Chapter 6

# Calculations of Heat Transfer in the Furnaces of Steam Boilers According to the Laws of Radiation of Gas Volumes

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Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.75529

**Abstract**

The laws of heat radiation from black body and the laws of Stefan-Boltzmann (Jožef-Ludwig) , Max Planck, and Wilhelm Wien are fundamental laws of physics. All in all, a little more than 30 fundamental laws of physics, studied by pupils and students worldwide, were disclosed. Scientific disclosure of fundamental laws influences mainly power technology, fuel, and energy resource saving. In the late nineteenth century, the laws of heat radiation from gas volumes and the laws of Makarov were disclosed. Since the radiation laws from blackbody are fundamental laws of physics, then the laws of heat radiation from gas volumes are fundamental laws of physics. The effect of using laws of heat radiation from gas volumes on fuel saving and reduction of development pressure on the environment in many countries of the world is shown.

**Keywords:** physics, scientific discovery, laws, Nobel prize, heat radiation, gas volumes, combustion chamber

## 1. Introduction

Radiant heat transfer is the main kind of heat transfer in furnaces and combustion chambers and accounts for 90–98% of the total heat transfer in steam boiler fireboxes [1–3].

Since the late nineteenth century and throughout the twentieth century, heat transfer in torch furnaces, fireboxes, and combustion chambers was calculated based on the law that was experimentally established by Stefan in 1879 in studying radiation from solid bodies, which was then theoretically substantiated by Boltzmann in 1884. In the late nineteenth to the early twentieth century, solid lumped fuel (coal, peat, and wood) was fired in furnaces on fire grates, and the first descriptions of heat transfer processes were essentially descriptions of problems and calculation of radiant heat transfer between two arbitrarily located surfaces (a fuel bed and a heating surface) on the basis of Stefan-Boltzmann's law. In 1924, Kirpichev gave an analysis of methods for solving this problem that had been developed by different researchers [4], and Stefan-Boltzmann's law is presently formulated as follows:

$$q = c_s \varepsilon_{red}\left[\left(\frac{T_1}{100}\right)^4 - \left(\frac{T_2}{100}\right)^4\right]\varphi_{12}, \tag{1}$$

where q is the density of heat flux radiated from the fuel to the heating surface (W/m$^2$), cs is the black body emissivity factor (W/(m$^2$ K$_4$)), $\varepsilon_{red}$ is the reduced emissivity, $T_1$ and $T_2$ are the temperatures of fuel bed and heating surface (K), and $\varphi_{12}$ is the view factor for radiation from the fuel bed on the heating surface.

In the twentieth to the twenty-first centuries, flaring of gas, liquid, pulverized fuel in furnaces, fire boxes, and combustion chambers was widespread. Fuel flaring is characterized by volume emission, a three-dimensional radiation model [1–6]. In torch, gas volume emits $10^{15}$–$10^{30}$ particles of atoms. Radiation of each particle and atom on the calculated area should be considered. The calculation of heat radiation on the calculated area of all the atoms in the gas volume and the torch requires the solution of triple integral equations [7–10]. The solution of triple integral equations to determine the average path length of beams from the emitting particles, atoms, and angular radiation coefficients of the gas volume on the calculated area in the twentieth to the twenty-first centuries has not been found [7, 8]. The laws of radiation from gas volumes were not disclosed.

It is considered that the problem of calculating heat transfer in torch furnaces, fireboxes, and combustion chambers was solved with the appearance of computers and the use of numerical simulations of integral equations of heat transfer [11, 12]. However, long-term analytical and experimental studies of heat transfer have shown that the results of the numerical solution of integral equations of heat transfer on computers are not valid [9]. The method uses the laws of heat radiation of a blackbody, solid bodies, and Stefan-Boltzmann law (1); however, gas volume radiation is not subject to the laws of Stefan-Boltzmann [9, 10]. This method uses the Stefan-Boltzmann law and a large mass of approximate values of the temperatures and optic coefficients of surface and volume zones, and the accuracy of calculations is 40–80% [9–13].

Paradoxical cases are observed using the existing calculation methods. The torch power can be increased by additionally heating the air supplied to the burner. For example, with air heated from 20 to 600°C, the torch power increased by 17%, and its temperature rose from 1300 to 2000°C, i.e., by a factor of 1.5 [14]. According to expression (1), the density of heat flux radiated from the torch to the calculated zone should increase by a factor of 5, and the heating rate of articles being processed should also increase by a factor of 5, which is in contradiction with the energy conservation law. Under the real conditions of heating furnace operation, with air subjected to preheating and with the torch power increased by 17%, the heat flux density and the heating rate increase by 12–15%, i.e., in direct proportion to the growth of torch power and not to the fourth power of temperature [14].

http://dx.doi.org/10.5772/intechopen.75529

In the twentieth century, the torches and emitting gas volumes remained a “black box” despite the applied enormous intellectual resources to solve the problem. Formulas for determining the main parameters of heat radiation from gas volumes, torches, formulas for determination average beam path length from quadrillions of radiating atoms, and the local angular coefficients of radiation from radiation flux densities on the calculated area were not available. The solution to the problem has stalled.

## 2. Laws of radiation from spherical and cylinder gas volumes

At the end of the twentieth century, in 1996–2001 the laws of heat radiation from gas volumes [13, 15, 16] and the laws of heat radiation from gas isothermal isochoric concentric spherical (**Figure 1**) and coaxial cylinder gas volumes (**Figure 2**) were dislosed, the volumes, that the torches, gas volumes of the furnaces, fireboxes, and combustion chambers are currently modeled by [17–19].

The laws are called Makarov’s laws with the goal of adherence to the age-old scientific traditions and copyright [13]. Based on the scientific discovery, geometric, physical, and mathematical models of gas volume and torch as a source of heat radiation have been developed. In the gas volumes formed during flare combustion of the fuel, spherical or cylindrical gas volumes are inscribed. Radiating gas atoms are simulated by emitting quadrillions of spheres, uniformly filling the spherical and cylindrical gas volumes.

