Efficiency of application of various layout arrangements of oil-gas burners in thermal power plant boilers

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Abstract. The necessary intensity of burning and completeness of fuel burning out in furnace volume are reached by the correct supply organization and the subsequent mixture of fuel with secondary air that is provided with burner devices. Experimental research of fuel oil and gas combustion efficiency in boiler furnaces of thermal power plant has shown that, the peripheral axial twist executed in the form of two channels with axial scapular air rotator is preferable. The combined gas supply is perspective: tubular peripheral and pilot central. For fuel oil combustion at large expenses the most effective burning is reached due to application of steam-mechanical nozzles which main lack is the considerable length of a torch. The two-tiered arrangement of burners in boiler at combustion of gas and fuel oil is more effective, in comparison with single-tier, both at the counter direction, and at unilateral frontal. For increasing the efficiency of combustion of fuel at some burners types in a boiler furnace the ascending vertical rotation of a torch can be created by the asymmetrical counter arrangement of burners of the first and second tiers. Use of the smoke exhauster of gases recirculation for reduction of harmful emissions of nitrogen oxides with boilers flue gases gives bigger effect in comparison with optimization of the choice of a layout arrangement of burners and parameter of a twist.

Keywords. Boiler efficiency, fuel oil, burner, flame temperature, air swing, burning, natural gas, torch, tier, radiation.

1. Introduction
The efficiency of combustion of fuel oil in power coppers depends on a number of factors which configuration and design features of torches is among. The general is fall of temperature of products of combustion of fuel oil at the exit from a fire chamber and decrease in efficiency of coppers upon transition from combustion of gas to combustion of fuel oil. However by application of optimal technical solutions when designing new torches, modernization of the existing torches and the choice of parameters of process of combustion of fuel oil can increase the efficiency of coppers at combustion of fuel oil. In the real work the efficiency of combustion of fuel oil in coppers with various configuration of torches is experimentally investigated. Experimental research of fuel oil and gas combustion efficiency in boiler furnaces of thermal power plant has shown that, the peripheral axial twist executed in
the form of two channels with axial scapular air rotator is preferable. The combined gas supply is perspective: tubular peripheral and pilot central.

2. Materials and Methods

Objects of a research are steam power boilers of the thermal power plants using for gas and fuel oil combustion oil-gas burners with a mechanical and steam-mechanical fuel oil atomization. Experiments were made on drumbeat boilers of TGM-84A, TGM-84B, TGM-96B, TG-104, PK-47, TPE-429, TGME-464 and direct-flow PK-41 boilers. PK-47 and PK-41 double-hulled boilers, and PK-41 is a supercritical pressure boiler. TGME-464 boiler with natural circulation is drumbeat gas-tight under pressurization with balanced thrust and also has the smoke exhauster of gases recirculation. TG-104 boiler has the smoke exhauster of flue gases recirculation which is switched-off at big steam loadings.

Schemes of burners arrangement on the researched boilers are given on fig. 1. TGM-84A and TGM-84B boilers have the two-light screen in a boiler furnace, and TGM-96 boiler at the same sizes of a boiler furnace and bigger thermal power doesn't contain the screen. On TGM-84A TGM-84B, TGM-96, TG-104 boilers burners are located unilaterally on frontal walls, and on PK-47 and PK-41 boilers – opposite on side walls. PK-47 boiler has an asymmetrical arrangement of burners which provides at the top view the vortex ascending in height current of combustion products with right-hand rotation.

On a TPE-429 boiler burners are located opposite in one tier on frontal and back walls of a boiler furnace. On a TGME-464 boiler burners are located in two tiers on a back wall of a boiler.

![Figure 1. Schemes of burners arrangement on the researched boilers](image)

Rating technical characteristics of the researched boilers are given in table 1.

Width of a boiler furnace is measured on a frontal wall, height – from the middle of a cold funnel to the middle of the horizontal gas flue. On the Surgut state district power plant reserve fuel oil isn't used. The technical characteristics of burners brands, given in tab. 1, can differ considerably in comparison with factory owing to their modernization in use. Such modernization is executed on TGM-96B boiler by application of nozzle gas-distribution, instead of conic nozzle with openings, either on peripheral, or on the central gas supply.

| Table 1. Rating technical characteristics of the researched boilers. |
Technical characteristics of burners applied on the researched boilers are given in table 2.

