Journal of Applied Physics & Nanotechnology

(ISSN 2638-5104)

Research Article

Calculations of Heat Transfer in Torch Furnaces under the Laws of Radiation from Gas Volumes

This article was published in the following Scient Open Access Journal:
Journal of Applied Physics & Nanotechnology
Received May 27, 2019; **Accepted** June 03, 2019; **Published** June 10, 2019

Anatoliy Nikolaevich Makarov*

Department of Electrical Supply and Electrical Engineering, Faculty of Mechanical Engineering, Tver State Technical University, 22, nab. A. Nikitina, Tver, 170026, Russia

***Corresponding Author:** Anatoliy Nikolaevich Makarov, Department of Electrical Supply and Electrical Engineering, Faculty of Mechanical Engineering, Tver State Technical University, 22, nab. A. Nikitina, Tver, 170026, Russia, Email: tgtu_kafedra_ese@mail.ru

Abstract

Heat transfer by radiation is the main type of heat transfer in electric arc steelmaking and torch furnaces, fire boxes, combustion chambers and is 90-98 % of the total heat transfer in furnaces, fire boxes, and combustion chambers. The geometrical, physical models of electric arcs and torches of furnaces, fire boxes, combustion chambers are developed. The results of calculation of heat transfer in furnaces using the developed model of the torch are presented. The error of calculations does not exceed 10 %. The performed calculations using established model of the torch allowed to reveal uneven heating of products and to develop innovative torch furnaces, in which the heat flows are aligned on the heating surfaces, the heating time and fuel consumption are reduced.

Keywords: Heat transfer, Torch, Gas radiating volume, Furnace, Heating, Scientific discovery.

Introduction

Heat transfer by radiation is the main type of heat transfer in furnaces (Figure 1), fire boxes, combustion chambers and is 90-98% of the total heat transfer in steam boiler boxes, torch heating and melting furnaces [1-6], arc and plasma arc steelmaking furnaces [7-10].

Figure 1 shows the heating furnace of the forging shop (a), the oxy-fuel burner (OFB) used to heat the products in the furnace (b), the vertical torch (c), the horizontal torch (d) formed by the OFB.

The torch is a geometrical body in the form of an ellipsoid of rotation in which a combustion reaction occurs (Figure 2). Fuel combustion is accompanied by transition of the atoms involved in the combustion reaction of substances from one stationary state to another with the emission of a quantum of heat radiation. The emission of a quantum of heat radiation occurs during the transition of an electron from a more distant orbit from the nucleus to a closer one (Bohr's second postulate). Combustion

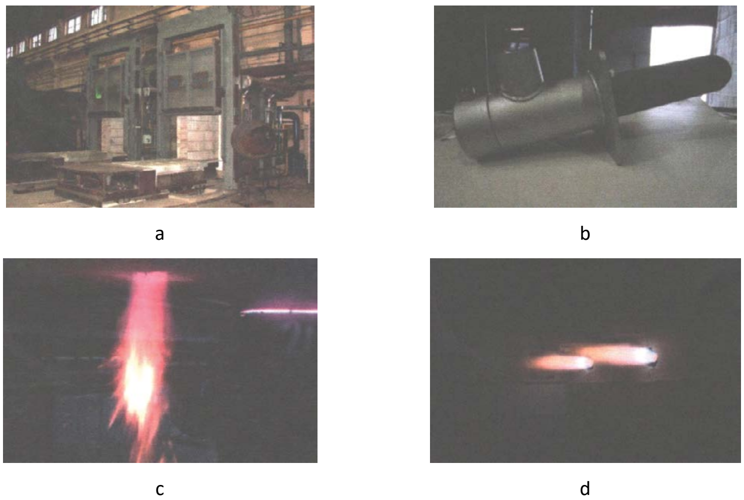

Figure 1 Heating furnace (a), burner (b), vertical torch (c), horizontal torches (d).

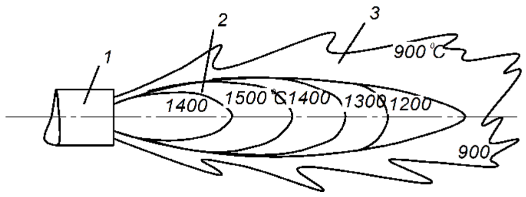

Figure 2. Single ignition torch: 1 – burner, 2 – torch, 3 – combustion products.

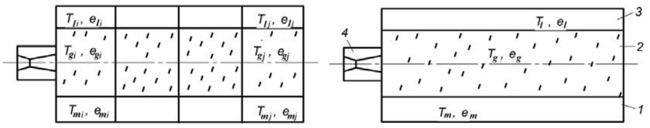

Figure 3. Modeling of a torch with isothermal gas volumes (a) and a rectangular parallelepiped (b) in torch furnaces: T_{li}, T_{gi}, T_{mi} is the temperature of lining, gas, metal, respectively; e_l, e_g, e_m is the coefficient of radiation from lining, gas, and metal, respectively.

products 3 are displaced by new portions of the reacting fuel from the active volume 2 and occupy the entire free volume of the furnace, fire box (Figure 2).

Numerical and zonal methods for calculating heat transfer in torch and heating furnaces

Throughout the twentieth century the calculations of heat transfer in torch furnaces were carried out by numerical, zonal and other methods [11, 12] before the laws of heat radiation from gas volumes of the torches by the author of this article were discovered. In numerical or zonal methods the furnace volume is divided into a number of isothermal volumes (Figure 3a) or one isothermal volume (Figure 3b).

When using the zonal method, the resulting flux to the i –th zone of the system from n calculated zones, separated by a gas medium with the temperature Tg is determined by the following expression [2]

$$q_{res} = c_s \cdot \varepsilon_1 \left\{ \left[\left(\frac{T_g}{100} \right)^4 - \left(\frac{T_i}{100} \right)^4 \right] - \sum_{k=1}^{n} \varepsilon_k \left[\left(\frac{T_g}{100} \right)^4 - \left(\frac{T_k}{100} \right)^4 \right] \Psi_{ik} \right\} \quad (1)$$

Where ε_i, T_i, ε_k, T_k are radiation coefficients and temperatures of the i-th and k-th zones, respectively; ψ_{ik} is the resolving angular radiation coefficient of the i – Th zone to the k-th zone,

which is determined by the expression:

$$\psi_{ik} = \left(1-\varepsilon_g\right)\phi_{ik} + \sum_{j=1}^{n}\left(1-\varepsilon_j\right)\left(1-\varepsilon_g\right)\phi_{ij}\psi_{jk} \quad (2)$$

where φ_{jk}, φ_{jj} are average angular coefficients of radiation from the i–th to the k-th zone and the i-th to the j-th zone, respectively; ε_j is the emissivity factor of the j–th zone; ψ_{ik} is the resolving generalized angular coefficient of radiation from the j-th to the k-th zone.

