Computer simulation of processes in the dead-end furnace

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Abstract. We study turbulent combustion of natural gas in the reverse flame of fire-tube boiler simulated with the ANSYS Fluent 12.1.4 engineering simulation software. Aerodynamic structure and volumetric pressure fields of the flame were calculated. The results are presented in graphical form. The effect of the twist parameter for a drag coefficient of dead-end furnace was estimated. Finite element method was used for simulating the following processes: the combustion of methane in air oxygen, radiant and convective heat transfer, turbulence. Complete geometric model of the dead-end furnace based on boiler drawings was considered.

Introduction

Several advantages of Decentralized heating jointly with other economic and organizational causes led to the overall use of fire-tube boilers. The performance coefficient of the fire-tube boilers reach 95%, and there are additional advantages – best maintainability, full automation and low price in comparison to water-tube analogues.

The fact that the fire-tube boiler furnace normally has a water-jacket draws attention to questions connected with optimal temperature distribution along the furnace volume. Because of high volumetric thermal stress in fire-tube furnace the flame profile becomes the main characteristic of burner device. Estimated size of the flame should exclude every local contact of fire with the metal for all modes of boiler operation. Irregular and fluctuating sweep of gases may provoke excess of acceptable local thermal loads and cause reliability degradation of boiler operation.

It is well known fact that appropriate organization of furnace aerodynamics can influence burning stability, lead to required speed and temperature values in the furnace volume and reduce the level of toxic emission into environment. Therefore, improving aerodynamic characteristics of the fire tube is a main task in elaborating the fire-tube boiler construction. It is particularly relevant to the dead-end furnace types where aerodynamics of the reverse flame includes interaction between the straight-through flow and reversed flow.

The lack of a regulatory framework for the dead-end fire-tube furnace calculations and design indirectly indicates the complexity of the real thermal processes occurring in its volume. Full-scale multiple-factor experimental research of three-dimensional dynamics of turbulent burning flare is quite labor-consuming. Therefore, nowadays computational modeling with the use of wide approved application packages is used to solve complex problems of combustion aerodynamics optimization [1].

The present article is aimed at computer simulation of the turbulent combustion of methane-air mixture in a fire-tube boiler. The flame structure has been determined computationally, contours of average speed, temperature and concentrations have been acquired.

The subject of studying: complex of characteristics with space-time fields of the aerodynamic structure, range and aperture angle of the flame, pressure distribution, turbulent intensity and quite a number of other operation factors. Quantitative dependence of construction characteristics and operation conditions on aerodynamic parameters should be also estimated.

Principles and object of study

For the computational research, a full geometrical model of the dead-end fire-tube furnace is implemented. A computational grid designed by means of the ANSYS Workbench based on the boiler drawings contains about $8 \cdot 10^5$ control volumes. A diagram with the boiler's construction scheme is presented on Figure 1.
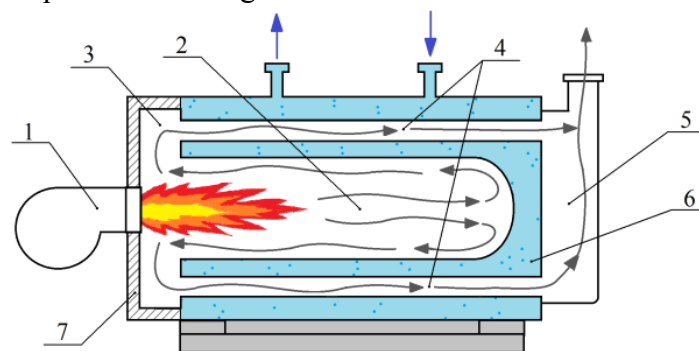

Figure 1. Fire-tube boiler's construction scheme
1 – burner; 2 – dead-end fire-tube ; 3 – turning chamber; 4 – convection fire-tube bank; 5 – collecting box; 6 – water-jacket; 7 front cover

The boiler has a dead-end fire-tube 2 with a bottom that causes the flame to turn 180 degrees in the direction of the boiler's front door 7. Then, moving along the periphery of the furnace, the combustion products flow into the turning chamber 3 where they turn 180 degrees again and flow into the convection fire-tube bank 4 with the water-jacket 6. Next moving inside these tubes, the combustion products flow into the collecting box 5, then to the chimney.