The statement of the scientific disclosure is as follows. “The average path length of beams from quadrillions of radiating particles of each isochoric isothermal concentric spherical or coaxial cylindrical gas volumes to the calculated area is equal to the arithmetic mean distance from the symmetry axis of volumes to the calculated area and the angular coefficients, flux densities of radiation from gas volumes on the calculated area are equal. The flux density of radiation from the central spherical or central cylindrical gas volume of a small diameter on the calculated area is equal to the sum of the fluxes of the radiation fluxes from all the concentric spherical or coaxial cylindrical volumes on the calculated area at the radiation power released in the

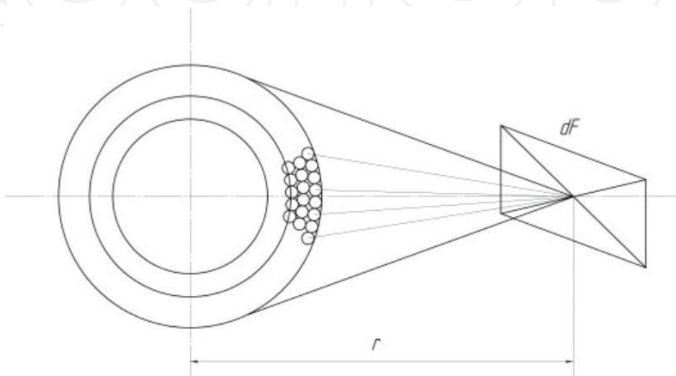


**Figure 1.** The radiation from isothermal isochoric concentric spherical gas volumes on the calculated area dF.

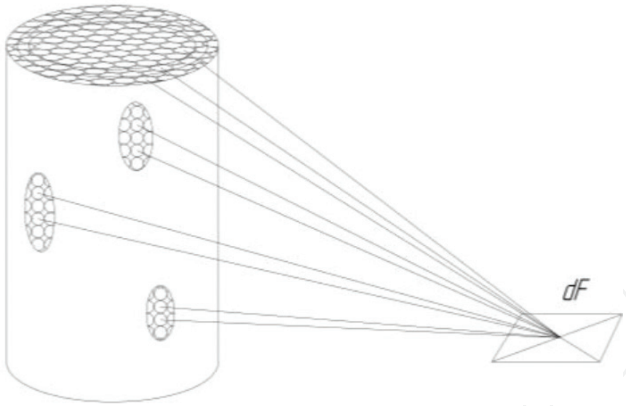


**Figure 2.** The radiation from isothermal isochoric coaxial cylinder gas volumes on the calculated area dF.

volume of a small diameter, equal to the sum of the radiated powers released in all spherical or coaxial cylindrical gas volumes radiating on the calculated area.

The density of the heat flux incident from the cylindrical or spherical gas volumes to the calculation area is directly proportional to the power, the local angular emission factor of the gas volume to the calculation area and inversely proportional to the absorption coefficient of the gas medium, the average path length of the rays from the emitting particles of the gas volume to the calculation area and the area of calculation area."

Mathematical notation of the laws is as follows:

$$l_1 = l_2 = l_3 = \ldots = l_i = \left( \sum_{i=1}^{n} \frac{l_i}{n} \right) = l \tag{2}$$

where $l_1$, $l_2$, $l_3$, and $l_i$ are the average beam path lengths from the first to the ith cylindrical or spherical gas volumes to the calculated area dF and l is the arithmetic mean distance from the axis of symmetry of the cylindrical volumes or the center of symmetry of the spherical volumes to the calculated area dF:

$$\varphi_{F_1dF} = \varphi_{F_2dF} = \varphi_{F_3dF} = \ldots = \varphi_{F_idF} \tag{3}$$

where $\varphi_{F_1dF}$, $\varphi_{F_2dF}$, $\varphi_{F_3dF}$, $\varphi_{F_idF}$ is the local angular coefficient of radiation from a surface of the first, the second, the third, and the ith coaxial cylindrical or concentric spherical gas volumes on the calculated area dF, respectively:

$$q_{F_1dF} = q_{F_2dF} = q_{F_3dF} = \ldots = q_{F_idF} \tag{4}$$

where $q_{F_1dF}$, $q_{F_2dF}$, $q_{F_3dF}$, $q_{F_idF}$ is the density of the radiation fluxes incident from the first to the ith coaxial cylindrical or concentric spherical gas volumes on the platform dF:

$$q_{F_1dF} = \sum_{i=1}^{n} q_{F_idF} \tag{5}$$

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where $q_{F_1dF}$ is the density of radiation flux incident from the central cylindrical or spherical gas volumes of a small diameter on the calculated area dF:

$$q_{FdF} = \frac{\varphi_{F_0dF} \cdot P_F \cdot e^{-kl}}{F_0} \tag{6}$$

where $\varphi_{F_0dF}$ is a local angular coefficient of radiation from the central cylindrical or spherical gas volumes of a small diameter on the calculated area dF, $P_F$ is the radiation power of the central cylindrical or spherical gas volumes, and $F_0$ is the area of the calculated platform dF.

Mathematical notation of the laws of heat radiation from gas volumes and the laws of Makarov is obvious and grounded in a similar manner to the statement and mathematical notation of Newton's third law of motion in texts on physics for students of secondary schools and technical universities:

"The force with which two bodies act upon each other are equal in magnitude and opposite in direction":

$$F_1 = -F_2, \tag{7}$$

where $F_1$ is the force with which body 1 acts on body 2 and $F_2$ is the force with which body 2 acts on body 1.

Laws of heat radiation from gas volumes possess the compactness and the accuracy of the description of physical phenomena in a similar manner to the fundamental laws of physics. For example, a fundamental law of physics, Ohm's law, describes the relationship between the current I flowing in the conductor and the voltage U applied to the conductor and the conductor resistance R:

$$I = \frac{U}{R} \tag{8}$$

Similarly, the law of heat radiation from gas volumes characterizes the dependence of flux density of heat radiation q of gas volume from the angular coefficient of the radiation φ, radiated power P, and the average beam path length rays l of gas volume. For the calculation of parameters of heat radiation from gas volumes (6) φ, P, and l analytical expressions, formulas were derived [16–19].

A unique, natural harmony of heat radiation from quadrillions of particles of spherical and cylindrical gas volumes is disclosed, namely, that the average beam path length from these particles is equal to the arithmetic mean distance from the symmetry axis of volumes to the calculated area.

Complex, a triple integration of no solution within the gas volume to determine the average beam path length is reasonably replaced by computing actions of elementary mathematics and analytic geometry; this produces the same result, which would have been gotten in triple integration.

The uniqueness of the scientific discovery is that the flux densities of radiation and angular radiation coefficients of spherical, coaxial, and cylindrical gas volumes to the calculated area are equal and it is sufficient to hold a single integration of trigonometric functions within the height of the cylindrical gas volume of a small diameter, located on the axis of symmetry to define them [15–22].

Heat radiation from cylindrical gas volumes of diameter 2, 5, and 10 m and more in calculations can be equivalently modeled by heat radiation from cylindrical gas volumes of an infinitely small diameter and the axis of their symmetry. Scientific discovery of heat radiation from gas volumes provides researchers and designers with great opportunities for improvement of electric arc and torch furnaces, fireboxes, and combustion chambers.

With the discovery and development of the laws of geometrical, physical, and mathematical models of torch, the radiating gas volumes and torches as sources of heat radiation become an investigated physical phenomenon, not a "black box." The formulas for calculating the density of the radiation flux from the gas volume, the torch on the calculation area (6), for determining the local angular coefficients of gas volumes on the calculation area [15–22], for determining the mean path length of quadrillion rays (2) from gas volumes on the calculation area were obtained. Basing on the scientific discoveries of the laws of heat radiation from gas volume, the theory of thermal radiation from the gas volume and the new concept of calculating heat transfer in torch furnaces, fire chambers, and combustion chambers were developed [19]. The theory of thermal radiation of the gas volume includes the output 14 of the formulas for calculating the coefficients and fluxes of the radiation of the flame on the heating surface in Vivarelli, mutually perpendicular coils and arbitrarily located planes.

