Gas dynamics of reactive gases in swirling-type furnace

A I Akhmetshina¹, G I Pavlov¹, A N Sabirzyanov¹, O A Tikhonov¹

¹Kazan National Research Technical University — KAI named after A. N. Tupolev

E-mail: galimova.alfiya@mail.ru

Abstract. It is known from the literature that for the complete reaction of two gases (fuel and oxidizer), it is necessary to fulfill three basic conditions: the stoichiometric ratio of reactive gases, qualitative mixing and ensuring the cooling of combustion products without "quenching". Of the above-stated conditions it is more difficult to organize a qualitative mixture formation. This physical process requires additional expenditure of energy flow. In this work we present the results of experimental and theoretical studies of the gas dynamics of a reactive gas mixture in a swirling-type furnace. The design scheme of the furnace includes two reaction zones for combustible components: the first zone is the zone of generation of combustible gases which composition is constant; the second zone of the furnace - zone of a homogeneous combustion reaction.

The problem of determining the necessary parameters is practically not solved because of the complexity of the physicochemical processes taking place in the first zone. The methods for calculating gas-dynamic parameters in homogeneous reacting mixtures have been sufficiently tested. The solution of gas dynamics problems in the second zone is classical and can be successfully solved using existing software packages.

The composition of the generator gases at the outlet from the first zone and the corresponding flow parameters were used as initial data. These parameters are determined by thermodynamic calculation under certain assumptions. The adequacy of the results of thermodynamic calculations and also the results of computational experiments in the second zone were verified by experiments.

A fire stand was designed for the experiments. The fire stand includes a model of a swirling-type furnace and a system for measuring the parameters of gases (velocity, temperature, composition of gases). A detailed description of the stand is described in work [1].

The complete geometric model is executed in the SIEMENS NX version 9.0 graphics package. The appearance of the furnace is shown in Figure 1a, the design of the internal parts of the boiler furnace without the elements of supplying secondary air into the reaction area is shown in Figure 1b.
The swirling-type furnace has two reaction zones for the combustible components with air. In the first zone the combustion of a combustible substance takes place in a layer on the grate. Sleepers in the form of chips are used as fuel. This zone is characterized by such complex physicochemical processes as heating and thermal decomposition of wood chips, impregnating substances, partial combustion of the gas phase and so on. These phenomena occur due to the heat released during the combustion of a portion of the gas phase and coals. Air in the grate part of the furnace is supplied in an amount necessary for burning a small part of the combustible gases and afterburning of the solid residue (coals).

Further the gas mixture consisting of combustible gases of thermal decomposition of sleepers and combustion products of coals enters the second zone located above. Secondary air is supplied through different belts in the same zone. Air is supplied in the form of separate jets at different angles to the radius, thereby forming a vortex flow of different structures. Air in the furnace space is fed by a fan. The air supply system allows you to distribute the air through the combustion zones according to the set program. The zone from the grate to the gas phase where the primary heated air is supplied cannot be considered during the combustion process modeling. In the second zone air supply is carried out according to various design schemes: radially, tangentially and chordally.

To realize these schemes, air blocks in the form of cylindrical collectors with air nozzles (three blocks) are made which make up the lateral wall of the swirling-type furnace. The design of the furnace allows you to change the position of the blocks relative to each other and form 6 variants of air supply. In the body of the furnace there are technological hatches for inserting probes of measuring instruments into the investigated space of the furnace.

The following options of secondary air supply are considered:

