THERMOELECTRIC POWER STATIONS

IMPROVEMENT OF THE OPERATING PROCESSES IN BOILER FURNACES OF TÉTs-21 WITH THE HELP OF NUMERICAL SIMULATION OF THERMAL GAS DYNAMIC PROCESSES

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The use of numerical simulation and advanced means of computational hydrodynamics (domestic FlowVision software) for simulating the processes of flow and combustion in the systems for air and gas feeding, mixers, burners, and boiler furnaces has made it possible to advance the recirculation system and burners of the TÉTs-21 cogeneration plant and considerably reduce the NO_x emissions.

Keywords: Ecology, nitrogen oxides, boiler, furnace, recirculation, computational hydrodynamics.

In the 1990s the TÉTs-21 cogeneration plant began to work actively on improving the ecological parameters of steam and hot-water boilers. Toxic emissions due to combustion of natural gas and oil fuel are primarily represented by nitrogen oxides NO_x. According to the acting regulations their concentration in flue gases reduced to NO_2 at 6% oxygen should not exceed 125 mg/m^3 for the case of gas firing and 250 mg/m^3 for the case of fuel oil firing. In the early 1990s the actual emissions exceeded these norms considerably for any boiler. Of the two possible methods for decreasing the emissions of NO_x, i.e., cleaning of the flue gases and prevention of formation of nitrogen oxides known as a process method, the latter was preferred as less expensive and quite effective.

The main variants of the process method of decreasing the concentration of NO_x in flue gases are stage firing, use of low-toxicity burners, and recirculation of flue gases. The efficiency of these variants may differ, but their combination commonly makes it possible to meet the requirements with respect to NO_x emissions without noticeable losses in the efficiency and reliability of the operation of boiler units.

Stage firing of the fuel is provided by redistributing the fuel flows over the burner tiers or by feeding a part of the air (up to 20 – 25%) into draft nozzles positioned above the combustion zone; these measures decrease the concentration of NO_x during gas combustion by a factor of 1.5 – 2. In the case of oil firing the combustion is commonly limited by the possibility of the appearance of hydrogen sulfide near the waterwalls and the occurrence of high-temperature corrosion of the metal of the pipes. Low-toxicity burners commonly realize the principle of stage firing of the fuel and thus lower the concentration of NO_x in the combustion products by 30 – 40%.

The possibilities of decreasing the emission of nitrogen oxides by feeding cooled flue gases into the combustion zone (recirculation) are also quite high. In the case of natural gas firing the addition of 10% flue gases into the draft air (degree of recirculation $r = 10\%$) decreases the concentration of nitrogen oxides by a factor of 3 – 4, and at $r = 20\%$ this concentration is decreased by a factor of 7 – 10. In the case of oil firing the concentration of nitrogen oxides at $r = 20\%$ is about halved.

Provision of efficient operation of the system of recirculation of flue gases. In the beginning of the 1990s specialists of the ROSAVIAKOSMOS Central Research Institute for Basic Engineering resorted to simulation of the thermodynamic properties of combustion products and the kinetics of chemical processes using advanced methods and software [1] and established that the efficiency of the recirculation could be quite high. These theoretical results were confirmed experimentally by the practice of the Mosénergo Company for boilers of type TGMP-314 and KVGM-180 at the TÉTs-26 cogeneration plant [2, 3]. Various estimates of

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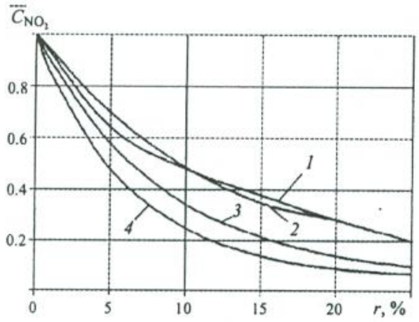

Fig. 1. Decrease in the concentration of nitrogen oxides in flue gases as a function of the degree of recirculation for the case of mixing the recirculation gases with the draft air as given in different publications: *1*, data from [7]; *2*, data from [6]; *3*, *4*, data from [2, 3, 10]: *3*, $t_a = 300°C$; *4*, $t_a = 10°C$.

the possibilities of recirculation are presented in Fig. 1 in the form of the ratio of the concentration of NO_x at a certain value of r to the concentration of NO_x at $r = 0$. Curves *3* and *4* were obtained by computation for hot (3) ($t_a = 300°C$) and cold (4) ($t_a = 10°C$) air under the condition of mixed feeding of the gases and the working air.

