Organization of vortex smoke gaz movement over the fuel layer to increase the efficiency of the work boiler unit KVm-2,5 in the village of Mishelevka, Usolsky district, Irkutsk region

V A Bochkarev¹, I V Dykus², A G Frolov¹ and V V Khan¹

¹ Irkutsk National Research Technical University, 664074, Lermontov str. 83, Irkutsk, Russia

²Irkutsk State Agrarian University named after A.A. Ezhevsky, 664038, Irkutsk region, Irkutsk district, Molodezhny settlement, Russia

E-mail: bochkarev@ex.istu.edu

Abstract. Comparative experimental studies of the boiler unit KVm-2.5 in the layer combustion and in the organization of vortex motion of flue gases (VMFG) were carried out in this work. Analysis of the boiler showed that the layer combustion is marked by low efficiency of the boiler unit, excessive fuel consumption, a large amount of harmful emissions into the atmosphere. One of the ways to improve the efficiency of fuel combustion and reduce harmful emissions is the organization of VMFG over the fuel layer. The results of heat-engineering calculations, which allow to estimate economic and ecological expediency of introduction of VMFG are presented in this article.

1. Introduction

At present time more than 60% of boiler houses operate on solid fuel [1], where fuel is burned in a layer, in Russia. There are 1108 large and small boiler houses on the territory of the Irkutsk region. Of these, 621 boiler houses operate on coal (56%), 284 (26%) are electric boiler houses, 157 (14%) boiler houses working on wood and wood chips, 42 boiler houses are working on fuel oil (4%).

The main method of burning solid fuel used in low and medium power boilers is combustion in a bed, in which fuel is fed from above to the grate and is blown through with blast air supplied from below. The rate of coal burning is highly dependent on the intensity of the air supply.

When burning solid fuel in a bed, it is necessary to maintain an optimal layer thickness and achieve an even distribution of fuel on the grate. An uneven layer of fuel leads to air breakthroughs through the grate into the furnace. This air does not fully participate in the combustion process and passes in transit to the outlet of the boiler.

2. Model and research methods

Combustion of solid fuels is a heterogeneous reaction. In layered combustion, combustion usually occurs in a diffusion-dependent region. This is confirmed by the strong dependence of the solid fuel burnup rate on the rate of oxygen supply to the surface of the fuel particle.

The rate of a heterogeneous reaction is measured by the amount in grams of carbon burned in one second per square centimeter of the reacting fuel surface - g/(cm²*s). This rate, in addition to temperature, pressure and concentration of reactants, depends on the rate of diffusion of the oxidant to the surface of the fuel particle. Near the fuel surface (in the boundary layer), the concentration of
reactants decreases, while the concentration of combustion products (CO, CO$_2$, H$_2$O and SO$_2$) increases. This boundary layer of solid fuel combustion products prevents the supply of oxygen and the rate of the combustion reaction will depend on the rate of diffusion of the oxidant through the boundary layer.

The combustion reaction rate depends on the thickness of the boundary layer, on temperature, and on the difference in oxygen concentrations in the flow CO$_2$ and on the surface of the burning particle $C_O^2$. The thickness of the boundary layer depends on the flow rate and the reduced diameter value of the fuel particle. Carbon monoxide combustion process near the surface of a burning coal particle blown by an air stream occurs mainly at the rear, i.e. opposite particle side to the direction of blowing.

Behind the rear coal particle side, carbon monoxide burns in the form of a bluish flame. In addition, uneven burnout of the frontal and rear parts of the coal particle is observed, the more the higher the blowing speed is. On the frontal solid fuel particle side, the boundary layer thickness reaches zero at a certain speed of the incoming air flow, and the particle will burn intensively in this place. In the rear part, the coal particle burns out less intensively due to the interception of oxygen by a layer of burning carbon monoxide. Thus, the combustion of carbon monoxide inhibits the combustion of the coal particle itself.

The resulting rate of the combustion reaction is determined by which of the constituent processes - diffusion or the actual combustion reaction - is the limiting one. If the temperature is relatively low, then the combustion process depends on the rate of the chemical reaction; at higher temperatures, the combustion reaction rate is so high that the combustion process of solid fuel depends on the diffusion rate, i.e. determined by a physical factor.

In the kinetic region, the combustion rate grows rapidly with increasing temperature and does not depend on the flow rate. Upon transition to the diffusion region, the curve is divided into three branches depending on the flow rate: the higher the flow rate, the higher the rate of the solid fuel combustion reaction.

