Thermal and aerodynamic characteristics of tube furnaces with wall burners of two types

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Abstract. Tube furnaces of the petrochemical and oil refining industries are energy-intensive devices. The differential method for calculating the complex heat transfer in the furnaces is used to study the flow fields and the temperature of the combustion products in the radiation chambers of technological tube furnaces with two types of wall burners, which are placed on several levels on the sidewall. In a furnace designed for the conversion of methane mixed with steam in the reaction tubes, acoustic burners for burning natural gas near the wall are installed in three tiers on the side lined sidewalls of the radiation chamber. In the primary reforming furnace of natural gas for the production of ammonium nitrate, wall-type burners are installed on six levels. The method used is based on the joint numerical integration of the two-dimensional differential equations of energy transfer by radiation using the S₂-approximation of the discrete ordinate method, the energy conservation equations, the equations of turbulent motion of a gas mixture, the k-ε turbulence model and the two-stage gas fuel combustion model. The calculated fields of temperature and flue gas flow obtained with the help of a computer program implementing the proposed method are discussed.

1 Introduction

In the petrochemical and oil refining industries, furnaces are widely used, with the short-term residence of the reaction mixture in tubular reactors. When designing such furnaces, it is necessary to make decisions that allow providing intense heat fluxes along the reaction tubes of a certain profile. To do this, in practice, cup-shaped injection burners or flameless panel burners are used, as well as burners that provide combustion of gaseous fuel near the wall. The burners of the latter types are placed on the sidewalls of the radiation chamber of the furnace on several levels. Certain uses have gas acoustic burners with a flat flame (Acoustic Gas Burner, AGB) [1].

Figure 1 demonstrates a scheme of the fourth part of the radiation chamber of a tubular furnace equipped with AGB burners, which are placed in three tiers on the sidewalls. The mixture of water vapor and gaseous hydrocarbons moves inside the vertical pipe with the rings of the catalyst and is heated to the desired temperature due to the radiant heat flux from the combustion products and the hot surfaces of the walls of the furnace. The flame in the form of circles along the sidewalls of the 18 burners heats the masonry walls and provides radiation heat flows to the pipes.

A simplified scheme of the radiation chamber of the tubular furnace of primary reforming of ammonium nitrate production, which is the main device at the gas preparation stage and is designed to produce converted gas using steam catalytic conversion of natural gas, is shown in figure 2. Two hundred and eighty eight vertical

reaction tubes with nickel-containing catalyst R67R-7H / R-67-7H are located in the middle of the radiant chamber of the primary reforming furnace of natural gas for produced ammonium nitrate. This furnace consists of two lined radiation chambers, where exhaust fans create soft vacuum. On the sidewalls of the radiation chambers mounted horizontal burners (720 pieces in two chambers) with natural air supply for combustion. To ensure smooth heating of the reforming furnace at startup, the project provides for the placement of two types of burners of different capacities. On the first level we place Warlord WA4 burners with power of 266 W (120 pcs.). The remaining five levels are outfitted with burners of Warlord WA5 type with power of 530 W (30 burners on every sidewall on one level).

2 Method of research

A review of the methods of mathematical modeling of physical processes of heat and mass transfer in furnaces is available in [2]. Modern methods for the numerical study of the thermal radiation of combustion products in high-temperature power plants have been considered previously [3]. An analysis of recent publications devoted to the study of energy transfer by radiation is given in [4].

One can distinguish integral, zonal and differential methods for calculating complex heat transfer in furnaces. The first method is based on the theory of similarity, including the standard method for tube furnaces [3]. The integral method does not provide local values of heat fluxes on the heated surface and local

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values of the temperature of the lining. In zonal methods of calculation, the internal space of the furnace and the boundaries of the emission system are divided into several optically and thermally homogeneous zones. The zonal method uses a large amount of empirical data [5]. For example, application of the zonal method for furnaces of this type is described in [6], although it does not include results of the calculation. Recently, engineers have started to use methods based on a joint numerical solution of the equations of energy transfer by radiation and gas dynamics, written in differential form. In [7], a method was proposed for modeling heat and mass transfer in the three-dimensional space of a furnace taking into account combustion and recirculation gas flow, as well as combined heat transfer. In [8], some results of a numerical study of the flow of unsteady MHD of freely convective heat and mass transfer of a viscous, incompressible, and electrically conductive fluid over an infinite vertical plate in the presence of thermal radiation are presented. Thermal radiation is taken into account in a simplified form in the gray approximation. The results of calculating complex heat transfer in the chamber of a technological tube furnace in three-dimensional geometry with methane combustion in air with acoustic burners of a wall flame are given in [9].

