (\rho hw)}{\partial z} = \frac{\partial}{\partial x} \left( \frac{\mu}{\rho} \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left( \frac{\mu}{\rho} \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left( \frac{\mu}{\rho} \frac{\partial h}{\partial z} \right) + \frac{\partial p}{\partial x} \]  \(5\)

where $P_r$ – is the Prandtl number, $P_\tau$ – is the turbulent Prandtl number, $h$ – is the enthalpy:
  \[ h = \sum_a Y_a (\Delta h^a_w + \int_0^T \rho C_p(T) \, dT) \]

Where $Y_a$ – is the mass fraction of the component $a$, and $T$ – is the temperature.  

(5)
The transport equation of turbulent kinetic energy and its rate of dissipation:
\[
\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho k u_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left( \frac{\partial k}{\partial x_j} \right) + \frac{\partial}{\partial x_j} \left( \frac{\partial \epsilon}{\partial x_j} \right) - \rho \frac{G - \rho c}{\epsilon}.
\]
(7)

The turbulent viscosity was determined using the Kolmogorov-Prandtl formula:
\[
\mu_t = \frac{C_p \rho k^2}{\epsilon},
\]
(10)
and the effective viscosity calculate at formula:
\[
\mu = \mu_t + \mu_{\text{mol}}.
\]
(11)

Where \( \mu_{\text{mol}} \) – is the molecular viscosity. The values of constants were assumed to be equal \( C_p = 0.09, C_t = 1.30, C_r = 1.92, \sigma = 1.0, \sigma = 1.3, P_i = 0.7, S_i = 0.7 \).

The density \( \rho \) was determined from the equation of state:
\[
P = \frac{\rho R_0 T}{M},
\]
(12)
where \( R_0 \) is the universal gas constant, and the pressure \( P \) was assumed to be equal to atmospheric pressure.

3 Results
A modern smoke pipe, as a rule, consists of a supporting structure – a shell, a gas exhaust trunk or lining and a foundation. The smoke pipe shell must provide high strength of the structure to the impact of its own weight, wind load, as well as to seismic and meteorological impacts. As shells for the smoke pipes of modern thermal power plants, structures made of monolithic reinforced concrete of conical shape with a height-varying wall thickness have been exceptionally used. According to the design of the gas exhaust trunk, modern smoke pipes are divided into two groups: without gas exhaust trunks separated from the shell, and with gas exhaust trunks separated from the shell and a passage gap between them. Pipes of the first type are more common. The choice of smoke pipe design depends on the aggressiveness of the smoke gases, their composition and dew point, the power plant capacity and its type. The aggressiveness of smoke gases is determined by the content of aggressive components and moisture in the fuel, the difference between the dew point temperature and the temperature of the wall of the exhaust trunk. The main aggressive components of smoke gases are sulfur and sulfur anhydrides, which form an aggressive liquid, then diffuse into the concrete body, reach the metal reinforcement, and thus have a destructive effect on the entire structure [26, 27]. In [28] it is indicated that until recently, the reasons for the penetration of smoke gases outside the barrel have not been sufficiently studied, and in [1] a significant influence of gas-dynamic factors is stated. To detect the presence of excessive static pressures inside the barrel, L.A. Richter [29] proposed a special criterion:
\[
R = \frac{(\lambda + 8i)P_{\text{in}}}{g \rho D_h},
\]
(13)
where \( \lambda \) – coefficient of hydraulic resistance of the trunk (for pipes with brick lining of \( \lambda \) is usually taken equal to 0.05), \( i \) – is the slope of the generatrix of the wall of the barrel of the pipe, \( P_{\text{in}} \) – dynamic pressure at the mouth of the barrel, Pa; \( D_h \) – the diameter of the mouth, m, \( \Delta P \) – the difference of density of air and smoke gases, kg/m\(^3\) (density of gases, was adopted unchanged for the height of the pipe), \( g \) – gravitational acceleration, m/s\(^2\). If \( R \) is less than or equal to 1, then the entire
pipe is rarefied and the penetration of aggressive gases outside is impossible. If \( R \) is greater than 1, then in some sections of the pipe there is excessive static pressure on the wall, which increases the filtration of aggressive gases through the lining. To date, design and repair organizations use a one-dimensional model of the flow of gases in the smoke pipe when performing work [30].

