Efficiency assessment of bi-radiated screens and improved convective set of tubes during the modernization of PTVM-100 tower hot-water boiler based on controlled all-mode mathematic models of boilers on Boiler Designer software

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Abstract. This work contains analysis of technical values of tower hot-water boiler PTVM-100 when operating on gas and oil residual. After the test it became clear that due to the construction deficiency during the combustion of oil residual, it is not possible to provide long-term production of heat. There is also given a short review on modernization of PTVM-100 hot-water boilers. With the help of calculations based on controlled all-mode mathematic modules of hot-water boilers in BOILER DESIGNER software, it was shown that boiler modernization by use of bi-radiated screens and new convective set of tubes allows decreasing sufficiently the temperature of combustor output gases and increase reliability of boiler operation. Constructive changes of boiler unit suggested by authors of this work, along with increase of boiler’s operation reliability also allow to improve it’s heat production rates and efficiency rate up to 90.5% when operating on fuel oil and outdoor installation option.

1. Introduction
As peak and general capacities for district heating in Kazakhstani cities high capacity heating boilers are used. Among high capacity hot-water boilers the biggest spread got PTVM-100 hot-water tower boilers. Hot-water heating boilers of PTVM-100 type are widely used on Combined Heat and Power Plant (CHP) and boiler-houses not only in Kazakhstan, but also in Russia and Belarus, as well as in several countries of Eastern Europe. Tower boilers have small dimensions and operate by combusting the gas and fuel oil in cold air stream, they are also equipped with individual vest tubes with natural air draft. They are located directly above the boiler and armored concrete constructions, and provide degasification with the help of smoke exhausters specially installed behind the boiler [1], [2], [3], [4], [5]. There are over 40 PTVM-100 hot-water boilers [3], [6], [7] operating across Kazakhstan. More than a 50-year exploitation experience of tower arrangement type PTVM hot-water boilers, revealed serious constructive deficiencies, which led to load decreases, reliability and operating economy decrease of boilers [3], [6], [8], [9], [10], [11]. In its turn this has led to of repair and exploitation costs growth, as well as unreasoned increase of polluting emissions and decrease of ecological indexes.
2. Characteristics Analysis of PTVM-100 Hot-Water Boilers

There are lot of possible reasons for decrease of PTVM-100 boilers’ operating reliability, that’s why heat production rates of CHPs operating on sulfur fuel oil and high-sulfur fuel oil are dropped at the moment to the 75.5…87.2 MW/h mark. Constrained load decrease in its turn has led to huge gaps between actual or available capacity and designed capacity. [3], [6].

On the basis of data analysis given in works [6], [8], [9], [10] operating deficiencies may be divided into constructive, project and exploitation ones, primarily connected with violation of combustion, water-chemical and hydraulic modes.

Constructive deficiencies of PTVM-100 hot-water boiler were admitted by exploitation, scientific-research and adjustment organizations of heat power engineering profile such as SDB (Special Design Bureau) ARTEI (JSC “VTI”), CDBE (“CKBE”) Moscow, “Kaztechenergo”, “KazNIIEnergetics”, NPF “Kvazar” Almaty and etc., Main constructive deficiencies may be limited to the following:

- Low combustor volume and height with high heat strain of unit’s volume (557.07-kW/m3) [6], and convective heating surfaces of first two rows of tubes (3534.9 kW/m2) [3], [6];
- Small gaps (relatively small distance from one tube to another) in U-shape sections of convective tubes, which causes the formation of plug and partial blockade of gas sections by ash and furnace black;
- Small diameter of convection tube bank (28x3mm), which in case of insufficient quality of delivery water causes the formation of plug by internal deposits up to complete blockade of cross-section of convective tubes;
- Low speed of gases in the second convective pack, which causes the formation of ash and furnace black plug in the space between tubes;
- Absence of equipment for air cleaning of convective packs;
- Fuel combustion when the air is cold [12].