In accordance with the new concept and the theory, cylinder gas volumes, from which the calculation of radiation fluxes on the calculated areas and heating surface is performed, are inscribed in torches.

Radiation fluxes from torch, heated surfaces, and combustion products are determined for each calculated area taking into account multiple reflections and torch for each calculated area platform determined by taking into account multiple reflections and absorptions. The calculations of heat transfer in steam boiler boxes [9, 10, 18–20], torch heating furnaces [7, 8, 15–17], and combustion chambers of gas turbine installations [19] are made with the use of the new concept.

The calculations allow to determine rational energy modes of electric arc and torch furnaces, fireboxes, and combustion chambers in which fuel consumption reduces and operational life increases. In 15 years since the first publication of the author of scientific discovery in printing, the theory of thermal radiation of the gas volume and the new concept of calculating heat transfer in torch furnaces, fire chambers, and combustion chambers have been tested by time; the results of calculations are confirmed by the results of experimental studies on existing kilns, furnaces, and combustion chambers; and the accuracy of calculations does not exceed 10%. Since the radiation laws of a blackbody and the laws of Stefan-Boltzmann and Planck, these wines belong to the fundamental laws of physics, and the laws of radiation by gas volumes are both fundamental laws of physics.

The laws of heat radiation, the theory of heat radiation from gas volumes, and the new concept of calculation in electric arc and torch furnaces, fire boxes, and combustion chambers were published in the form of text [19], which is used for teaching university students. The method for calculation that had existed until the scientific discovery had not allowed to calculate and to manage rational heat transfer in torch furnaces, since the error of calculations was 20–50%, so the efficiency of fuel energy in torch furnaces is 25–45% at the present time. The use of scientific discovery and its base-developed theory allows to determine the rational parameters of the torch (capacity, length, expansion angle) and its spatial position to the heating surface (vertical, horizontal, inclined at a certain angle).

Rational position of products and torches and burners will increase consumption efficiency of fuel energy half-twofold from 25–45 to 65–75% and decrease fuel consumption twofold over the coming years all over the world.

## 3. Calculation of heat transfer in steam boiler furnaces

### 3.1. Calculation of heat transfer in the firebox of a TGMP-204 steam boiler

A unified procedure for calculating heat transfer in electric arc and torch furnaces, fireboxes, and combustion chambers has been developed proceeding from the discovered regularities pertinent to heat transfer in torch gas layers [19]. The resulting integral heat fluxes consisting of radiant fluxes falling on the heating surfaces from the torch, wall and arch lining, combustion products, and convective fluxes are all calculated according to this procedure. Innovative designs of torch furnaces and fireboxes have been developed proceeding from the discovered regularities, and the use of which makes it possible to obtain a higher output from fireboxes, more uniform steam generation in tubes, more uniform heating of articles, and smaller consumption of fuel.

The distribution of integral radiant fluxes over the boiler firebox walls and bottom surfaces was calculated taking the TGMP_204 boiler as an example used as part of a 800 MW power unit, and the firebox of which has the shape of a rectangular parallelepiped of height $H_f$ = 46 m, width $a$ = 20.66 m, and depth $b$ = 10.40 m. The firebox rear wall has an aerodynamic nose in its upper part. The boiler operates on fuel oil and is equipped with 36 double-flow vortex burners with a throughput capacity of 5.2 t/h each, which are installed in opposite directions in three tiers on the front and rear walls of the firebox. The burners installed on each wall are placed in a common duct through which air and recirculating gases are supplied. The air excess factor in the furnace $\alpha$ = 1.03, and the gas recirculation ratio $r$ = 0.14. With these values of air excess factor and gas recirculation ratio, the average values of particle diameter $d$p, density ρ, concentration μ, and the medium attenuation coefficient $k$ are determined from the formulas given in [1–3]. The calculated values of these parameters were found to be $d_p$ = 0.278 μm, ρ = 2 × 103 kg/m$^3$, μ = 0.06 g/m$^3$, and $k$ = 0.162.

The distribution of temperature along the height of steam boiler fireboxes was investigated [23–25]; the results of temperature measurements are reported in many publications, e.g., in

[12]. The torch fills the entire firebox chamber and has the shape of a straight elliptical cylinder; the isotherms shown in **Figure 4** divide it along the height into six volume bodies.

Five volume bodies with ellipses in their bases and vertices and with a parabolic generatrix (the torch vertical parts) have the shape of elliptical paraboloids resting on the sixth volume body having the shape of a truncated ellipsoid of revolution (the horizontal part of torch 7).

The own radiation from gas volumes and the radiation power decrease along the firebox height in accordance with temperature variation along the flame height. Below, we denote the power releasing in the flame horizontal part by *P*h and the powers releasing in five vertical volume zones (from the bottom to top) by *P*1–*P*5. The power releasing in the torch is determined from the expression as follows:

$$P_{tr} = Q_i^r B_r, \tag{9}$$

where $Q^r_i$ is the fuel heating value equal to 41 MJ/kg and *B*f is the fuel flow rate (kg/h). During the operation of 36 burners with a throughput of 5.2 t/h, the fuel flow rate will be $B_f = 187.2 \times 103$ kg/h, and the torch power will be $P_{tr} = 2155$ MW.

Introducing the assumption that the radiating volumes are isothermal within the confines of their volume zones and taking into account that the volume bodies have identical bases and different heights, we can write the following proportion for determining the power releasing in each of the six volume zones:

$$P_r : P_1 : P_2 : P_3 : P_4 : P_5 = T_r^3 h_r : T_1^3 h_1 : T_2^3 h_2 : T_3^3 h_3 : T_4^3 h_4 : T_5^3 h_5, \tag{10}$$

where $T_h$ and $T_1$–$T_5$ and $h_h$ and $h_1$–$h_5$ are the temperatures and heights of the corresponding zones.

The following values of powers releasing in the torch volume zones were obtained from expression (10): MW: $P_h = 645$, $P_1 = 905$, $P_2 = 216$, $P_3 = 172$, $P_4 = 129$, and $P_5 = 87$.

For calculating the integral radiation fluxes falling from the torch on the waterwall surfaces and for reducing the calculation error, the torch should be decomposed as follows: three straight circular cylinders are inscribed into the straight elliptical cylinder representing the torch vertical part (see **Figure 3**) and these circular cylinders will model the radiation from the flame vertical part both over its height and volume, i.e., over the firebox width and depth. The way in which the radiation fluxes from the cylinder are distributed over the heating surface does not depend of the cylinder diameter; therefore, the torch vertical part should be subdivided into 15 small-diameter cylinders representing linear radiation sources by 3 in each vertical volume zone.