1. option 1 - all units are tuned to the tangential air supply;
2. option 2: the first block - the tangential scheme; the second block is a radial scheme; the third block is the tangential scheme;
3. option 3 - the first block - the tangential scheme; the second block is a chordal scheme at an angle of 260 degrees to the tangent; the third block is a tangential diagram;
4. option 4 - the first block is the tangential scheme, the second block is a radial scheme; the third block is a chordal scheme at an angle of 260 degrees to the tangent;
5. option 5 - the first block is a tangential scheme; the second block is a radial scheme; the third block is a chordal at an angle of 450 degrees to the tangent;
6. option 6 - the first block is chordal scheme at an angle of 450 to the tangent; the second block is a radial scheme; the third block is the tangential scheme.
Numerical studies were based on the statistical approach (RANS) which is based on averaging the equations of motion. According to this model, all studied parameters are decomposed into the mean and turbulent components, and turbulence is modeled on the basis of semiempirical models. A laminar micro flame model for a non-blended mixture was used as a combustion model. The physical essence of the laminar micro flame model is the separate supply of components which leads to the fact that the combustion process is largely limited by mixing. However, in turbulent flames due to a considerable deformation of the flame front, the diffusion transfer rate increases substantially which leads to a noticeable deviation from the chemical equilibrium. To avoid large errors in the calculations, the transition from complete chemical equilibrium to partial is accomplished, when individual parts of the chemical process proceed with finite velocities and all the rest are infinitely fast. This approach is equivalent to the idea of a turbulent flame front, as an ensemble of laminar micro flames. The parameters of the laminar flame are preliminarily calculated and stored as a table, and then the laminar flame is introduced into the turbulent flow using statistical methods. A large number of computational experiments were carried out on the basis of the above-described model. The results of the experiments were reproduced in the form of fields and graphs.

Figure 2 shows the distribution of static temperature fields in the furnace with the supply of secondary air in two ways: Figure 2a - option 1, Figure 2b - option 4.

![Figure 2a and Figure 2b](image)

**Figure 2.** The distribution of static temperature fields in the z = 0 plane: (a) - according to the option 1, (b) - according to the option 4

It can be seen from Figure 2a that the temperatures in the combustion chamber are distributed as follows: the temperature near the chamber axis reaches 1960 °K, near the walls is about 500 °K, and in the collector 300 °K. Other temperatures are observed in the picture shown in Figure 2b - the temperature in the greater part of the chamber volume is 1500-2000 °K. When air is supplied by a combined method (variant No. 4), the temperature gradient in the furnace is greatly reduced along the radius and the axis. On the basis of the calculations obtained, it is possible to arrive at an unambiguous conclusion that a change in the scheme for supplying secondary air to the combustion chamber can be controlled by a temperature field. The change in the nature of the temperature field due to a change in the air supply to the furnace is explained by the influence of the intensity of the twist of the air flow, the effects of breaking up a single jet and the elimination of the conditions for cooling down the combustion products. This hypothesis is confirmed by the results of an analysis of the velocity field along the axis of the furnace which is shown in Figure 3.
Figure 3. Distribution of the velocity component in the z = 0 plane: (a) - option 1, (b) - option 4

Figure 3. shows the velocity distribution in the plane z = 0, which is determined by the intensity of the twist and the separation of the combustion products flow by secondary air. Option 1 is characterized by a distribution of the values of the velocity characteristic of a single swirling flow. It can be noted in variant 4 that there are practically no stagnant zones in the furnace - the reacting gas mixture moves from bottom to top with the same speed. Changes in gas-dynamic processes in the furnace affect the concentrations of combustion products. The results of calculations of the mole fractions of CO, CO2, SO2, H2S at the output section of the chamber are given in Table 1. According to the table values, it is possible to evaluate the effectiveness of one or another air supply to the furnace.

Experiments were carried out to verify the adequacy of the calculations’ results. For this purpose a fire stand was created, in the article [1] is given a detailed description of it. During the experiments following parameters were obtained: the temperature of the reacting mixture in the combustion chamber, the content of harmful gases at the outlet from the furnace, and the excess air factor in the furnace.