Project deficiencies include: partially opened arrangement of boiler at several CHPs and boiler-houses, which causes difficulties during the repair service of screens and convective heat surfaces during the winter; absence of reliable and functional regulatory elements in gas ducts in case of installation of several boilers connected to one chimney flue and their operation with natural draw; absence of stationary systems for acid cleaning of boiler’s heating surfaces, as well as absence of delivery water purification from particulate matters before supplying it into boiler at the part where heat network turns and when hot-water boilers start operating.

Exploitation deficiencies should include: big differences in blowers capacities (6400-10500 m³/h), discharge characteristics of atomizers (5-20%); high excess rates of air beyond the boiler, caused by the cold air inflow through the leaks in brickwork and not working torch; poor-timed replacement of atomizers when their discharge characteristics change due to erosive wear or coking; incomplete or prolonged combustion of oil fuel within the cold air stream, and especially at the moment of boiler kindling; fuel oil’s low temperature before torches (358-383 K), which may be noticed on several boilers installed in CHPs and boiler-houses; insufficient filtration of fuel oil from particulate matters; many CHPs and boiler-houses have no quality and quantity control of deposits in tubes, no time control of surface heating, no boilers’ malfunction statistics and it’s reasons; low temperature of delivery water on boiler’s inlet when boiler is operating in main mode, as well as in peak mode, which causes the low-temperature sulfuric corrosion of screen tubes; frequent use of boiler’s convective packs water washings, caused by their overpollution from ash and furnace black deposits in result of stated violations of fuel oil combustion modes; high concentration of iron oxides and particulate matters in delivery water at the section where heat network turns and at the beginning period of boiler’s operation (month, or month and a half), and delivery of water with mentioned quality through the hot-water boilers; big hydraulic offsets in water distribution over convective tube packs, which is caused by hydraulic imperfection and internal deposits and that does not allow to provide in-depth regulation (if necessary) of delivery water flow, less than 60% [10], through the boiler.

3. Short Review of PTVM-100 Hot-Water Boilers Modernization Works

During the whole exploitation period of PTVM-100 boilers by project, adjustment and design organizations together with boilers-operating staff and CHPs, there were serious efforts made in order
to improve the design of boilers and to reach actual improvements in efficiency rates, which would be close to its design rates.

One of the first PTVM-100 reconstruction events within the SDB ARTEI's project was the 30 m³ increase of combustor volume by partial angle decrease of cold leader head sides and reposition of top burner tier underneath the main burner tier.

In addition to already mentioned project, “Kaztechenergo” suggested to perform staged combustion, when outermost torches of top burner tier were going away. Air from fans of these burners was then directed above main burners through the combined case and from this case under 10° angle (relatively to horizontal axis) going through the jet pipe down to combustor volume, but above the main burners. Axes of two remained torches were rotated down by 15° angle, and outermost torches of main burner tier were additionally rotated by 15° angle to the center of the combustor, and two torches of top burner tier were repositioned underneath the main burner tier [7].

Torchers’ design undertook reconstruction: airflow section increased, were used swirl vanes with the shock-free flow inlet, and as the result of such changes burners’ efficiency has increased by 20-30% in comparison with stock construction. Such reconstruction scheme was initially applied on boilers No.3, 4, 7 (“Almaty electric stations” Ltd.) [7]. Trial test of reconstructed unit has resulted in improvement of heat capacity, increase of time gaps between washing periods, decrease of nitrogen oxide emissions by 21%. That’s why it was suggested to apply staged combustion on boilers of Heat Complex of Western Kazakhstan (HCWK) (Almaty city) [7].

One of the options for reconstruction was substitution of 16 gas-fuel oil burners with individual fans by six swirl burners with double air flow, which should have been installed on the 6450 mm mark on all walls of the furnace but on different angles with average burners angle of - 20° downwards, so that burners would organize swirl combustion in the middle of the furnace. For fuel oil pulverization purposes were used steam-mechanical atomizers “Titan”. Set of test have revealed a number of deficiencies in operation of reconstructed PTVM-100 boiler, and taking into consideration the large amount of work during reconstruction and miserable effect, this reconstruction option was not applied to other boilers.

