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Engineering method for thermal calculation of the vortex combustion in dead-end fire-tubes

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Abstract. In article the method for predicting the vortex formation in the dead-end furnace is described. Mass and heat balances of environment in the vortex are calculated using the computer simulation with ANSYS Fluent software. Engineering approach for quantitative analysis of singularities in the reversible flame is proposed. Assessment of vortices integral characteristics, including effects on the aerodynamics and heat transfer processes in dead-end furnace, is given.

1. Introduction

Thermal processes occurring in fire-tube furnace are usually connected with complicated vortex aerodynamics and three-dimensional turbulent combustion [1]. In engineering practice, the theoretical calculation and prediction of these processes is difficult. Therefore, fire-tube boilers construction and design operations are usually associated with a costly and labor-intensive experimental research. Full-scale field tests of the combustion chamber require multiple-factor detailed experimental research of three-dimensional turbulent combusting dynamics.

Nowadays computer-aided simulation with the use of approved computer aided engineering software became widespread solution for complex problems of combustion aerodynamics optimization [2]. Computer simulation can reduce designing expenses by excluding costly field experiments of the production cycle.

However, the basis of most known approaches is the finite element method, which involves the installation of special software and requires a significant amount of time for calculations and setting the initial and boundary conditions [2]. This makes impossible using of such techniques for optimization tasks requiring the calculation of a large number of options for the design layouts.

For calculation of heat transfer in the boiler with a more complex configuration that does not require high accuracy, it is desirable to have an engineering calculation method, which takes lesser process time than finite element computer-aided simulation. Such engineering calculation method is advantageous to use while developing the new boiler design, when it comes to spending a lot of estimations.

Improvement of fire tube aerodynamics is a main task in elaborating the boiler furnace design. It is particularly relevant to the dead-end furnace types where complicated aerodynamics of the reverse flame includes interaction between the straight-through flow and reversed flow.

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2. Object of study

In papers [3, 4] is shown that low inlet pressure at the dead-end furnace entrance provokes formation of scorching furnace gas vortexes, circulating to the burner slot (Figure 1). So in reversive flame between the two coaxial counter flows recirculation vortex is observed. The swirling area is bounded by stream of fuel-air mixture, on the one hand, and the reverse wall surface flow on the other.

Kinetic energy of turbulence reaches its maximum in the emerging vortex resulting to a high burning rate on its narrow boundaries. Described vortex is filled by combustion products produced at a temperature close to the flame temperature. The gas mixture in the recirculation area consists of hot combustion products: carbon dioxide, nitrogen and its oxides, water vapor. Its temperature is close to combustion temperatures far exceeding 1000 °C. For this reason, the new fuel-air mixture, contacting with vortex flue gases, almost immediately heats up by convection and heat conduction. Described vortical aerodynamics of reversive flame intensifies burning and enables the process at a low air excess, but increases aerodynamic furnace resistance..

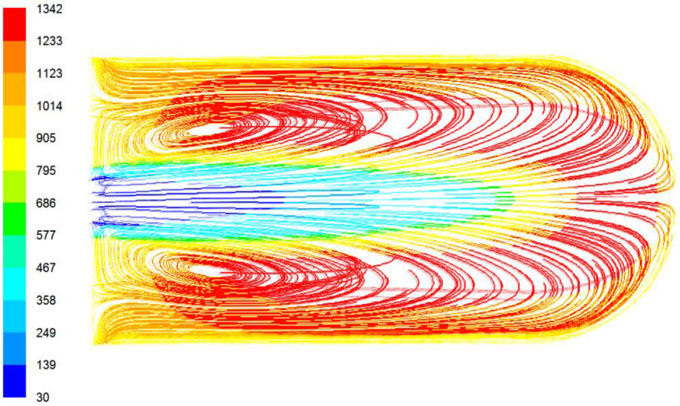


Figure 1. Pathlines in the reversive flame with color indexation according to the temperature (°C).

The aerodynamic structure of straight-flow fire-tube furnaces differs from described above. In furnaces of this type vortex motion also occurs. The swirling area is bounded by stream of fuel-air mixture, on the one side, and the wall on the other. On the axial plane of the fire tube, this zone looks like elliptical swirls along both sides of the flame (Figure 2), whereas spatially it is a single quasi-stationary toroidal vortex whose rotation coaxial with the burner's central axis. However, there is no intensive mixing of recirculated gases with air-fuel mixture due to the high density difference. The amount of combustion products in the vortex is quasi-permanent, because substance does not enter or leave the vortex.