In the zonal and numerical methods of calculation, the active volume, the torch is not separated from the products of combustion. However, the source of heat energy in the furnace is the torch; the products and lining of the walls, arch, hearth are warmed by it. The calculations performed with separate calculation of the heat radiation from the torch and the combustion products showed, that the radiation from combustion products filled the furnace on the heating surface is little compared to the radiation from the torch [13].

Currently, a lot of facts have been accumulated for proving the need to adjust the existing zonal and numerical methods for calculating heat transfer by radiation in torch furnaces, fire boxes, combustion chambers. The radiation from carbon dioxide and water vapor, the main components of the gas volume of the torch, is characterized by a weaker dependence on temperature than the radiation from gray solids. The radiation from carbon dioxide vapors is proportional to the temperature in the degree of 3, 5 and the radiation from the water vapor to the temperature in the degree of 3 [4]. In practical calculations, in order to simplify the calculation methods, it is conditionally assumed that the radiation from gases is proportional to their temperature in the fourth degree, temperature corrections are amended to the emissivity factor of these gases [4]. However, such a simplification leads to gross errors in the calculations.

Thus, when the air is heated from 20^0C to 600^0C in a torch heating furnace, the power of the torch increased by 17% from 5 MW to 5.85 MW, and the temperature of the torch increased from 1300°C to 2000°C , that is 1.5 times [14]. According to the expression (1), the density of the resulting radiation flux to the calculated zone from the torch should increase 5 times; the heating rate should also increase 5 times, which contradicts the law of conservation of energy. Under actual operating conditions of the furnaces, when the air is heated and the power of the torch increases by 17%, the heat flux density and heating rate increase by 17%, that is, directly proportional to the increase in the power of the torch, and not the temperature in the fourth power [14].

The error in the calculation of heat transfer in torch furnaces by zonal and numerical methods using the Stefan-Boltzmann law is 100–400%, since the radiation from gas volume of the torch does not obey the Stefan-Boltzmann's law of radiation from solids. The calculation error was compensated by long-term, expensive, time-consuming experimental studies of heat transfer in torch furnaces.

Laws of heat radiation from gas volumes.

The calculation of heat transfer in torch furnaces with high accuracy has become possible with the scientific discovery of the laws of heat radiation from gas volumes. The second postulate of Bohr stated that each atom of the gas volume of the torch, including quadrillions (10^{20}-10^{30}), radiates to each calculated area of heating surface. Calculation of heat transfer based on the heat radiation from each atom to the calculated area is made possible by using the disclosed laws of heat radiation from cylindrical gas volumes (Figure 4), inscribed into the gas volume of the torch in accordance with the location of isotherms over the torch volume [15].

The laws of heat radiation from gas volumes of the torches, disclosed in 1996-2001, are named after their author, Makarov's laws in the diploma for scientific discovery, articles, textbook with the objective of complying with the age-old scientific traditions and copyright, such as the laws of Stefan-Boltzmann, Planck, Wien, the laws of radiation from blackbody.

(Figure 5) shows the radiation from cylindrical gas volumes to the calculated area. Mathematical notation of the laws of heat radiation from cylindrical gas volumes of the torches is given in (Table 1) [16].

In (Table 1) the following symbols are used : q is the density of the heat flux incident on the calculated area (CA) from the cylindrical gas volume (CGV), kW/m^2; φ is the angular radiation coefficient (a portion of the radiation) from the CGV to the CA; P is the radiation power of the CGV, kW; k is the absorption coefficient of the CGV; l is the average beam path length from all atoms of CGV to the CA, m; F is the surface area of the CA, m^2; indices denote the numbers of gas volumes from 1 to n.

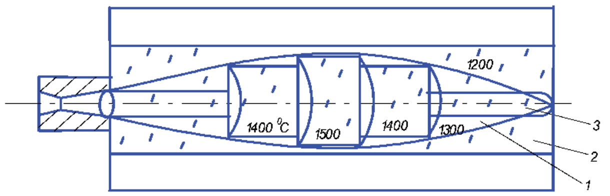

Figure 4. Geometrical model of the torch in the form of cylindrical gas volumes: 1 - torch; 2 - combustion products; 3 - cylindrical gas volumes of different diameters.

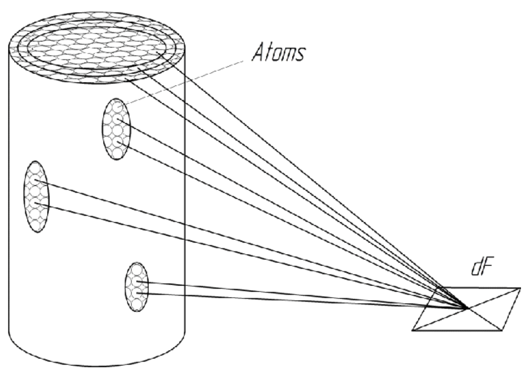

Figure 5. Radiation from isothermal isochoric coaxial cylindrical gas volumes to the calculated area dF.

In 2011 the author of this article Makarov A. N. received a diploma for the scientific discovery [13]. According to the first law of heat radiation from cylindrical volumes, the heat radiation flux density of cylindrical gas volume to the calculated area q_{FodF} is directly proportional to the radiation power of the volume P_F, the proportion of the radiation to the calculated area φ_{FodF} of the total radiation from the volume and inversely proportional to the site area F_0, the absorption coefficient of the gaseous medium k, the average beam path length l from the atoms of the volume to the area.

The multidisciplinary approach to the laws of heat radiation from gas volumes.

The laws of heat radiation from gas volumes are among the fundamental laws of physics, the laws of Stefan-Boltzmann, Planck, Wien, the postulates of Bohr. Planck, Wien, Bohr won Nobel prizes for the discovery of the fundamental laws. The laws of heat radiation from gas volumes of Makarov, as well as the laws of heat radiation from solids of Planck, Wien, Bohr's postulates, have multidisciplinary nature and are used to calculate heat transfer in torch heating furnaces in various industries, metallurgy, steam boiler boxes and combustion chambers in the energy sector.