After that, we determine the density of integral radiation flux from each *j*th cylindrical source in the horizontal and vertical volume zones falling on the *i*th elementary area on the wall surface:

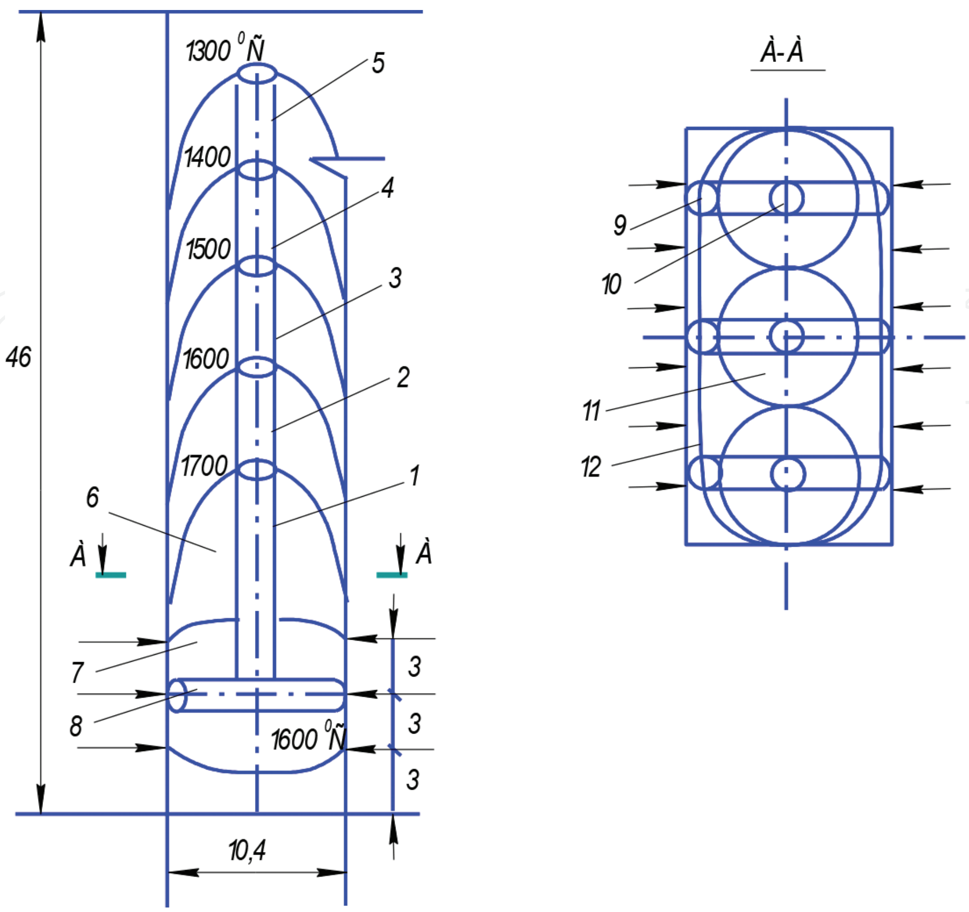


**Figure 3.** Schematic design of the regenerative soaking pit with a two-tier unit of regenerators (a) and the distribution of integral heat fluxes falling on the lateral surfaces facing the soaking pit longitudinal symmetry axis over the ingot height (b). (*1*) chamber; (*2*) cover; (*3–5*) rear, lateral, and front walls, respectively; (*6*) regenerator units; (*7* and *8*) air and gas regenerators; (*9*) mixing chamber; (*10*) technological holes; (*11*) ingots; and (*12*) torch.

$$q_{itrj} = \frac{\varphi_{ji} P_j e^{-kl}}{F_i}, \tag{11}$$

where *j*th is the cylindrical radiation source on the *i*th area, which is determined from the analytical expressions given in [19]; *Pj* is the power of the *j*th cylindrical source (MW); *Fi* is the surface area of the *i*th elementary area (m$^2$); and *l* is the average beam length (m).

The density of incident integral radiation flux from the torch on the *i*th elementary area is determined as the sum of integral heat flux densities from all cylindrical sources, i.e.,

$$q_{i\text{in.tr}} = \sum_{j=1}^{18} q_{itrj}. \tag{12}$$

The distribution of integral radiation fluxes falling on the front and rear walls of a TGMP-204 steam boiler firebox is almost the same and is characterized by curves *1* and *5* (**Figure 4a**),

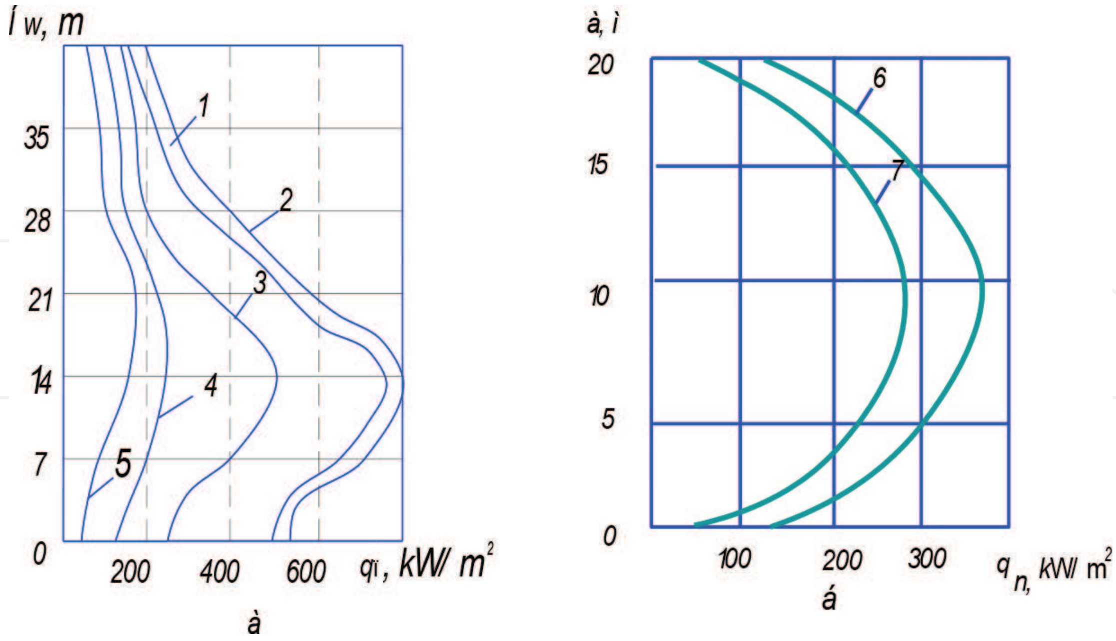


**Figure 4.** Distribution of the integral radiation flux density over the walls (a) and bottom (b) of the TGMP-204 boiler firebox. (*1*) Results of calculation over the front wall symmetry axis; (*2*) measurement results for the same; (*3–5*) results of calculation over the lateral wall vertical symmetry axis, over the lateral wall height at a distance of 4 m from the lateral wall vertical symmetry axis and over the front wall height at a distance of 8 m from the front wall vertical symmetry axis; and (*6* and *7*) results of calculation over the bottom's major symmetry axis and over the horizontal line parallel to the bottom major symmetry axis at a distance of 4 m from it.

and so is the distribution of integral radiation fluxes falling on the firebox right- and left-hand walls, which is characterized by curves *3* and *4*. The calculation results coincide with the results from measurements of integral radiation flux densities along the frontal wall vertical symmetry axis [1], testifying that the developed torch mathematical model adequately reflects the real conditions.

