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Laws of Heat Radiation from Spherical Gas Volumes.
Part I. Laws Formulation

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***Abstract*— *In 2014-16 the author of this article disclosed the laws of heat radiation from isothermal isochoric concentric spherical gas volumes, that the article presents. Radiating gas volumes of any complex form can be entirely filled by concentric spherical together with coaxial cylinder gas volumes and calculate heat radiation from gas volumes, furnace torches, fire boxes, combustion chambers on the heating surfaces with high accuracy.*

Keywords—Scientific Disclosure, Laws, Heat radiation, Torch, Furnaces. Fire Boxes.

I. INTRODUCTION

This monograph is the continuation of the research work, which results are presented in [1,2]. Flaring of gaseous, liquid, pulverized fuel in furnaces, fire boxes combustion chambers is characterized by volume heat radiation. Quadrillions of particles, atoms radiate in torch. We need to consider radiation from every particle, atom to the calculated area.

To calculate the heat radiation from all the atoms that make up the torch to the calculated area it is necessary to solve triple integral equations. The solution for triple integral equations to determine the average beam path length from the radiating particles, the angular radiation coefficients of gas volumes to the calculated area was not found in the 20th century [1,2].

It is considered, that the problem of calculation heat radiation in torch furnaces, fire boxes, combustion chambers was solved with the appearance of computers and use of numerically modeled heat transfer integral equations. However, long-term analytical and experimental studies of heat transfer showed, that the results from numerical solution of integral heat transfer equations on computers are not entirely correct.

This method uses the laws of heat radiation from solid bodies, Stefan-Boltzmann law, large mass of approximate temperatures and optical coefficients of surface and volume zones and error made in calculations accounts for 20-40% [3,4].

At the end of the 20th century, in 1996-2001 the laws of heat radiation from isothermal isochoric coaxial cylinder gas volumes were disclosed [5].

The laws are called Makarov's laws with the goal of adherence to the age-old scientific traditions and copyright [4,5]. Based on the scientific discovery the new heat transfer calculation concept in torch furnaces, fire boxes, combustion chambers is developed [4-6].

In accordance with the new concept and method for calculation, cylindrical gas volumes, from which the calculation of radiation fluxes on the calculated areas and the heating surfaces, inscribe in the torches.

In accordance with the new concept and the method for calculation, cylinder gas volumes, from which the calculation of radiation fluxes on the calculated areas and heating surfaces is performed, inscribe in torches.

Radiation fluxes from the torch, heated surfaces, combustion products are determined for every calculated area including the multiple reflection and absorption of radiations. The new concept and method of calculation stood the test of time, the calculation results are confirmed by experimental studies on the operating furnaces, fire boxes, combustion chambers, calculation error does not exceed 10%.

In 2001-16 the author continued investigation of heat radiation from torches of furnaces, fire boxes,
combustion chambers, symmetrical radiating gas volumes.

In 2014-16 the author of this article disclosed the laws of heat radiation from isochoric isothermal concentric spherical gas volumes.

This article informs the scientific community of the scientific discovery and its practical use of heat transfer calculations in furnaces, fire boxes, combustion chambers.

II. LAWS OF HEAT RADIATION FROM SYMMETRICAL GAS VOLUMES

2.1. Laws of heat radiation from cylindrical gas volumes

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Symmetrical radiating gas volumes include cylindrical and spherical radiating gas volumes, which possess a number of unique properties.

To calculate heat radiation incident on the calculated area from gas volumes of any arbitrary form, it is necessary to solve two problems.

The first problem is to calculate elementary angular coefficient of radiation from gas volume on the calculated area. The second problem is to calculate the average path length of beams from quadrillions of radiating particles of gas volume to the calculated area [1].

Elementary angular radiation coefficient from gas volume to the calculated area shows heat radiation ratio from gas volume to the calculated area of all heat radiation from gas volume in the surroundings.