There are several commercial universal software packages such as ANSYS FLUENT, CFX, FlowVision, etc. We can also mention packages like VP2/3 and σ -Flow [10], which are adapted for simulation of a 3D flow accounting for combustion of gaseous, liquid or pulverized fuel and convective-radiative heat transfer.

As noted above, the method used is based on the joint numerical integration of the following two-dimensional equations: the radiation energy transfer in the approximation of the discrete ordinate method (1), the flow energy conservation equation (2), the turbulent flue gas flow (3), and the two-parameter model of turbulence k - ε (4), the equations of continuity of the flow and the state of the gas mixture (5), the equations of turbulent diffusion for the transport of air and fuel components (6):

$$\mu_m \frac{\partial I_m^k}{\partial x} + \xi_m \frac{\partial I_m^k}{\partial y} = \int_{\lambda_{k-1}}^{\lambda_k} I_{b\lambda} d\lambda - \quad (1)$$

$$-(\alpha_k + \beta_k) I_m^k + \frac{\beta_k}{4\pi} \sum_{m'=1}^{N_g} w_{m'} \varphi_{m'm} I_{m'}^k$$

$$\rho c_p u \frac{\partial T}{\partial x} + \rho c_p v \frac{\partial T}{\partial y} = \frac{\partial}{\partial x} \left(\lambda_{ef} \frac{\partial T}{\partial x} \right) + \quad (2)$$

$$+ \frac{\partial}{\partial y} \left(\lambda_{ef} \frac{\partial T}{\partial y} \right) + (q_v - \text{div} q_p),$$

$$\left. \begin{aligned} \rho u \frac{\partial u}{\partial x} + \rho v \frac{\partial u}{\partial y} &= -\frac{\partial p}{\partial x} + \frac{\partial}{\partial x} \left(\mu_{ef} \left(2 \frac{\partial u}{\partial x} - \right. \right. \\ &\left. \left. - \frac{2}{3} \text{div} v \right) \right) + \frac{\partial}{\partial y} \left(\mu_{ef} \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) \right) + f_1, \\ \rho u \frac{\partial v}{\partial x} + \rho v \frac{\partial v}{\partial y} &= -\frac{\partial p}{\partial y} + \\ &+ \frac{\partial}{\partial x} \left(\mu_{ef} \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) \right) + \frac{\partial}{\partial y} \left(\mu_{ef} \left(\frac{\partial v}{\partial y} - \frac{2}{3} \text{div} v \right) \right), \end{aligned} \right\} \quad (3)$$

$$\frac{\partial}{\partial x} (\rho u \phi) + \frac{\partial}{\partial y} (\rho v \phi) = \frac{\partial}{\partial x} \left(\Gamma_\phi \frac{\partial \phi}{\partial x} \right) + \quad (4)$$

$$+ \frac{\partial}{\partial y} \left(\Gamma_\phi \frac{\partial \phi}{\partial y} \right) + S_\phi,$$

$$\frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} = 0, \quad p = \frac{\rho}{\mu_{\text{mix}}} RT. \quad (5)$$