The disclosure of the laws of heat radiation from cylindrical gas volumes solved an extremely complex problem that existed throughout the twentieth century: researchers, engineers enable to calculate the heat radiation from furnace torches, fire boxes, combustion chambers on the heating surface, taking into account heat radiation from each atom of gas volume [15-18]. The complexity of the problem characterizes the number of radiating atoms in the torch. The boiler torch of 800 MW power unit burns 180 tons of fuel oil per hour or, when the furnace is running on gas, the amount of gas equal to the calorific value of 180 tons of fuel oil. The number of torch atoms participating every second in the heat radiation on the heating surface is 10^{45}, which is approximately equal to the number of grains of sand in the Sahara Desert.

The disclosed laws of heat radiation from cylindrical coaxial gas volumes show, that radiation from any cylindrical gas volume of large diameter and any height in calculations of

Table 1. Mathematical notation and formulation of the laws of heat radiation from cylindrical gas volumes.

Law number	Mathematical notation of the law	Law formulation
I	$q_{FdF} = \frac{\varphi_{F_0dF} \cdot P_F \cdot e^{-kl}}{F_0} = \frac{\varphi_{F_0dF} \cdot P_F}{F_0 \cdot e^{kl}}$	Heat radiation flux density incident on the calculated area from the cylindrical gas volume is directly proportional to its power, the angular radiation coefficient and is inversely proportional to the absorption coefficient, the average beam path length from the atoms of the volume to the site and the site area.
II	$l_1 = l_2 = l_3 = \ldots = l_i = \left(\sum_{i=1}^{n} \frac{l_i}{n} \right) = l$	The average beam path length from radiating atoms to the calculated area is equal to the arithmetic mean distance from the symmetry axis to the calculated area.
III	$\varphi_{F_1dF} = \varphi_{F_2dF} = \varphi_{F_3dF} = \ldots = \varphi_{F_idF}$	Angular coefficients of radiation from coaxial cylindrical gas volumes to the calculated area are equal.
IV	$q_{F_1dF} = q_{F_2dF} = q_{F_3dF} = \ldots = q_{F_idF}$	Flux densities of radiation from coaxial cylindrical gas volumes to the calculated area are equal.
V	$q_{F_1dF} = \sum_{i=1}^{n} q_{F_idF}$	Flux densities of heat radiation from cylindrical gas volume of large diameter and its cylindrical axis of symmetry to the calculated area are equal when the heat capacities released in them are equal.

heat radiation can be equivalently replaced by radiation from cylindrical symmetry axis of the cylindrical gas volume, virtually concentrating all the radiating atoms of the gas volume of the torch on it. In this case, the heat radiation power of the cylindrical axis of symmetry will be equal to the heat radiation power of the cylindrical gas volume. When we concentrate all radiating atoms on the cylindrical axis of symmetry of the gas volume, it is possible to calculate the heat radiation from each atom and all atoms together on any calculated area using the formula, according to the first law of heat radiation from cylindrical gas volumes of small diameter.

The average beam path length from atoms to the calculated area, that applies to the formula of the first law, is determined by the second law, under which the average beam path length to the calculated area from all radiating atoms of a cylindrical gas volume of large diameter and height is equal to the average beam path length to the calculated area of all atoms concentrated on the cylindrical axis of symmetry of the gas volume. The average beam path length of all atoms of the gas volume concentrated on the cylindrical axis of symmetry of the volume is determined by a single mathematical calculation as an arithmetic mean distance from the axis of symmetry to the calculated area (Table 1).

The angular coefficient of radiation from gas volume to the calculated area that applies to the formula of the first law of heat radiation is determined by the third law, under which the angular coefficients of radiation (radiation fractions) of cylindrical gas volumes of large diameter and its cylindrical axis of symmetry to the calculated area are equal. It should be understood that all the radiation of the cylindrical gas volume into the environment, on the surfaces, surrounding gas volume are equal to one. When calculating the Radiative heat transfer r in torch furnaces, fire boxes, combustion chambers according to the first law of heat radiation from gas volumes (Table 1), we use the absorption coefficient of the gas medium characteristic of the real dispersed arrangement of all radiating and absorbing atoms in the gas volume, that is, we use the calculated or experimental absorption coefficient of the gas volume. Since, according to the 4th and 5th laws (Table 1) heat radiations from a cylindrical gas volume of a large diameter and its cylindrical axis of symmetry to the calculated area are equal, the heat radiation from a cylindrical gas volume of a large diameter in the calculations can be equivalently replaced by heat radiation from its cylindrical axis of symmetry with a concentrated arrangement in it of all atoms of a cylindrical gas volume of a large diameter and, accordingly, equal to the heat radiation from a cylindrical gas volume of a large diameter and its cylindrical axis of symmetry.

Thus, according to the disclosed five laws (Table 1), heat radiation from gas volume of any form can be equivalently replaced by heat radiation from cylindrical gas volumes, inscribing them in gas volumes of torches of furnaces, fire boxes, combustion chambers and modeling in calculations heat radiation of cylindrical gas volumes by heat radiation from their cylindrical axes of symmetry. The disclosed laws allow for a single integration of trigonometric functions when replacing the heat radiation from a cylindrical gas volume of large diameter by heat radiation from cylindrical volume of small diameter in the calculations of angular radiation coefficients from the cylindrical volume to the calculated areas in their arbitrary position to each other in the working space of furnaces, fire boxes, combustion chambers, which was done by the author of scientific discovery. With the use of single integration of trigonometric functions, characterizing the mutual arrangement of the cylindrical axis of symmetry and calculated area we received 14 formulas for calculating angular radiation coefficients of the cylindrical gas volume to the calculated area when they are parallel, orthogonal and arbitrary to each other [19].

Figure 6. Torch brick furnace.

Torches in furnaces, fire boxes, combustion chambers, formed by single burners, are ellipsoids of rotation (Figures 1, 2, 4 and 6), by inscribing cylindrical gas volumes in the torches (Figure 4), we create the conditions for calculating heat transfer in torch furnaces, fire boxes, combustion chambers, taking into account the heat radiation from all atoms involved in the heat radiation from the torch. In the calculations, the length of the torch is equal to the length of the ellipsoid of rotation, inside which burns at least 97 % of the fuel [20-21].

