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Modeling of a Torch and Calculations of Heat Transfer in Furnaces, Fire Boxes, Combustion Chambers

Part II. Calculations of Radiation from Gas Volumes by the Laws of Radiation from Cylinder Gas Volumes

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Abstract— *On the basis of scientific discovery the major scientific problem is solved, analytical expressions, formulas for calculation heat radiation from gas volumes, torches on the heating surfaces are obtained. The example of calculation of radiation fluxes from torch on the heating surface is given. Scientific discovery allows designers from many countries worldwide to create new and improved the operating torch heating furnaces, steam boiler boxes, combustion chambers of gas-turbine installations of power stations.*

Keywords*— scientific discovery, laws, heat radiation, torch.*

I. INRODUCTION

Flaring fuel is characterized by volume heat radiation, three-dimensional model of radiation. Quadrillions of particles, atoms, electrons radiate in torch. In the calculations of heat transfer, we need to consider heat radiation from every particle separately and all the particles together to the calculation surface.

When calculating the heat transfer, we must take into account heat radiation of each particle separately and all particles together on the calculation area.

With the appearance of computers in the 1940s, hundreds of programs for computer numerical modeling of integral equations for radiative heat transfer in torch furnaces, fire boxes, combustion chambers were established.

For surface and volume regions heat fluxes and zone temperatures are calculated using a computer on the basis of discrete approximation of integral equations of radiative heat transfer.

However, this method for calculation uses the laws of radiation from solid bodies and a large mass of values of temperatures and optical coefficients of surface and volume areas.

In the late 20th century, the author disclosed the laws of heat radiation from gas volumes [1].

An analytical model of the torch and the modern method for calculating heat transfer in torch furnaces, fire boxes, combustion chambers are developed on the basis of scientific discovery [2-6].

Theoretical studies are confirmed by the experiments and used in the textbook [7] for training university students.

II. CALCULATION OF ANGULAR COEFFICIENTS OF RADIATION AND RADIATION FLUXES FROM GAS VOLUMES, TORCHES ON CALCULATION AREAS

2.1. Calculation of angular coefficients of radiation from cylinder gas volumes on heating surfaces

Fig . 1 shows the upper and the lower torches 1, formed by single burners 2. The upper torch has a small expansion angle and a large length, the lower one has a large expansion angle and a small length.

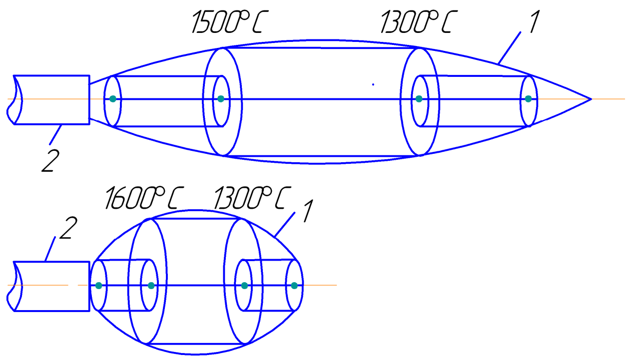

Fig. 1: Modeling of torches by cylinder gas volumes

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Torches are divided by isotherms by three gas volumes. At the upper long torch, isotherms of 1500°C and 1300°C divide it by three gas volumes. To make calculations, three cylinder gas volumes are inscribed in three gas volumes, for which the calculation of local angular coefficients of radiation, the average beam path length, densities, radiation fluxes incident on the calculation area is made.

Similar schemes and calculations are carried out for the lower short torch. Let inscribe coaxial cylinder gas volume of infinitely small diameter equal to the diameter of cylinder axis in each of cylinder gas volume. The publications [1-6] contain no derivation of analytic expressions for determining the local angular radiation coefficients of the gas cylinder volume of a small diameter to the calculation area.

Let determine the local angular coefficient of radiation from cylinder source of radiation of a small diameter on the surface of elementary area *K*, located between the normals *N3* and *N4*, passing through the center of the top and the bottom base circles of cylinder radiation source (Fig. .2).

