Furnace devices aerodynamics optimization for fuel combustion efficiency improvement and nitrogen oxide emission reduction

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Abstract. MPEI conducts researches on physical and mathematical models of furnace chambers for improvement of power-generation equipment fuel combustion efficiency and ecological safety. Results of these researches are general principles of furnace aerodynamics arrangement for straight-flow burners and various fuels. It has been shown, that staged combustion arrangement with early heating and igniting with torch distribution in all furnace volume allows to obtain low carbon in fly ash and nitrogen oxide emission and also to improve boiler operation reliability with expand load adjustment range. For solid fuel combustion efficiency improvement it is practical to use high-placed and strongly down-tilted straight-flow burners, which increases high-temperature zone residence time for fuel particles. In some cases, for this combustion scheme it is possible to avoid slag-tap removal (STR) combustion and to use Dry-bottom ash removal (DBAR) combustion with tolerable carbon in fly ash level. It is worth noting that boilers with STR have very high nitrogen oxide emission levels (1200-1800 mg/m³) and narrow load adjustment range, which is determined by liquid slag output stability, so most industrially-developed countries don’t use this technology. Final decision about overhaul of boiler unit is made with regard to physical and mathematical modeling results for furnace and zonal thermal calculations for furnace and boiler as a whole.

Overhaul of boilers to provide staged combustion and straight-flow burners and nozzles allows ensuring regulatory nitrogen oxide emission levels and corresponding best available technology criteria, which is especially relevant due to changes in Russian environmental regulation.

1. Introduction
Accordingly to current legislation, hazardous substances emission fee is calculated depending on hazardous substances concentration in surface layer of the atmosphere and isn’t relevant to technological standards fulfillment, so if hazardous substances concentrations in surface layer are less, than MPC levels, it is considered, that plant fulfills environmental standards and hazardous substances emission fee is calculated with coefficient of 1. Most of thermal power plants have high smokestacks, resulting in fulfillment hazardous substances concentrations in surface layer standards, so hazardous substances emission fees are minimal. So, right now even low-cost environmental measures aren’t economically feasible and enterprises aren’t interested in hazardous substances emissions reduction.
Situation will change, when in 2020 new RF[1] environmental legislation, accordingly to which technology violation fee will sharply increase, will fully take effect. At present time technological regulations for power plants are listed in [2] and many power plants doesn’t fulfill them in the part, concerning nitrogen oxide emissions. These regulations especially violated by solid-fuel boilers in the area of nitrogen oxides specific emissions, and highest violations have slag-tap removal (STR) boilers. Nitrogen oxides concentration in boilers flue gases for slag-tap removal usually about 1200 – 1900 mg/m³, which is 2-3 times higher, than technological standards. For emissions higher, than technological standards, fee will be calculated with coefficient of 100. So, hazardous substances emission fee will be comparable with the best available technology costs and power plants will have economic interest in hazardous substances emission reduction and fulfillment of technological standards.

MPEI has big experience in cost-effective overhaul of gas-oil and coal-dust boilers by implementation straight-flow burners and nozzles for improvement of their integrated performance indexes. Especial attention is payed to environmental safety of boiler equipment [3]. Straight-flow burners efficiently and reliably burn solid fuel only in efficient interaction of burner and air jets in the burner volume. Aerodynamic optimization in the MPEI scientific works have been based on research of mathematical and physical models of boiler furnaces.

2. Computer simulation of fuel combustion in boiler furnaces

Current level of computer equipment allows high precision simulation of power equipment processes and obtaining necessary data without high-cost physical or full-scale experiments. In simulation of solid fuel combustion in coal-dust boiler burner should be considered torch gas and disperse components, heat exchange between them and heating surfaces, solid fuel particles heating process and combustion of volatile flux and coke residue.

Burner mathematical model includes conservation differential equations (mass, energy, momentum), turbulence equation, diffusion equation, radiation energy transmission, condition equation and discrete phase equation.

On the global market there are a lot of software packages for hydrodynamic computations, which typically have module structure, graphical interface and wide range of instruments for creating and importing of 3D objects, live grids building and setting of boundary data and initial data.

In Russia we usually use following commercial software: STAR-C/CD/STAR-CCM+, ANSYS Fluent, ANSYS CFX, FlowVision, Gas Dynamics Tool, SigmaFlow, Fire 3D and others. First three packages (STAR-C/CD/STAR-CCM+, Fluent, CFX) are “heavy-class” SW by integrity level of physical and mathematical models and intended for solving wide range of hydro-gas dynamics and heat-exchange problems. Along with big model base, these software packages provide choice of different schemes and algorithms and their parameters, allow creating difference grids with mixed cell type (cube, prism, tetrahedron etc.), and user programming. They support most of the 3D models and grid formats from third-party software.