The maximal integral radiation fluxes are observed on the front and rear walls at a height of 12–16 m (4–5 m above the top tier of burners). The waterwall surfaces at a height of 12–16 m experience the maximal radiation from the horizontal volume zone and from the torch's first vertical volume zone. The densities of integral radiation fluxes reach here 780 kW/m$^2$ on the front and rear walls and 520 kW/m$^2$ on the lateral walls. The integral radiation fluxes observed on the walls at the firebox bottom level are a factor of 1.7–1.9 smaller and equal to 460 and 270 kW/m$^2$, respectively. This is because the wall lower belt is located at a considerable distance away from the first vertical volume zone and the more so from the second to the fifth volume zones. The density of integral radiation fluxes falling from the torch on areas lying at a height of above 20 m decreases along the wall height in a similar manner.

The densities of integral radiation fluxes on the walls under the ceiling are equal to 150 and 110 kW/m$^2$, respectively, on the front and lateral walls along the vertical symmetry axis. Such decrease of integral radiation fluxes on the wall surfaces under the ceiling is due to the fact that the wall upper belt is situated at a considerable distance away from the torch horizontal and first vertical volume zones, in which 72% of the torch power is released, whereas only around 10% of the torch power is released in the nearby fourth and fifth vertical volume zones.

The variation of integral radiation flux densities over the wall perimeter is also essentially nonuniform in nature. The densities of integral fluxes radiated from the torch in the front and rear wall "hot belt" situated at a height of 12–16 m vary from 780 kW/m$^2$ at the wall vertical symmetry axis to 180 kW/m$^2$ at their periphery; i.e., they drop by a factor of 4.3. This is because the vertical symmetry axes of the front and rear walls are situated at the shortest distances from the linear sources and from the central and peripheral cylinders by which the torch is modeled.

The densities of integral fluxes radiated from the torch at the vertical symmetry axis and at the periphery of lateral walls differ from each other to a significantly lesser extent. The densities of integral fluxes radiated from the torch at a height of 12–16 m are equal to 520 and 290 kW/m$^2$, respectively, at the vertical symmetry axis and at the periphery of lateral walls. The flux densities in the underceilng zone of lateral walls differ from each other to a still lesser extent and are equal to 120 and 95 kW/m$^3$, respectively, at the vertical symmetry axis and at the periphery. This is because the distance from the cylindrical sources of radiation to the vertical symmetry axis of lateral walls differs insignificantly from the similar distance to the periphery of lateral walls [19].

**Figure 4b** shows the calculated distribution of integral radiation flux densities over the bottom surface. The 250 kW/m$^2$ isorad forms an elliptic hot spot in the bottom surface center with the sizes along the major and minor axes equal to 12 and 8 m. The integral radiation fluxes at the bottom periphery do not exceed 125 kW/m$^2$.

As is well known [23], the surface density of deposits inside the tubes increases with the density of integral radiation flux falling on the waterwall surfaces. With a heat flux equal to 200 kW/m$^2$, the surface density of deposits inside the tubes is 0.1 kg/m$^2$, whereas at 500 kW/m$^2$, it is equal to 0.3 kg/m$^2$; that is, the density of deposits inside the tubes grows in proportion to the heat flux. Hence, reducing the densities of integral heat fluxes and making them more uniform over the perimeter and height of steam boiler firebox walls are presently a topical problem.

An experimental confirmation of the results obtained from the performed calculations aimed at determining the distribution of integral radiation flux densities over the surfaces of the TGMP-204 steam boiler firebox can be found in [1], as well as in [24, 25].

In [19], the experimentally determined distribution of integral radiation fluxes over the height of the left-hand lateral waterwall of a TGMP-204 KhL steam boiler firebox is presented for the case of boiler operation in the mode of power unit maximal load equal to 800–820 MW1. The difference between the maximal local incident radiation fluxes in the firebox of a TGMP-204 steam boiler obtained by calculation (780 kW/m$^2$) and by measurements (870 kW/m$^2$) [25] does not exceed 12%, which confirms that the developed torch mathematical model adequately reflects the real conditions.

Nonuniform distribution of the densities of integral fluxes radiated from the torch over the wall perimeters and heights gives rise to similar nonuniformity of steam generation and deposits in the tubes. Engineers who develop and design steam boilers, as well as researchers in this field, should apply additional efforts on improving the designs of fireboxes aimed at decreasing the heat fluxes over the wall perimeters and heights and at making them more uniform, which will lead to similar reduction and more uniform distribution of deposits in the tubes. The shortcoming of the considered firebox of a TGMP-204 boiler is that the waterwall heating surfaces in the furnace lower part experience high heat loads, which result in a high growth rate of deposits inside the tubes. High heat loads entail a growth of temperature of waterwall tube metal surfaces and facilitate the occurrence and development of high-temperature corrosion in these surfaces. All the abovementioned factors have a negative effect on the service life of waterwall heating surfaces and, hence, result in less reliable operation of the entire boiler.

The use of the proposed calculation procedure allows one to get a more comprehensive idea about heat transfer and to design new improved fireboxes for steam boilers. This improvement is achieved through changing the shape of firebox and waterwall surfaces and the inclination angle of oppositely arranged burners, which leads to rational distribution of heat loads [26, 27].

In [27], a firebox for firing gas and oil fuel was proposed. This firebox consists of a bottom, arch, walls, waterwalls repeating the firebox inner surface, and oppositely placed burners built in the walls. The firebox is made in the form of two truncated cones with their larger bases facing each other. The firebox bottom serves as the base of the lower cone; the lateral walls of the upper cone are matched with vertical walls forming the shape of a straight cylinder. The burners are inclined to a horizontal plane at an angle of 5–10°.