Table 1. The results of experimental studies

| Options | Total static pressure, \( P \), Pascal | Static temperature, \( T_s \), K | Mole fractions |
|---------|----------------------------------------|------------------|----------------|
|         |                                        |                  | CO  | CO2 | SO  | SO2 | H2S |
| 1       | 12,070                                 | 1083,62          | 0.00961 | 0.06535 | 1.9×10^{-5} | 2.14×10^{-5} | 1.3×10^{-4} |
| 2       | 11,005                                 | 1234,98          | 0.00044 | 0.07707 | 1.61×10^{-6} | 2.43×10^{-3} | 4.87×10^{-7} |
| 3       | 11,229                                 | 1088,20          | 0.01049 | 0.07340 | 2.65×10^{-5} | 2.19×10^{-3} | 1.39×10^{-4} |
| 4       | 9,230                                  | 984,75           | 0.05308 | 2×10^{-6} | 1.13×10^{-8} | 1.26×10^{-3} | 8.26×10^{-9} |
| 5       | 10,819                                 | 1219,00          | 0.00184 | 0.07608 | 5.88×10^{-6} | 2.45×10^{-3} | 5.53×10^{-6} |
| 6       | 10,904                                 | 1234,47          | 0.00094 | 0.07720 | 3.33×10^{-6} | 2.45×10^{-3} | 1.61×10^{-6} |

The temperature was chosen as the physical parameter for comparing the calculated data with the experimental ones. This is justified by the fact that the temperature is an integral quantity that characterizes indirectly the influence of the studied factors (air jet flow schemes) on heat and mass transfer processes. The gas temperature was measured by an electronic device TK-1 with a maximum measurement range up to 1200 °C.
Figure 4. The results of measurements of the gases temperature in the combustion chamber (a) - according to option 1: 1- 420 ºK; 2 - 600 ºK; 3- 1200 ºK; 4-900 ºK; 5-430 ºK; 6 - 620 ºK; 7 1200 ° K; 8-1010 ºK; 9 -480ºK; 10-570 ºK; 11-1100ºK; 12- 1250, (b) - according to the option 4: 1- 1280 ºK; 2 - 1100 ºK; 3- 1100 ºK; 4-1100 ºK; 5-730 ºK; 6 - 1320 ºK; 7- 1300 ºK; 8-370 ºK; 9-6800 K; 10-1370 ºK; 11-1380ºK; 12-1050.

The zones where the gas temperature was recorded are shown in numbers in Figure 4. From the analysis of temperature data obtained by the calculation method and by measurement, it can be concluded that the proposed theoretical model reproduces the qualitative picture of the temperature field in the combustion chamber with sufficient accuracy. At the studied points the difference between the measured temperature values and the calculated values reaches up to 35%. Large differences in the values of temperatures are typical for the central zone of the furnace. The gas dynamic processes proposed by the model are described more precisely near the walls of the furnace. Thus, the difference between the calculated temperature and measured at points 1,5, 9 is not more than 21%. The large temperature gradient in the combustion chamber along its radius shows that the tangential flow of air jets into the cavity of the combustion chamber adversely affects the intensification of heat and mass transfer and, as a result, the completeness of combustion of the gas phase.

It is possible to see from Figure 6b that the temperature gradient in the combustion chamber, both radially and along the axis of the chamber, differs greatly from the analogous parameter obtained for variant 1 in the case of air distribution according to variant 4. In this case the temperature field is more uniform. In the combustion chamber, there are no clearly defined regions with a low gas temperature. Analysis of the quantitative values of temperature indicates that optimal temperature levels are created in the combustion chamber for oxidation-reduction processes. The difference in the measured temperature values from the calculated values in the considered zones reaches up to 28%. Qualitatively, the distribution of the calculated temperature values in the combustion zone of the gas phase is in good agreement with the temperature field obtained experimentally. This allows us to judge the adequacy of the theoretical model proposed for the calculation of gas dynamic processes in the combustion chamber of the chosen design scheme.

Thereby, the numerical studies have established that the direction of the supply of air jets to the combustible gas stream exerts a strong influence on the combustion processes in the swirling-type furnace. Optimal directions of supply of air jets in relation to the direction of movement of products of thermal decomposition of wood waste are determined. The developed mathematical model makes it possible to simulate the formation of CO, NO, sulfur compounds, as well as the completeness of
combustion of combustible gases depending on the flow rate, location and scheme of supply of air jets to the reaction zone. Optimal conditions are determined when the concentration of harmful substances at the outlet from the furnace and the temperature gradient in the combustion chamber are minimal. Experimentally measured values of temperatures confirm the reliability of the results of numerical studies with a certain error.

References
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