In numerical analysis of intraflow processes most suitable is ANSYS Fluent, which have been tested in solving of wide range of problems – from coal-dust boilers of medium power to circulating fluidized bed boilers. On the basis of all mentioned above we choose this software product. By this SW we determined temperature fields, burner aerodynamics, and gas component concentration in combustion products (volatile, O₂, CO₂, NO) for various furnace devices and burner arrangements. Temperature fields for various tiers burners for 2-tier arrangement are shown as example in the Fig. 1. Example of burner aerodynamics with separate visualization of gas flow path and solid particles motion paths is shown in the Fig. 2.
Fig. 1. Temperature field, K:
a – in axial cross-section of coal-dust burner; б – in horizontal cross-section at 1st horizon burner mark; в – in horizontal cross-section at 2nd horizon burner mark

Fig. 2. Burner aerodynamics:
a – velocity vectors in axial cross-section of coal-dust burner, m/s; б – gas flow lines, m/s; в – solid particles motion paths (burner time for particles indicated by color)
3. Physical modeling of boiler furnaces aerodynamics

Physical models can be of isothermal and fire style. In the Thermal power station department of MPEI isothermal simulation has good reputation and has been applied for long time for steam boiler burner volume aerodynamics on air models. The main feature of this method – consistency of fluid in motion density and viscosity in whole model [4]. Isothermal simulation of burner volume aerodynamics is based on equality of proportions for dynamic pressure of jets on the each direct-flow channel tip (burner device, secondary and tertiary air nozzles, release nozzle for drier agent etc.) and flue gases flow at their level in model and in the real boiler, i.e.:

\[ \frac{H_i}{H_{ri}} = \frac{h_i}{h_{ri}}, \]  

where \( H_i \) – jet dynamic pressure at the direct-flow burner and nozzle output, kgf/(m\(^2\)); 
\( H_{ri} \) – average combustion products dynamic pressure in the burner chamber horizontal cross-section at the burner/nozzle level, kgf/(m\(^2\)); 
\( h_i \) – jet dynamic pressure at the burner/nozzle in the model, kgf/(m\(^2\)); 
\( h_{ri} \) – average air dynamic pressure in the burner chamber horizontal cross-section, kgf/(m\(^2\)).

After expression of dynamic pressures in equation (1) through corresponding formulas, after transformations we will get the main relation, which is used in thermal models computation for square cross-section burners and nozzles:

\[ f_i = F_i \cdot m^2 \cdot \sqrt{\frac{\rho_i}{\rho_{ri}}} \]  

where \( f_i \) – burner/nozzle tip cross-section, in the model, m\(^2\); 
\( F_i \) – burner/nozzle cross-section, m\(^2\); 
\( \rho_i \) – jet density at the burner/nozzle tip, kg/m\(^3\); 
\( \rho_{ri} \) – combustion products temperature averaged density in the furnace at the upper generating direct-flow burners/nozzles, kg/m\(^3\); 
\( m \) – modeling scale for furnace geometry dimensions, which is equal:

\[ m = \frac{a_n}{A_x} = \frac{b_n}{B_x} \]  

where \( a_n \) and \( b_n \) – model width and depth; 
\( A_x \) and \( B_x \) – furnace width and depth.

For circular cross-section burners and nozzles after transformation (2) relationship will be following:

\[ d_i = D_i \cdot m \cdot \left( \frac{\rho_i}{\rho_{ri}} \right) \]  

where \( d_i \) – diameter of burner/nozzle in the model, m; 
\( D_i \) – diameter of burner/nozzle in the real boiler, m.

From relationships (3) and (4) follows, that burners and nozzles in isothermal simulation decrease in the smaller scale, than furnace linear dimensions. After preliminary design of fuel combustion arrangement and with calculated dimensions, we make furnace model from acrylic glass, which simulates furnace chamber of boiler. Because it is hard to work with very big and very small models, we choose model geometrical scale \( m \) for obtaining most convenient model size.

Before model computation it is necessary to determine average flue gases temperature at the upper generating burners/nozzles. After model study and boiler thermal computations (including furnace zonal computations) on the base of blow results, it is necessary to compare calculated flue gas temperature at the burners/nozzles level with previously determined. If difference bigger, than 50 °C, it is necessary to correct model computation scheme.

Model with transparent walls is connected to 7,5 kW centrifugal fan intake, which has guide vanes to regulate underpressure and mouth with the spark-guard to exhaust air into laboratory room Fig. 3. Tubes, which are direct-flow burners and nozzles, remain open and connected to environment. Underpressure in model volume is determined by damper position in fan pipe, i.e. it provides target jet velocity at burners and nozzles tips (Reynold's number should be bigger, than 10\(^3\)). Such Reynold's
numbers, as researches has shown, provides self-similarity of jets and their interaction in furnace volume.