**Table 2.** Technical characteristics of burners applied on the researched boilers.

| Brand of a boiler and installation place | Width, depth and height of a boiler furnace, m | Productivity, t/h | Pressure and steam temperature | Brand of a burner and power, MW | Brand of a nozzle |
|-----------------------------------------|-----------------------------------------------|------------------|--------------------------------|---------------------------------|------------------|
| TGM-84A, Nizhnekamsk TPP-1              | 16×7,5×23                                     | 420              | 14 MPa, 560°C                  | HF-CKB-VTI-TKZ, 77             | FUZ-7500         |
| TGM-84B, Nizhnekamsk TPP-1, Naberezhnye Chelny TPP | 16×7,5×23                                    | 420              | 14 MPa, 560°C                  | TKZ, 53                         | FUZ-5000         |
| TGM-96B, Nizhnekamsk TPP-1              | 16×7,5×23                                     | 480              | 14 MPa, 560°C                  | HF CKB-VTI-TKZ, 89             | FUZ-9000         |
| TG-104, Surgut SDPP                    | 18,6×7,2×29                                   | 670              | 14 MPa, 560°C                  | GMU-45m, 45                     | -                |
| PK-47, Zainsk SDPP                     | 9,5×9,5×28 (on 2 housings)                   | 640              | 14 MPa, 545°C                  | ZIO, 50                         | FM-5000          |
| PK-41, Karmanovo SDPP                  | 17,3×8,7×32 (on 2 housings)                  | 950              | 25 MPa, 545°C                  | ZIO, 50                         | FM-5000          |
| TPE-429, Kazan TPP-3                   | 12×8×30                                       | 400              | 14 MPa, 560°C                  | GMU-45-12, 45                   | FUZ-5000         |
| TGME-464, Hizhnekamsk TPP-2            | 12×8×30                                       | 500              | 14 MPa, 560°C                  | GMU-45-12, 45                   | FUZ-5000         |

On TG-104 boiler (see table 2) burners with the combined gas supply are applied: the main peripheral tubular and additional pilot central with conic nozzle with openings.
Apparently from table 2, the largest parameter of a twist is reached with application of peripheral axial scapular air stream vortex generator that provides the best mixing him with fuel.

During the experiments mode parameters of boilers operation and heat fluxes falling from a torch on boiler furnace screens were measured. During the measurements of operational mode parameters tenured instruments were used. Measurements of nitrogen oxides content and oxygen content in the leaving combustion products in mode cross section were carried out using DAG-500 gas analyzer. Temperature of the leaving gases in balance cross section was measured by a method of two thermocouples [1-5] along with the tenured station temperature sensor. Measurement of the heat fluxes falling from a torch on boiler furnace screens is executed by a noncontact method using the radiometer TERA-50 with RK-15 graduation via hatches within the walls of boiler furnaces. The error of experiments during the measurement of heat fluxes from a torch for determination of temperature reached ±2,76 %. The error of determination of boilers efficiency on the reverse balance calculated by a technique [10-13,15] reached ±3,51 %.

3. The received results and their discussion

Comparative experimental data in parameters of boilers operation at various steam loadings at gas combustion in burners of various designs and layout in a boiler furnace are given in table 3.

Table 3. Experimental data in parameters of boilers operation at various steam loadings at gas combustion in burners of various designs.