The optimistic estimates of the 1990s were based on the values obtained under actual conditions, but these values were lower than the theoretical estimates because the joint feeding of gases and the working air did not provide their appropriate mixing and uniform distribution of the gases over the burners. This distribution was sometimes so nonuniform that it could extinguish individual burners, lead to accumulation of the gas-air mixture, and cause subsequent "shot" combustion.

By providing uniform feeding of gases over the burners and their good mixing with the air in the combustion space the concentration of NO_x was reduced to the theoretical values presented in Fig. 1, which made it possible to simultaneously solve the problems of safety of operation. The level of uniformity of gas feeding over the burners and the quality of mixing with air (concentration pulsations) sufficient for successful operation were evaluated at 20% [2].

The problem of uniform recirculation of gases over the burners is not simple to solve, especially under the conditions of size and air- and gas-pressure constraints. The normal operation of a boiler can be disturbed by the arrival of too much recirculation gases at individual burners. For example, the recirculation system of KVGM-180 hot water boilers mounted at TÉTs-27 in autumn 1992 was equipped with commercial "shadow" mixers. Due to the nonuniform distribution of the recirculation gases in the season of 1992 – 1993 the boilers were run without recirculation, and the NO_x emissions were reduced by decreasing the load. Foreign specialists successfully resort to physical modeling with air or water as the working medium for solving the problem of uniform feeding of gas and air. In the recent decade numerical simulation of three-dimensional turbulent flows has become a very popular approach.

These possibilities became accessible for commercial use in the middle 1990s. They radically improved the quality of engineering decisions in the development of aero and hydrodynamic devices, mixing processes, firing, etc. Today the domestic market possesses all the necessary components for numerical simulation [4]. This allows us to pass from creating prototypes, making laboratory experiments, and in-situ testing to obtaining optimum solutions with the help of numerical simulation and designing ready devices without full-scale testing for the provision of expected results.

In 1994 a TGM-96A boiler was installed at station No. 3 of TÉTs-21 in accordance with the design of the All-Russian Thermal Engineering Institute (VTI); the recirculation system provided up to 18% recirculation of flue gases in the draft air. The boiler had 18 burners arranged in three tiers on the front wall and one tier with 6 secondary draft nozzles. Low-toxicity GMPV-20 burners designed by ÉKOTOP-TsKTI provided the concentration of nitrogen oxides $C_{NO_2} = 270$ mg/m^3 at the rated load without air feeding to the nozzles and $C_{NO_2} = 210$ mg/m^3 with air feeding. The air was fed to the burners and the nozzles from an annular pipe duct. The design stipulated the introduction of recirculation gases directly into the annular pipe duct, but testing showed that they arrived at the burners very nonuniformly. One of the burners had to be disconnected immediately in order to avoid extinction. In this condition the recirculation of flue gases was dangerous for the operation of the boiler.

Numerical simulation yielded a solution in which the already created circulation system was preserved but in the final segment the gases were not fed into the annular pipe duct but rather went into the hot air at the outlet from the regenerative air heater (RAH). At the outlet from each of the three RAH the air divided into two channels, in each of which the flow turned by 180° and entered the bottom part of the annular pipe duct. The length of this channel was about 3.5 m.

It was decided to mount a mixer with fed-in recirculation gases at the inlet to each of the six channels after the RAH. The mixer had five windows of different sizes on two sides, through which the recirculation gases were distributed. The geometry of the mixer, of the windows, and of the protection of the gas jets from the air flow was carefully checked using the Flow Vision software for simulating three-dimensional turbulent flows [4] so that a well-mixed air-and-gas mixture arrived at the annular pipe duct before going to the burners. The distribution of the recirculation gases was worked out after estimating the expected decrease in the NO_x concentration, according to which we could expect $C_{NO_2} = 76$ mg/m^3 at $r = 18\%$.