In addition to reconstruction works performed by SDB ARTEI, there was performed another reconstruction of boiler No.3 of Almaty CHP, which included reconstruction of convective pack of tubes, and more specifically U-shape tubes of Ø 28×3 mm in diameter by NPF “Kvazar” project [7] were substituted by straight tubes of Ø32×3 mm in diameter.

There are 44 PTVM-100 hot-water boiler currently operating across the whole Kazakhstan. Heating capacity increase and PTVM-100 hot-water boilers’ efficiency increase up to 93.5-94% from actual operational 86.8% [13], if modernization performed properly, calculated economy within 3600 hours of 1 year would be 12464500 kg of fuel oil [14].

Authors of this work have performed detailed design analysis of all reconstruction events of PTVM-100 hot-water boilers across the whole Kazakhstan. This analysis is based on heat calculations and heat tests of mentioned boiler compared with each other and stock PTVM-100.

Analysis of PTVM-100 reconstruction results showed that technical-and-economic indexes of reconstructed boilers and non-reconstructed boilers have not big differences in efficiency. After the reconstruction of boilers, efficiency rate of some of them has increased only up to 90.5% mark, and some boilers began to operate even worse due to reduction of convective part. After the reconstruction, combustor exhaust gases’ temperature almost didn’t change. Exception was the PTVM-100 reconstruction option with missing dump burners and low-temperature swirl burning of fuel oil.

In the middle 90-ies there was undertaken an attempt to replace 16 burners by 8 swirl pre-combustion units in accordance with Patent of Republic of Kazakhstan (RK) No. 2318 “cyclone furnace unit” [15], and with Patent RK No. 21479 “Hot-water boiler” [16]. PTVM-100 of CHP-1 in Astana was the first unit to adopt such scheme. Authors’ main idea for this reconstruction was the provision of preliminary thermal treatment of pulverized fuel oil with regulated excess of air in swirl chamber. That allowed to control fuel oil thermal treatment procedure outside the furnace volume, depending on fuel oil quality and boiler’s operating mode. Nevertheless, attempt to reach nominal heating capacity with use of such
scheme has failed. We should consider rather wide range of reconstruction works of furnace screens and arrangement options of eight swirl combustion chambers with selection of forced-flow fans. That’s why PTVM-100 reconstruction works performed were focused, first of all, on reliability of separate pieces and units, which included boiler’s circulation scheme, convective tube packs operation, boiler and burners operation, rather than on reach of nominal capacity or it’s increase. Calculated operation rates of reconstructed boilers remained the same as stock rates. Some deficiencies remained even after the reconstruction. Specialists of OAO “Dorogobuzhktomash” (Russia) were the closest to find solution for boilers’ efficiency rate increase and provision of nominal heating capacity of PTVM-100 tower hot-water boiler construction, and what they did was that have changed the circulation scheme and furnace screen construction. OAO “Dorogobuzhktomash” launched the production of new tower hot-water boilers KV-GM-69,8-150 (PTVM-60 E) and KV-GM-139,6-150 (PTVM-120 E) with one bi-radiated screen and angled tubes going from center and along the sides at the top part of furnace before convective pack, which allowed to solve the issue, but only partially [17].

4. Efficiency Assessment of Bi-Radiated Screens and New Convective Tubes pack Application During the Modernization of PTVM-100 Tower Hot-Water Boilers

Authors of this work suggested the constructive solution, which is completely different from all previous works on modernization of old PTVM-100 boilers. This solution includes the use of two bi-radiated screens, which allow to increase massively the radiated heating surface in furnace space [18]. Overall view of boiler with two bi-radiated screens and cold spaced out tubes pack installed before new convective pack is shown on figure 1. For efficiency assessment of bi-radiated screens after modernization of PTVM-100 hot-water boilers, there was performed an analysis based on controlled all-mode mathematical models of boilers in BOILER DESIGNER software [19]. Authors simulated traditional construction of PTVM-100 and with installed bi-radiated screens. Calculated model included the boiler’s gas duct model, water circuit model, furnace screens, as well as air, water and fuel controllers. Calculations were performed during the combustion of gas as well as during the combustion of fuel oil. Calculated model of gas duct for PTVM-100 boiler with results of calculations when operating in main mode under nominal load is shown on figure 2. General technical characteristics and values of boiler operation under nominal load if operating on gas or fuel oil are shown in Table 1.