To increase the efficiency of fuel combustion in the layer, it is proposed to organize the vortex movement of air and flue gases in the combustion chamber above the fuel layer [2]. To organize VMFG, it is necessary to install air collectors on the front and on the back wall of the combustion chamber.

Fuel is supplied to the grate by the traditional method (manual or mechanized), the combustion chamber does not need for reconstruction. Air nozzles are installed in the combustion chamber in such a way that a vortex movement of flue gases and supplied air is formed above the fuel layer (figure 1).

**Figure 1.** Scheme of organization of VMFG.

1 - front collector; 2 - rear manifold; 3 - vortex zone; 4 - air supply under the grate; 5 - layer grating; 6 - blowing fan.

Up to 15% of the theoretically required combustion air is supplied over the fuel layer through nozzles 1 and 2. Due to the created vortex motion, the process of mixing the fuel with the oxidizer improves, the number of zones with a lack of oxygen decreases, the combustion process of the fuel improves in the combustion chamber and a reducing environment is created (in the vortex zone), in
which chemical reactions of reduction of the formed nitrogen oxides take place, as well as combustion carbon monoxide. VMFG above the fuel layer makes it possible to intensify heat transfer in the combustion chamber by increasing the proportion of convective heat transfer.

As an example, a comparative experimental study of the KVm-2.5 boiler unit in the village of Mishelevka, Usolsky district, was carried out.

The boiler house has four KVm-2.5 hot water boilers with a thermal capacity of 2.15 Gcal / h (2.5 MW) (figure 2). The main fuel is coal from the Cheremkhovo deposit. The boilers are equipped with mechanized fuel supply and ash removal systems. The heating system is two-pipe. Heating system temperature curve 95 to 75° C. Domestic hot water temperature 60° C. The heat balance of the boiler is shown in table 1.

For the KVm-2.5 boiler, to organize the VMFG, it is necessary to perform an aerodynamic calculation to determine the number of air supply nozzles above the fuel layer and the range of the air blast jets.

According to aerodynamic conditions, the range is influenced by vortex movement of gases and supplied air above the fuel layer, i.e. on the extent of active action that would ensure the flow of gases to be drawn into the vortex motion over the entire section of the combustion chamber.

Thus, having a longitudinal section of the combustion chamber, it is possible, after the place for air blast entry point for organizing the VMFG would be selected, to determine the optimal blast range, taking into account some curvature of the aerodynamic axes of the jets under the influence of the ascending gas flow.

3. Results and discussion
The blower fan VTs-14-46-2.5 type is included in the project to supply air to the boiler furnace, with the following characteristics:
- electric drive power 3 kW,
- rotation speed 3000 rpm,
- air pressure up to 1kPa.

The range of a sharp blast is determined by the formula [3]:
\[
h = k \cdot d_e \cdot w_2/w_1(t_1 + 273)/(t_2 + 273)^{1/2},
\]
where \( k = 1.9 \) is an experimental coefficient depending on the relative step between the jets \( s/d_e \); \( d_e \) is equivalent diameter of the nozzle at the mouth, equal to 30 mm; \( w_2 \) - air velocity at the nozzle.
mouth, m/s; \( w_1 \) - gas flow velocity in the furnace, m/s; 
\( t_2 = 30 ^\circ C \) - air temperature; 
\( t_1 = 1320^\circ C \) - temperature of gases above the fuel layer.

The air velocity at the mouth of the nozzle is determined by the formula [3]:

\[
 w_2 = 4.43 \cdot \frac{h}{(\rho(1 + \xi))^{1/2}} = 30 \text{ m/s.}
\]

where \( h \) is pressure of the blowing fan equal to \( = 80 \text{ Pa} \); \( \rho = \) is specific gravity of air at a temperature of \( 30^\circ \text{C} \), equal where to \( 1.165 \text{ kg}\/\text{m}^3 \); \( \xi = 0.5 \) is the coefficient of local resistance when air enters the nozzle from the collector.

The gas flow rate in the furnace is determined by the formula:

\[
 w_1 = \frac{Q_g}{F}, \quad (2)
\]

where \( Q_g \) is the volume flow of flue gases in the furnace, \( \text{m}^3/\text{s} \); \( F = 2.8 \text{ m}^2 \) - the area of the grate.