The design was realized in autumn 1994, the distribution of the recirculation gases over the burners turned out to be uniform enough, and the concentration of NO_2 in the case of gas feeding was 80 mg/m^3. The recirculation system tested in the boiler of station No. 3 was later installed in the same-type boilers of stations Nos. 1, 2, 4, 5, and 6 of the TÉTs-21 cogeneration plant. When working on natural gas they provided a concentration of NO_x in the flue gases at the level of 50 – 85 mg/m^3. In the oil-fired mode the concentration of NO_x decreased from 480 mg/m^3 at $r = 0$ to 135 – 230 mg/m^3 at $r = 12 - 18\%$ at opened dampers of the overdraft nozzles.

The use of numerical simulation for the design of the system for gas recirculation into the draft air for boilers of type TGM-96B of stations No. 7 and 10 of TÉTs-21 provided a full theoretically expected effect of recirculation at very simple devices for gas feeding. For example, the device for feeding gases into air for the boiler of station No. 7 consists of two pipe ducts feeding the gases over a tangent into the air duct at the outlet from its turn in order to intensify the steam vortex appearing at the turn of the flow [5]. The reliable mixing of the gases and the air provided the theoretically expected result for operating recirculation system. In the gas-fired mode $C_{NO_2} = 70$ mg/m^3 for the boiler of station No. 7 and $C_{NO_2} = 85$ mg/m^3 for the boiler of station No. 10. At a disabled recirculation gas extractor in boiler No. 10 the concentration of nitrogen oxides at the rated load amounted to 625 mg/m^3, i.e., the concentration of NO_x at $r = 18\%$ was decreased by a factor of 7.3; in the oil-fired mode with recirculation C_{NO_2} was about 250 mg/h for both boilers.

When gas-fired, PTVM-180 boilers with commercial burners produce a concentration of NO_x of up to 300 mg/m^3, and the use of recirculation for improving this parameter is complicated by the fact that the boiler has 20 burners, each of which can be disabled in the course of operation of the boiler, and the density of the assembly in the boiler body is quite high. No mixer can be mounted into the air ducts due to the high velocity of the air and possible growth in the resistance. As a rule, the consumer desires to preserve the systems of gas and air feeding without installing new dampers and regulators.

Under these conditions we had to take the following measures for creating a recirculation system and decreasing the emissions of NO_x. The gases for recirculation were taken from the space behind the convective part; if necessary, up to 30% of the gases taken after the bottom part and heated to 420°C could be mixed up in order to eliminate water condensation due to mixing of the gases with the draft air at low temperatures. It was decided to feed the gases continuously into all the air ducts whether the burner was enabled or disabled. Since the 8 burners of the top tier were enabled less often than the 12 burners of the bottom tier, the volume of the gases fed to the top burners was 0.7 of the volume fed to the bottom burners.

In order to mix the gases with the air, the former were fed into the air duct in two tangent jets immediately after the damper and before the turn in order to intensify the steam vortex appearing at the turn and to obtain intense convective flows matching the simulation results. These measures were suggested by G. G. Kirsanov of the Mosénergo Company. They were realized at the TÉTs-21 cogeneration plant in 1996 for a PTVM-180 boiler of station No. 1. All the boiler parameters were as required, and the concentration of nitrogen oxides $C_{NO_2} = 75$ mg/g at recirculation $r = 12\%$ (at an expected value of $C_{NO_2} = 80$ mg/m^3).

Turning again to Fig. 1 we will see that the foreign data [6] and the recommendations of domestic regulations [7] still underestimate the possibilities of recirculation as a means for decreasing the emissions of NO_x in the gas-fired mode. We cannot agree with the recommendations to lower the emissions by raising the degree of recirculation to $r = 0.3$ and even to $r = 0.35$ [8, 9]. It would be much more expedient to fully realize the recirculation possibilities at $r = 15 - 25\%$, which follows from curves *3* and *4* in Fig. 1. The maximum values of $r = 15 - 17\%$ for the mode without air heating and $r = 17 - 20\%$ for operation on hot air seem to be the optimum variant.

