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Modeling of a Torch and Calculations of Heat Transfer in Furnaces, Fire Boxes, Combustion Chambers. Part I. Calculations of Radiation from Solids and Gas Volumes by the Laws of Radiation from Solid Bodies

Prof., Dr. A. N. Makarov

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

Abstract— *Through the 20th century scientists, researches made many attempts to solve important complex scientific problem. The solution to the problem was to derive analytical expressions, formulas for calculating heat radiation from gas volumes, torches on heating surfaces. However, the formulas were not derived in the 20 th century. At the beginning of the 21st century the author of this article disclosed the laws for heat radiation from cylinder gas volumes. On the basis of the scientific disclosure the problem was solved, analytical equations for calculating heat transfer in torch furnaces, steam boiler boxes, combustion chambers of gas-turbine installations were obtained. To assess the scientific disclosure and its present and future roles, the analysis of methods for calculating heat transfer in furnaces, fire boxes, combustion chambers was performed.*

Keywords— Scientific disclosure, Laws, heat radiation, Torch.

I. INTRODUCTION

Torch is formed during combustion of gas, liquid, pulverized fuel in heating furnaces, steam boiler boxes, combustion chambers of gas-turbine installations of power plants. The torch presents a high temperature gas volume in furnaces, fire boxes, combustion chambers. The results of investigations and analysis from heat transfer in torch furnaces, fire boxes, combustion chambers, carried out by several hundreds of Russian and foreign scientists in 1920-2010 were the same: 85-95% of torches power during combustion of fuel is released as heat radiation flux and convective flux to heat conduction accounts for 5-15 % of torches power[1-3].

In the beginning of Industrialization solid fuel (coal, peat, slates, wood) was fired in furnaces, fire boxes on fire grates. In the late 19th – early 20th century Stefan, Boltzmann, Planck, Wienn disclosed the laws of radiation from solid bodies, that bear their names.

Wienn and Planck received the Nobel Prize in Physics 1911 and 1918, respectively, for the disclosure.

The laws of radiation from solid bodies were used in the 19 - 20th century and continued to be used for calculating heat radiation from solid bodies, solid fuel.

Since solid bodies radiate by surface, two-dimensional models were used for calculating their heat radiation. Solution of double integral differential equations for heat body radiation by surface was found in the 20-th century [1-3].

It was in the 20- 21th century widespread practice to flare gas, liquid, pulverized fuel in furnaces, fire boxes, combustion chambers. To calculate heat radiation from torches, gas volumes, we need to solve triple integral equations for volume radiation from torches.

Throughout the 20th century researches tried to solve triple integral equations, obtain formulas for heat radiation from gas volumes. But the solution to triple integrals in the form of analytical equations, formulas was not found.

In the 20th century the calculations of heat radiation from gas volumes are based on the laws of heat radiation from solids, the radiation from gas volume is modeled by the radiation from their surfaces.

Such assumptions affect the accuracy of the calculations, the uncertainty is 20- 40% [4].

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In 1996-2001 the author of this article disclosed the laws of heat radiation from isothermal isochoric coaxial cylinder gas volumes.

In the diploma for scientific discovery gas volume radiation law is called Makarov's law with the goal of adherence to the age-old scientific traditions and copyright [4].

Based on the disclosed law of heat radiation from cylinder gas volumes, the author of this article developed geometrical, physical and mathematical torch model as a source of heat radiation and modern method for calculating heat transfer in torch furnaces, fire boxes, combustion chambers [5-9].

The modern method allows accurately calculate heat transfer, determine rational sizes and location of torches, burners in gas heating furnaces, steam boiler boxes, combustion chambers of gas-turbine installations of power stations.

The method for calculating heat transfer in torch furnaces, fire boxes, combustion chambers are presented by the author of scientific disclosure in his textbook [10]. The textbook was adopted by the Ministry of Education and Science of the RF and is used for university training in metallurgical and energy universities, as well as in metallurgical and energy companies of Russia. We carry out a brief review of methods for calculating heat radiation of solids, surfaces and gas volumes on the heating surfaces.