On the basis of the disclosed laws of heat radiation from cylindrical gas volume, the author of the discovery developed the modern theory of heat transfer in electric arc and torch furnaces, fire boxes, combustion chambers and the method for calculating heat transfer in electric arc and torch furnaces, fire boxes, combustion chambers [19]. The results of the calculation performed by the method for calculating heat transfer in electric arc and torch furnaces, fire boxes, combustion chambers based on the disclosed laws of heat radiation from ionized and non-ionized cylindrical gas volumes are confirmed by numerous experimental studies of the scientific groups of the author of the scientific discovery, as well as research teams of research institutes, universities on operating electric arc and torch furnaces, fire boxes, combustion chambers [22-28]. The author of the scientific discovery and textbook [19] was awarded Silver medals at International exhibitions "Metal-EXPO 2018", "EXPROPRIORY2013".

The disclosed laws of heat radiation from gas volumes and their practical use in the calculation of heat transfer in torch furnaces allowed to determine with high accuracy the distribution of the radiation fluxes from the torch along the perimeter and height of the furnaces, to identify the causes of burnout of burner units in furnaces, uneven deposits inside the pipes along the perimeter and height of the pipes and to develop innovative steam boiler boxes, which eliminate the above shortcomings. The practical use of the laws of heat radiation from gas volumes in the calculations of heat transfer in torch heating furnaces allowed to calculate the distribution of the radiation fluxes from torches on the heating surfaces, to find out the reasons for the uneven distribution of heat fluxes on the surfaces of heated products and to develop innovative torch furnaces with a rational arrangement of burners and torches in the furnaces, which aligns the distribution of heat fluxes on the heated products, reduces the heating time of products, fuel consumption, increases the productivity of the furnaces. Use of the disclosed laws and these laws-based method of calculating heat transfer in the combustion chambers of gas turbine plants allows to determine the location of the torch radiation fluxes on the flame tube surface at the design stage of combustion chambers, to organize effective cooling of the flame tube surface onto which the maximum heat flux of the flame falls, to exclude burnout of a flame tube, increase its service life, reduce the cost of experimental studies of combustion chambers and to create conditions for long-term reliable operation of the combustion chambers at the stage of design.

Methods of calculating heat transfer in torch heating furnaces based on the laws of heat radiation from gas volumes.

The methodology for calculating heat transfer in torch furnaces, fire boxes, combustion chambers derived from the disclosed laws of heat radiation from cylindrical gas volumes is as follows. The power released in the torch Pt, is defined by the formula:

$$P_t = Q_i^r B_r \tag{3}$$

Where Q_i^r, B_k are the heat of combustion and the fuel consumption, accordingly.

A share of the power released in each cylindrical gas volume, inscribed in the torch, we determine by the following proportion:

$$P_1 : P_2 : \ldots : P_n = T_1^3 V_1 : T_2^3 V_2 : \ldots : T_n^3 V_n \tag{4}$$

where T_1, T_2, ..., T_n is the temperature of the cylindrical gas volume; we assume, that the radiation from the main components of the gas volume is proportional to the temperature in the third degree [4,19]; V_1, V_2, ..., V_n is the volume of gas divided by isotherms and into which radiating cylindrical volumes are inscribed.

Since the power released in the cylindrical gas volume is proportional to the volume of gas into which the cylinder is inscribed, and the temperature in the third degree, then making the proportion (4) we determine the share of the power released in any of the inscribed cylindrical gas volumes from all power of the torch (3). Multiplying the share of power released in a cylindrical gas volume by the power of the torch, we will determine the power of any cylindrical volume constituting the torch.

Since after heating the refractory lining of the furnace by torches and combustion products of the wall, the arch, the hearth radiate heat flux on the heated products, therefore, in the torch furnace, a separate calculation of the heat radiation on the products of the torch, the heated surfaces of the walls, the arch, the hearth and the combustion products is required. Calculations of heat transfer in the torch furnace is carried out taking into account multiple reflections of radiation fluxes from the furnace surfaces and the absorption of radiation by combustion products. Since the fluxes of heat radiation caused by multiple reflections of the gas volume of the torch from the surfaces of the walls, the arch, the hearth are evenly distributed over the calculated heating surfaces, similarly, each of the radiation is evenly distributed over the heating surfaces, and the heat radiation from the torch and the heat radiation from the walls, the arch, the hearth are unevenly distributed over the calculated heating surfaces, therefore, they require separate calculation [19].

In accordance with the developed theory and the proposed method, the total heat fluxes are calculated, consisting of the radiation fluxes falling on the heating surface from the torch, the lining of the walls, the arch, the hearth and the convective fluxes of the combustion products.

The density of the heat flux incident on the i-th elemental area on the heating surface is determined from the expression:

$$q_{in} = q_{\text{int}} + q_{inrt} + q_{ins} + q_{inrs} + q_{i\text{con}} + q_{icp}, \tag{5}$$

where q_{int} is the density of the heat radiation flux incident on the i-th area from the torch, taking into account the absorption of the torch radiation; q_{inrt} is the density of the heat radiation flux incident on the i-th area, caused by the reflection of the torch radiation from the walls, arch, hearth, products; q_{ins} is the density of the heat radiation flux incident on the i-th area from the radiating walls, arch, hearth, taking into account the reflection and absorption of radiation; q_{inrs} is the density of the heat radiation flux incident on the i-th area, caused by the reflection of radiation surfaces from the walls, hearth, cover, ingots; q_{icon} is the density of the convective flow from the torch and combustion products on the i-th area; q_{icp} is the density of the radiation flux from combustion products to the i-th area.