The concentration of NO_x reduced to NO_2 at $O_2 = 6\%$ can be evaluated by the following formulas:

$$C_r = \left[(C_0 - C_f)K_r + \frac{C_f}{1+2r}\right](1+r),$$

where C_0 and C_r are the used concentrations of NO_2 for the modes without and with recirculation, C_f is the concentration of fast oxides, and r is the degree of the recirculation; the concentration is determined as the ratio of the flow of the recirculating gases to the flow of the gases removed at the extraction point; $K_r = (0.1 t_a^{0.2})^{10r}$, t_a is the temperature of the draft air,°C; at $t_a < 50$°C we take $t_a = 50$°C; $C_f = 20$ at $t_a < 50$°C and $C_f = 30$ at $t_a > 200$°C.

Curves *3* and *4* in Fig. 1 are plotted for C_0 equal to 450 and 300.

Organization of the process in the furnace. The KhF burner of the TGM-96B boiler has three air channels, namely, the central, the internal, and the peripheral ones. The air arriving at the last two channels is swirled in the elbow and by tangential blade swirlers. The air from the central channel that has a narrow cross section 225 mm in diameter arrives without swirling. Simulation of the processes in the burners and in the furnace showed that the design of the used commercial burner did not stabilize the flame by the return flow near the axis of the swirled flow, i.e., in this region the return flow was absent. The flame of the burner was stabilized under the operating conditions due to the ignition of the flame over the periphery by the furnace gases; the ignition occurred at a distance from the burner throat, the flame extended, and the combustion of the gas propagated to the rear wall.

In order to remove the defects the designers decided to mount swirlers in the final conical regions of the central channels; the swirlers were constructed so that the flame acquired the necessary structure and provided cooling of the oil atomizer. In addition, the IPD pipes of burners Nos. 1 and 2 equipped with an ignition-protection device (IPD) were transferred to the central channel.

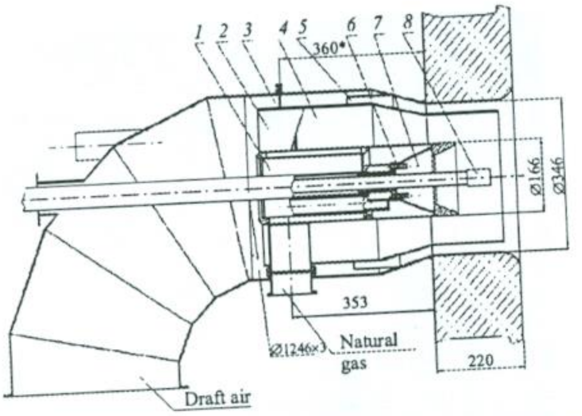

Fig. 2. Sketch of a GPS-8 burner: *1*, central air flow; *2*, blades for swirling the internal air; *3*, peripheral air flow; *4*, internal air flow; *5*, annulus for regulating the flow rate of the peripheral air; *6*, four gas pipes; *7*, conical swirler; *8*, oil-feeding thrower.

These alterations were implemented, and in November –December 2002 the boiler was tested in the gas- and oil-firing modes. Testing showed that the modification of the design of the burners improved the quality of gas and oil firing, the flames became shorter, the combustion started at the throat, and the flame tips did not reach the wall of the furnace at any load on the boiler. The temperature of the jacket of the rear wall of the furnace operating on natural gas under rated loads was 35 – 40°C; in the oil-firing mode the temperature in the central part of the rear wall attained 60 – 70°C. However, the final estimate of the reliability of the thermal insulation of the rear waterwall of the boiler will be made after a year of its operation.

Development of low-toxicity burners. In addition to recirculation of flue gases, nonstoichiometric firing of the fuel is widely used for lowering the emission of NO_x. The direct-flow/vortex burners designed by ÉKOTOP-TsKTI and the GDS two-stage combustion burners designed by VTI successfully realize this principle.

Starting from 1996 the TÉTs-21 cogeneration plant has been working with low-toxicity GPS burners (burners with preliminary mixing). Figure 2 presents a sketch of a GPS-8 burner (improved in the operating process from 1997 to 2000) with a thermal power of 8 MW, which is used in the PTVM-100 boiler of station No. 3 of TÉTs-21.