II. HEAT RADIATION FROM SOLID BODIES, SURFACES

2.1. Calculation of radiation flux from solid fuel to heating surface

Consider the radiation from solid fuel, radiating by the surface F_1 to the calculation area F_2, located on the heating surface (Fig. 1). The environment is diathermic.

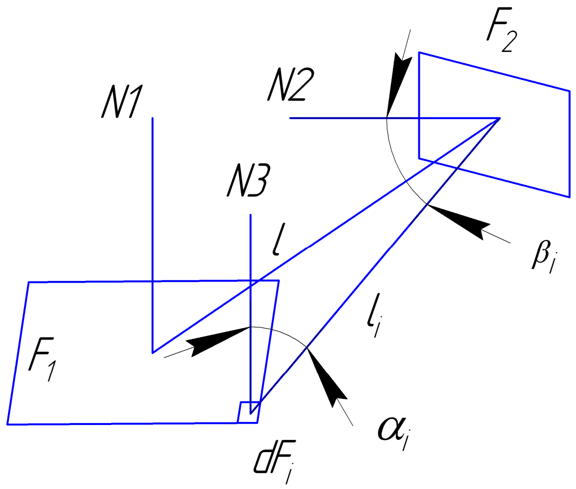

Fig.1:Solid fuel radiation, radiation from the surface F_1 to the calculation area F_2

The radiation from solid fuel is performed by the surface layer of atoms, as radiation from deep, inner layers of atoms is absorbed by the neighboring layers.

Many of the atoms in the top layer, the surface F_1 are modeled by a lot of multiple areas dF_i of a small size.

Fig. 1 uses the following notation: N_1, N_2 are perpendiculars to the centers of symmetry, the surfaces F_1 and the platform F_2, respectively; l is the distance between the centers of symmetry F_1 and F_2; dF_i is the elementary area on the surface F_1; N_3 is perpendicular to the center of symmetry dF_1; l_i is the distance between the centers of symmetry of dF_i and F_2; α_i, β_i are the angles between the beam l_i and perpendiculars N_3 and N_2, respectively.

The temperature of the surface F_1 and the area F_2 are T_1, T_2, respectively.

The density of the incident radiation flux q_{12} of the surface F_1 on the calculation area F_2 in the diathermic environment is determined by the Stefan-Boltzmann law:

$$q_{12} = \frac{\varphi_{12} \cdot q_1}{F_2} = \frac{\varphi_{12} \cdot \varepsilon_1 \cdot c_S \cdot T_1^4}{F_2}, \qquad (1)$$

where φ_{12} is the local angular coefficient of radiation from surface F_1 on the area F_2, shows the portion of radiation from F_1 on F_2, of all the radiation from F_1 into the surroundings; q_1 is the flux density of heat radiation from a unit of the surface F_1; F_1, F_2 are the surface areas, F_1 and F_2, respectively; c_s is the coefficient of blackbody radiation ; ε_1 is the coefficient of surface radiation F_1.

The temperature T_1, surface areas F_1, F_2, coefficients of radiation c_S, ε_1 are known in the calculations. Determination of the local angular coefficient φ_{12} involves a certain difficulty in the calculations. Assume, that the sizes of the surface F_1 are the following: the length a, the width b. The surface F_1 is divided into several hundreds of elementary areas dF_i and the local angular coefficient of radiation is determined by the equation:

$$q_1 = \int_a \int_b \frac{\cos\alpha_i \cdot \cos\beta_i}{\pi \cdot l_i^2} \cdot da \cdot db, \qquad (2)$$

Double integrals (2) were solved in the 20 th century when placing surface and calculation area in mutual parallel, perpendicular and arbitrary located planes. Analytical expressions, obtained in solving double integrals are detailed in the referenced data, for instance [2].

The disclosure of the laws by Stefan, Boltzmann, Planck, Wien in the late 19-early 20th century, and development on their basis the calculation procedures by scientists in the middle and the end of the 20th century and their use in practice allowed to increase fuel efficiency in solid fuel furnaces, fire boxes from 25- 35 % at the beginning to 70-90% at the end of the 20th century.