The question of what are the values of the pressure on the wall of the gas outgoing channel of the smoke pipe in its various cross sections is very important when predicting the location of the most vulnerable to corrosion zones of its inner surface. It is believed that this process is particularly intense in those cases and in such places where the gas pressure inside the trunk exceeds atmospheric pressure. The preparation of pressure diagrams (figure 2) and their characteristic points finding make it possible to approach the choice of the geometry of the gas outlet channel when developing a pipe project more purposefully, and, moreover, to analyze easily the working conditions of existing chimneys when changing the operating modes of the equipment connected to them. The results of calculations obtained on the basis of a one-dimensional model of smoke gas flow, in the construction of which a number of simplifying assumptions were adopted, and which in principle (due to one-dimensionality) are not able to adequately take into account the flow behavior at a very important inlet section of the trunk, where the flow has a clearly expressed three-dimensional character, and this flow largely depends on the flow characteristics at other sections of the gas outgoing channel of the smoke pipe.

![Figure 2](image.png)

**Figure 2.** Diagrams of parameters distribution of \( \Delta \rho \), \( S \), \( \Phi \) for a smoke pipe height of 180 meters calculated:

a) from a one-dimensional flow model and b) from a three-dimensional flow model:

\[
\Delta \tau = \frac{\Delta \rho \cdot w^2}{\rho_0 w^2_0} - \text{pressure drop on the barrel wall from the flue gas side}
\]

and barometric pressure in the corresponding cross section; \( S = \frac{2g\Delta \rho h}{\rho_0 w^2_0} \), – relative gravity;

\[
\Phi = \Delta \tau + S - \text{form parameter of the gas outgoing channel of the smoke pipe.}
\]

The main reason for the difference in the results of calculations performed on the one- and three-dimensional models of flows are swirls in the form of large vortices (figure 3) and a significant transformation of the kinematic structure in the height of the channel. Due to the rotational movement of the smoke gas flow, centrifugal forces appear in the barrel, which create additional (to static) dynamic pressure on its wall. As the smoke gases flow moves towards the mouth of the shaft, the rotational movement weakens at a certain height (in this example \( \approx 30 \) meters) and then gradually degenerates. The direction of flow becomes completely axial with a practically uniform velocity distribution over the cross section.
The transformation of the kinematic structure of flue gases, which occurs as it moves along the chimney stack, is a cause of significant unevenness in the distributions of pressure, temperature, and the kinetic energy of turbulence in the working space of the barrel, which is responsible for the intensity of heat and mass transfer processes in the pipe.

To determine the possibility of reducing the rotational movement of smoke gases in the socle part of the gas outgoing channel pipe, calculations were performed for the socle without a partition (figure 4a) and for a socle with a partition (figure 4b). The results of calculations showed that this undesirable phenomenon – the movement of smoke gases rotating relative to the pipe axis noticeably weakens when a partition is installed at the inlet of the gas outgoing channel. Figure 4b shows the localization of vortices at a much smaller distance and the formation of an axial flow with a practically uniform velocity distribution over the cross section.

4 Discussions

This article discusses the results of calculations performed on one- and three-dimensional models of flows. Today, companies that conduct inspections of chimneys, as well as perform design and repair
work, use in their practice a one-dimensional mathematical model of smoke gas flow. Comparison of the results of calculations carried out on the one- and three-dimensional models showed that the results are ambiguous, which is caused by simplifying assumptions accepted in the one-dimensional model. The calculation results obtained by the three-dimensional model made it possible to reveal the movement of flue gases in the root part rotational relative to the axis of the pipe, which, in turn, creates pressure on the walls of the chimney barrel due to the centrifugal component, stimulates sulfuric corrosion and the processes that destroy the structure as a whole. As a counteraction to swirling smoke gas flows, it is proposed to install a partition in the root part of the smoke gas of the gas outgoing channel of the smoke pipe, which prevents the flow from swirling, localizes eddy formation and stimulates the process of forming the axial flow of smoke gases.

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