The main features of the burner are as follows. The air flow is divided into three parts, i.e., about 4% air goes through the central unit, about 27% goes through the peripheral channel, and the remaining 69% goes through the internal channel. A low amount of the gas (about 4%) is fed through the center, and the main flow arrives at the annular collector of the center and then is dispensed in transverse steams into the air of the internal channel. The conical swirler of the center provides a stabilizing flame. It is very stable and is "suspended" in the air without touching the structural elements. Since the stabilization of the flame is provided by the central unit, the main air stream of the burner can have any shape, i.e., a straight or a swirled one, in order to meet the mixing conditions, the geometry of the burner flame, or the available head pressure provided by the fan. The air-fuel mixture passing through the internal channel with an excess air factor $\alpha \approx 0.7$ is ignited by the central flame, burns out, and then the peripheral air mixed with furnace gases is added to the combustion products.

Tests of the PTVM-100 boiler equipped with GPS-8 burners performed by Mosénergonaladka in 1999 showed that the flame was steady at a gas pressure $P_g = 0.02 - 0.6$ kgf/cm² and at an air pressure $P_a = 20 - 130$ kgf/m². The concentration of nitrogen oxides at the rated load was 130 mg/m³. A photograph of the furnace (Fig. 3) taken through the scuttle during operation of eight GPS-8 burners shows the glowing luting of the furnace walls near the throat used to prevent the action of the flame of a conventional burner or a GDS burner. The flame of the GPS burner does not touch the walls, which makes it possible to remove the walling-up and to increase the area of the radiation-receiving surface of the furnace by 5 – 8%.

In 2002 we finished certification testing of the GPS-12 burner based on the 12-MW GPS-8 design and developing for PTVM-180 boilers. A photograph of the flame is presented in Fig. 4. A fully loaded boiler produces 180 mg/m³ NO_2. It should be noted that the walls of the PTVM-180 boiler are also densely luted to the level of the top tier. The removal of this luting should decrease the emissions of NO_x, raise the efficiency of the boiler, and promote the operation of the convective heat exchangers.

In the oil-fired mode of operation of GPS burners the mechanical atomizer is placed close to the central unit section, which provides good stabilization and development of the flame. Note that before testing in the oil-fired mode the GPS-8 burner had a straight-flow channel for the peripheral air, but the straight flow interrupted the oil flame. A turn by 30° towards the axis of the burner provided a stable flame in oil firing.

The possibility of flowback is an important problem for burners with preliminary mixing. During the tests of GPS8 and GPS-12 burners the problem arose even at the lowest velocity of the air-fuel mixture, i.e., at 7 – 10 m/sec. It should be noted that the described burners are the third of four tested variants. The development of their design required additional money for fabricating the variants, mounting, and updating at the site. The repair group of the boiler shop of TÉTs-21 contributed much to this effort.

At the same time, all the burner designs and their variants chosen after numerical simulation of the processes in the burner and in the furnace functioned normally right after they had been mounted, and the modifications were commonly required for oil-firing or operation in transient modes, which had not been simulated for the lack of appropriate possibilities. The design of the GPS-12 burner remained un-

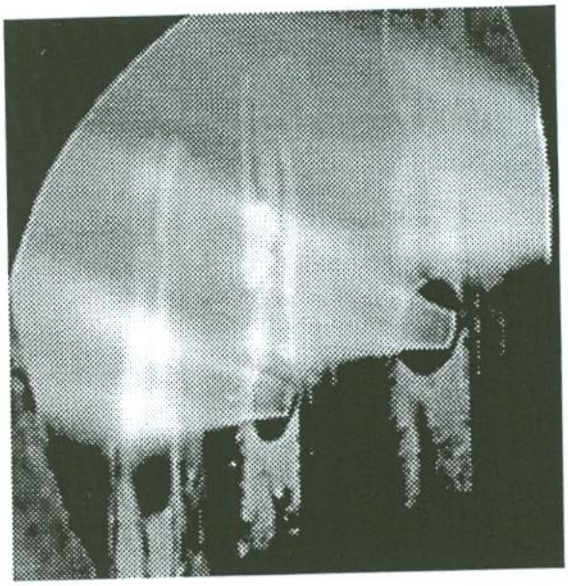

Fig. 3. The furnace of a PTVM-100 boiler operating with 8 enabled GPS-8 burners.