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The result of radiant heat transfer between the surfaces F1 and F2 depends on the temperatures T1 and T2 and is characterized by the density of net radiation flux q_{net12} which is determined by the following equation:

$$q_{net12} = \varphi_{12} \cdot \varepsilon_1 \cdot c_0 \cdot \left[\left(\frac{T_1}{100} \right)^4 - \left(\frac{T_2}{100} \right)^4 \right] \cdot F_2^{-1}, \quad (3)$$

where c_0 is the coefficient of black body.

The net radiation flux density can also be determined by the difference between the density of the incident radiation flux and its own radiation flux from the area F2 . With the known incident radiation flux density, the calculation of the net flux is not difficult, therefore carry out the calculation of the incident radiation flux densities.

2.2. Calculation of radiation from surface on the area in absorbing medium

In the process of solid fuel combustion the furnace is filled with absorbing gas and the part of surface radiation F_1 is absorbed by gas (Fig. 1).

The density of incident radiation flux q_{12} of the surface F1 falling on the calculation area F_2 in the absorbing medium is determined by the expression :

$$q_{12} = \varphi_{12} \cdot \varepsilon_1 \cdot c_S \cdot T_1^4 \cdot F_2^{-1} \cdot e^{-kl_{av}}, \quad (4)$$

where k is the gas medium absorption coefficient; l_{av} is the effective, average beams path length.

The average path length of beams l_{av} is determined as the arithmetic mean distance from the elementary areas dFi to the symmetry center of the area F_2. For instance, when dividing the surface F1 into 500 elementary areas dF_i, the average beams path length is determined as follows:

$$l_{av} = \left(\sum_{i=1}^{500} l_i \right) / 500 \quad (5)$$

To determine the average beams path length from a few hundred radiating areas dF_i to the calculation area F_2 it is necessary to solve the dual integral similar to (2) in the unknown l_i within the F_1 area sizes.

III. HEAT RADIATION FROM GAS VOLUMES

3.1. Calculation of radiation from gas volume to the area by the laws of radiation from black body.

Radiating and absorbing gas volume is formed in flaring gas, liquid, pulverized fuel.The torch, formed during combustion of gas, liquid, pulverized fuel, is removed from the heating surface, combustion products fill the whole furnace, fire box, combustion chamber. Gas volume of the torch radiates heat on the heating surface.

Consider the radiation from the torch volume part, representing isothermal gas volume in the form of rectangular-parallelepiped of a × b × h = 3 × 3 × 3 meters on the calculation area F_2 (Fig. 2).

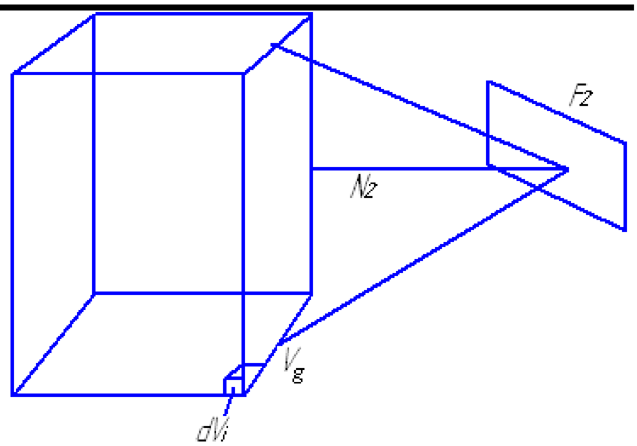

Fig.2: Gas volume radiation V_g on the calculation area F_2

Gas volume is filled with the radiating particles and is simulated in the calculations by a variety of elementary rectangular parallelepipeds of infinitesimal height dV_i, filling the volume V_g from the bottom to the top base.