| Boiler     | Loading D, t/h | Air excess coefficient, α | Leaving gases temperature tyx, ºC | The NOₓ content in flue gases calculated as α=1,4, mg/m³ | Efficiency gross η, % |
|------------|----------------|---------------------------|-----------------------------------|-----------------------------------------------------------|----------------------|
| TGM-84A    | 210            | 1,07                      | 109                               | 92                                                        | 94,96                |
|            | 300            | 1,06                      | 116                               | 114                                                       | 95,04                |
|            | 350            | 1,06                      | 120                               | 124                                                       | 94,97                |
|            | 420            | 1,05                      | 125                               | 132                                                       | 94,83                |
| TGM-84B    | 210            | 1,09                      | 105                               | 105                                                       | 94,65                |
|            | 260            | 1,07                      | 113                               | 125                                                       | 94,77                |
|            | 320            | 1,06                      | 123                               | 150                                                       | 94,75                |
|            | 420            | 1,05                      | 136                               | 190                                                       | 94,39                |
| TGM-96B    | 240            | 1,07                      | 114                               | 128                                                       | 94,23                |
|            | 300            | 1,06                      | 118                               | 160                                                       | 94,34                |
|            | 420            | 1,05                      | 125                               | 220                                                       | 94,34                |
|            | 480            | 1,05                      | 130                               | 235                                                       | 94,17                |
| TG-104 (with SEGR) | 335       | 1,1                       | 112                               | 30                                                        | 94,54                |
|            | 440            | 1,05                      | 116                               | 40                                                        | 95,11                |
|            | 510            | 1,045                     | 118                               | 50                                                        | 95,22                |
|            | 670            | 1,04                      | 124                               | 160                                                       | 95,12                |
| PK-47, housing A | 180      | 1,12                      | 120                               | 210                                                       | 92,8                 |
|            | 255            | 1,06                      | 125                               | 250                                                       | 93,6                 |
|            | 320            | 1,05                      | 130                               | 288                                                       | 93,4                 |
| PK-41, housing A | 205      | 1,09                      | 124                               | 190                                                       | 91,7                 |
|            | 265            | 1,07                      | 128                               | 200                                                       | 92,2                 |
|            | 365            | 1,06                      | 130                               | 300                                                       | 91,8                 |
Air twist parameter is high at the same time and is also equal to 1.8. Except the applied burners small NOX nitrogen oxides emissions concentrations at low steam loadings in a TG-104 boiler were reached due to recirculation of flue gases in a boiler furnace. Technically recirculation was carried out by selection from the lowering gas flue up to 10% of all volume of flue gases in the field of the economizer by means of the recirculation smoke exhauster and supplying them through the mixer in an air duct in front of burners [6-9]. Increase of NOX nitrogen oxides concentration at loadings of 670 t/h is explained by the termination of recirculation in connection with technical need of turning on of the intermediate steam reheater in work. At the same time temperature in a boiler furnace increases that leads to an intensification of thermal NOX nitrogen oxides formation.

The increased efficiency values of TGM-84A boiler are explained with a good mixing of air with natural gas in burners at peripheral tubular gas-distribution and a peripheral axial twist in the applied burners of TG-104 boiler it is reached the high efficiency values and low values of harmful NOX nitrogen oxides emissions concentrations in all range of steam loadings. Air twist parameter is high at the same time and is also equal to 1.8. Except the applied burners small NOX nitrogen oxides emissions concentrations at low steam loadings in a TG-104 boiler were reached due to recirculation of flue gases in a boiler furnace. Technically recirculation was carried out by selection from the lowering gas flue up to 10% of all volume of flue gases in the field of the economizer by means of the recirculation smoke exhauster and supplying them through the mixer in an air duct in front of burners [6-9]. Increase of NOX nitrogen oxides concentration at loadings of 670 t/h is explained by the termination of recirculation in connection with technical need of turning on of the intermediate steam reheater in work. At the same time temperature in a boiler furnace increases that leads to an intensification of thermal NOX nitrogen oxides formation.

The counter arrangement of burners in PK-47 and PK-41 boiler furnaces doesn't increase efficiency of natural gas combustion. Values of parameter of a twist are low. PK-47 boiler, in comparison with PK-41 boiler, provides the best mixing of air and fuel at the expense of the ascending vertical twist of a torch that allows to increase efficiency. However in both cases in PK-47 and PK-41 boiler furnaces due to counter collision of torches there are sites with the increased temperature which is the reason of increase of harmful NOX nitrogen oxides generation [14,16-20].

Experimental data in parameters of boilers’ work at various steam loadings at M100 fuel oil combustion are given in tab. 4. Experiments on TG-104 and TPE-429 boilers at combustion of fuel oil weren't conducted as they weren't exploited in this operating mode.