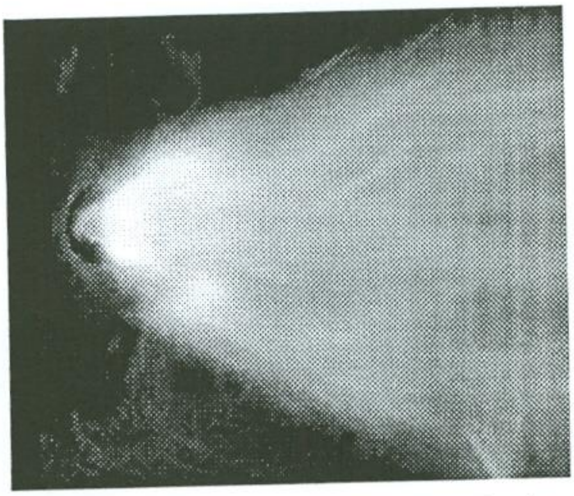

Fig. 4. Flame of a GPS-12 burner operating at the rated mode.

changed in the last version, the only modification being a new shim for controlling the gas flow into the center.

Today we face the problem of widening the possibilities of the FlowVision software to the case of oil firing and computation of the concentration of NO_x. This would allow us to further advance the characteristics of steam and hot water boilers at a low cost.

CONCLUSIONS

The wide use of simulation of three-dimensional turbulent flows with allowance for the combustion process and the chemical kinetics for improving the firing processes in boiler furnaces at the TÉTs-21 cogeneration plant has made it possible to find effective engineering solutions at a low cost and provide high ecological parameters and reliability of the units. Widening of the use of such methods and their possibilities is an important reserve for raising the efficiency of power plants.

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REFERENCES

1. V. E. Alemasov, A. F. Dregalin, A. P. Tishin, and V. A. Khudyakov, *Thermodynamic and Thermophysical Properties of Combustion Products. A Handbook* [in Russian], Izd. AN SSSR, Moscow (1971).
2. A. P. Tishin, V. A. Khudyakov, and A. K. Artamonov, *A Study of the Possibilities of Decreasing the Concentration of Nitrogen Oxides in Fuel Firing at Power Units* [in Russian], Izd. TsNIIMASh, Korolev, Moscow Region (1994).
3. A. P. Tishin, V. A. Khudyakov, and A. K. Artamonov, *Dependence of the Emission of Nitrogen Oxides from Power Units on the Degree of Recirculation of Flue Gases, the Temperature and Moisture Content in the Draft Air* [in Russian], Izd. TsNIIMASh, Korolev, Moscow Region (1996).
4. A. A. Aksenov and V. N. Kon'shin, "FlowVision: a new generation of CAE," *SAPR Grafika*, No. 11 (2002).
5. I. E. Idelchik, *A Handbook on Hydraulic Resistances* [in Russian], Gosénegroizdat, Moscow (1960).
6. R. Stephan, *Turns. An Introduction to Combustion*, McGraw-Hill International Editions (2000).
7. *RD 34.02.304-95. Methodological Instructions to Computing Emissions of Nitrogen Oxides with Flue Gases of Thermal Power Plant Boilers* [in Russian], Izd. VTI-TsKTI, Moscow (1996).
8. V. R. Kotler and Yu. P. Enyakin, "Realization and efficiency of process methods for suppressing nitrogen oxides at TPP," *Teploénergetika*, No. 6 (1994).
9. Yu. P. Enyakin and A. M. Bykov, "Wide commissioning of process methods for suppressing nitrogen oxides on gas-and-oil boilers," in: *Nature-Protective TPP Processes* [in Russian], Izd. VTI, Moscow (1996).
10. D. V. Volkov, S. A. Zaitsev, A. P. Tishin, and V. A. Khudyakov, *Dependence of the Concentration of Nitrogen Oxides Formed Near the Flame Front ("Fast") during Methane Combustion on the Excess Air Factor, the Air Temperature, and the Degree of Recirculation of Flue Gases* [in Russian], Izd. TsNIIMASh, Korolev, Moscow Region (1999).