Summands in the expression (5) are determined by the formulas:

$$q_{int} = \sum_1^n \frac{\phi_{tji} P_{tj}}{F_i} e^{-kl} \tag{6}$$

where k is the absorption coefficient of the gas medium; l is the average beam path length from radiating atoms to the calculated area; φ_{tji} is the local angular coefficient of radiation from the j-th cylindrical source on the i-th area (calculated according to the formulas set out in [19]; P_{tj} is the power of j-th cylindrical source; F_i is the area of the i-th elemental area;

$$q_{inrt} = \sum_1^n \frac{P_{tj}(\psi_{tjk} - \phi_{tjk} e^{-kl})}{F_k} \tag{7}$$

Where ψ_{tjk} is the generalized angular coefficient of radiation from the j-th volume zone (the j-th cylindrical source) on the k-th surface; φ_{tjk} is the average angular coefficient of radiation from the j-th cylindrical source on the k-th surface;

$$q_{ins} = \sum_1^n \frac{\phi_{ji} Q_{jc}}{F_i} e^{-kl} \tag{8}$$

Where φ_{ji} is the local angular coefficient of radiation from the j-th surface on the i-th area (calculated by formulas [2, 5]); Q_{js} is the self-radiating flux from the j-th surface;

$$q_{inrs} = \sum_{1}^{n} \frac{Q_{js}(\psi_{jk} - \phi_{jk} e^{-kl})}{F_k} \qquad (9)$$

Where ψ_{jk} and φ_{jk} are generalized and average angular coefficients of radiation from the j-th surface on the k-th surface;

$$q_{icon} = \alpha_{con}(t_{gav} - t_p) \qquad (10)$$

Where $t_p = 20^0C$ is the temperature of products; $t_{gav} = 1400^0C$ is the average temperature of combustion products, gas; α_{con} is the heat transfer coefficient by convection, with free convection $\alpha_{con} = 11{,}6\ W/(m^2 \cdot {}^0C)$ [2]; at the beginning of heating $q_{icon} = 16{,}2\ kW/m^2$, convective fluxes are evenly distributed over the heating surfaces of the furnace, fire box;

$$q_{icp} = \sum_{1}^{n} \frac{\phi_{cpji} P_{cpj}}{F_i} e^{-kl} \qquad (11)$$

Where φ_{cpji} is local angular coefficient of radiation from the j-th volume of combustion products on the i-th area; P_{cpj} is the power of the j-th volume of combustion products.

Self-radiating flux from the j-th surface

$$Q_{js} = \varepsilon_j c_s (T_j/100)^4 F_j \qquad (12)$$

Where ε_j is the coefficient of radiation from the j-th surface; c_s is the emissivity of the blackbody; T_j is the temperature of the surface; F_j is the area of the j-th surface.

Let we combine the formulas for calculating heat transfer in torch furnaces, fire boxes, combustion chambers in the (Table 2).

We use the model of the torch in the form of radiating cylindrical gas volumes to calculate heat transfer in the heating torch furnace. Calculate the heat transfer in the recuperative heating pit with one upper burner and ejection of air from the recuperators [19].

The results of calculating heat transfer in torch heating furnaces under the laws of heat radiation from gas volumes

Chamber 1 of the pit is a straight parallelepiped, 8 m in length, 3 m in width,4 m in height (Figure 7). The camera is equipped with 14 bars, 7 tons, 2.4 height each. Power of the torch is 4.1 MW.

The results of the calculation by the formulas in (Table 2) are shown in (Figure 8) in the form of graphs of the distribution of falling heat fluxes on the lateral surfaces of the ingots. As shown in Fig. 8, the heat fluxes are distributed unevenly both along the height of the ingots and the different faces of the ingots, which leads to an increase in fuel consumption and heating time to equalize the temperature on all faces and the volume of the ingots.

Calculation under the laws of heat radiation from gas volumes made it possible to obtain for the first time complete information about the fluxes of heat radiation from the torch, heated walls, arch, hearth, combustion products falling on all faces of ingots and other heated products, taking into account the rereflection

Table 2. Equations, formulas for calculating heat transfer in torch furnaces, fire boxes, and combustion chambers.

№	Name of formula, equation	Equation, formula	Measure unit
1	The density of the total heat flux incident on the calculated area	$q_{in} = q_{int} + q_{inrt} + q_{ins} + q_{inrs} + q_{icon} + q_{icp}$,	kW/m²
2	The share of the power emitted on the calculated area	$P_1 : P_2 : \ldots : P_n = T_1^3 V_1 : T_2^3 V_2 : \ldots : T_n^3 V_n$	-
3	The density of the heat flux of radiation incident on the calculated area from the torch (the first law of heat radiation from cylindrical gas volumes)	$q_{int} = \sum_{1}^{n} \frac{\phi_{tji} P_{tj}}{F_i} e^{-kl}$	kW/m²
4	The density of the heat flux of radiation caused by the reflection of the torch radiation from the surfaces to the calculated area	$q_{inrt} = \sum_{1}^{n} \frac{P_{tj}(\psi_{tjk} - \phi_{tjk} e^{-kl})}{F_k}$	kW/m²
5	The density of the heat flux of radiation incident on the calculated area from the radiating surfaces	$q_{ins} = \sum_{1}^{n} \frac{\phi_{ji} Q_{js}}{F_i} e^{-kl}$	kW/m²
6	The density of the heat flux of radiation caused by the reflection of radiation from the surfaces and incident on the calculated area	$q_{inrs} = \sum_{1}^{n} \frac{Q_{js}(\psi_{jk} - \phi_{jk} e^{-kl})}{F_k}$	kW/m²
7	The density of the convective flux from the torch and products of combustion on the calculated area	$q_{icon} = \alpha_{con}(t_{gav} - t_p)$	kW/m²
8	The density of radiation fluxes from products of combustion on the calculated area	$q_{icp} = \sum_{1}^{n} \frac{\phi_{cpji} P_{cpj}}{F_i} e^{-kl}$	kW/m²
9	The flux of the corresponding surface radiation	$Q_{js} = \varepsilon_j c_s (T_j/100)^4 F_j$	kW

and absorption, to identify the causes of uneven heating, develop methods and devices for heating, which increases the uniformity of heating products, reduces the heating time and fuel consumption, increases the productivity of furnaces (patents for inventions) [8-13]. The design of a heating pit has not changed for 80 years. Patents for inventions of torch furnaces are received: I – with 2 burners; II – with 6 burners; III – with 12 burners.

(Figure 9) shows the scheme of the recuperative heating pit with two torches and the distribution of heat fluxes along the height of the ingots.

(Figure 10) shows a recuperative heating pit with 6 torches [23].

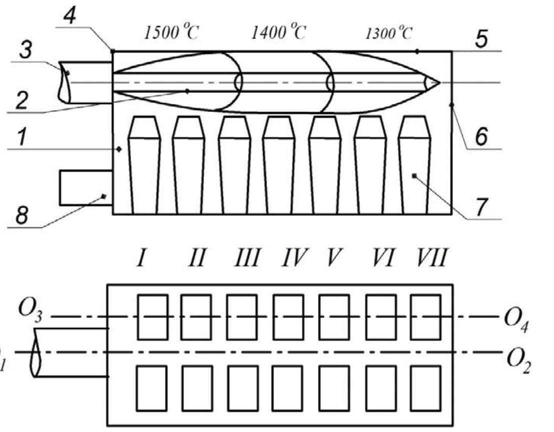

Figure 7. Scheme of the working space of the heating pit and placement of ingots in it: I – VII – the number of ingot rows, 1 – camera; 2 – torch; 3 – burner; 4 – frontal wall; 5 – arch; 6 – back wall; 7 – ingots; 8 – channels.