The fuel-air mixture enters the furnace through the burner 1 under the pressure of 200 PA which allows overcoming of the aerodynamic resistance of the gas path inside the boiler. The furnace length along the shaft from the burner to the bottom equals 1800 mm, a diameter of the fire tube is 884 mm.

A complete geometric model of the furnace, including the burner slot and the reversing chamber is used for computer simulation.

Once-through fuel supply is considered for better calculation performance since the influence of the twist parameter on the heat exchange in the reversing flame is insignificant [2].

Turbulent combustion of natural gas in the reverse flame of fire-tube boiler was studied by means of the ANSYS Fluent 12.1.4 engineering simulation software. The following processes were modelled through the finite-element method: methane burning in atmospheric oxygen, turbulence, convectional and radiant heat exchange. The gas-phase was simulated according to the Euler's approximation. Aerodynamic calculations were performed using laws of flow continuity and energy conservation.

The radiant heat exchange calculation was conducted by the method of spherical harmonics in 1 approximation (P_1-model). Differential equations used by the given radiative heat transfer model are presented in [3].

RNG k-ε model was used to simulate turbulence. This model is justified for fully advanced turbulence flow, i.e. for high Reynolds numbers, where the direct viscosity influence on the turbulence structure is small to negligible.

For the numerical simulation of chemical processes in turbulent stream, the Spalding model (Eddy-Break-Up) and the kinetic model were implemented jointly. It was supposed that fuel oxidation occurred irreversible in two stages: $2CH_4 + 3O_2 = 2CO + 4H_2O$; $2CO + O_2 = 2CO_2$. The accuracy of the chosen mathematical model was confirmed by the field tests [2, 4].

The initial data for calculation included: fuel – methane (100%); oxidant – atmospheric oxygen; theoretically required air volume for complete combustion – 9.52 m^3/m^3 , excess air coefficient 1.03; mass flow of fuel-air mixture at 0.2 kg/sec; its temperature 20 °C (which equals the air temperature in the boiler room); average water temperature 92.5 °C.

Calculation results

The computation results display the processes within the furnace to be axisymmetric. Pathlines in the furnace medium (Fig. 2) indicate its double change in the direction. When moving towards the back part of the furnace, fresh air-fuel mixture heats up, ignites and burns out, afterwards combustion products move from the furnace centre to the periphery and at last smoke fumes along the furnace sides return to the front part and leaves the fire-chamber.
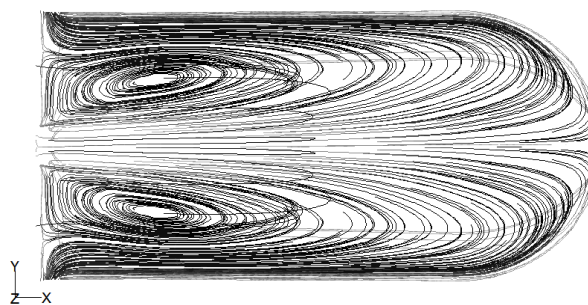
Fig. 2 Pathlines in the reversive flame