The density of the incident radiation flux q_{V2} of gas volume V_g on the calculation area F_2 in the absorbing medium is determined by an expression similar to (4):

$$q_{V2} = \varphi_{V2} \varepsilon_g c_S T_g^4 F_2^{-1} e^{-kl_{av}}, \quad (6)$$

where φ_{V2} is the local angular gas volume coefficient V_g on the area F_2; ε_g, T_g are the emissivity and the temperature of gas volume, respectively. The local angular coefficient of radiation from gas volume V_g on the area F_2 is determined by the equation [10]:

$$\varphi_{V2} = \int_a \int_b \int_h \frac{\cos\alpha_i \cos\beta_i}{2\pi l_i^2} dadbdh, \quad (7)$$

The expression (7) shows the symbols used in the expression (2). Solution to the expression (7) was not found in the 20th century and no solution was found to the expression (6).

To determine the average length of the beams path from a set of infinitesimal volumes, elementary rectangular parallelepipeds, filling gas volume, it is necessary to solve triple integral within the gas volume. The problem of determining the average length of the beams path with a triple integration within gas volume is not solved.

For an approximate solution to the problem for determining the average angular coefficient of radiation, the average length of the beams path, the density of the incident radiation flux from gas volume, the zonal method is offered and was used during the 20th century [1-3].

It was offered to model the radiation from gas volume by the radiation from its surface. Non-isothermal gas and the shell closing it are divided into a number of volumes and spaces, which are considered to be isothermal. For surfaces, limiting the gas volume, we determine the

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average length of the beams path to the calculation area, the calculations are summarized in the table [2]. For each volume and area we write down the energy balance equation. A system of equations is obtained in the unknown heat fluxes and temperatures, which is solved by computers numerical method.

Calculations are based on the laws of radiation from solid bodies, the volume radiation is modeled by surfaces radiation, the calculation use a large mass of approximate values of temperatures, emissivity, absorption.

The accuracy of calculations is 20-40%. Low accuracy of the zonal method recognized Siegel R. and Howell Y. [2].

The problem of solving average angular coefficients of radiation from gas volumes on the calculation areas and determining the average path length of the beams was solved with the discovery of the laws of radiation from isothermal isochoric coaxial cylindrical gas volumes [4].

3.2. Calculation of heat radiation from gas volumes on the heating surfaces by the laws for radiation from cylinder gas volumes.

Put the cylinder 1 with a diameter of 3 m (Fig. 3) in gas volume that represents a rectangular parallelepiped of size 3×3×3 m (Fig. 2).

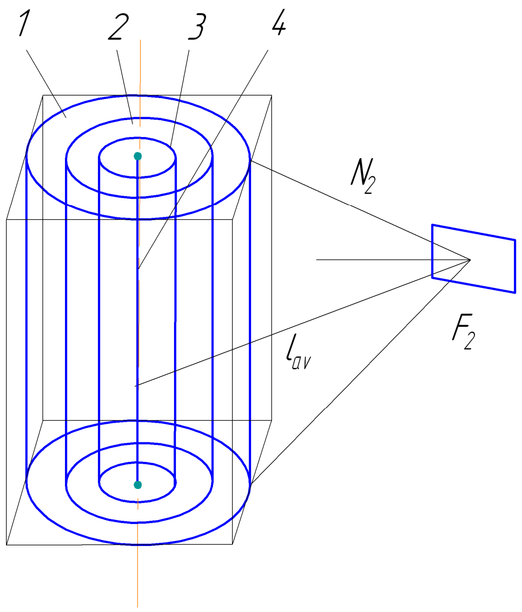

Fig.3: Radiation from coaxial cylinder gas volumes on the calculation area F_2

Assume,15•10^{15} atoms, uniformly filling the volume V1, simultaneously emit in the gas volume 1.

Inscribe cylinder 2 and 3 in the cylinder 1, while the volume of radiating gas between the cylinders 1 and 2, 2 and 3, and also the cylinder 3 are the same.

We have three isochoric isothermal coaxial cylinder gas radiating volumes 1-3, each of which has 5•10^{10} atoms (Fig. 3).