The proposed devices and methods of heating allow aligning the distribution of heat fluxes by the heating surfaces, reducing heating time, fuel consumption, and improving the performance of furnaces.

Similarly, the calculation of heat transfer in the regenerative heating pit (Figure 11).

(Figure 11) uses the following designations: 1 – combustion products; 2 – cover, 3 – ingots; 4, 5 – air and gas regenerator, respectively; 6-8 – rear, side, front walls, respectively, ; 10 – pit chambers; I-IV – ingot numbers along the length of the pit.

The results of calculating heat transfer in the recuperative pit showed a significant unevenness of the distribution of heat fluxes along the height and faces of the ingots (Figure 11 a, b, c, d). The correctness of the calculation, the correspondence of the calculation results to the real heat transfer in the furnace is confirmed by experimental measurements of the temperature along the height of ingots (Figure 5b). The design of the heating pit has not changed for 80 years. Calculations based on the disclosed laws of heat radiation from gas volumes allow to obtain a complete picture of heat transfer in the regenerative heating pit and any other torch furnace and to develop new design of the pit (Figure 12) and torch heating furnaces and methods of heating products in them (Figure 13). Patents for new structural design for torch furnaces and ways of heating products in them were awarded.

(Figure 12) uses the following designations:1 – camera; 2 – cover; 3-5 back, side, front walls ; 6 – regenerator units, respectively; 7,8 – air and gas regenerators, respectively; 9 – mixing chamber; 10 – technological opening ; 11 – ingots; 12 – torch.

Patents for inventions of torch furnaces were obtained: I –

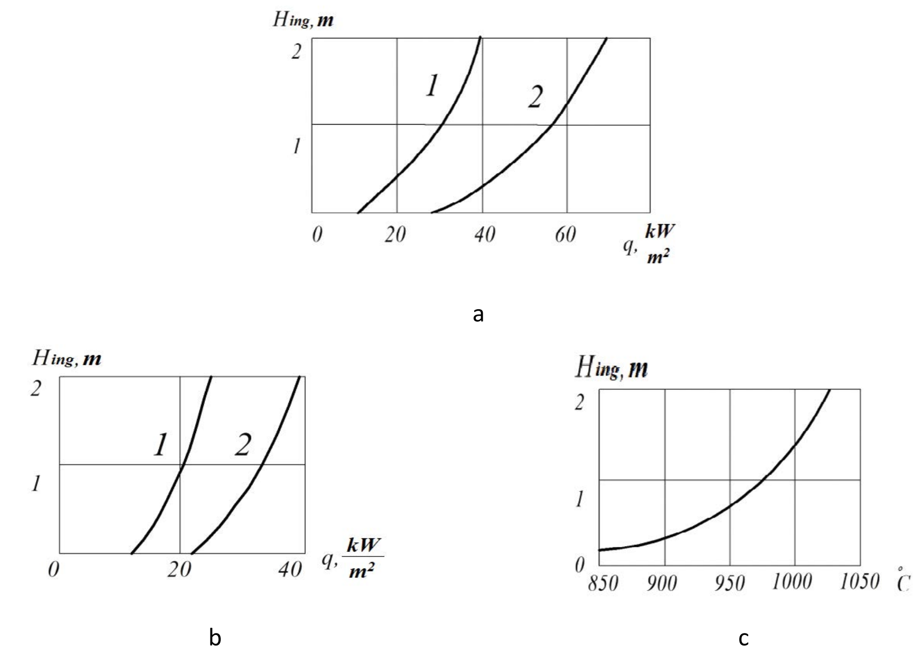

Figure 8. Graph of the distribution of total heat fluxes along the height of the side surface of the ingots facing the walls surface (a) and to the O_1O_2 axis (b); a: 1 – by the height of the I, II, IV rows; 2 - by the height of the III – V, VII ingots; b: 1 – by the height of ingots of the I, II, VI, VII rows ; 2 – by the height of ingots of the III – V rows; c –temperature change by the height of ingots at a distance of 80 mm from the surface during heating .

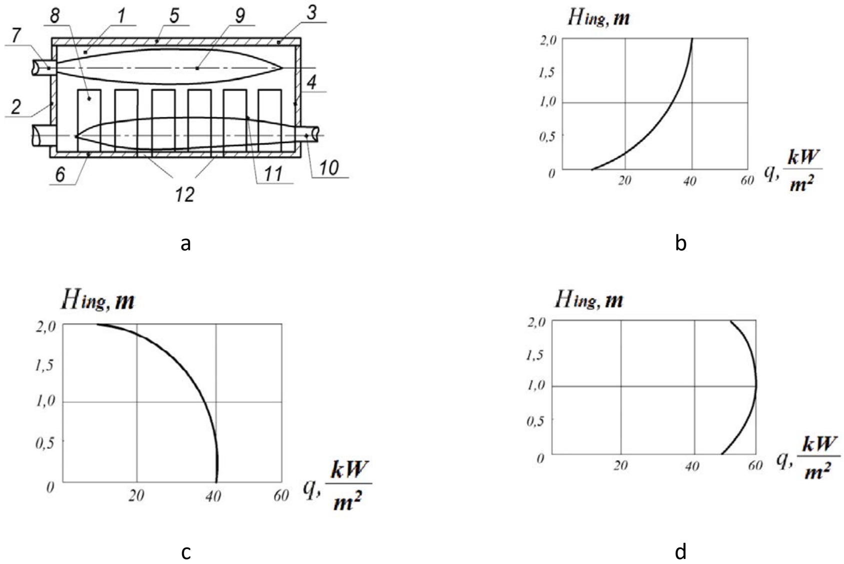

Figure 9. Scheme of the recuperative heating pit with two torches (a) and the distribution of the average heat fluxes along the height of the ingots when the upper burner works (b), the lower burner works (c), the upper and lower burners work together (d):1 – camera, 2 – frontal wall, 3 – side wall, 4 – back wall, 5 – moving cover, 6 – arch, 7 – burner, 8 – ingots, 9 – upper torch, 10 – burner, 11 – lower torch, 12 –air supply holes.