From tab. 4 it is visible that pressurization in combination with recirculation of flue gases in a TGME-464 boiler furnace allows to receive at M100 fuel oil combustion quite high efficiency which exceeds value of this efficiency during the work on gas. It is connected with the fact that temperature of the leaving gases during the smoke exhauster operation of flue gases recirculation in a boiler furnace decreases. At the same time during the work of TGME-464 boiler on fuel oil it is equal to 106...118 °C, and at gas combustion to 115...141 °C.

The two-tiered unilateral arrangement of burners in TGM-84B and TGME-464 boilers at their increased number gives the best mixing of the dispersed fuel oil drops with air and, as a result increase in efficiency (see tab. 4) in comparison with an arrangement of burners and their number in amount of four on TGM-84A, TGM-96B boilers and a single-tier counter arrangement on PK-41 boiler or with the reduced number of burners on the first tier in PK-47 boiler (see figure 1).
Table 4. Experimental data in parameters of boilers’ work at various steam loadings at M100 fuel oil combustion

| Boiler          | Loading D, t/h | Air excess coefficient, $\alpha$ | Leaving gases temperature $t_{vx}$, ºC | The NO$_x$ content in flue gases calculated as $\alpha=1,4$, mg/m$^3$ | Efficiency gross $\eta$, % |
|-----------------|----------------|---------------------------------|----------------------------------------|-----------------------------------------------------------------|-----------------------------|
| TGM-84A         | 220            | 1,1                             | 150                                    | 339                                                             | 90,85                       |
|                 | 300            | 1,08                            | 157                                    | 351                                                             | 91,29                       |
|                 | 360            | 1,07                            | 163                                    | 360                                                             | 91,25                       |
|                 | 420            | 1,06                            | 167                                    | 365                                                             | 91,17                       |
| TGM-84B         | 300            | 1,14                            | 144                                    | 520                                                             | 93,42                       |
|                 | 360            | 1,13                            | 150                                    | 545                                                             | 93,34                       |
|                 | 400            | 1,12                            | 152                                    | 555                                                             | 93,32                       |
|                 | 420            | 1,11                            | 155                                    | 565                                                             | 93,25                       |
| TGM-96B         | 340            | 1,11                            | 148                                    | 333                                                             | 92,23                       |
|                 | 400            | 1,08                            | 153                                    | 331                                                             | 92,1                        |
| PK-47, housing A| 186            | 1,15                            | 154                                    | 349                                                             | 92,6                        |
|                 | 255            | 1,09                            | 155                                    | 360                                                             | 92,8                        |
|                 | 313            | 1,08                            | 159                                    | 370                                                             | 92,7                        |
| PK-41, housing A| 265            | 1,12                            | 150                                    | 320                                                             | 92,9                        |
|                 | 365            | 1,09                            | 155                                    | 350                                                             | 92,8                        |
|                 | 480            | 1,08                            | 160                                    | 450                                                             | 92,6                        |
| TGME-464 (under pressurization with SEGR) | 300 | 1,06 | 106 | 240 | 94,95 |
|                 | 400            | 1,05                            | 113                                    | 300                                                             | 94,71                       |
|                 | 500            | 1,05                            | 118                                    | 370                                                             | 94,35                       |

The important characteristic of efficiency of fuel combustion in a boiler furnace is the uniformity and value of density of the thermal radiation falling on screens from a torch. As process of burning happens in diffusive area, density of thermal radiation is connected with intensity of fuel and air mixture.

Experimental values of streams of a torch $q_\phi$ thermal radiation at height $h$ of boiler furnaces of the researched boilers at gas combustion at the largest steam loadings specified in tab. 3 are given in figure 2.

Apparently from figure 2, TG-104 boiler has the largest thermal streams from torch $q_\phi$ at the level of burners equal to 480 kW/sq.m, that is connected with its steam loading of 670 t/h and applied peripheral axial twisting of air stream with the parameter of a twist of 1,8 (see table 2). TGM-84A boiler has the smallest streams of radiation from torch $q_\phi$ at the level of burners equal to 220 kW/sq.m that is connected with the applied peripheral tubular gas supply and a peripheral tangential air twist with the parameter of a twist of 1,1 (see table 2).
Experimental values of temperature of torch $t_h$ at height $h$ of boiler furnaces of the researched boilers at gas combustion at the largest steam loadings specified in table 3 are given in figure 3.