The following notation is applied here: I_m^k - spectral radiation intensity in the selected direction $S_m \{m = 1, N_0\}$, and these directions are set by a set of parameters $\{\mu_m, \xi_m\}$; $I_{b\lambda}(T)$ - spectral radiation intensity for a black body at temperature T ; α_k, β_k - average absorption and scattering coefficients in narrow spectral range k ; w_m - weight coefficients [11]; u, v - velocity components of the flue gas velocity vector v along the x and y axes; ρ - the density of the mixture of flue gases; c_p - isobaric heat capacity mixture of flue gases; $\lambda_{ef} = \lambda + \lambda_t$ - coefficient for effective thermal conductivity; p - pressure, μ_{mix} - molar mass of flue gases; R - universal gas constant; q_v - volume density of thermal emissions of chemical reactions; $\text{div} q_p$ - power of radiant flux density; $\mu_{ef} = \mu + \mu_t$ - effective viscosity of flue gases; these coefficients of turbulent viscosity and thermal conductivity are determined by the formulas: $\mu_t = c_\mu \cdot f_\mu \cdot \rho k^2/\varepsilon$, $\lambda_t = c_p \mu_t / \text{Pr}_t$; where Pr_t - turbulent Prandtl number; $f_1 = -\rho g(1 - \beta(T - T_\infty))$ - mass force, where $\beta = (1/\rho)(\partial\rho/\partial T)$ is the volumetric expansion coefficient; g - gravity acceleration; $T_\infty = 300 \text{ K}$ - standard temperature when calculating to calculate the buoyancy force of Archimedes; $\phi = \{k, \varepsilon, m_{\text{CH}_4}, m_{\text{CO}}, m_{\text{air}}\}$; k, ε - kinetic energy of turbulent pulsations and kinetic energy dissipation rate; S_ϕ - source term [12]; $\Gamma_\phi = \mu + \mu_t/\sigma_\phi$ - transfer coefficient in equation (4), m_{CH_4} and m_{CO} - mass concentrations of CH_4 and CO ; m_{air} - mass concentrations of air; $S_f = 0,53 \rho g_f^{1/2} \varepsilon/k$ - rate of chemical reaction of combustion defined from "vortex break" model [13], $g_i = 2,27(\mu_t k/(\rho \varepsilon)(\partial m_i/\partial y)^2)$ - root-mean-square pulsation component of fuel, $i = \text{CH}_4, \text{CO}$; $\Gamma_\phi = \mu/\sigma_t$ - transfer coefficient in equation (4), where σ_t is the Schmidt number. The constants for k - ε model and expression for f_μ - data recommended in [13]. Equation of type (4) also applies to for m_{air} . The source term in the equation for the mass concentration of air for combustion is calculated from the ratio $S_{\text{air}} = S_f A$, where A is the stoichiometric amount of combustion air 1 kg of fuel ($\Gamma_f = \Gamma_{\text{air}}$).

The turbulent flow of combustion products in the radiation chambers of technological tube furnaces is subsonic and the flow velocity does not exceed 10 m/s. The Reynolds number, calculated from the width of the radiation chamber section, is $6 \cdot 10^4$. Questions of setting boundary conditions for equations (1) - (5), the method of difference discretization of the initial differential equations and methods of iterative numerical solution of the resulting system of algebraic equations are considered in detail in [2, 14].

In this paper, to take into account the selectivity of the radiation of combustion products, the Edwards wide band model, often used in technical calculations, is used. In this case, nine spectral bands are distinguished: four bands correspond to H_2O , two bands belong to CO_2 , one band takes into account the transparent spectral region for gas emission, and two more bands arise due to the overlap of two pairs of bands: $2.7\ \mu m$ for H_2O and CO_2 , $10\ \mu m$ for H_2O and $15\ \mu m$ for CO_2 . In addition, to reduce the number of bands, the Planck averaging method was applied in overlapping pairs of bands. As a result, in the calculations, the equation of energy transfer by radiation is solved for six bands. A description of this model with reference to the original works is given in [2].

Given the low content of soot particles in the products of combustion of gaseous fuels, their spectral absorption coefficient was calculated using an empirical formula [11, 15].

3 Discussion of results

For two-dimensional modeling of the operation of an acoustic burner, it is assumed that the fuel gas partially mixed with air is fed into the furnace through two narrow slots parallel to the walls (see Fig. 3). Secondary air enters through other parallel channels. As the walls are heated, the air-gas mixture is ignited, and combustion occurs near the side walls. Modeling scheme of burners of the WELLARD shown in figure. Through the middle channel comes fuel gas partially mixed with air. Secondary air flows out through two parallel channels.