The hot combustion products make the first pass in the boiler, i.e. on the near-wall zone of the furnace, flowing in a circumferential direction of the fire tube from the heel to the front. The flue gas stream thickness on the near-wall zone lies between 130 and 135 mm. The chamber bottom is normally considered to be the twist point for the flame and the starting point for the initial path of smoke gases. However, pathlines (Fig. 2) and vector field of average speed (Fig. 3) indicate that turn of the combustion products holds the whole flare length.
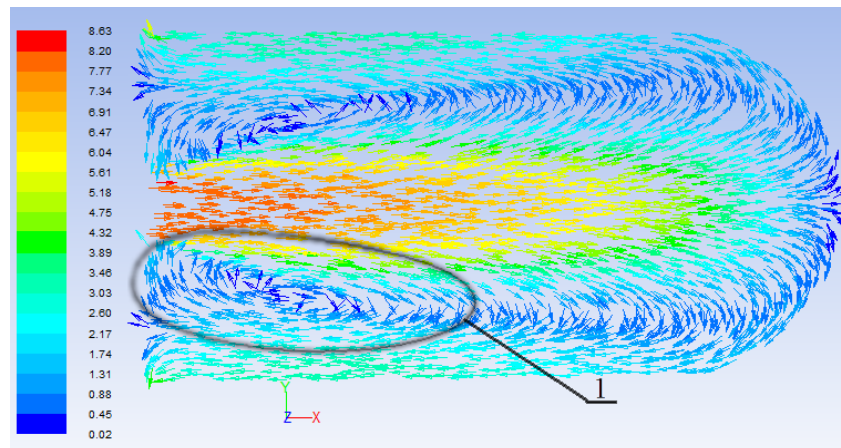
Fig. 3. Vectors of furnace medium velocity with color indexation according to the velocity magnitude (m/sec):
1 – area with recirculation

Low inlet pressure at the furnace entrance provokes formation of scorching furnace gas vortexes, circulating to the burner slot (Fig. 2). Some furnace gases do not leave the combustion chamber, rather revert to the burner and mix with the fresh air-fuel mixture. Thereby, an area for recirculation of some combustion products toward the burner root occurs in furnaces of the reverse flame type with an external formation of air-fuel jet. On the axial plane of the fire tube, this zone is provided by elliptical vortexes along both flare sides (Fig. 3), whereas spatially it is a single vortex in a toroidal form whose rotation axis coincides with the burner's central axis (Fig. 4).
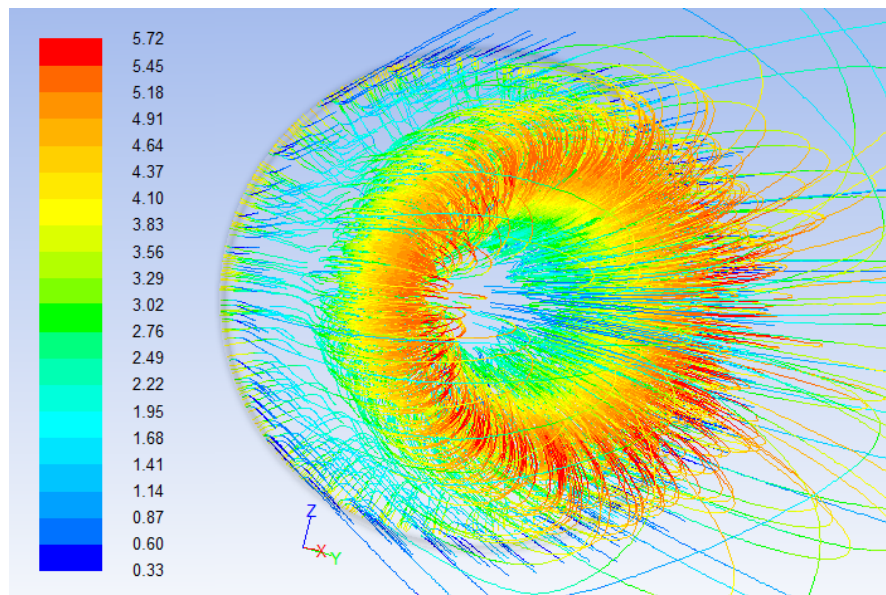

Fig. 4. Pathlines in the recirculation area with color indexation according to the kinetic energy of turbulence (m^2/sec^2)

The gas mixture in the recirculation area consists of hot combustion products: carbon dioxide, nitrogen and its oxides, water vapor. Their temperature is close to that in the burner

core far exceeding 1000 °C. For this reason, the new fuel-air mixture, blending with recirculation gases, almost immediately heats up to 270 °C. The rotation frequency of the whirl recirculating towards the burner slot is approximately 2.5 revolutions per second. The mass flow of whirl gases is 0.057 kg/sec making 30% of the mass entering through the fuel-air mixture burner.