The volume flow of flue gases in the furnace is determined by the formula:

\[
 Q_g = B_g V_g T_g / 273, \quad \text{m}^3/\text{s} \quad (3)
\]

where \( B_g \) is fuel consumption, kg/s, estimated by expression:

\[
 B_g = B(1 - 0.01 q_4) = 0.175 \text{ kg/s};
\]

\( q_4 = 8 \) - heat loss with mechanical underburning, \%; \( V_g = 6.59 \) is the volume of flue gases generated during the combustion of 1 kg of Cheremkhovo coal with an excess air ratio of 1.4 \( \text{m}^3/\text{kg} \); \( T_g = 1593 \text{ K} \) - temperature of gases in the furnace. Substituting these values in (3), we get \( Q_g = 6.73 \text{m}^3/\text{s}, \ w_1 = 2.4 \text{ m/s}, \ h = 1.63 \text{ m} \).

The amount of air supplied to the furnace is determined by the formula:

\[
 Q_a = \frac{B_a V_0 (\alpha_t - \Delta \alpha_t) T_g / 273}{\alpha_t}, \quad \text{m}^3/\text{s}, \quad (4)
\]

where \( T_g = t_2 + 273 = 303 \text{K} \) is the temperature of the air supplied for combustion; \( \alpha_t = 1.4 \) is the coefficient of excess air at the outlet from the furnace; \( V_0 = 4.36 \) is the theoretically required amount of air required for complete combustion of 1 kg of Cheremkhovo coal, \( \text{m}^3/\text{kg} \) [4], \( \Delta \alpha_t = 0.1 \) - air suction into the furnace. Substituting these values in (4), we get \( Q_a^\ominus = 1.1, \text{ m}^3/\text{s} \).

The cross-sectional area of one nozzle (\( F_n \)) is equal:

\[
 F_n = \pi \cdot \frac{d_e^2}{4} = 0.0007065 \text{ m}^2.
\]

The number of air nozzles is determined by the formula

\[
 n = \frac{Q_a}{(F_n w_2)}, \quad (5)
\]

where \( Q_a \) is the amount of air supplied above the grate (15% of 100%) \( \text{m}^3/\text{s} \):

\[
 Q_a = 0.15 \cdot Q_a^\ominus = 0.165, \text{ m}^3/\text{s}.
\]

\[
 n = 0.165/0.0007065 = 7.78 \approx 8 \text{ ps}.
\]

Based on the performed aerodynamic calculation, air nozzles number for the installation are accepted to be 8. The air supply scheme above the fuel layer above the fuel layer is shown in figure 3.

The air above the fuel layer is supplied through 5 pipes (nozzles) as long as 150-200 mm with an outer diameter of 34 mm and a wall thickness of 2.0 mm. For a more filling of the furnace volume with flue gases and an increase in the residence time of coal particles in the furnace, 3 pipes (nozzles) push the flue gas flow to the boiler front (figure 3). All nozzles have the same geometric dimensions, are located evenly across the width of the combustion chamber and are welded into an air manifold 1100 mm long with a diameter of 180 mm and a wall thickness of 3.5 mm.
Figure 3. Scheme of the organization of air supply above the fuel layer in the KVm-2.5 boiler.

Due to intensive heat exchange in the combustion chamber and cleaner surfaces of the boiler (the coefficient of thermal efficiency of the furnace walls increases), which sometimes leads to an increase in the heat output of the operating boiler unit, the temperature of the flue gases decreases, and the heat losses $q_2$, $q_3$, $q_4$ also decrease (table 1).

Possibility for reducing amount of excess air arise due to its more complete usage. Measurements of the concentration of nitrogen oxides (NO$_x$) and carbon monoxide (CO) in boilers with VMFG show a decrease in the concentration of nitrogen oxides up to 30%, carbon monoxide by 2 times [5,6,7]. Emissions of ash, sulfur dioxide (SO$_2$), benzo (a) pyrene (BP) decrease in proportion to a decrease in fuel consumption, due to an increase in the efficiency of the boiler unit and a decrease in fuel consumption. Comparative calculated values of emissions of harmful substances into the atmospheric air from the KVm-2.5 boiler, made according to the method [8], are presented in Table 2.