From figure 3 it is visible that at the level of burners the highest values of a torch temperature at gas combustion are received in TGM-96B and TG-104 boiler furnaces respectively for steam loadings of 480 t/h and 670 t/h.

High values of temperature of a torch for TGM-96B boiler are connected with the nozzle gas-distribution applied in burners (see table 2) at which the stream of gas leaves perpendicular to the twisted air stream. At the same time length of a torch becomes shorter in comparison with gas-distribution with conic nozzle with openings and concentration of combustion products at small value of parameter of a twist equal to 0.94 leads to growth of temperature. Values of nitrogen oxides content in combustion products increase and are equal to 235 mg/m$^3$ for TGM-96B boiler (see table 3).

In TG-104 boiler at an axial peripheral twist of air with high value of parameter of a twist equal to 1.8 time of stay of burning products in a zone of high temperatures is reduced and generation of nitrogen oxides decreases that is characterized by their contents in the leaving combustion products by value of 160 mg/m$^3$ (see table 3).

Efficiency values and temperature $t_{yx}$ of the leaving gases depending on the parameter of a peripheral tangential twist and steam loadings of boilers are given in figure 4-a for gas combustion during gas-distribution with conic nozzle with openings and in figure 4-b for M100 fuel oil combustion with application of steam-mechanical nozzles.

Apparently from figure 4, efficiency $\eta$ considerably depends on temperature $t_{yx}$ of the leaving gases which takes place at this value of parameter of a twist $n$ and arrangement of burners in boiler furnaces.
At gas combustion at identical parameters of the twist $n=1,5$ a two-tiered arrangement of burners in TGME-464 boiler (see figure 1) and smaller values of $\alpha$ air excess coefficient at the expense of a gas-dense furnace efficiency are higher in comparison with TPE-429 boiler.

Reduction of burners number to two on the second tier in a TGM-84B boiler furnace lowers temperature at the exit from furnace in comparison with a TGME-464 boiler furnace having four burners on the second tier. At TGM-84B boiler furnace exit it leads to decrease temperature $t_{yx}$ of the leaving gases and to increase in efficiency (see figure 4-a).

At M100 fuel oil combustion in TGME-464 boiler the high efficiency $\eta$ values are connected with the lowered temperatures on the exit from a boiler furnace at four burners on the second tier in comparison with TGM-84B boiler.

The counter single-tier arrangement of burners on frontal and back walls of a PK-41 boiler furnace at fuel oil combustion as a result of torches collision increases temperature at the exit from boiler furnace, leads to growth of temperature $t_{yx}$ of the leaving gases and is followed by decrease in efficiency $\eta$ in comparison with TGM-84B and TGME-464 boilers (see figure 4-b).

Values of NO$_x$ nitrogen oxides (mg/m$^3$) concentration in flue gases and $\alpha$ air excess coefficient depending on the parameter of a peripheral tangential twist and steam loadings of boilers are given in figure 5-a for gas combustion during gas-distribution with conic nozzle with openings and in figure 5-b for M100 fuel oil combustion with application of steam-mechanical nozzles.
Apparently from figure 5-a, during gas combustion the smallest values of harmful nitrogen oxides NO\textsubscript{x} concentration are observed for TGME-464 boiler that is explained by recirculation by means of SEGR of flue gases in boiler furnace from the lowering gas flue and smaller, in comparison with TGM-84B boiler, values of \( \alpha \) air excess coefficient. For TPE-429 boiler increase in parameter of a twist up to \( n=1.5 \), in comparison with \( n=1.05 \) for TGM-84B boiler, doesn't lead to reduction of nitrogen oxides NO\textsubscript{x} concentration. The frontal two-tiered arrangement of burners in a TGM-84B boiler furnace is constructively more effective in comparison with a counter single-tier arrangement of burners in TPE-429 boiler furnace for elimination of zones in a torch with the increased temperatures at which there is an intensive thermal nitrogen oxides generation [21-30].

