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CALCULATION OF RADIANT HEAT EXCHANGE IN POWER INSTALLATIONS WITH VORTEX FURNACES

Problem statement. In recent years, decentralized and individual heat supply systems satisfying existing needs of population in thermal energy are progressing rapidly. Such systems use steam and water-heating boilers in which vortex method of fuel burning is applied. The method allows to provide for uniform temperature distribution in furnace and prevents heat exchange surface burning-out.

Heat exchange by radiation is the principal process in boiler furnaces, and its calculation is an intricate problem. This paper considers the method of determining the angular coefficients of radiation of a cylindrical source (to which torch can be assigned) on parallel and perpendicular planes.

Results and conclusions. Analytical expressions for determining local angular coefficients of a linear source radiation on an elemental area are obtained at their relative position in parallel and perpendicular planes. The expressions are used in calculation of radiant heat exchange in boilers with vortex furnaces. The use of such devices will enhance boiler service life and magnify coefficient of efficiency of a boiler due to the reduction of heat losses caused by chemical and mechanical underburning and to increase durability of a boiler.

Keywords: boiler, radiant heat exchange, angular coefficient of radiation.

Introduction

The basic way to get heat in a cold season involves combustion of fossil fuel in various furnaces. Lately, more attention has been given to the development of decentralized and individual heat systems. These systems typically have fairly short heating mains, low fuel transportation costs and therefore provide low heat losses and high cost-efficiency. They utilize steam and water boilers. Experience from operating these furnaces revealed a whole range of factors affecting the working procedure in furnaces.

Heavy heat loads of furnaces call for a series of procedures, particularly to protect screen surfaces of a steamheater from overheating. In fact, temperature in a furnace space more often than not deviates from its average values, by as much as several hundred degrees at times. Heat inequality resulting from that can often lead to a burning-out or a drop in the quality of the operation of a furnace. This all means that solving the problem of heat inequalities is a pressing problem now.

One of the ways to solve it is to use the vortex principle of fuel combustion. The point is that a vortex flow of reacting particles of fuel and oxidizing agent is generated in a furnace chamber using appropriate delivery or a vortex generator. Twist of a stream in the furnace space is achieved by the tangential introduction of a fuel-air mixture into the furnace chamber. Rotation speeds in the furnace chamber reduce a discharge component of the absolute speed and therefore increase the amount of time when combustible gases remain in the furnace chamber and also reduce heat losses associated with chemical and mechanical underburning. A high speed and a high turbulization degree of a twisted flame lead to an increase in the coefficient of heat transfer of gases to heating surfaces, which is supposed to improve the performance of a furnace.

An attempt has been made to design a swirling-type furnace together with an approximate calculation method for the radiant heat exchange as well. Heat flows falling on a heating surface from a gas, fuel oil, coal-dust flame consist of radiation flow to the extent of 85—95 % and of convective stream to the extent of 10—15 %.

Evaluating total integral heat flows and angular coefficients of radiation

According to A. N. Makarov’s technique [1], total integral heat flows consisting of radiation falling down from the flame, lining of the walls and the lid and convective streams are calculated. Density of aj integral stream falling on the i-th elemental area of the heating surface is estimated using the following expression

$$q_{in} = q_{in.ф} + q_{in.оф} + q_{in.п} + q_{in.о.п} + q_{iкон}, \tag{1}$$

where $q_{in.ф}$ is density of an integral radiation stream falling on the *i*-th area away from the flame with respect to absorption of radiation emitted by the flame; $q_{in.оф}$ is the same for a stream generated by reflection of radiation from the walls, floor and lid; $q_{in.п}$ is the same for a stream coming from radiating walls, floor and lid with respect to reflection and absorption of radiation; $q_{in.o.п}$ is the same for a stream caused by reflection of radiation off the surface of walls, floor and lid; $q_{iкон}$ is density of a convective stream on the above area.

The most complicated problem that has to be faced when using this method is to estimate angular coefficients. In practice, analytical expressions are necessary for estimating angular coefficients of radiation for a cylindrical source (that a flame actually is) and elemental area in parallel and perpendicular planes.