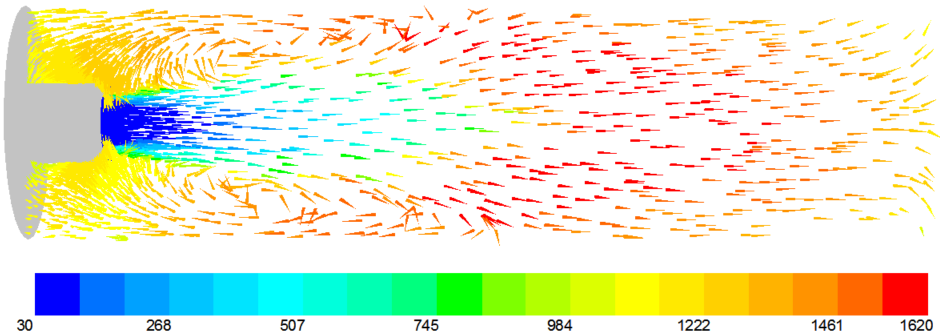


Figure 2. Motion vectors in straight-flow fire-tube furnace with color indexation according to the temperature.

3. Balances of heat and mass

To assess the effect of the vortex on the heat transfer in the reverse flame convenient to use a modified model of straight-flow furnace (Figure 3). Second channel for combustion products outlet was added at the furnace frontal slit segment. This modification also causes a mass outlet from previously stationary vortex. With such aerodynamic organization motion in the vortex ceases to be a stationary-closed circular motion. Combustion products inside the vortex move over the helical paths to new outlet opportunity (Figure 3).

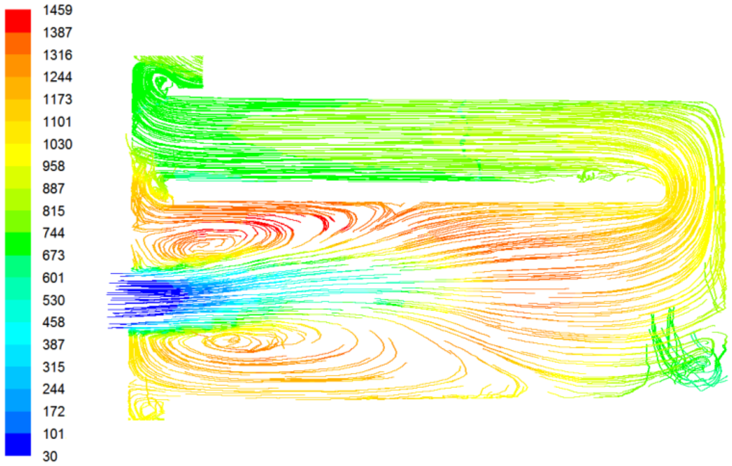
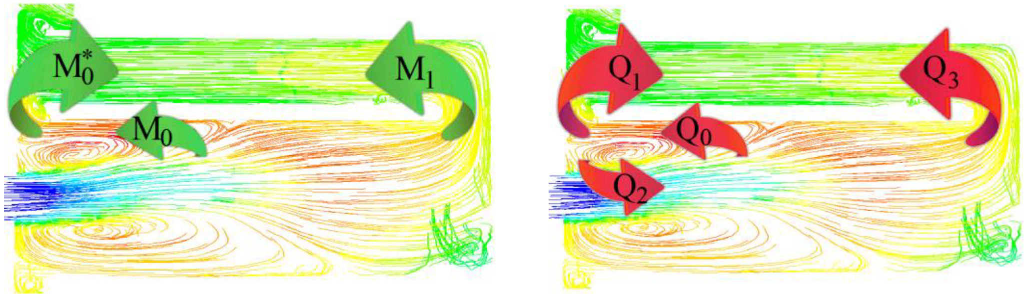


Figure 3. Pathlines in modified straight-flow furnace with color indexation according to the temperature (°C).

The fuel mixture is supplied to furnace by the burner and combusted in its volume. Then total amount of flue gases is divided into two flows. Main flow (M_1) goes to second process through the channel at the rear part of the furnace. Another part of flue gases (M_0) moves inside the vortex over the helical paths to second process through the channel at the front of the furnace (Figure 4, a).

According to the terms of jets continuity and the law of mass conservation, the total mass in the vortex should remain constant over time: $M_0 - M^*_0 = 0$ or $M^*_0 = M_0$. As a result vortex mass outlet M^*_0 will be replenished with new products of combustion from the flame M_0.



(a) (b)

Figure 4. Mass (a) and Heat (b) balances of the vortex in modified straight-flow furnace.

Main part of heat (Q_3) released from the burnt fuel leaves the furnace through the rear channel with the exhaust gases. But there is another part, released during the reaction at the inlet of the vortex. This part of heat caught in a vortex (Q_0) will be used for heating new coming fuel-air mixture (Q_2) by means of heat conduction until leaving with the heat of vortex mass outlet (Q_1). The intensive heat transfer from the flame leads to a reduction of the flame core medium temperature. However, there is no intensive mixing of recirculated gases with air-fuel mixture due to the density difference.