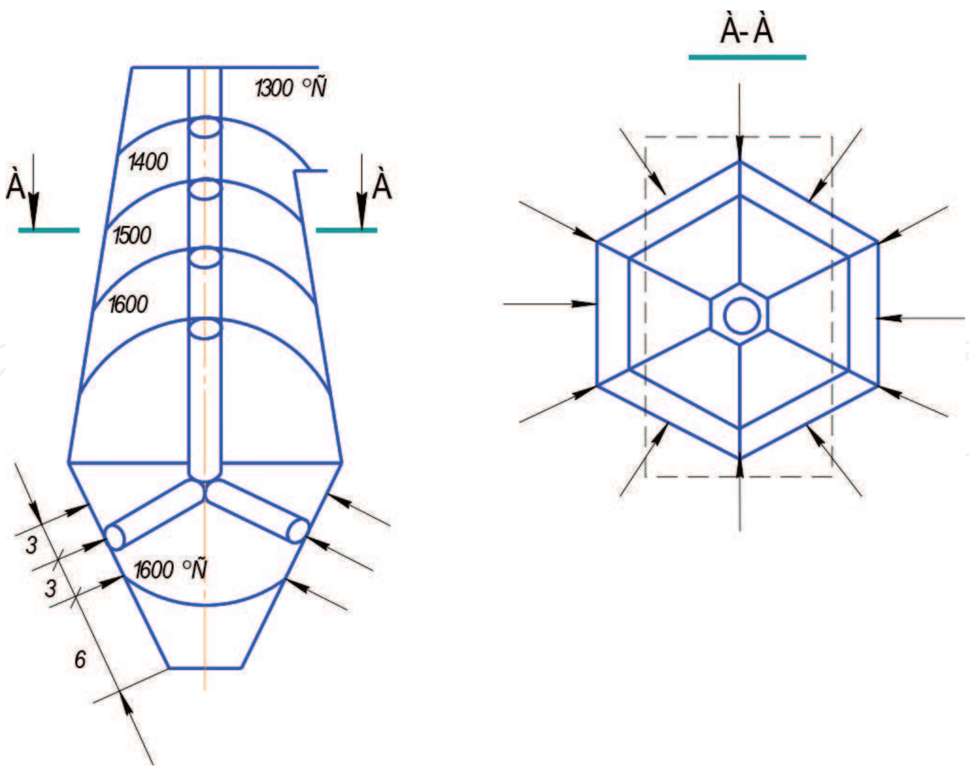


**Figure 5.** Firebox of the TGMP-204-I steam boiler (the dashed line in view *A–A* depicts the section of the TGMP-204 boiler furnace).

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**Figure 5** shows the innovative firebox of a TGMP-204-I steam boiler with rational distribution of heat loads intended for use as part of an 800 MW power unit. This furnace has the form of two truncated hexagonal pyramids with a common base having the shape of a regular hexagon with a radius of 9.6 m. The firebox is fitted with 36 vortex double-flow burners with a throughput of 5.2 t/h each. The burners are installed in three tiers uniformly over the perimeter of walls at the corners and in the middle of each face of the lower inverted pyramid. The firebox has a height of 46 m, and its volume is approximately equal to that of the TGMP-204 steam boiler. The air excess factor in the TGMP-204-I boiler firebox $\alpha = 1.03$, the gas recirculation ratio $r = 0.14$, the concentration of particles $\mu = 0.06$ g/m$^3$, the particle diameter $d$p = 0.278 μm, the particle density $\rho_p = 2 \times 10^3$ kg/m$^3$, and the attenuation coefficient $k$ in the medium = 0.162.

**Figure 5** shows the expected distribution of temperature over the height of the TGMP-204-I boiler firebox. Owing to the sloped walls, the firebox has a larger volume in the zone of burners; the maximal expected temperature in the active fuel combustion zone is 1600°C, and the temperature of combustion products leaving the firebox chamber is 1300°C. The torch is modeled by a vertical cylinder with five volume zones and by 12 inclined cylinders (**Figure 5**). The torch power $P_{tr}$ = 2155 MW. The procedure described above was used to calculate the densities of heat fluxes falling from the torch on the waterwall surfaces (**Figure 6**).

Owing to the fact that all waterwall surfaces and all faces of the truncated pyramid are situated at the same distance from the torch and from the cylindrical sources of radiation by which the torch is modeled, the integral radiation flux density along the wall symmetry axis and at the wall periphery is characterized by one curve shown in **Figure 6**. The integral radiation flux density has the same distribution over all waterwall surfaces and over all faces of the upper and lower truncated pyramids. The heat flux density in the zone of maximal heat loads at a height of 12–16 m in the TGMP-204-I boiler firebox is by 200 kW/m$^2$ lower than it is in the

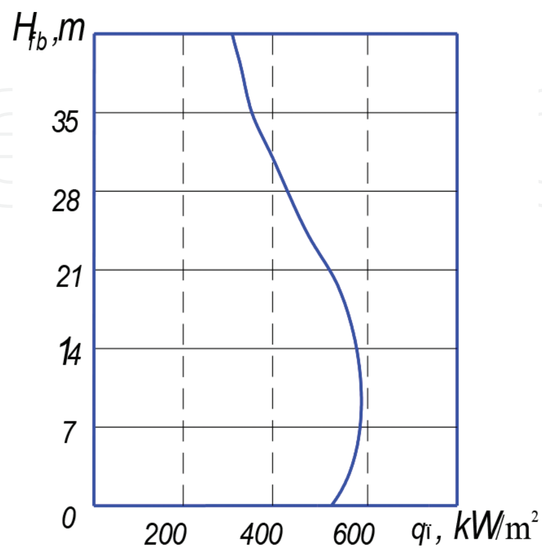


**Figure 6.** Distribution of integral radiation flux density over the walls of the TGMP-204-I boiler furnace.

TGMP-204 boiler firebox. As a result, more uniform steam generation is obtained in all tubes of waterwall surfaces over the firebox perimeter.

Owing to lower heat loads, the waterwalls operate at lower temperature, which result in a lower rate of their corrosion. This, in turn, results in a longer service life of waterwall heating surfaces and in a longer interval between their outages for cleaning the boiler with acid.

The proposed design of the steam boiler firebox has also other advantages over the existing ones. The new firebox has a larger volume in its part opposite to the burners, and the torch has a lower temperature in this volume, which results in less intense generation of nitrogen oxides. In addition, the waterwall surfaces in the firebox upper part are situated closer to the torch axis, due to which the working fluid absorbs heat more intensely and the heat fluxes are distributed along the firebox height more uniformly (see **Figure 6**). It is expected that the formation of deposits inside the tubes will be less intense in the proposed steam boiler firebox, that its operational costs will be reduced, that the firebox will have higher efficiency, and that the waterwall surfaces and working fluid will absorb heat more intensely [26].

Comparison between the distribution pattern of integral radiation fluxes over the TGMP-204 boiler firebox walls and that of the TGMP-204-I boiler firebox with the similar capacity testifies that the latter has certain advantages over the former: the heat loads of the waterwall surfaces are more uniformly distributed over the firebox height, the maximal heat loads in the burner zone are decreased by 25%, the torch has a lower temperature, and a smaller amount of nitrogen oxides is generated.