Using invariance properties of radiation of a coaxial cylinder, it can be assumed that radiation of coaxial cylindrical gas volumes can be replaced by an equivalent radiation of cylindrical gas volume of a small diameter provided that it emits a power equal to the total power of radiation of coaxial cylindrical volumes. It is the practice in thermal physics to call a radiating cylinder of a small diameter a linear radiation source, which we will do in further calculations.

Let us determine a local angular coefficient of radiation of a cylindrical source of radiation onto a surface of the elemental area *K* placed between the normals *N*3 and *N*4 that pass through the centre of the upper and lower circles of the base of a linear radiation source (Fig. 1).

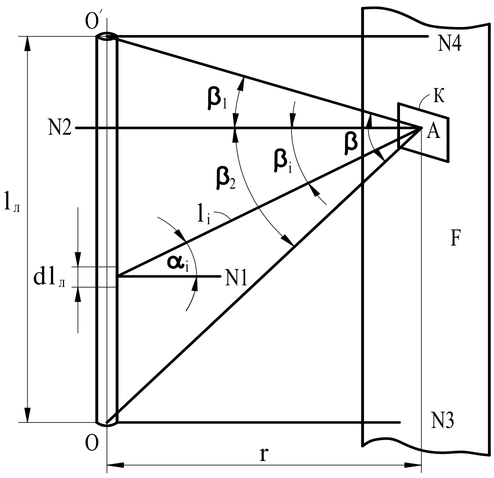

Fig. 1. Geometrical construction for estimating local angular coefficients of the linear source radiation on the elemental area in mutually parallel planes

The elemental plane lies in the plane *F* that is parallel to a cylindrical radiation source with the height $l_л$. Let us single out an element $dl_л$ on the cylindrical radiation source. Since the cylindrical radiation source is a cylinder of infinitely long diameter, the element $dl_л$ is an elemental cylinder, i. e. a cylinder of infinitely small diameter and infinitely small height $dl_л$. The elemental angular coefficient of radiation $d\varphi_{ik}$ off the surface of an elemental cylinder to the surface of an elemental area is described by the following expression

$$d\phi_{ik} = \frac{\cos\alpha_i \cos\beta_i F_k dl_л}{\pi^2 l_i^2 l_л}, \quad (2)$$

where α_i is an angle between the normal $N1$ to the axis of an elemental cylinder and direction of radiation, degrees; β_i is an angle between the normal $N2$ to the centre of the elemental area and direction of radiation, degrees; F_k is an area of the surface of the elemental area, m^2; l_i is a distance from the elemental cylinder to the elemental area, m.

Let us designate the centre of the elemental area as A and minimal distance from the point A to the cylinder axis — as r. Let us draw rays AO and AO' from the point A into the centres of the circles of the linear radiation source. Let us designate the angle between the straight line $AN2$ and the ray AO' as β_1 and the angle between $AN2$ and the ray AO — as β_2. This construction indicates that the linear source radiates into the point A within the angle β, with $\beta = \beta_1 + \beta_2$.

The local angular coefficient of radiation of the linear source on the surface of the elemental area is determined by integrating the expression (2) over the height of the radiation source:

$$\phi_{ik} = \int_{l_л} \frac{\cos\alpha_i \cos\beta_i F_k}{\pi^2 l_i^2 l_л} dl_л. \quad (3)$$

In the expression (3) we have three variables. Substitution eliminates two of them and the integration over the height $l_л$ is replaced by the integration over the angle β. According to Fig. 1, we have

$$\angle\alpha_i = \angle\beta_i, \ \cos\alpha_i = \cos\beta_i, \quad (4)$$

$$\cos\alpha_i = r / l_i, \ l_i = r / \cos\alpha_i, \quad (5)$$

$$dl_i \cos\beta_i = l_i d\beta. \quad (6)$$

After the insertion of (4)—(6) into (3) and integration over the angle β, we get the expression for determining a local angular coefficient of a linear radiation source on the elemental area:

$$\phi_{lk} = \frac{F_k}{2\pi^2 r l_л}\left[\beta + \sin\beta\cos(\beta_1 - \beta_2)\right], \quad (7)$$

where β is an angle at which a linear source radiates on the elemental area, rad.