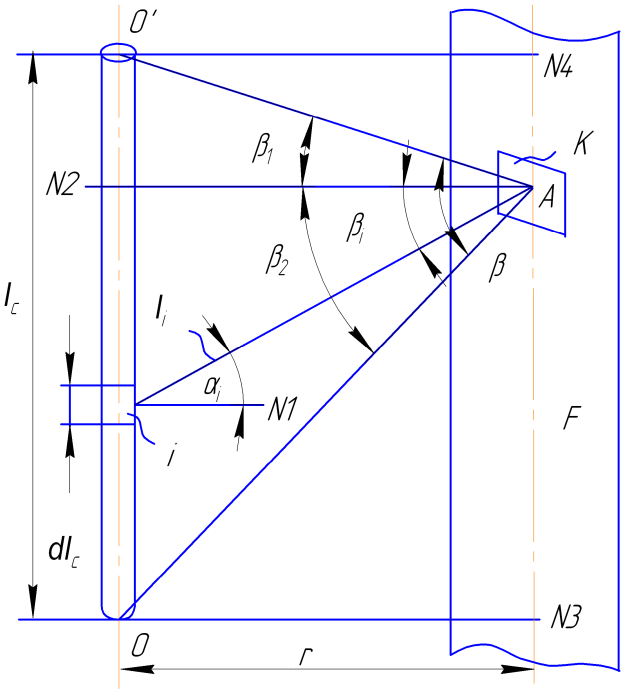

Fig. 2: Mathematical constructions for determination local angular coefficients of radiation from cylinder source on the elementary area in mutual parallel planes

Elementary area lay in the plane *F*, parallel to the axis of cylinder source of radiation of ℓ_c height. Let select the element $d\ell_c$ on cylinder source of radiation. Since a cylinder source presents an infinitely small diameter cylinder, element $d\ell_c$ presents an elementary cylinder, that is an infinitely small diameter cylinder and infinitely small height $d\ell_c$. Characteristics of elementary cylinder radiation and its geometrical relationship with the elementary area considered in detail in [7]. From [7] follows, that the elementary angular coefficient of radiation $d\varphi_{ik}$ from the surface of elementary cylinder on the surface of elementary area is determined by the equation:

$$d\varphi_{ik} = \frac{\cos\alpha_i \cos\beta_i F_k d\ell_c}{\pi^2 \ell_i^2 \ell_c}, \qquad (1)$$

where a_i is the angle between the normal *N1* to the axis of elementary cylinder and the direction of radiation, °C ; β_i is the angle between the normal *N2* to the center of elementary area and, the direction of radiation, °C ; F_k is the area surface of the elementary area, m^2; l_i is the distance from elementary cylinder to the elementary area, m.

Let designate the center of the elementary area by the letter *A*, the minimum distance from the point *A* to the cylinder axis we denote *r*. From the point *A* we run the beams *AO* to the centers of circles of cylinder radiation source. Let β_1, be the angle between the straight *AN2* and the beam AO', β_2 be the angle between *AN2* and the beam *AO*. As is seen from constructions, cylinder source radiates to the point *A* within the angle β, while $\beta = \beta_1 + \beta_2$.

Local angular coefficient of radiation of cylinder source on surface of elementary area is determined by integrating the expression (1) over the height of radiation source:

$$\varphi_{\ell k} = \int_{\ell_c} \frac{\cos\alpha_i \cos\beta_i F_k}{\pi^2 \ell_i^2 \ell_c} d\ell_c, \qquad (2)$$

Expression (2) has three variables, get rid of two of them by substituting, besides, integration over the height ℓ_c we replace by integration over the angle β. From the Fig. 2 we have:

$$\angle\alpha_i = \angle\beta_i, \quad \cos\alpha_i = \cos\beta_i, \qquad (3)$$

$$\cos\alpha_i = r/l_i, l_i = r/\cos\alpha_i, \qquad (4)$$

$$d\ell_i \cos\beta_i = \ell_i d\beta . \qquad (5)$$

Having substituted (3) - (5) in (2), integrated over the angle β, we obtain the expression for determining the local angle coefficient of radiation of cylinder source of radiation on the elementary area:

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$$\varphi_{\ell\kappa} = \int_{-\beta_2}^{+\beta_1} \frac{\cos^2\beta_i F_k}{\pi^2 r\ell_c} d\beta = \frac{F_k}{2\pi^2 r\ell_c} \times \times[\beta + \sin\beta\,\cos(\beta_1 - \beta_2)], \quad (6)$$

where β is the angle of radiation from cylinder source on the elementary area, rad.