Isolines of static gauge pressure (Fig. 5) quantitatively demonstrate its decline in longitudinal section of the furnace. The total pressure drop along the length of the flare is 34 Pa (from 200 Pa to 166 Pa) meanwhile more that 70% from this value is lost in the first section beyond the burner caused by form loss. At the periphery of the flare the pressure declines from 166 Pa to 156 Pa (about 23% from total aerodynamic furnace resistance).
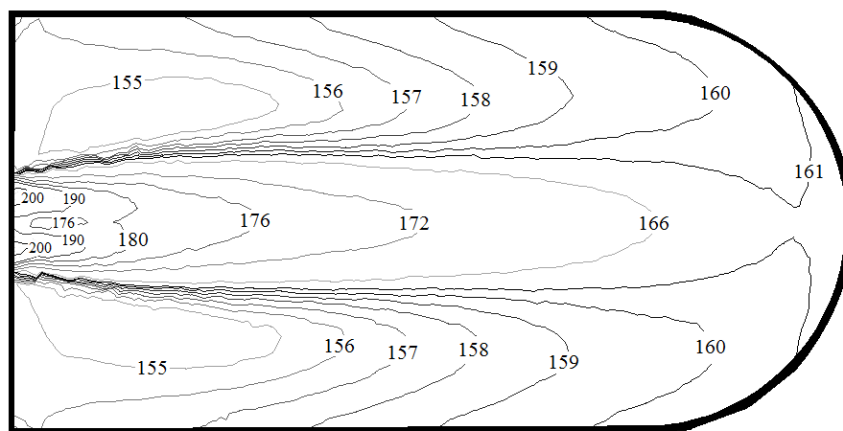

Fig. 5 Isolines of static gauge pressure (Pa) in the furnace

As can be concluded from above that resistance in the fire tube with the reverse flame can generally be estimated by form loss at the output of burner and by resistance created by vortex from the recirculation area. Turn and friction resistance values along the length of the fire tube are not significant.

The aerodynamic resistance of the fire-tube (Δp) with reversive flame can be determined by calculations according to the normative method [5] through the average speed of air-fuel jet ϖ :

$$\Delta p = \zeta \frac{\varpi^2 \rho}{2}, \text{Pa}$$

Use of vortical burner devices intensifies burning and enables the process at a low air excess, but increases aerodynamic furnace resistance in comparison with the direct-flow organization of fuel supply. Quantitatively, the turbulence intensity is estimated by the n twist parameter, which is calculated from velocity field and furnace environment pressure values. Calculations and computer simulations have displayed that in case of direct-flow and weakly swirled air-fuel mixture supply (n ≤ 0,9) the aerodynamic resistance coefficient ζ turned into a function little depending on the swirling degree, and thus, with acceptable accuracy, it can equal 1.35 in a wide range of design characteristics. With an increase in swirling n > 0.9, increase of aerodynamic resistance coefficient occurs in a fire tube with various intensity depending on different design characteristics. This is caused by gas recirculation intensification in the reverse flame.

Changes in air excess in the interval of values approaching one do not influence the coefficient of aerodynamic resistance.

Summary

Using the ANSYS software obtained a detailed picture of the turbulent combustion in dead-end firetube, which is suitable for qualitative analysis of singularities in the reversible flame.

In accordance with the computer simulation results, it is possible to conclude that the processes occurring in the furnace of the boiler under study are axially symmetric. Gases pathlines of the furnace medium change its direction twice. First, the new fuel-air mixture moving in the direction of the furnace heel, warms up, inflames and burns off; then combustion products flow from the center of the chamber to the periphery, and finally, flue gases along the fire-tube wall return to the front segment of the boiler and leave the furnace chamber. Aerodynamic resistance in the fire tube with the reverse flame can generally be estimated by form loss at the output of burner and by resistance created by vortex from the recirculation area. Turn and friction resistance values along the length of the fire tube are not significant.

For further development required to investigate a dependence of construction and mode characteristics of the boiler on aerodynamics and thermal parameters applied to dead-end firetubes.

References
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