To visualize jet motion paths we make spark-blowing in the furnace chamber model. Sawdust filtered through 200 micrometer mesh is annealed in muffle furnace without air and then pan with smoldering sawdust (more exactly – coke particles) is exposed to fuel intake channels, secondary and tertiary draught. Because of some slide of sawdust particles relative to airflow, they ignite and visualize flow path. Motion pattern of glowing particles in the model is recorded by Nikon D3100 digital camera on-mount. Better contrast and sharpness is obtained by special spotlight illumination. Pictures are being taken through transparent sides and bottom of model (Fig. 4).

![Test rig scheme for USCP boiler furnace model with M-shape](image)

**Fig. 3.** Test rig scheme for USCP boiler furnace model with M-shape:
1 – VR-12-26-4K1 fan impeller; 2 – guide vanes; 3 – 7,5 kW asynchronous electric motor; 4 – spark guard; 5 – connecting compartments; 6 – support blocks; 7 – laboratory floor level; 8 – USCP boiler furnace model with M-shape; 9 – position axis of burners and nozzles pipes
Furnace chamber aerodynamics research cycle usually includes flow motion patterns visual observations (and digital recording) in sparkler blowing, qualitative observation by brush sensors and wind vanes and quantitative research of velocity and temperature fields. Detailed description of all methods will be provided below.

In directflow-swirl torch aerodynamic research the ejection capability of fresh burner jets, i.e. increase of jet flow due to combustion products added mass, is important parameter. Before to performing of special measurement methods to determine jet flow increase, necessary measurement parameters should be determined.

It is recommended to use following equation for determining of jet relative mass flow increase:

$$\Delta \tilde{\bar{\alpha}}_c = k \cdot \sqrt{\frac{T_0}{T_u}} \cdot \bar{I}$$

where $k$ – jet ejection capability coefficient; $T_0$ and $T_u$ – jet temperature at burner tip and cross flow temperature; $\bar{I}$ – relative distance from burner tip.

From well-known enthalpy conservation equation for jet from [5], and also from universal Schlichting velocity profile for average axial velocity distribution in jet cross-section [6], after corresponding transitions we will get formula for relative quantity of ejected flue gases at initial part of air-fuel jet as follows :

$$\Delta \tilde{\bar{\alpha}}_c = \frac{\bar{R}^2 \cdot [\bar{w}_u + 0.258 \cdot (\bar{w}_m - \bar{w}_u)]}{\eta_w} - 1,$$

where $\bar{R} = R/R_o$, $R$, $R_o$ –relative radius, current radius, and nozzle tip radius of jet correspondingly; $\bar{w}_m$, $\bar{w}_u$ – axial velocity at the jet axis and at jet outer boundary; $\eta_w$ – velocity variation factor for nozzle tip cross-section.

Increase of mass flow can be calculated by equation (6), when jet parameters are known (jet velocities and relative radius).

For determining of jet boundaries we used electrical heating of burner flow. At one of the burners 100 V electrical heater with nichrome wire and auto-transformer power source have been installed. We measured thermal fields in 5 jet cross-sections by triple-junction chromel-copel thermocouple with junction size of 0.3 mm which is fixed in axis controller (cold junction have been placed in laboratory room at constant temperature). Axis controller can move thermocouple in 3 mutually perpendicular planes and has rheochord for transformation of coordinate position to electrical current signal. For
measuring of velocities and temperatures of burner jets instead of frontal wall of model, special flaps have been installed, which permit probes movement in all planes and prevent cold air from room to enter into model through rubbing elements touch points.

Signal from precalibrated triple-junction thermocouple in the form of thermal electromotive force as well as current signal from rheochord has been connected to digital multichannel data recorder S-Recorder-L and after that to PC. So, for each pass of thermocouple in horizontal cross-section system plots dependence of flow temperature from coordinate, relative to equivalent burner tip diameter. In the experiment we considered that temperature boundaries correspond to velocity ones. Jet boundary has been determined by sharp increase of thermal electromotive force of thermocouple. For each thermocouple pass jet boundary coordinates have been determined and cross-sections have been plotted (see Fig. 5), and their square has been determined by mechanical integrator (planimeter) of Amsler-Coradi. Jet velocities have been measured by Prandtl tube.

Functional dependencies of following values from burner tip distance have been established on experiment results and their processing:
- jet relative radius;
- maximum relative jet velocity at jet axis;
- jet relative mass flow increase;
- ejection capability coefficient.

In Fig. 6 examples of jet relative mass flow increase can be seen for two boilers. For better visibility we additionally put in fig. the curve of relative mass flow increase for immersed axial-symmetrical jet of equivalent radius with uniform initial exhaust velocity. For axial-symmetrical jet $\Delta \tilde{G}$ have been determined accordingly recommendations from [7] for initial stage of its development. Velocity variation factor at the burner tip $\eta_w$ have been determined experimentally, on physical model.