### 3.2. Calculation of heat transfer in the firebox of a TGMP-314 steam boiler

Here, we examine calculations of heat transfer in the furnace of a type TGMP-314 steam boiler with modeling of the flare by radiative zones and large cylindrical gas volumes.

The TGMP-314 steam boiler furnace for a 300 MW power-generating unit is in the shape of a rectangular parallelepiped (**Figure 7a**, **b**) with height $H$w = 35 m, width $a$ = 14 m, and depth $b$ = 7 m. The boiler runs on fuel oil and has 16 burners with a combined capacity $B$b = 67 torch-mounted counter to one another in two rows of eight burners each, at heights of 3 and 6 m from the bottom surface. The minimum heat of combustion of the fuel oil is $Q^r_1$ = 41 MJ/kg. The attenuation coefficient for radiation in the medium in the furnace is $k$ = 0.162 [19]. The distribution of isotherms along the height of the furnace with oppositely mounted burners is shown in **Figure 7a**. In terms of its height and perimeter, the flare fills the entire furnace and is in the shape of a right elliptical cylinder. The isotherms divide it height-wise into seven volumes. Six of these volumes, with ellipses at their base and top, and a parabola as a lateral generator, are elliptical purebloods which lie on the seventh volume, which is a truncated ellipsoid of rotation. An ellipsoid of revolution formed by the 1900°C isotherm is contained within the truncated ellipsoid.

**Figure 7c** shows the calculated radiative fluxes incident on the shielding surfaces of the furnace walls of a TGMP-314 steam boiler furnace. The distribution of the integrated radiative flux along the vertical axis of symmetry of the front wall is characterized by graph 1, which

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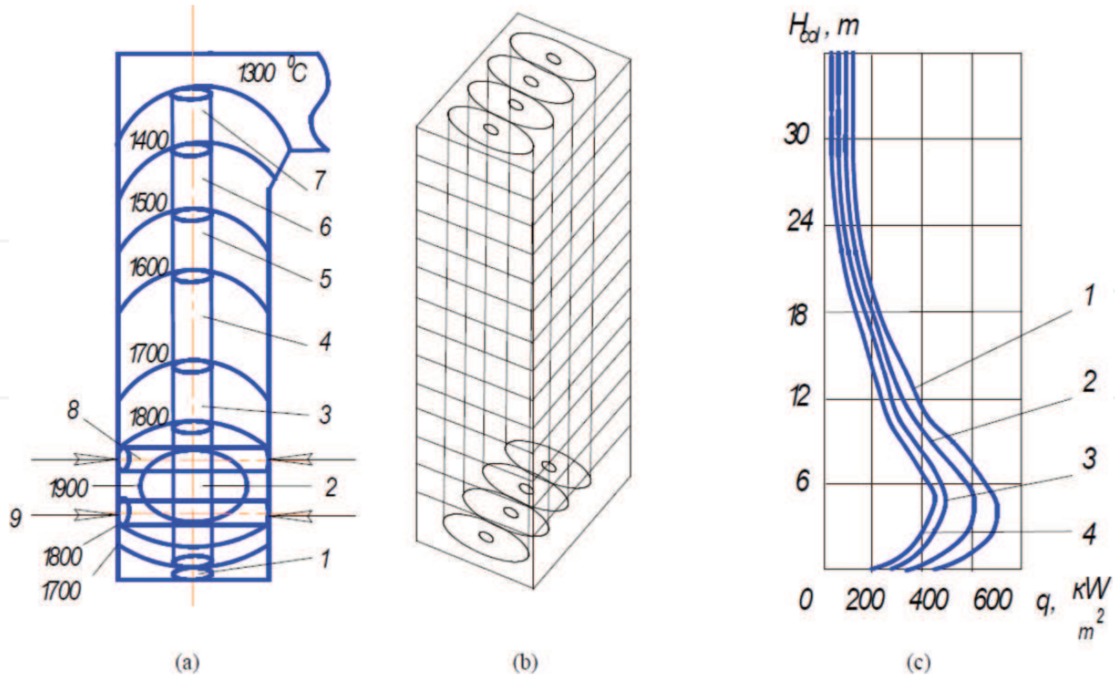


**Figure 7.** A type TGMP-314 steam boiler furnace with modeling of the flare by radiating cylindrical volumes: (a) distribution of isotherms and cylindrical radiation sources, (b) dividing the furnace into large cylindrical radiating volumes, and (c) the distribution of the integrated radiative flux along the height of the front and side walls: (*1*–*7*) arrays of vertical cylindrical sources; (*8* and *9*) arrays of horizontal cylindrical sources; (*10*) measurement and computational results along the vertical axis of symmetry of the front wall; (*11*) calculated results along the vertical axis of symmetry of the side wall; and (*12* and *13*) calculated results along the heights, respectively, of the side wall (at a distance of 2 m from its vertical axis of symmetry) and the front wall (at a distance of 4.7 m from its vertical axis of symmetry).

also illustrates the distribution of the integrated radiative flux along the vertical axis of symmetry of the rear wall.

The measured and calculated integrated radiative fluxes along the vertical axis of symmetry of the front wall differ by less than 10% [28, 29]. This confirms the adequacy of the model developed here for the flare in type TGMP-314 steam boiler furnaces. The maximum heat release zone, located at a height of 2–5 m from the bottom of the furnace, is characterized by maximal integrated radiative fluxes of the flare onto the front and rear walls at a level of 680 kW/m$^2$. At heights of 2–5 m on the side walls, the radiative fluxes along the axis of symmetry are 590 kW/m$^2$; at a distance of 2 m from the axis of symmetry, they fall to 440 kW/m$^2$.

On the periphery of the front wall at a height of 2–5 m, the radiative fluxes from the flare fall to 250 kW/m$^2$. The heat release in the flare decreases along the height of the furnace; the integrated radiative fluxes of the flare on the shielding surfaces also decrease.

The nonuniform distribution of the radiation fluxes from the flare along the perimeter and height of the screen surfaces of the walls gives rise to similar nonuniformity of vaporization and deposits in the tubes [2, 3]. The high heat loads in the bottom part of the front and back walls increase the temperature of the screen tubes and promote high-temperature corrosion in them. As a result of this, the problem of lowering the maximum temperature of the flare and equalizing the radiation flux densities on the screen surfaces along the height and perimeter of the firebox walls of steam boilers is of high priority. The importance of finding a solution to this problem also increases because the temperature in the fuel combustion zone affects thermal nitrogen oxide NOx emissions the most [30].

An innovative modification of the shape of the firebox of a steam boiler was proposed in order to obtain a rational distribution of the heat loads along the screen surfaces and to reduce nitrogen oxide emissions. The bottom part remains a rectangular parallelepiped; it is expedient to make the top part (**Figure 8a**) a truncated four-sided pyramid [26].