To solve the first and the second problems, it is necessary to solve two triple integral equations with limits of integration by the gas volume.

In the 20th century the solution for triple integral equations was not found, the problem has reached a deadlock. The formulas for calculating the elementary angular radiation coefficients of gas volumes and the average beam path length were not developed.

In the 20th century, the double integral equations were solved, formulas for calculating the average beam path length and elementary angular coefficients of radiation from flat and convex surfaces on the calculated areas at their any spatial collocation were obtained and referenced [3].

Formulas for calculating the average beam path length and elementary angular coefficients of radiation from surfaces were used for calculating heat radiation from gas volumes, the radiation from volumes were replaced by the gas volume bounding surface and calculations were performed by the laws for radiation from solid bodies.

The error made in calculations was 20-40%.

The study of heat radiation from symmetrical radiating gas volumes, isochoric isothermal coaxial cylinder gas volumes allowed to disclose their unique properties, the laws of Makarov, and derive formulas for calculating local angular radiation coefficients of gas volume and determining the average beam path length from all of the radiating particles of gas volume to the calculated area [1,2].

In exercise the copyright, the author has combined four laws of heat radiation from isochoric isothermal coaxial cylinder gas volumes into one law read as follows.

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

The flux density of heat radiation from the central coaxial cylinder volume of a small diameter on the calculated area is equal to the sum of the densities of radiation fluxes from all 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 calculated area".

Naturally occurring harmony, consistency of heat radiation from quadrillions of radiating particles of isothermal symmetrical radiating volumes is discovered.

The uniqueness, harmony, consistency of heat radiation from quadrillions of radiating particles is that the average beam path length from these particles is equal to the arithmetic mean distance from the calculated area to the symmetry axis of the particles.

Complex triple integration within the gas volume to determine the average beam path length [1], that doesn't have the solution is reasonably replaced by simple arithmetic operations of addition and division, the result, which would have received in triple integration is obtained.

As a result of harmonious coherent heat radiation of quadrillions of particles radiating isochoric isothermal coaxial cylinder gas volumes, radiation flux densities, angular radiation coefficients of gas volumes are equal and for their definition it is sufficient to carry out a single integration of trigonometric functions within the height of the cylindrical volume along the axis of their symmetry.

On the basis of the scientific discovery a new concept and method for calculating heat transfer in furnaces, fire boxes, combustion chambers is developed [4-6]. The new concept and method for calculation included in the textbook [7], which was approved by Educational Association of Ministry of Education and Science of the Russian Federation for training university students in metallurgical and energy specialties. The tutorial [7], as well as a monograph of 1992 [8] are used in metallurgical and energy companies for selection the rational heat conditions of the operating and constructed electric arc and torch furnaces, fire boxes, combustion chambers.

The new concept and method for calculating heat transfer in furnaces, fire boxes, combustion chambers allow thousands of researchers and engineers in dozens of countries worldwide to save millions of tons of gaseous, liquid, pulverized fuel.

Fuel saving is achieved by selection of rational sizes and location of the burner torches, optimization of heat conditions in the operating constructed furnaces, fire boxes, combustion chambers.

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This statement is confirmed by the following facts. Currently, about 40% of the steel in the world is melted in arc steel melting furnaces (ASFs). Until 1978, arc steel melting furnace (ASF) represented a "black box", uninvestigated phenomenon, qualitative method for calculating heat transfer in ASFs was not available.

In 1978-82 years the author developed geometric, physical, mathematical model of the electric arc, the main source of energy in the ASF as ionized gas radiating cylinder gas volume [9, 10].

Electric arc model as a radiant heat source was defended by the author of this article in 1982 at Moscow Power Institute in the form of a master's thesis.

In 1983-92's, the author of this article developed experimental investigations in metallurgical plants of Russia: Severstal, Chelyabinsk, Orsk-Khalilov, Oskol Electric and others.