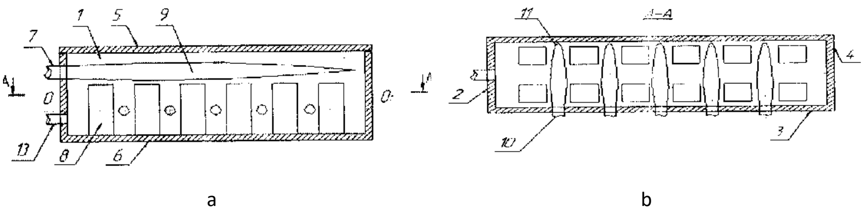

Figure 10. Recuperative pit, side views (a), top view (b), designations similar to those shown in Fig. 9.

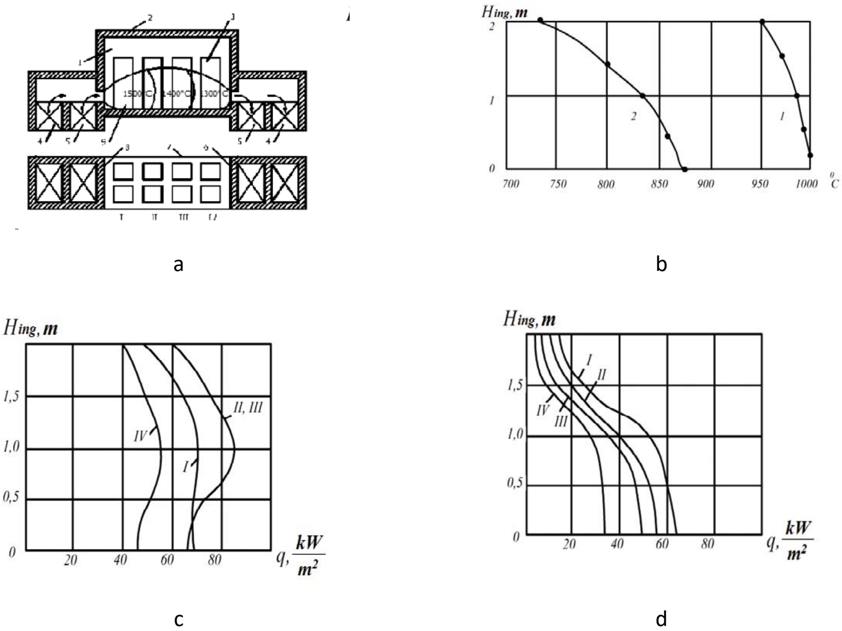

Figure 11. Scheme of the regenerative heating pit (a), the temperature change along the height of the side surface of the ingots facing the wall of the pit (1) and the longitudinal axis of symmetry of the pit (2) after 3 hours from the beginning of heating (b), the distribution of the height of the ingots of integral heat fluxes falling on the side surfaces facing the side wall of the pit (c) and the longitudinal axis of symmetry of the pit (d).

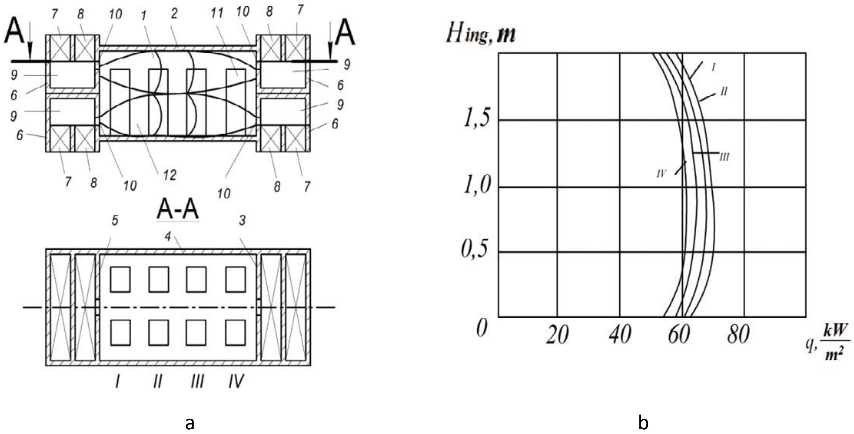

Figure 12. Scheme of the regenerative heating pit with a block of regenerators in two tiers (a) and the height distribution of ingots of integral heat flows falling on the side surfaces facing the longitudinal axis of symmetry of the pit (b) [24].

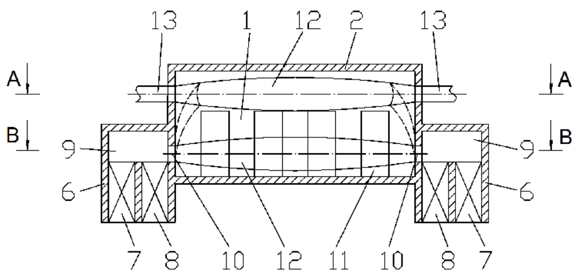

Figure 13. Scheme of the regenerative heating pit with the upper and lower torches, designations similar to those shown in Fig. 12.

with 2 tiers of regenerators; II – with the upper and lower torch; III – with the lower and 5 upper torches [24-28].

Conclusions

1. Existing methods for calculating heat transfer such as zonal, numerical, Pl - approximation, Monte Carlo, Schuster-Schwarzschild, Eddington, Chandrasekhar, spherical harmonics and others use the Stefan-Boltzmann law of heat radiation from solids. However, the radiation from gas volumes of electric arcs and torches is not subject to the Stefan-Boltzmann law of radiation from solids and the calculation error is 70-90% or more.

2. In the twentieth century in articles, monographs, textbooks of Russian and foreign scientists, designers century there was no data on the causes of uneven wear and low resistance of the lining of the walls, the arch of electric arc steel melting furnaces, uneven melting of the charge, the temperature of the metal around the perimeter due to the lack of the laws of heat radiation from gas volumes and the inability to accurately calculate the heat transfer. There were no results of the calculation of the distribution of the heat radiation fluxes from the torch along the height and perimeter of the furnaces, the burner device, there was no explanation for the unevenness of vaporization and deposits in the pipes. There was no data on the distribution of heat fluxes on all surfaces, faces and height of heated products in torch furnaces. There were no calculated data on the distribution of the heat radiation fluxes from the torch along the flame tube and the burner device of the combustion chambers.