As it is already noted above (see table 3), during gas combustion TG-104 boiler has the smallest emissions of nitrogen oxides (NO\textsubscript{x}=50 mg/m\textsuperscript{3} at \( D=510t/h \) with recirculation of flue gases and a frontal two-tiered arrangement of burners with an axial peripheral twist and parameter of a twist \( n=1.8 \). The gas-dense TGME-464 boiler under pressurization and with recirculation has nitrogen oxides concentration in flue gases higher and equal to 100 mg/m\textsuperscript{3} at the same loadings. The shutdown of the smoke exhauster of gases recirculation in TG-104 boiler at loading of 670 t/h connected with steam reheaters operation has led up to growth of temperature of a torch and intensification of nitrogen oxides emission to 160 mg/m\textsuperscript{3}.

During M100 fuel oil combustion (see figure 5-a) gas-dense TGME-464 boiler under pressurization and with gases recirculation in a boiler furnace gives the smaller nitrogen oxides content in flue gases in comparison with PK-41 and TGM-84B boilers. Experiments on M-100 fuel oil combustion in TPE-429 and TG-104 boilers weren't conducted in this work. As well as during gas combustion, for fuel oil combustion essential decrease in nitrogen oxides content in flue gases with reduction of \( \alpha \) air excess coefficient during the work of various boilers with various layout arrangement of burners in a boiler furnace is characteristic. With growth of steam loading \( D \) there is a decrease in \( \alpha \) air excess coefficient in flue gases [31]. However at the same time there is a growth of temperature of a torch that causes increase in nitrogen oxides concentration in flue gases. Lower values of air excess coefficient for PK-41 boiler and counter layout arrangement of burners, in comparison with TGM-84B boiler, have reduced nitrogen oxides concentration in flue gases at fuel oil combustion.

4. Conclusions
1. The efficiency of fuel combustion at a frontal two-tiered arrangement of oil-gas burners in a boiler furnace very strongly depends on the applied way of a peripheral air twist and the most optimum is using of axial peripheral turning scapular air rotator.
2. For gas combustion the most effective is the combined peripheral tubular and central with conic nozzle gas supply that allows at rotary heads of the gas-distributing pipes to eliminate torch throw on the back screen at a frontal arrangement of burners. 3. Using of the smoke exhauster of gases recirculation for reduction of harmful nitrogen oxides emissions with flue gases of boilers gives bigger effect in comparison with optimization of the choice of a layout arrangement of burners and parameter of a twist.

References
[1] Taymarov M A, Sungatullin R G, Stepanova T O and Almuhametov R S 2016 Optimization of management of physical and chemical process of gas fuel burning in a radiant boiler furnace Bulletin of Kazan technological university 19(13) pp 142-4
[2] Taymarov M A, Akhmetova R V, Chiklyayev D Ye, Chiklyayev Ye G and Sungatullin R G 2016 Education and ways of decrease in nitrogen oxides in TG-104 boilers with direct-flow and vortex burners and peripheral supply of gas News of HEI. Power problems vol 9-10 pp 83-90
[3] Taymarov M A, Akhmetova R V, Safin R G and Lavirko Y V 2016 Calculation of Fuel Oil Drop Burnup Time Dependence on Intensity of Flame Radiation Research Journal of Applied Sciences Year vol 11 pp 1660-5
[4] Taymarov M A, Akhmetova R V, Chiklyayev D Ye, Chiklyayev Ye G and Sungatullin R G
2016 Burning of methane-hydrogen fraction and fuel oil in TGM-84A boilers KSPEU bulletin vol 4 pp 83-95

[5] Taymarov M A and Lavirko Y V 2018 Reduction in emissions of nitrogen oxides energy boilers European Journal of Technical and Natural Sciences vol 1 pp 27-30

[6] Taymarov M A, Lavirko Y V and Chiklyayev D G 2017 Burner for combustion of gas and fuel oil Patent for useful model № 170609

[7] Taymarov M A, Lavirko Y V and Akhmetova R V 2017 The nozzle Patent for useful model № 174497

[8] Taymarov M A, Akhmetova R V and Sungatullin R G 2017 Boiler installation Patent for useful model № 169930

[9] Taymarov M A and Lavirko Y V 2015 Boiler installation Patent for useful model № 154647