Numerical studies of external heat transfer and flue gas aerodynamics for the case of near-wall combustion using acoustic burners (Fig. 1) were performed for a tube furnace with two-sided irradiation of a tubular screen. In

this type of furnace, the radiation chamber consists of two sections located symmetrically with respect to a single row of vertical reaction pipes. Acoustic burners were installed on three levels: the lowest ones $1.5\ m$ above the bottom of the furnace radiation chamber, and the height interval between levels is $2.5\ m$. In our calculations, methane was used as fuel gas. The gas flow rate for a half-chamber was $B_f = 0.198\ m^3/s$, the lower calorific value is $Q_l^p = 35818\ kJ/m^3$. A uniform distribution of fuel across all burners was assumed. The effective emissivity factor of the tubular screen was 0.79 . It was assumed that solid surfaces emit and reflect diffusely. The emissivity factor for the side wall was $\varepsilon = 0.42$ and the thermal conductivity coefficient for multi-layered walls was $\lambda = 0.35\ W/(m \cdot K)$. Heat loss occurs due to the thermal conductivity of the walls. The temperature of the outer surface of the furnace walls was taken equal to $300\ K$. The wall thickness was $0.45\ m$. The emissivity for the ceiling was 0.67 , and for the hearth of the furnace it was 0.69 .

The system of coordinates and isotherms within the radiation chamber of the furnace with acoustic burners is shown in fig. 5a. For the convenience of consideration, this figure is placed rotated by an angle of 90° (in fact, the x-axis is directed upwards towards the ceiling of the chamber). The figure shows that in this combustion regime, the maximum temperature of the combustion products is achieved in close proximity to the side walls near the zone of combustion. Most of the volume of the radiation chamber is filled with combustion products with a gradually decreasing temperature from $1500\ K$ to $1420\ K$ (near the tubular screen). The temperature of flue gases when they enter the convection section is reduced to $1270\ K$: this corresponds to the experimental data for the furnace with an accuracy of $\pm 5\ K$ (normal operation).

Fig. 1. Coordinate system and isotherms within the radiation chamber.

Fig. 2. Streamlines pattern.

Figure 1 *b* shows the coordinate system and the isotherms of flue gases of one section of the radiation chamber of the primary reforming furnace for production of ammonium nitrate (Fig. 2) obtained by calculation. Combustion of methane in the burners of the furnace of the primary reforming is carried out with the air excess factor $\alpha = 1.1$, which is gets from the atmosphere through the burner registers. The flue gas temperature at the outlet of each radiation chamber of the primary reforming furnace (inlet to the convective section) is measured by instruments 1-TIAH-12025A and 1-TIAH-12025B. The temperature of gas does should exceed 1060 °C because of the material of the reaction tubes. If the flue gases temperature reaches 1075 °C the alarm is sounded on the central panel. As shown in Fig. 5 *b*, under normal operation of the burners, the temperature of the combustion products at the outlet of the radiation chamber does not exceed the permissible values.

Figure 2 *a* shows the lines of the current function ψ for one section of the radiation chamber of the furnace with acoustic burners (Fig. 1). As noted above, in reality, the *x* axis is directed up. Figure 2 *b* shows the lines of the stream function in the radiation chamber of the primary reforming furnace (Fig. 2). In both cases, a complex flow field is formed with zones of forward and reverse flows. The reverse flow zones arise at the mouth of the burner. The suction of high-temperature flue gases to the mouth of the burners contributes to the stability of combustion.

4 Conclusion

1) As can be seen from Figures 1 and 2, the actual temperature field is very heterogeneous. The calculated temperature level is obtained only closer to the tubular screen. At the same time, at the pass (transition to the

convection section), the gas temperature corresponds to the calculated value.

2) Even the use of a large number of wall burners does not provide a completely uniform temperature field in the combustion chamber (isothermal medium) and a uniform distribution of heat fluxes along the reaction tubes. At the same time, when using acoustic burners located on three levels, a more uniform temperature field is achieved near the reaction tubes than when using six levels of WALARD-type burners. However, even in this case, the necessary amount of heat for carrying out the required chemical transformations for the steam conversion of hydrocarbons in the reaction tubes is transferred and the required temperature of the reaction mixture is obtained at the outlet of the reaction tubes.

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