In the case when the elementary area is located, that the normal *N3* (or the *N4*) passes through the point *A*, the expression (6) takes the form:

$$\varphi_{\ell k} = \frac{F_k}{2\pi^2 r\ell_c}\left(\beta + \sin\beta\ \cos\beta\right) = = \frac{F_k}{2\pi^2 r\ell_c}\left(\beta + \frac{1}{2}\sin 2\beta\right), \quad (7)$$

In the case when the elementary area is located outside of the projection of cylinder source of radiation on the plane F (Fig.3), the calculation is as follows.

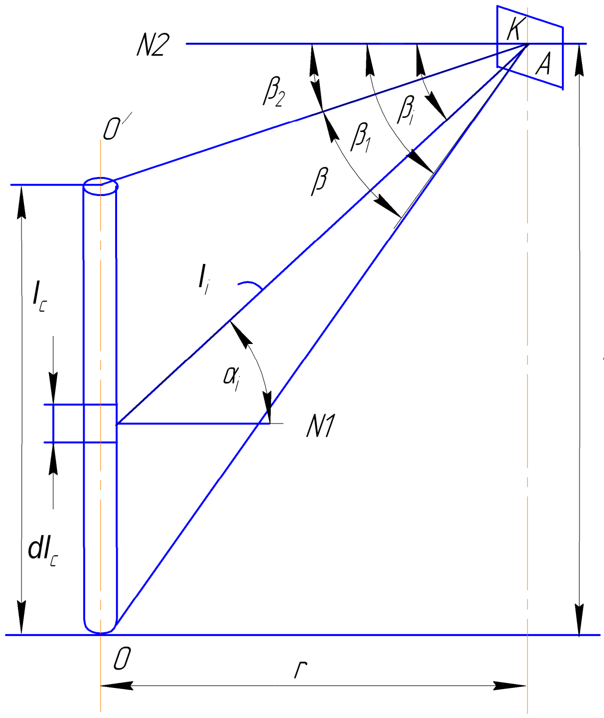

Fig. 3: Mathematical constructions for determination local angular coefficients of radiation when passing elementary area on the vertical plane at arbitrary height

Let elementary area center *A* is located at the distance *h* from the plane which passes through the base of cylinder radiation source, while $h > \ell_c$. The angle of radiation from cylinder source on the elementary area is formed by the beams *AO* and *AO*′ and equals β. Let β_1 be the angle between the normal *N2* to the point *A* and the beam *AO*, β_2 be the angle between *N2* and the beam *AO*. From Fig. 3 is seen, that expression (3) - (5) are acceptable in this case of location of the elementary area and cylinder source of radiation.

To determine the local coefficient of radiation from cylinder source on the elementary area, we substitute (3) - (5) in (2) and integrate the obtained expression within the angle β.

In this case, the limits of integration will changed:

$$\varphi_{\ell k} = \int_{\beta_2}^{\beta_1} \frac{\cos^2\beta_i F_k}{\pi^2 r\ell_c} d\beta = \frac{F_k}{2\pi^2 r\ell_c} \times \times[\beta + \sin\beta\,\cos(\beta_1 + \beta_2)], \quad (8)$$

The correctness of analytical reasoning in the derivation of the expression (8) can be checked as follows.

When $\beta_2 = 0$ and $\beta_1 = \beta$ from (8) we should get the expression (7), since under these conditions the elementary area is located on the normal *N4* (see. Fig.2).

In fact, substituting β2 = 0 and β1 = β in (8), we obtain the expression (7).

Thus, we obtain analytical expressions for determining local angular coefficients of radiation from cylinder source of heat radiation on the elementary area in parallel planes. According to scientific discovery [1], the derived analytical expressions can be used for calculation the local angular coefficients of radiation form isothermal cylinder gas volumes of any diameter on the calculation area at the location of the axis volume and the calculation area in parallel planes. As the average beam path length of radiating particles of cylinder gas volume is determined as the average distance from volume symmetry axis to the calculation area, we obtain all the necessary analytical expressions for calculation heat radiation from cylinder gas volume on the calculation area, when its axis and calculation area are in mutual planes. Let's give an example of such a calculation.

2.2. Calculation of heat radiation from cylinder gas volume on the calculation area

Consider the radiation of the part of the torch (Fig. 1), one of its cylinder gas volumes. Cylinder isothermal gas volume V_g radiates on the calculation area F_2 (Fig.4). The area size is 0,5×0,5 m.