To assess the effect of eddy processes in the furnace thermal processes is convenient to use the magnitude of the mass fraction of gas vortex as ratio of mass flow rate through the vortex M_0 (kg/s) to the total flow of combustion products: $r = M_0/(M_1 + M_0)$.

Since the combustion products are drawn into the recirculation zone directly from the flame, vortex heat input (Q_0) can be calculated as the multiplication of mass fraction of the recirculation (r) by gases temperature T_0 in the flame and heat capacity of combustion products c: $Q_0 = r \cdot c \cdot T_0$, kJ/kg.

The portion of recirculation heat, perceived by new coming air-fuel mixture may be determined as: $Q_2 = Q_0 - Q_1$, kJ/kg; where heat of vortex mass outlet (Q_1) can be calculated as: $Q_1 = r \cdot c \cdot T_1$.

Heat of the combustion products moving to second process through the channel at the rear part of the furnace: $Q_3 = (1 - r)\cdot c\cdot T_3$, kJ/kg. Total heat of exhaust gas at the furnace outlet: $Q_{out} = r\cdot Q_1 + (1 - r)\cdot(Q_3 - \Delta Q)$, where ΔQ is the second process surface heat absorption, which can be calculated using [5].

Mass fraction r is a value depending on the geometric parameters and remains constant for predetermined design. The calculated value of r is satisfactorily described by a power equation $r = 3{,}16\cdot e^{-0{,}8\cdot f}$, where $f = D/S$ – the ratio of the diameter of the burner channel (*D*) to the width of the exit window (*S*).

4. Engineering method

In dead-end furnace $\Delta Q = 0$, since the return motion of combustion products is performed inside the furnace, but not through a separate tunnel of the second process. Additionally, in the dead-end furnace mass flow M_1 and mass flow M_0 leave the furnace through a single output (see Figure 1). Therefore, temperatures T_1 and T_3 will be approximately equal to the average flow area temperature: $T_1 = T_3$. Thus, knowing this temperature (T_1 or T_3) makes possible calculation of the vortex effect the furnace heat transfer processes.

Fig. 5 is a flow chart of heat transfer engineering calculation in the dead-end furnace. Heat removal from the reaction zone Q_0, reduces flame temperature, while Q_2 heat warms up air-fuel mixture and intensifies an ignition. Thus, the adiabatic combustion temperature can be calculated as: $T_a = (Q_r - r\cdot Q_0 + r\cdot Q_2)/c$ or $T_a = (Q_r - r\cdot Q_1)/c$, where Q_r – is total heat in the furnace. The temperature of the flame according to [6] may be determined as $T_0 = (1-\psi)^{0.25}(1-r^{1+4r})$.

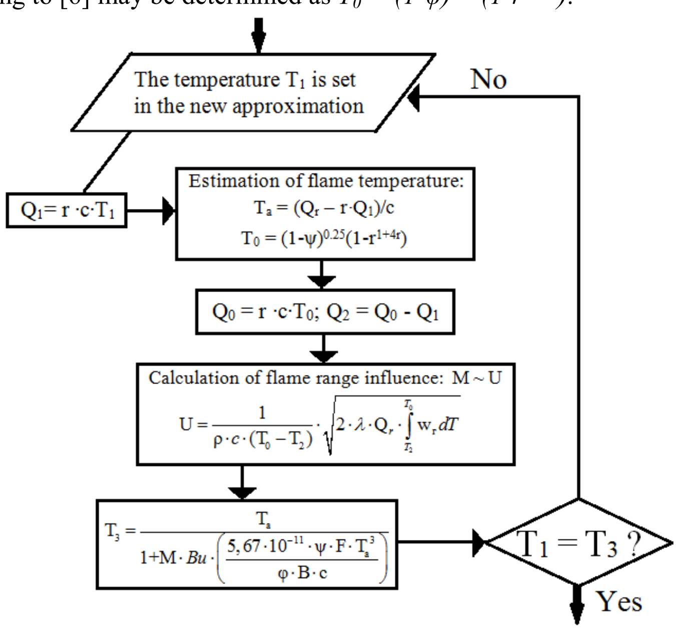


Figure 5. Engineering algorithm for thermal calculation of the vortex combustion in dead-end fire-tubes.

5. Conclusion

A method for predicting the vortex formation in the dead-end furnace is described. Proposed approach is also suitable for quantitative analysis of singularities in the reversible flame. Furthermore, assessment of reversive flame vortices integral characteristics, including effects on the aerodynamics and heat transfer processes, was evaluated.

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