The theory of heat transfer and the results from experimental researches are defended by him in the form of a doctoral thesis at St. Petersburg Electrotechnical University in 1995.

The results from theoretical and practical studies of heat transfer in ASFs are published in 1992 in Moscow publishing house "Energoatomisdat" in the form of a monograph "The optimal thermal conditions of ASFs" [8].

Since 1992 the monograph has been a major reference book on heat transfer in ASF within Russian metallurgists, as well as teachers and students of metallurgical faculties of universities.

Over 60-hundred-ton electric arc furnaces with a capacity of 90 MW are installed at Russian metallurgical plants with a productivity rate of 1 million ton of steel each.

At the end of the 1980s the specific energy consumption in these furnaces was 450-460 kWh, the total consumption of a furnace was 450-460 million kWh per year.

By 2015, due to technological factors and the proper organization of heat transfer, the specific energy consumption in these furnaces has decreased to 350-360 kWh, total energy consumption has decreased to 350-360 million kWh per year by a furnace.

Energy saving is 100 million kWh per year for a furnace.

Some of the credit for energy savings at metallurgical plants, reduction fuel consumption for the production of this energy belongs to the author of this article, the developer of rational methods of calculating heat transfer in electric arc furnaces. The developer of the new concepts and techniques with students continue to develop new cost-effective ways for smelting steel in ASFs [11].

In 2001-16 the author continued investigation of heat radiation from torches of furnaces, burners, combustion chambers, symmetrical radiating gas volumes. In the years 2014-16 the author of this article discovered the laws of heat radiation from isochoric isothermal concentric spherical gas volumes.

This article informs the scientific community about scientific discovery and practical use of it in heat transfer calculations in furnaces, fire boxes, combustion chambers.

2.2. Laws of Heat Radiation from Spherical Gas Volumes.

In accordance with the new concept and the method for calculation radiating cylinder gas volumes, from which the calculation of radiation fluxes on the calculated areas and heating surfaces is performed, inscribe in torches.

However, torches, gas radiating volumes may have a complex three-dimensional from, which cylindrical gas volumes cannot fullfill. The parts of the gas torch volume, which radiation are not included in the calculations, remain unfilled.

To increase the accuracy of calculations and further filling of gas radiating volumes, the author studied heat radiation of spherical gas volumes in 2010-16.

During the study of heat radiation from spherical gas volumes, the scientific laws for heat radiation was discovered. The essence of scientific discovery is in the following.

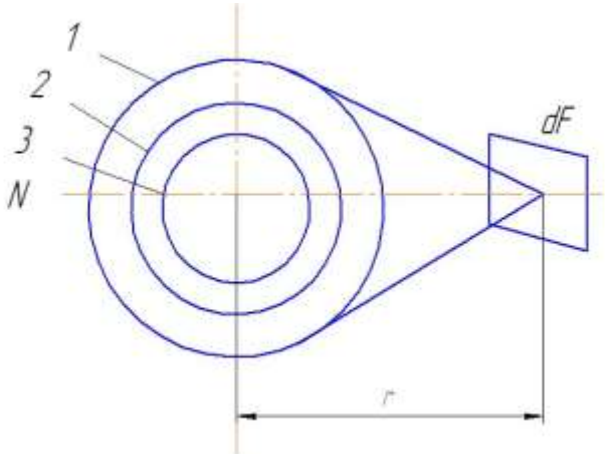

Fig.1: The radiation from spherical gas volume on the calculated area dF.

Consider the radiation from isothermal spherical gas volume of diameter D_1 = 3m on the calculated area dF, sizes 0,5x0,5m located on a vertical surface at a distance r =3m from the spherical gas volume (Fig. 1).

Perpendicular N to the area dF passes through the center of spherical gas volume. For example, $15 \cdot 10^{15}$ atoms, uniformly filling the volume, radiate in spherical gas volume at the same time. The power, radiated by the gas volume is P = 42 MW [2], the volume of gas confined in the sphere is $V = \pi D^3 / 6 = 14{,}13\ m^3$.