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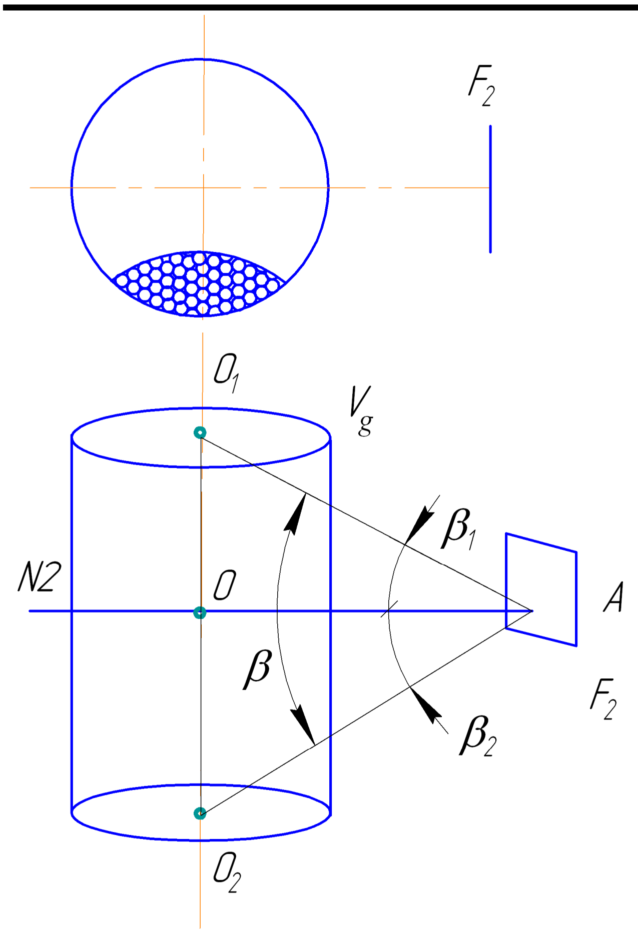

Fig.4: Radiation from cylinder gas volume on the calculation area F_2

The diameter of cylinder volume is 3m, the height is 3m. Assume, that at the same time $15\cdot10^{15}$ atoms uniformly filling the volume, radiate in the gas volume. The atoms that make up the gas volume, we simulate by spheres (Fig. 4).

Perpendicular N_2 to the center A of the area F_2 passes through the center of the volume symmetry and the symmetry axis of cylinder gas volume (point O) and bisects O_1O_2 axis between the upper and the lower volume base. The distance between the point O and the center of symmetry of the area F_2 is 3 m. The power released in the cylinder gas volume P_c, torch during combustion of fuel is determined as a product of heat of combustion and fuel consumption [2,7]. We assume for the calculation case, that P_C = 42 MWt, the absorption coefficient of the gas medium k=0,162 [6]. In [1,4] we proved the fallacy of using Stefan-Boltzmann law for calculation of heat transfer between gas volumes and heating surfaces. Radiation from gas volumes, torches is not subject to the Stefan-Boltzmann law, the law of proportionality of the incident radiation flux to temperature of the gas in the 4th degree from gas volume to the calculation area. For example, when air supplied to the burner is heated from 20°C to 600°C, the torch power increased by 17% and the torch temperature increased from 1300 ° C to 2100°C [1,7]. The radiation flux density incident on the calculation area under air heating, calculated by the Stefan-Boltzmann law, increased by 5 times, contrary to the law of conservation of energy. Under the real operation conditions of furnace, the radiation flux density from the torch and the rate of heating product increased by 17%, that is directly proportional to the increase in the power of the torch [7]. In [1-7] it is proved, that the gas, torch power need to be used as the parameter most fully characterizing the radiation from torch gas volume. The formula for calculating radiation flux density q_{g2} incident on the calculation area F_2 (Fig. 2) from the gas volume V_g has the form:

$$q_{g2} = \varphi_{g2} P_c F_2^{-1} e^{-k\cdot l_{av}}, \qquad (9)$$

where φ_{g2} is the local angular coefficient of radiation from gas volume V_g on the area F_2, of the surface area F_2; k is the gas volume coefficient of; l_{av} is the average path length of the beams of radiating particles, atoms to the calculation area. According to the scientific discovery, the laws [1-7], the average beam path length from $15\cdot10^{15}$ atoms to the calculation area F_2 is equal to the arithmetic mean distance from O_1O_2 to F_2.