![Figure 1](image-url) Modified hot-water boiler PTVM-100 (PTVM-125) by AUPET project
Figure 2. Calculated model of gas duct for PTVM-100 boiler with results of calculations (Qaver=116.3 MW/h; tout.air =252 K). Left: fuel – natural gas; right: fuel – M-100 fuel oil.

Table 1. General technical characteristics and values of ptvm-100 boiler operation (main mode).

| Characteristics names                      | PTVM-100 (gas) | PTVM-100 (fuel oil) | PTM-100 (gas operation standard) |
|--------------------------------------------|----------------|--------------------|----------------------------------|
| 1. Heating capacity, MW/h                  | 116.3          | 116.3              | 116.3                            |
| 2. Operating water pressure, bar           | 12             | 12                 | 12                               |
| 3. Inlet water temperature, K              | 343            | 343                | 343                              |
| 4. Outlet water temperature, up to K       | 423            | 423                | 423                              |
| 5. Water temperature differences, K        | 353            | 353                | 353                              |
| 6. Boiler’s hydraulic pressure resistance, bar | 3.6            | 3.6                | 2.5                              |
| 7. Gases temperature when leaving the furnace, K | 1673           | 1588               | -                                |
| 8. Coefficient of air excess               | 1.05           | 1.05               | 1.05                             |
| 9. Exhaust gases temperature, K           | 426.6          | 495                | 453                              |
| 10. Design air temperature, K             | 252            | 252                | 252                              |
| 11. Consumption of water, kg/sec          | 343.6          | 343.6              | 343.05                           |
| 12. Boiler’s furnace volume, m³           | 245            | 245                | 245                              |
| 13. Furnace walls’ surface, m²            | 228.2          | 228.2              | 228.2                            |
| 14. Convective surface, m²                | 2997           | 2997               | 2997                             |
| 15. Fuel energy value, kW/kg               | 13.13          | 10.95              | 10.95                            |
| 16. Consumption of fuel, kg/sec           | 2.68           | 3.37               |                                  |
| 17. Heat losses q₂, %                     | 7.72           | 10.66              | 7.69                             |
| 18. Heat losses q₁, %                     | 0.1            | 1.5                | 0                                |
| 19. Heat losses q₅, %                     | 0.4            | 0.4                | 0.05                             |
| 20. Boiler’s efficiency, %                | 91.78          | 87.44              | 92.26                            |

As you can see in Table 1, efficiency value when operating on fuel oil under nominal value is 87.44%. Nevertheless, in practice this value sufficiently decreases, especially during the period of long-term exploitation between washings, when ash and furnace black intensively form deposits on heating convective surfaces. Figure 3 shows data on temperature of gases when leaving the furnace of boiler.
No.2 at Almaty CHP-1, received at different time and period of exploitation between washings by water.

![Figure 3](image3.png)

**Figure 3.** Temperature values of leaving gases depending on load, line shows calculated value of temperatures (boiler No.2 at ACHP-1).

As you can see from figure 3, actual temperature differences of leaving gases are sufficiently higher than calculated (standard) values. High temperatures on furnace outlet causes the formation of ash and furnace black deposits on convective packs, which leads to choking of heating convective surfaces, increasing it’s heat absorption ability, decreases the rate of efficiently absorbed heat by unit, causing the efficiency drop. Figure 4 shows the dependency of calculated efficiency values from choking coefficient of heating convective surfaces, obtained during the simulation of boiler’s operation in BOILER DESIGNER software.

![Figure 4](image4.png)

**Figure 4.** Dependency of calculated efficiency values from choking coefficient of heating convective surfaces during the combustion of M100 sulfur fuel oil.