Divide isothermal spherical gas volume into three equal volume spherical volumes with a common center. The diameter of the first spherical volume is D_1 = 3m, the second is D_2 = 2,62 m, the third is D_3 = 2,08m.

The volume of radiating isothermal gas in each space between 1 and 2, 2 and 3, and also within the third sphere is $V_1 = V_2 = V_3 = V / 3 = 4{,}71 m^3$. We got three isochoric isothermal concentric spherical gas volumes that radiate on the calculated area dF.

Assume, that the radiation from inner layers of concentric spherical gas volumes is absorbed by neighbor layers and radiation from only external surface layer of spheres of gas spaces goes outward.

In this case, the isochoric isothermal radiation from three concentric spherical gas volumes can be represented by radiation from three spheres F_1-F_3.

Formulas for calculating angular radiation coefficients from one surface to another were obtained in the 20th century [3, 12].

Angular radiation coefficient φ_{dFF} of dF area on the sphere F is determined by the expression [12]:

$$\varphi_{dFF} = \frac{\cos\alpha}{H^2}, \qquad (1)$$

where α is the angle between the perpendicular N to the center area dF and the ray connecting the center of the area and sphere; H = r / (D / 2).

Elementary angular radiation coefficients of concentric spheres to the area dF 1-3 are defined as follows:

$$\varphi_{F_1dF} = \frac{\varphi_{dFF_1} F_{dF}}{F_1} = \frac{0{,}25\cdot 0{,}25}{3{,}14\cdot 3^2} = 0{,}0022;$$
$$\varphi_{F_2dF} = \frac{\varphi_{dFF_2} F_{dF}}{F_2} = \frac{0{,}189\cdot 0{,}25}{3{,}14\cdot 2{,}62^2} = 0{,}0022; \qquad (2)$$
$$\varphi_{F_3dF} = \frac{\varphi_{dFF_3} F_{dF}}{F_3} = \frac{0{,}121\cdot 0{,}25}{3{,}14\cdot 2{,}08^2} = 0{,}0022,$$

where φ_{dFF1}, φ_{dFF2}, φ_{dFF3} – angular radiation coefficients of dF area on the spheres1-3, respectively; F_{dF} - the area of dF platform ; F_1-F_3 – the area of spheres 1-3.

From the calculation results (2) follows the first law of heat radiation from isochoric isothermal concentric spherical gas volumes: "Elementary angular radiation coefficients of isochoric isothermal concentric spherical gas spaces, layers are equal."

Angular coefficients of radiation are the main design quantities of radiative heat transfer in furnaces, fire boxes, combustion chambers.

When modeling the radiation from hundreds and thousands of concentric spheres, including in the volume of the first sphere, we would get the same result: elementary angular radiation coefficients of concentric gas layers are equal.

From the first law follows, that when calculating angular radiation coefficients φ_{VdF} of isochoric isothermal concentric gas spaces we need not solve triple integral, similar to that described in [1]:

$$\varphi_{VdF} = \iiint_V \frac{\cos\alpha_i \cos\beta_i}{2\pi^2 l_i^2}\, d\alpha\, d\beta\, dl \qquad (3)$$

From the first law follows, that for the calculation of the angular radiation coefficients of isochoric isothermal concentric gas volumes it is sufficient to determine the angular radiation coefficient of concentric spherical gas volume of infinitesimal diameter that is, perform a single integration.