According to the laws of Makarov, the local angular coefficient of radiation from gas volume V_g on the calculation area F_2 is equal to the local angular coefficient of radiation from the small diameter cylinder O_1O_2 on the area F_2.

The symmetry axis of cylinder gas volume, cylinder of infinitely small diameter O_1O_2 we divide into 5 sections and determine the distance from the midpoint of each section to the area F_2, then the average beam path length from $15\cdot10^{15}$ radiating atoms to the calculation area F_2:

$$l_{av} = \left(\sum_{l=1}^{5} l_i\right)/5 = (3{,}2+3{,}1+3{,}0+3{,}1+3{,}2)/ \qquad ,(10)$$
$$/5 = 3{,}12 \text{ m}$$

The local angular coefficient of radiation from gas volume V_g per unit area of the area F_2 we determine by the eq. (6) dividing it by F_2:

$$\varphi_{g2} = \frac{F_2}{F_2 2\pi^2 r l_c}\cdot[\beta + \sin\beta\cos(\beta_1-\beta_2)] =$$
$$= \frac{0{,}25}{0{,}25\cdot2\cdot3{,}14^2\cdot3\cdot3}\cdot\left[\frac{52}{57}+\sin52^\circ\cos0^\circ\right] =, \quad (11)$$
$$= 0{,}0086$$

We insert (10) and (11) in (9) and determine the density of incident heat radiation flux on the calculation area form gas volume:

$$q_{g2} = \varphi_{g2} P_c e^{-k \cdot l_{av}}$$
$$= 0{,}0086 \cdot 42 \cdot 10^3 \cdot e^{-0.162 \cdot 3.11} = 217{,}1 \frac{kWt}{m^2}, \quad (12)$$

Thus, we calculate the flux density incident on the calculation area from gas volume. Similarly, we determine radiation flux densities, incident on the calculation area from other gas volumes (Fig.1) and total radiation flux density from torch gas volumes. In [7] we derive analytical equations for determining local angular coefficients of radiation from small-diameter cylinder gas volumes at arbitrary attitude of volume and calculation surface. Similarly, (12) the density of the incident radiation flux from the flame to any settlement area during their arbitrary location in space is determined.

The author-developed and described in [2,3,7] computational procedure for calculating heat transfer in furnaces, fire boxes, furnaces, combustion chambers includes the following calculations of heat flows.

The heat radiation fluxes are determined for each calculation area: torch radiation flux ; torch flux reflected from the heating surfaces; streams of radiation hard surfaces; radiation fluxes from solid surfaces; radiation fluxes from surfaces reflected to surfaces on the calculation area; radiant and convective fluxes from torch combustion products.

Computational program for heat transfer in torch furnaces, fire boxes, combustion chambers is developed and used for the sake of automatic calculation. The calculation results from heat transfer in torch furnaces, fire boxes, combustion chambers are presented in [2-7]. The calculation results agree well with the results from experimental measurements of heat fluxes, temperatures in heating furnaces, steam boiler boxes, combustion chambers of gas-turbine installations. The discrepancy in calculated and experimental data doesn't exceed 10%. The author plans to present the results of heat transfer in torch furnace in the next article.

III. CONCLUSION

Thus, difficulties in calculating the average path length of the beams from a variety of radiating particles of gas volumes, torches, existed in the 20th century and determining the angular radiation coefficients of the gas volumes on the calculation surfaces with the disclosure of the laws of radiation from cylinder gas volumes were overcome. In [1-7] we presented the results of calculations from heat torch in torch furnaces, steam boiler boxes, combustion chambers of gas turbine installations. Calculations showed, that the existing design of torch furnaces, fire boxes, combustion chambers are imperfect. To save energy, it is necessary to create new designs of torch furnaces, fire boxes, combustion chambers and optimize the arrangement of burners in them. A number of new designs of furnaces, fire boxes, combustion chambers, which reduce fuel consumption, equalize heat loads are developed by the author with the students and patented [8-12].

The disclosed laws of radiation from gas volumes, the laws of Makarov and the method of heat transfer calculation, developed on their basis, allow scientists, designers in many countries around the world to create new and improve the steam boiler boxes, combustion chambers of gas-turbine installations of power stations, save million kW · h of electricity and million tons of gas-turbine, liquid, pulverized fuel.

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