We shall examine heat transfer in such a firebox for the example of the previously studied boiler of the TGMP-314 power plant [19]. To suppress nitrogen oxide and organize two-step combustion of fuel, the nozzles are installed to feed air in amounts of 16 units (8 units per tier at heights 5.5 and 11 m). Oil is fed into a burner with air deficiency á = 0.8–0.85; the remaining air required for complete combustion of the fuel equals Äá = 0.2–0.25 and is fed through a nozzle higher up on the flare. The implementation of the two-step combustion of the fuel makes it possible to lower the temperature of the flare in the active burn zone and the nitrogen oxide emissions by 25–60%.

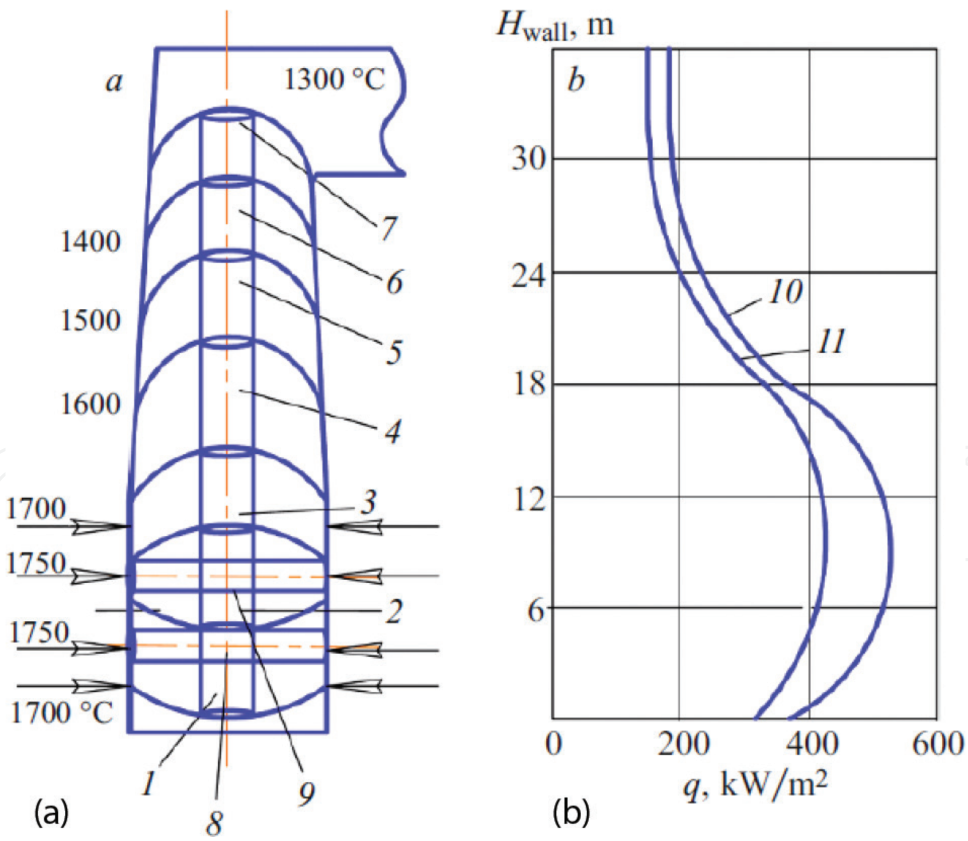


**Figure 8.** Firebox of TGMP-314 steam boiler with innovative modification: (a) distribution of the isotherms and cylindrical sources of radiation which are used to model the flare (same as in **Figure 7**) and (b) radiation flux density distribution along the height of the front wall 1 and side wall 2.

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In order that the implementation of two-step combustion of fuel not to increase the temperature of the combustion products at the outlet of the firebox, the radiative heat transfer was organized from the flare to the screen surfaces in the middle and top parts of the firebox. To this end, the front, back, and side walls are built to slope at 4–6° relative to the vertical axis starting from the height 15 m, forming a truncated pyramid of height hp. = 20 m. The walls converge onto the axis of the flare, the radiative heat transfer from the flare to the screen surfaces increases, the heat fluxes along the height of the screen surfaces equalize, and the temperature of the flare decreases. The expected distribution of the temperatures in the firebox of a TGMP-314 steam boiler modernized in this manner is shown in **Figure 8**. As a result of the two-step combustion of fuel, the temperature in the zone of active combustion decreases to 1750°C. As a result of the improvement of the radiative heat transfer, the temperature of the combustion products leaving the firebox does not exceed 1300°C with the walls converging on the flare. The heat transfer in the modernized firebox of the TGMP-314 steam boiler was calculated.

The computational results obtained from expression (12) are displayed in **Figure 8b**. It is evident that the highest values of the maximum radiation flux densities—546 kW/m$^2$—lie on the front walls at 10 m on the vertical axis. The radiation flux densities on the vertical axis of the front and side walls equal 352 and 306 kW/m$^2$, respectively, at a height of 18 m, 246 and 205 kW/m$^2$ at 24 m, and 175 and 148 kW/m$^2$ at 30 m. Comparing the radiation flux densities of the flare along the screen surfaces of the front side in the fireboxes of conventional and modernized TGMP-314 boilers (**Figure 8b**) shows that in the firebox of the modernized boiler the highest radiation flux densities on the screen surface decreased by 24% from 680 to 546 kW/m$^2$ in the bottom part, increased by 40% from 252 to 352 kW/m$^2$ at height 18 m, and increased by 47% from 167 to 246 kW/m$^2$. In the top part at height 30 m, the heat fluxes from the flare in the firebox of the modernized boiler increased by 41% compared with the conventional boiler: from 126 to 178 kW/m$^2$. Similar variation of the radiation flux density distributions also occurs along the height of the screen surfaces of the side walls.

Altering the configuration of the firebox of a steam boiler from a rectangular parallelepiped in the bottom part to a truncated rectangular four-sided pyramid whose walls incline at angle 5–6° to the vertical plane inside the firebox in the central and top parts made it possible to increase the heat fluxes on their screen surfaces and reduce the no uniformity of the heat flux distribution along the height and perimeter of the firebox.

These changes ease the operating conditions of the tubes in the bottom part, lower the maximum gas temperatures in the interior volume of the firebox and the gas temperature at the exit from the firebox, reduce the production of nitrogen oxides in the firebox, and increase the service life of the screens.

## 4. Conclusions

The scientific discovery of the laws and the development of the theory of heat radiation from gas volumes is a contribution to the foundation of modern physics, as it allows calculating and managing the transfer of heat around the world in tens of thousands of electric arcs and torch furnaces, steam boiler boxes, and combustion chambers of gas turbine units, reducing energy consumption and saving millions of tons of fuel, reducing emissions of pollutants and anthropogenic load on the environment, and improving the quality of life in many countries. The laws and the theory of heat radiation of the ionized and non-ionized gas volumes and the laws of Makarov were included in the text [19], in the amount of fundamental knowledge on the quantum nature of radiation, and are in line with the laws of heat radiation from absolutely black body and with even more than 30 fundamental laws of physics.

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