If the elemental area is located so that the normal *N*3 (or *N*4) goes through the point *A*, the expression (7) takes the form

$$\phi_{lk} = \frac{F_k}{2\pi^2 r l_л}\left[\beta + \sin\beta\cos\beta\right] = \frac{F_k}{2\pi^2 r l_л}\left(\beta + \frac{1}{2}\sin 2\beta\right). \quad (8)$$

If the elemental area is located outside the projection of the linear radiation source on the plane *F* (Fig. 2), the calculation will be performed as follows.

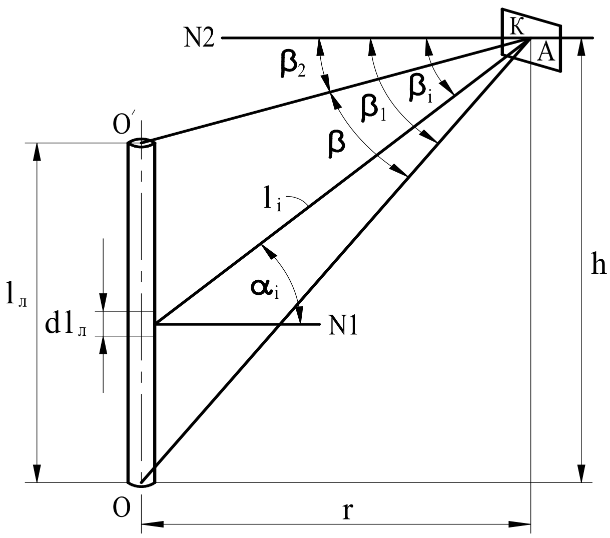

Fig. 2. Geometrical construction for estimating local angular coefficients of radiation when the elemental area is in a vertical plane at an arbitrary height

Let us assume that the centre of the elemental area *A* is located at the distance *h* away from the plane that passes through the base of the linear radiation source, with $h > l_л$. The angle at which the linear source radiates on the elemental area is formed by the rays *AO* and *AO′* is β. Let us designate the angle between the normal *N*2 at the point *A* and the ray *AO* as β_1 and the angle between *N*2 and the ray *AO′* as β_2.

Fig. 2 shows that the expressions (4)—(6) are applicable for this location of the elemental area and linear radiation source. To determine a local coefficient of radiation of a linear source on the elemental area, we insert (4)—(6) into (2) and integrate the obtained expression within the angle β:

$$\phi_{lk} = \frac{F_k}{2\pi^2 r l_л}\left[\beta + \sin\beta\cos(\beta_1 + \beta_2)\right]. \tag{9}$$

Let us examine the mutually perpendicular location of planes where linear sources of radiation and elemental area are. Let the plane with the elemental area pass through the base of the linear radiation source (Fig. 3). Let the shortest distance from the linear source to the point be *r*, the normal to the centre of the elemental area be *N*2 and the angle at which the linear source radiates on the point *A* be $\angle OAO' = \beta$.

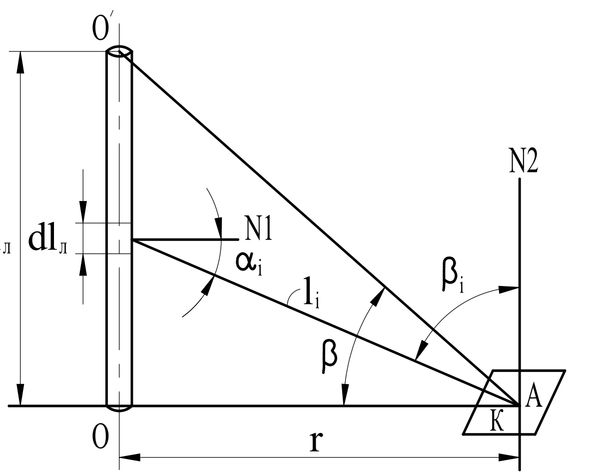

Fig. 3. Geometrical construction for estimating local angular coefficients of radiation when the elemental area is in mutually perpendicular planes