As you can see from figure 4, choking coefficient change by 15% leads to efficiency change by 1%. Besides, choking of convective surface, which is made with low pitch, increases aerodynamic resistance of boiler and limits the amount of load, even if smoke exhaust is installed. Ash and furnace black deposits are washed away with water, nevertheless, frequent washings of convective surfaces provoke sulfuric corrosion, which leads to damage of metal tubes of heating surfaces. PTVM-100 boilers modernization by installation of two bi-radiated screens with spaced out cold tubes would allow to lower the temperature of exhaust gases on the outlet and to prevent choking of convective packs with ashes and furnace black deposits by means of widening the radiation heating surface. Calculated model of gas duct of modified PTVM-100 boiler (there are two bi-radiated screens and spaced out pack of tube installed before convective parts) with calculation results during the work in main mode is shown on figure 5. Calculated model of water circuit of modified PTVM-100 boiler with installed two bi-radiated screens is shown on figure 6. Table 2 contains main technical characteristics of operation of modified PTVM-100 boiler under nominal load when operating on gas or fuel oil.
The use of sections to divide the text of the paper is optional and left as a decision for the author. Where the author wishes to divide the paper into sections the formatting shown in Table 2 should be used.

**Figure 5.** Calculated model of gas duct for modified PTVM-100 boiler with calculation results (Qaver=116.3 MW/h; tout.air =252K ). Left: fuel – natural gas; right: fuel – M-100 fuel oil

**Figure 6.** Calculated model of water circuit of modified PTVM-100 boiler with calculation results (main mode)
Table 2. Main technical characteristics of modified ptvm-100 boiler operation (main mode)

| Characteristics names                                    | PTVM-100 (gas) | PTVM-100 (fuel oil) |
|----------------------------------------------------------|----------------|--------------------|
| 1. Heating capacity, MW/h                                | 116.3          | 116.3              |
| 2. Operating water pressure, bar                         | 12             | 12                 |
| 3. Inlet water temperature, K                            | 307            | 307                |
| 4. Outlet water temperature, up to K                     | 423            | 423                |
| 5. Water temperature differences, K                      | 353            | 353                |
| 6. Boiler's hydraulic pressure resistance, bar           | 3.6            | 3.6                |
| 7. Gases temperature when leaving the furnace, K         | 1524           | 1426               |
| 8. Coefficient of air excess                             | 1.05           | 1.05               |
| 9. Exhaust gases temperature, K                         | 430.3          | 490                |
| 10. Design air temperature, K                            | 252            | 252                |
| 11. Consumption of water, kg/sec                         | 343.6          | 343.6              |
| 12. Boiler’s furnace volume, m³                          | 245            | 245                |
| 13. Furnace walls’ surface, m²                           | 228.2          | 228.2              |
| 14. Convective surface, m²                               | 2997           | 2997               |
| 15. Fuel energy value, kW/kg                             | 13.13          | 10.95              |
| 16. Consumption of fuel, kg/sec                          | 2.68           | 3.29               |
| 17. Heat losses q₂, %                                    | 7.89           | 10.38              |
| 18. Heat losses q₃, %                                    | 0.1            | 0.4                |
| 19. Heat losses q₅, %                                    | 0.4            | 0.4                |
| 20. Boiler’s efficiency, %                               | 91.61          | 89.12              |

As you can see from Table 2, boiler’s efficiency rate when operating on fuel oil under nominal load is equal to 89.12%, which is 1.7 more than in traditional construction, and it is quite high efficiency rate as well. Heat radiated surface of modified boiler’s furnace was enlarged by 246 m². Radiated surface to convective surface ratio was also increased up to 15.8% in comparison with old PTVM-100 boilers, where such ratio was only on 7.5% mark. Additional 246 m² of radiated surface receives more heat within furnace, and spaced out cold tubes completely screen and protect first row of convective tube packs. Temperature of gases when leaving the furnace and before convective packs lowered down by 423 K, whereas convective tubes operate in more favorable heat environment as in hot-water boiler of П-shape arrangement. Screen surfaces absorb 33% more heat if operating on gas, and 40% more if operating on fuel oil. Common share of radiation-heat transfer exceeds 40% if operating on gas and 49% if operating on fuel oil. Calculations performed by authors showed that, although, convective surfaces absorb about 50% of heat if operating on fuel oil, second convective pack absorbs only 15% of all convective heat amount having the same sizes of heat transfer surface, which says about necessity of construction optimization of boiler’s convective surfaces.