![Graph](image_url)

**Fig. 5.** Burner jet thermal bounds for physical model of boiler furnace for different outlet distances with electrical flow heating:
1 - $l/d_{eq} = 1.053$; 2 - $l/d_{eq} = 2.105$; 3 - $l/d_{eq} = 3.158$; 4 - $l/d_{eq} = 4.211$; 5 - $l/d_{eq} = 5.264$
On the base of dependencies, shown in Fig. 6, we made conclusion about great influence of schematic designs (direct-flow burners and secondary and tertial draught nozzles arrangement) to jet mass flow increase due to ejection. So, it can be seen, that for № 1 boiler arrangement, increase rate for burner jet mass flow is 1,1-2,4 times higher, than for recommended arrangement for № 2 boiler. It is explained by presence of tertial draught nozzles and increase of secondary draught nozzles tilt.

Big increase rate for jet mass flow due to interflow recycling will provide early ignition of coal dust and it’s stable combustion at low combustion rates.

![Graph](image.png)

Fig. 6. Jet flow relative increase rate:
1 – for boiler № 1 burner flow; 2 – for boiler № 2 burner flow; 3 – for immersed axial-symmetrical jet of equivalent radius

At the same time direct-flow immersed axial-symmetrical jet is significantly inferior to boiler jets of №1 and №2 boilers in ejection capability.

As result, after processing and analysis of experimental data, it has been decided for №2 boiler to return to tertial draught scheme, as more efficient and reliable.

4. Furnace process research results for TPP-210A boiler

As example of implementation of mentioned above method for overhaul of thermal power plant equipment we will consider TPP-210A boiler of TETs-22 PAO «Mosenergo». Research conducted has shown that main issues for double-furnace TPP-210A boilers with STR and using the TP grade Kusnetskiy coal and natural gas are:

- increased specific nitrogen oxide emission, when using coal fuel can reach $C_{NOx} = 1800-1900$ mg/m³, when standard is 540 mg/m³;
- necessity to illuminate coal-dust torch with gas by condition of reliable output of liquid slag from tapholes even at nominal load;
- increased specific nitrogen oxide emission, when using gas fuel ($C_{NOx} = 300-350$ mg/m³ when standard is 125 mg/m³) at the RGE full load;
- increased combustible losses (up to 3-3,5% when standard is 1,5%);
- increased exhaust gas temperature and electricity consumption at the exhaust of gas recirculation (RGE) on its full load due to necessity of decreasing of NOx emission.
Deficiencies, found in the research of TPP-210A boiler, associated mainly with decision of maker to produce boilers with high cross-section combustion rates, which for case rate of 515 t/h is \( Q_F = 4.34 \times 10^6 \) kCal/m²h when acceptable value for furnace volume load is \( Q_V = 127 \times 10^3 \) kCal/m³h.

For solving issues, mentioned above it has been proposed in [8] to switch the boiler to Dry-bottom ash removal (DBAR) mode with staged combustion arrangement by direct-flow burners and nozzles. After physical and mathematical simulations of furnace combustion processes and after zonal thermal calculations of furnace and boiler it has been decided to propose boiler overhaul variant, shown in Fig. 7,8.

Fig. 7. Burners and nozzles arrangement by furnace height for TPP-210A boiler with low combustion rates \( Q_F \) and \( Q_V \):
1 – coal-dust burner; 2 – oil-gas burner; 3 – air and recycle gases nozzle; 4 – combined nozzle; 5 – tertial air nozzle
For better perception, in Fig. 7 burners and nozzles arrangement is shown only for one vertical plane. In other vertical planes arrangement is in mirror order. Slag removal reliability and ash percentage (up to 10-15%) increase is guaranteed by low thermal load to boiler cross-section, by burners/nozzles down-tilt and by recycling gases intake into lower part of furnace hopper. Staged combustion of fuels with low percentage of primary air will provide more efficient suppression of fuel and “fast” nitrogen oxides, which amount 85-90% from their total emission. Generation of thermal
nitrogen oxides will be eliminated due to low thermal load of furnace cross-section, high internal flue gases recycling to burner jets with underburning products and also due to introducing external recycling to gas burning active zone.

**Conclusion**

Expected parameters of fuel efficiency, environmental efficiency and operational reliability for TPP-210A boiler of TETs-22 PAO Mosenergo after overhaul which shown at Fig. 7, 8, have been calculated accordingly methods from [8]:

- $q_4 = 1.6\%$, standard is 2\%;
- $C_{\text{NOx}} = 450 \text{ mg/m}^3$ standard [2] is 470 \text{ mg/m}^3;  
- boiler case minimal loading by coal-dust combustion reliability condition without torch gas illumination $D_{\text{min}} = 195 \text{ t/h}$.

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