[10] Akhmetova R V, Taymarov M A, Chiklyayev Ye G and Sungatullin R G 2017 Indicators of mode parameters of TGM-84B boilers when burning methane-hydrogen fraction in them KSPEU bulletin vol 3-4 pp 58-63

[11] Taymarov M A, Akhmetova R V, Sungatullin R G, Saltanayeva Ye A and Khusainov D G 2017 Research of mode parameters of boilers work at combustion of fuel oil with the increased content of water KSPEU bulletin vol 2 (34) pp 68-75

[12] Taymarov M A, Akhmetova R V, Margulis S M and Saltanayeva Ye A 2017 Thermal radiation in boiler furnaces (Kazan: KSPEU) p 124

[13] Taymarov M A, Akhmetova R V, Lavirko Y V, Sungatullin R G and Zhteltuhina Ye S 2017 Decrease in harmful emissions in the atmosphere of nitrogen oxides by boilers of thermal power plant KGACU news 1(39) pp 180-8

[14] Roslyakov P V and Yegorova L Ye 1996 Influence of the main characteristics of a zone of active burning on nitrogen oxides output Power system vol 9 pp 22-6

[15] Taymarov M A 2013 Development of methods of decrease in emissions of oxides of nitrogen by boilers of thermal power plant (Kazan: KSPEU) p 69

[16] Shimizu K, Hibi A, Koshi M, Morii Y and Tsuboi N 2011 Updated Kinetic Mechanism for High-Pressure Hydrogen Combustion Journal of Propulsion and Power vol 27 pp 383–95

[17] John C C 2004 Transient radiative transfer in 2D cylindrical medium with collimated pulse irradiation Journal of Quantitative spectroscopy and Radiative pp 299-313

[18] Mishra S C and Rath P 2003 Transient radiative heat transfer in participating media of Numerical heat transfer Int Journal of Heat and Mass pp 746-52

[19] Abdallah P B 2000 Thermal Emission of Semitransparent slab with variable spatial refractive index Journal of Quantitative spectroscopy and Radiative pp 185-98

[20] Krishna N A and Subhash C 2006 Discrete transfer method applied to radiative transfer in a variable refractive Index semi-transparent medium Journal of Quantitative Spectroscopy and Radiative pp 432-40

[21] Burke M P, Chaos M, Ju Y, Dryer F L and Klippenstein S J 2012 Comprehensive H₂/O₂ kinetic model for high-pressure combustion International Journal of Chemical Kinetics 44(7) pp 444-74

[22] Lu T J and Jin J M 2017 Electrical-thermal co-simulation for analysis of high-power rf/microwave components IEEE Trans. Electromagn. Compat. pp 93–102

[23] Skoplaki E and Palyvos J A 2009 On the temperature dependence of photovoltaic module electrical performance Solar Energy vol 63 pp 614-24

[24] Sánchez A L and Williams F A 2014 Recent advances in understanding of flammability characteristics of hydrogen Progress in Energy and Combustion Science vol 41 pp 1-55

[25] Rui Lou and Shu Bin Wu 2011 Products properties from fast pyrolysis of enzymatic/mild acidolysis lignin Applied Energy vol 88 pp 316-22

[26] Shen Y and Yoshikawa K 2013 Recent progresses in catalytic tar elimination during biomass gasification or pyrolysis Renewable and Sustainable Energy Reviews vol 21 pp 371-92

[27] Irannejad A and Jaberi F 2014 Large eddy simulation of turbulent spray breakup and
evaporation *International Journal of Multiphase Flow* vol 61 pp 108-28

[28] Taymarov M A, Sadykov R A and Chaykovsky V G 2016 Measurement of temperature of the falling streams in TG-104 boiler furnace of Surgut SDPP-1 *Messenger of mechanical engineering* vol 2 pp. 36-8

[29] Ahrenfeldt J, Thomsen T P, Henriksen U and Clausen L R 2013 Biomass gasification cogeneration- A review of state of the art technology and near future perspectives *Applied Thermal Engineering* vol 50 pp 1407-17

[30] Gelderen L, Malmquist L M V and Linus M V 2017 Vaporization order and burning efficiency of crude oils during in-situ burning on water *Fuel* vol 191 pp 528-37