The elemental angular coefficient of radiation $dl_л$ on the elemental area is determined by the expression (2). A local angular coefficient of radiation of the linear source on the elemental area is estimated by the integration of the expression (2) over the height of the linear source or, following appropriate substitutions, over the angle β. From Fig. 3 we have:

$$\cos\beta_i = \cos\alpha_i, \tag{10}$$

$$l_i = r / \cos\alpha_i, \tag{11}$$

$$dl_i \cos\alpha_i = l_i d\alpha. \tag{12}$$

Inserting (10)—(12) into (2) and integrating the obtained expression within the angle β, we get an analytical expression for calculating a local angular coefficient of radiation of the linear source on the elemental area in a perpendicular plane:

$$\phi_{lk} = \frac{F_k}{2\pi^2 r l_л} \sin^2 \beta . \qquad (13)$$

If the elemental area is at any height *h* away from the lower (or upper) base of the linear source, we have the following geometrical constructions (Fig. 4). The shortest distance from the point *A* to the linear source is *r*. Let us designate $\angle OAO' = \beta$, $\angle OAB = \beta_1$, $\angle O'AB = \beta_2$, $\beta_1 - \beta_2 = \beta$.

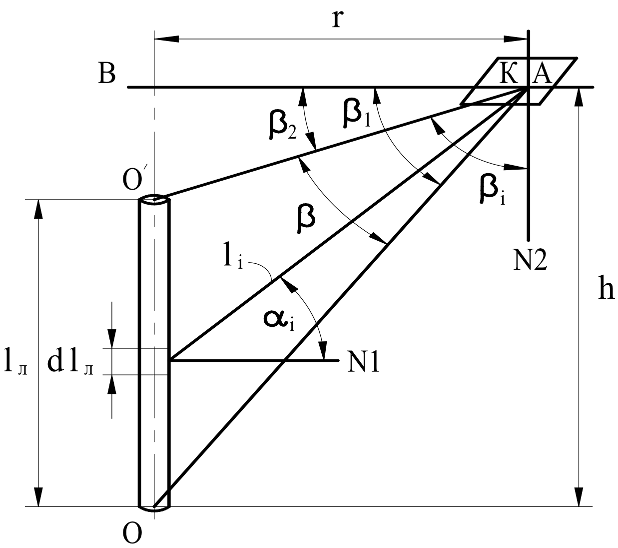

Fig. 4. Geometrical construction for estimating local angular coefficients of radiation when the elemental area is in a vertical plane at an arbitrary height

The data from Fig. 4 suggest that the equations (10)—(12) are applicable for a mutual location of the linear source and elemental area. To determine a local angular coefficient of radiation of the linear source on the elemental area, we should insert (10)—(12) into (2) and integrate within a change in the angle α_i, i. e. from β_2 to β_1:

$$\phi_{lk} = \frac{F_k}{2\pi^2 r l_л} \left(\sin^2 \beta_1 + \sin^2 \beta_2 \right) . \qquad (14)$$

The average angular coefficients of radiation of the linear source on the flat plane *F* (Fig. 1) ϕ_{lF} is defined as the total of the local angular coefficients of radiation of the linear source on the elemental areas on the plane *F*:

$$\phi_{lF} = \sum_{1}^{n} \phi_{lk} , \qquad (15)$$

where *n* is a number of elemental area on the plane *F*.

Conclusions

Analytical expressions have been obtained to evaluate local angular coefficients of radiation of a linear source (which a flame actually is) on an elemental area when they are mutually located on perpendicular planes that are used in calculating radiant heat exchange in boilers with swirling-type furnaces. The point is that a vortex stream of reacting fuel particles and oxidizing agent is generated in a furnace chamber using an appropriate delivery or a vortex generator. Rotation speeds in a furnace chamber decrease the discharge component of the absolute speed vector, which results in an increase in the time when combustible gases remain in a furnace chamber and decrease heat losses associated chemical and mechanical underburning.

Use of swirling-type furnaces assists in make heat exchange more swift, as well as in increasing the durability of furnaces by providing an even temperature distribution in them and cut down capital expenses and operational costs.

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