Table 1. Heat balance of the KVm-2.5 boiler

| Name of quantity, designation | Before reconstruction | After reconstruction |
|------------------------------|-----------------------|----------------------|
| The available heat of the fuel, $Q_{1r}$, kJ/kg | 16517 | 16517 |
| Flue gas temperature, $\theta_{fg}$, °C | 189 | 166 |
| Enthalpy of flue gases, $I_{fg}$, kJ/kg | 1846 | 1618 |
| Cold air temperature, $t_{cw}$, °C | 30 | 30 |
| Enthalpy of cold air, $I_{cw}$, kJ/kg | 174 | 174 |
| Heat loss from chem. underburning of fuel, $q_3$, % | 1.2 | 0.6 |
| Heat loss from mech. underburning of fuel, $q_4$, % | 8 | 5 |
| Heat loss with flue gases, $q_2$, % | 8.8 | 7.8 |
| Heat loss to the environment, $q_5$, % | 2.5 | 2.5 |
| Heat loss with the physical heat of the slag, $q_6$, % | 0.02 | 0.02 |
| The sum of heat losses in the boiler, $\Sigma q$, % | 20.52 | 15.92 |
| Boiler unit efficiency, $\eta_{br}^B$, % | 79.48 | 84.08 |
| Total fuel consumption, $B$, kg/h (kg/s) | 686 (0.19) | 649 (0.18) |
| Estimated fuel consumption, $B_e$, (kg/s) | 0.175 | 0.171 |

4. Conclusions

When air is supplied above the fuel layer, the reduction in fuel consumption during the heating period (240 days) will be 152 tons. With the cost of Cheremkhovo coal being 2000 RUB/t, the reduction in fuel costs will be more than 300 thousand RUB per year.

In addition, there will be a reduction in the cost of electric energy for the supply of coal, as well as for the creation of traction and blasting. Payments for emissions of harmful substances into the atmosphere will go down. Due to the introduction of this technology of coal combustion, the cost of the supplied heat energy can be reduced. The introduction of this method of fuel combustion does not
require large costs for the materials used, manufacturing and installation. Installation work on the boiler reconstruction will require 5 working days.

Along with the proposed measures, it is also advisable to consider options for using alternative fuels in order to further improve the efficiency and environmental friendliness of heat supply systems in small and medium-sized populated areas [9,10].

**Table 2.** Volumes of harmful emissions into the atmosphere from the KVm-2.5 boiler

| Harmful substances emission, tons/year | Before reconstruction | After reconstruction |
|----------------------------------------|-----------------------|----------------------|
| Sulfur oxide, $\text{M}_{\text{SO}_2}$ | 46                    | 43.6                 |
| Carbon oxide $\text{M}_{\text{CO}}$    | 50.9                  | 24.9                 |
| Solid particles, $\text{M}_{\text{PB}}$ | 45.3                  | 38.8                 |
| Nitrogen oxide $\text{M}_{\text{NO}}$  | 0.215                 | 0.16                 |
| Benz (a) pyrene $\text{M}_{\text{BP}}$ | $15 \cdot 10^{-6}$    | $10.2 \cdot 10^{-6}$ |

**References**

[1] Volynkina E P and Pryanichnikov E V 2002 Teploenergetika 2
[2] Obukhov I V Patent 2202068 RF. Boiler firebox
[3] Nechaev E V and Lubnin A F 1968 Mechanical furnaces for boilers of low and medium power
[4] Thermal calculation of boilers (Standard method) 1998
[5] Obukhov V 2003 Vestnik USTU-UPI 8 (28)
[6] Bochkarev V A 2011 Bulletin of ISTU 8 (55)
[7] Bochkarev V A and Potapov V 2002 Mat. Int. Conf. Moscow State University Ing. ecology June
[8] Committee on Environmental Protection 1999 Methodology for determining emissions of pollutants into the atmosphere during fuel combustion in boilers with a capacity of less than 30 tons per hour or 20 Gcal per hour
[9] Petrov A V and Efimova A K 2019 Nguyen Thanh Tung. Optimisation of technology used for restoring gas-ash concrete outdoor wall panels using modified structural and heat-insulating concrete Investment. Construction. Real estate 9(3) pp 542–549
[10] Moskvitin V A., Emelyanova N A. and Mashovich A Y 2019 Experimental studies of air permeability indicators of composite "Poroplast CF" Investment. Construction, Real estate 9 (2) pp 342–353
[11] Khan V V 2019 J.Phys.3A Conf._Ser. 1369 012011
[12] Lavygina O 2019 IOP Conf. Ser.: Mater. Sci. Eng. 667 012056