3. The lack of accurate data of heat transfer calculations was compensated by the results of numerous, expensive, time-consuming, long-term experimental studies of heat transfer and technical modes of operation of electric arc steelmaking and torch furnaces, fire boxes, combustion chambers.

4. At the end of the XX century, the laws of heat radiation from gas volumes, the laws of heat radiation from electric arcs of steel melting furnaces and torches of heating furnaces, fire boxes, and combustion chambers of gas turbine power plants were discovered. The disclosed laws of heat radiation from gas volumes, as well as the laws of heat radiation from solids of Planck, Wien, Stefan-Boltzmann belong among the fundamental laws of physics which have multidisciplinary and applicability in various fields of science and technology.

5. The discovery of the fundamental law of physics is an outstanding event in the history of mankind and takes place on average once in 50-80 years. Physics textbooks for schools and universities, which set out a little more than 30 laws discovered by humankind for three thousand years, since the third century BC from the law of Archimedes and to the last fundamental laws, postulates discovered by Bohr in 1913 are proof of this.

6. The scientific discovery and the calculation methods developed on its basis allow scientists, engineers, designers to calculate the heat transfer and improve the design of electric arc steelmaking and torch heating furnaces in metallurgy, in various industries, including various fields of mechanical engineering, the design of steam boiler boxes and combustion chambers of gas turbine plants in the energy sector, save millions of kW·h of electricity and millions of tons of fuel, reduce emissions of pollutants, reduce the anthropogenic load on the environment.

References

1. Blokh AG. Heat Radiation in Boiler Units. Leningrad: *Energiya*, Russian, 1967.

2. Blokh AG, Zhuravlev YA, Ryzhkov LN. Radiant Heat Transfer: A Handbook. Moscow: *Energoatomizdat*. Russian. 1991.

3. Nevskii AS. Radiant Heat Transfer in Furnaces. Moscow: *Metallurgiya*. Russian, 1971.
4. Kutateladze SS. Heat Transfer and hydraulic resistance: reference manual. Moscow: *Energoatomizdat*, Russian, 1990.
5. Siegel R, Howell Y. Thermal Radiation Heat Transfer. Moscow: Mir, Russian, 1975.
6. Ozirik MN. Radiative Transfer and Interaction with Conduction and Convection. Moscow: Mir, Russian, 1976.
7. A.N. Makarov, AD Svenchanskii. Optimal Operating Conditions of Arc Steel Melting Furnaces. *Energoatomizdat*. Russian. 1992.
8. Makarov A.N. Changing arcs efficiency during melting in EAF. *Metallurgist*. 2017;61(3-4):298-301.
9. Makarov A.N. Laws of heat radiation from surfaces and gas volumes. *Word Journal of Engineering and Technology*. 2015;3(4):260-270.
10. Makarov AN. Laws of radiation from large gas volumes and calculation of heat transfer in steam boiler boxes. *Mechanical Engineering Research*. 2015;5(1):42-55.
11. Alekseenko SV, Burdukov AP, Dekterev AA, et.al. Physical and mathematical modeling of aerodynamics and combustion in the combustion chamber of the power plant. *Teploenergetika*. 2011;9:67-72.
12. Maydannyk MN, Verbovetsky EH, Dekterev AA, Chernetsky MY. Mathematical modeling of fire box and rotary flue of furnace P-50 R in joint combustion of solid and gaseous fuels. *Teploenergetika*. 2011;6:17-42.
13. Makarov AN. Theory of Radiative heat exchange in furnaces, fire boxes, combustion chambers is replenished by four new laws. *Science Discovery*. 2014;2(2):34-42.
14. Mastryukov BS. Thermal Engineering Calculation of Industrial Furnaces. Moskow: *Metallurgia,* Russian, 1972.
15. Makarov AN. Calculation of Heat Transfer in the Furnaces of Steam Boilers According to the Laws of Radiation of Gas Volumes. *Heat Transfer-Models, Methods and Applications*. *London: InTechOpen*. 2018;111-130.
16. Makarov A.N. Fundamental Laws of Physics and Calculation of Heat Transfer in Combustion Chambers of Gas Turbine Plants. *Word Journal of Engineering and Technology*. 2017;5(3):358-375.
17. Makarov A.N. Calculation of heat transfer in torch furnaces by gas volume radiation laws. *Word Journal of Engineering and Technology*. 2016;4(3):488-503.
18. Makarov AN. Flare temperature and nitrogen oxide emission reduction in the TGMP314I steam boiler firebox. *Power Technology and Engineering*. 2016;50(2):200-203.
19. Makarov AN. Heat Exchange in Arc and Torch Metallurgical Furnaces and Power Stations: Studies. A Grant for Students of Higher Education Institutions. *St-Petersburg: Lan'*, Russian, 2014.
20. Mikel Ortiz, Mariluz Penalva, Edurne Iriondo, et.al.Investigation of Thermal-Related Effects in Hot SPIF of Ti–6Al–4VAlloy. International *Journal of Precision Engineering and Manufacturing-GreenTechnology* . (2019);2:1-19.
21. Amaia Calleja, Iván Tabernero, Jon Ander Ealo, et.al. Feed rate calculation algorithm for the homogeneous material deposition of blisk blades by 5-axis laser cladding.*The International Journal of Advanced Manufacturing Technology*. (2014);74(10):1219-1228.
22. Makarov A.N. Regularities of heat exchange in gas layers of a torch and screens of fire chambers of boilers. Part II. Examples of calculation of heat exchange in torch furnaces and fire chambers of boilers. *Thermal Engineering.* 2014;(61)10:717-723
23. Makarov AN, Sveshnikov IM. Patent 2637199. Recuperative heating pit. *Inventions.* 2017;34:45-46.
24. Makarov AN, Voropaev VV. Patent 2312907. Regenerative heating pit. *Inventions*. 2007;35:11-12.
25. Makarov AN, Andreev IA. Patent 2637200. Regenerative heating pit. *Inventions*. 2007;34:18-19.
26. Makarov AN, Voropayev VV, Krivnev EI. Patent 2285200. The fire chamber for combustion of oil-gas fuel. *Inventions*. (2006);28:36-37.
27. Makarov AN, Shevchenko M.N. Patent 2400668. A fire chamber for combustion of oil-gas fuel. *Invention*. 2010;27:39-40
28. Makarov AN. The Laws Heat Radiation from Solids, Gas Volumes and the Fundamental Laws of Physics. *Journal of Applied Physics & Nanotechnology*. 2019;1(2):1-5.