Let the cylinder gas volume of an infinitely small diameter with a height of 3 m, located on the axis of symmetry of coaxial cylindrical gas volumes be denoted by 4.

The author established the four laws of heat radiation from isochoric isothermal coaxial cylinder gas volumes [4].

For notational compactness of the laws, using copyright, the author combined the four laws of heat radiation from gas volumes in one law read as follows:

"The average path length of beams from quadrillions of radiating particles of each isochoric isothermal coaxial cylinder gas volume to the calculation area is equal to the arithmetic mean distance from the symmetry axis of coaxial volumes to the calculation area and angular coefficients of radiation, densities of radiation fluxes of isochoric isothermal coaxial cylinder gas volumes on the calculation area are equal.

The flux density of heat radiation from the central coaxial cylinder volume of a small diameter on the calculation area is equal to the sum of the densities of radiation fluxes from all isochoric isothermal coaxial cylinder gas volumes in radiation power released in a small diameter volume equal to the sum of radiation power released in all isochoric isothermal coaxial cylinder gas volumes radiating on the calculation area".

Theoretical justification of the scientific discovery and its experimental verification are presented in [4-10].

The author discovered a physical phenomenon, whereby the heat radiation from three isochoric isothermal coaxial cylinder gas volumes 1-3 can be replaced by an equivalent radiation from coaxial cylinder gas volume 4 of a small diameter in radiation power releasing in it equals the sum of power radiation from cylinder gas volumes 1-3 (Fig.3).

It is determined, that under this condition, the flux densities of radiation from coaxial cylinder gas volumes 1-3 and gas volume 4 of infinitely small diameter on the calculation area are equal. The local angular coefficients of radiation and the average path length of the beams of coaxial cylindrical gas volumes 1-4 on the calculation area are also equal.

Scientific discovery determined, that the average path length of the beams from quadrillions of radiating particles, atoms, coaxial cylinder gas volumes to the calculation are equals arithmetic mean distance from the axis of symmetry of coaxial volumes to the calculation area.

The uniqueness of the scientific discovery is that the determining the average path length of the beams from the quadrillions radiating particles doesn't require to perform triple integration within the gas volume with variable beam path length of from each radiating particle in the integrand.

To determine the average path length of the beams from quadrillions of radiating particles, it is sufficient to divide the height of the cylinder volume 4 of a small diameter, for example, into 10 segments and determine the average path length of the beams from their midpoints to the calculation area:

$$l_{av} = \left(\sum_{i=1}^{10} l_i \right) / 10, \qquad (8)$$

where l_i is the distance from the midpoint of the *i-th* segment to the area F_2.

The uniqueness of the scientific discovery is that at equivalent radiation of coaxial cylinder gas volumes 1-4 for determining the local angular radiation coefficients of gas volumes to the calculation area it is sufficient to carry out a single integration of varying geometric parameters within the height of coaxial cylinder gas volume 4 of a small diameter.

Single integration of variable functions is studied and widespread, there are tables of solution algebraic, exponential, trigonometric and logarithmic functions. The author found the solution of single integrals with trigonometric functions, similar to that used in (2), (7), in the integrand of equations [10].

IV. CONCLUSION

Thus, with scientific disclosure of the laws for heat radiation from coaxial cylinder gas volumes, which were called Makarov's laws [4] to adhere to copyright, the opportunity appeared to determine the average beams path length from quadrillions of radiating particles, local and the average angular coefficients of radiation from gas volumes in modeling them by cylinder gas volumes [4-10].

Thus, in the equations (6-7) undefined factors are left and radiation flux densities, the average length of the path of the beams, the local angular coefficients of gas volume radiation on the calculation areas can be calculated. Scientific discovery has created the possibility to calculate the radiative heat transfer in torch furnaces, steam boiler boxes, combustion chambers of gas turbine installations of power plants with high precision [10]. An example of the calculation procedures of angular radiation coefficients, the average path length of the beams, the flux density of radiation from gas volume on the calculation area is executed in the second part of the article.

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