For modified construction of convective pack suggested by authors [20] and optimized surface of gas duct were performed some heat engineering calculations, results of which are shown in Table 3.

Table 3. Main technical characteristics of modified ptvm-100 boiler (main mode)

| Characteristics names                                    | PTVM-100 (gas) | PTVM-100 (fuel oil) |
|----------------------------------------------------------|----------------|--------------------|
| 1. Heating capacity, MW/h                                | 116.3          | 116.3              |
| 2. Operating water pressure, bar                         | 12             | 12                 |
| 3. Inlet water temperature, K                            | 343            | 343                |
| 4. Outlet water temperature, up to K                     | 423            | 423                |
| 5. Water temperature differences, K                      | 353            | 353                |
| 6. Boiler’s hydraulic pressure resistance, bar           | 3.6            | 3.6                |
| 7. Gases temperature when leaving the furnace, K         | 1524           | 1426               |
| 8. Coefficient of air excess                             | 1.05           | 1.05               |
| 9. Exhaust gases temperature, K                         | 430.2          | 490                |
| 10. Design air temperature, K                            | 252            | 252                |
| 11. Consumption of water, kg/sec                         | 343.6          | 343.6              |
| 12. Boiler’s furnace volume, m³                          | 245            | 245                |
| 13. Furnace walls’ surface, m²                           | 228.2          | 228.2              |
| 14. Convective surface, m²                               | 2997           | 2997               |
| 15. Fuel energy value, kW/kg                             | 13.13          | 10.95              |
| 16. Consumption of fuel, kg/sec                          | 2.68           | 3.25               |
| 17. Heat losses q₂, %                                    | 7.89           | 9.01               |
| 18. Heat losses q₃, %                                    | 0.1            | 0.1                |
| 19. Heat losses q₅, %                                    | 0.4            | 0.4                |
| 20. Boiler’s efficiency, %                               | 91.61          | 90.49              |
As we can see from calculated data, due to operation optimization of second convective pack, the boiler’s efficiency if operating on fuel oil has increased up to 90,49%, which is 3% more that in traditional construction. If operating on fuel oil and locating of boiler unit indoors, with design air temperature of 293 K, boiler’s efficiency would be 92,1%. Besides, due to the changes of hydraulic scheme of boiler by installation of bi-radiated screens, was achieved heating capacity 1,25 times more than 116.3 MW/h.

5. Conclusion
Comparative analysis of bi-radiated screens application efficiency after the modification of PTVM-100 hot-water boilers based on controlled all-mode mathematical models of boilers in BOILER DESIGNER software has shown that after the modification by application of two bi-radiated screens and spaced out cold water tubes, located before first convective pack, it becomes possible to lower sufficiently gases’ temperature when leaving the furnace and prevent the pollution of compactly placed convective tube packs. Furnace outlet temperature under nominal load does not exceed 1423K if operating on fuel oil.

Making of second convective tubes pack with cross-section reducing as it goes along the way of gas flow and keeping the high level of gas speed, and heat output accordingly, which would allow to increase boiler’s efficiency by 1.5%.

Modernization of PTVM-100 hot-water boilers by installation of two bi-radiated screens and new convective packs, suggested by authors, would allow to provide 1,25 times increase of singular heat capacity of the new boiler, to increase of efficiency by 4-5% in average in comparison with existing boilers, to lower the pollute emissions rate, reduce the gap between design and actual capacity, to increase reliability of boilers and inter-repair period.

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