Let us calculate the heat radiation flux density incident on the calculated area dF from isochoric isothermal concentric spherical gas layers, which emits radiation power P1 = P2 = P3 = 42/3 = 14MW. We accept the parameters of gaseous medium inherent to steam boiler box , coefficient of absorption of the gas medium k = 0.162 [2.7]. The results from calculation of radiation flux densities of concentric spherical gas layers to the calculated area dF:

$$\begin{aligned} q_{F_1dF} &= q_{F_2dF} = q_{F_3dF} = \frac{\varphi_{F_1dF} P_1}{F_{dF}} e^{-kl_1} = \\ &= \frac{\varphi_{F_2dF} P_2}{F_{dF}} e^{-kl_2} = \frac{\varphi_{F_3dF} P_3}{F_{dF}} e^{-kl_3} = \\ &= \frac{0{,}0022\cdot 14\cdot 10^3}{0{,}25} e^{-0{,}162\cdot 3} = \\ &= \frac{0{,}0022\cdot 14\cdot 10^3}{0{,}25} e^{-0{,}162\cdot 3} = \\ &= \frac{0{,}0022\cdot 14\cdot 10^3}{0{,}25} e^{-0{,}162\cdot 3} = \\ &= 76{,}1\ kW/m^2 \end{aligned} \qquad (4)$$

where $l_1 = l_2 = l_3 = l$ – average beam path length of $1 – 3$ spherical layers to the calculated area.

Average beam path length l_{av} is determined as arithmetic mean distance from elementary particles, atoms, which surfaces of spheres consisted of to the calculated area dF [1].

Average beam path length of any spherical gas layer equals to arithmetic mean distance from the center of symmetry of concentric spheres to the calculated area. From the calculation results (4) follow another two laws of radiation from isochoric isothermal concentric spherical gas layers, spaces.

The second law:

«Average beam path length from isochoric isothermal concentric spherical gas volumes, layers to the calculated area equals the distance from ball centers to the calculated area»:

$$l = l_1 = l_2 = l_3 = r \qquad (5)$$

The third law: «Radiation flux densities, incident on the calculated area from isochoric isothermal concentric spherical gas coaxial volumes, layers, which arc and torch consisted of are equal».

Total radiation flux densities incident from three isochoric isothermal concentric spherical gas volumes, layers on dF area is determined according
to the principle of superposition, summation of radiation fluxes incident:
on the calculated area from individual sources of heat radiation [12]:

$$q_{FdF} = \sum_{i=1}^{3} q_{F_i dF} = 228{,}3 kW/m^2 \qquad (6)$$

Assume, that radiating power P=42 MW is generated in the third spherical gas space. Let find the heat radiation flux density of the third spherical gas volume on *dF area*:

$$q_{F_3 dF} = \frac{\varphi_{F_3 dF} P}{F_{dF}} e^{-kl_3} = \frac{0{,}0022 \cdot 42 \cdot 10^3}{0{,}25} e^{-0{,}162 \cdot 3} \qquad (7)$$

$$= 228{,}3 kW/m^2$$

The fourth law of heat radiation from isochoric isothermal concentric spherical gas spaces, layers is evident from the calculated data by equations (6) and (7):

«Total heat radiation fluxes density incident on calculated area from several radiative and absorbing isochoric isothermal concentric spherical gas spaces equals radiation flux density of concentric spherical gas space of small diameter on calculated area at radiating power, released in it that equals total radiated power, released in all concentric spherical gas spaces radiating on the calculated area»:

$$q_{F_3 dF} = q_{FdF} = \sum_{i=1}^{3} q_{F_i dF} \qquad (8)$$

The disclosed laws of heat radiation from isochoric isothermal concentric spherical gas spaces allow researchers, designers, calculate the heat fluxes , the average beam path length, the angular radiation coefficients of the gas spaces of any complex volume form, inscribing spherical volumes in them. An example of such a calculation is given in the second part of the article.

III. CONCLUSION

The laws of heat radiation from isochoric isothermal concentric spherical gas volumes are disclosed. Dozens, hundreds spheres of large, medium, small or infinitely small diameter can be inscribed in gas volumes depending on the complexity. Concentric spherical with coaxial cylindrical gas volumes can entirely fill radiating gas volumes of any complex volume form and calculate heat radiation from gas volumes to the heating surfaces with high accuracy.

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