CALCULATION OF MIXING QUALITY IN THE EMBRASURE OF A BOILER BURNER

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A method is described for calculating the qualtiy of mixing in the embrasure of a boiler burner. Results based on experimental data on the mixing of gas and air are presented.

Preliminary mixing of a gas with air is a necessary condition for forced burning. The design of powerful boiler burners presupposes that mixing is accomplished inside the embrasure when a gas broken up into jets is injected into the air stream (Fig. 1). In practice the technique of burner design [1] consists in determining the trajectories of the gas jets and in efficient filling of the embrasure section with gas. The efficiency of a chosen burner scheme cannot be established without appropriate industrial or bench tests. Analysis of the data of a number of papers [1–3] shows that the quality of mixing in the embrasure is determined mainly by the range of the gas jets, the character of the mass transfer, and the mixing path length.

In these conditions an analytic solution of the problem is possible under certain assumptions. Let us examine the mass transfer equation as applied to a circular embrasure, assuming that the flow velocity is constant along its section, that transport of material in the radial direction is accomplished by means of turbulent transfer, and that the mixing process results in the formation of a homogeneous mixture.

Taking account of the restrictions introduced, the mass transfer equation, written in dimensionless form, is

$$\frac{1}{\bar r}\frac{\partial}{\partial \bar r}\bar r\frac{\partial c}{\partial \bar r}+\frac{1}{4}\frac{\partial^2 c}{\partial \bar x^2}=\frac{1}{2\bar D}\frac{\partial c}{\partial \bar x} \tag{1}$$

and is subject to the boundary conditions

$$\begin{aligned}&\bar x=0, \quad c=c(\bar r);\\ &\bar x=\infty, \quad c=c_m;\\ &\bar r=1, \quad \frac{\partial c}{\partial \bar r}=0.\end{aligned} \tag{2}$$

The function $c(\bar r)$ reflects the nature of the gas concentration distribution in the initial section of the embrasure, which conventionally coincides with the plane containing the apertures discharging the gas.

Making use of the recommendations of [1], we shall determine the value of $c(\bar r)$ for a gas burner with gas injected in jet form into a carrier air stream. When injected into the stream, the gas jets interact with it, their range being determined as

$$\bar h = k\bar d\sqrt{\gamma_m w_m^2},$$

while the diameter of a gas jet at distance $\bar h$ from the discharge orifice is

$$\bar S = 0.75\bar h.$$

We shall suppose that the gas (with added mass of air) is distributed in the embrasure section at $\bar x = 0$ in the form of a ring whose mean radius, with peripheral gas supply, is $\bar r_p = 1 - \bar h$, and, with central supply, $\bar r_c = \bar h + \bar a/2$ (Fig. 1). The area of the ring is

$$\bar F_r = \frac{1}{4}b\bar S^2.$$

The radii of the limits of the ring, in the case of a peripheral burner, are determined by

$$\bar r_{1.2} = 1-\bar h \mp 0.0352\frac{b\bar h^2}{(1-\bar h)}. \tag{3}$$

The first of the boundary conditions (2) therefore takes the form

$$\begin{aligned}&c(\bar r)=c_g \quad \text{when} \quad \bar r_1\leqslant \bar r\leqslant \bar r_2,\\ &c(\bar r)=0 \quad \text{when} \quad 0\leqslant \bar r\leqslant \bar r_1, \quad \bar r_2\leqslant \bar r\leqslant 1.\end{aligned} \tag{4}$$

We note that, according to (2), when $\bar x = \infty$, $c_g = c_m/(\bar r_2^2 - \bar r_1^2)$. Solution of (1) by the method of separation of variables, allowing for boundary conditions (2) and (4), permits the change in gas concentration in the volume to be represented as

$$c = c_m\left\{\bar r_2^2-\bar r_1^2+2\sum_{n=1}^{n=\infty}\frac{[\bar r_2 I_1(\mu_n\bar r_2)-\bar r_1 I_1(\mu_n\bar r_1)]\, I_0(\mu_n\bar r)}{\mu_n I_0^2(\mu_n)}\exp\left[\left(\frac{1}{\bar D}-\sqrt{\frac{1}{\bar D^2}+4\mu_n^2}\right)\bar x\right]\right\}. \tag{5}$$

Here I_0 and I_1 are Bessel functions of zeroth and first order, and μ_n are roots of the equation $I_1(\mu_n) = 0$ ($\mu_1 = 3.83$; $\mu_2 = 7.01$; $\mu_3 = 10.17$; $\mu_4 = 13.32$).

The mixing quality in the burner embrasure may be conveniently assessed by the quantity $\varkappa$, introduced by [2, 3], and defined by the expression

$$\varkappa = \int_0^1 \left| \frac{c - c_m}{c_m} \overline{w\gamma} \right| d\bar{f}.$$

For a homogeneous mixture $\varkappa = 0$. It is not difficult to show that, when there is separate motion of gas and air,

$$\varkappa = \varkappa_0 = 2\alpha L/(\alpha L + 1).$$

Instead of $\varkappa$, the analogous quantity $\bar{\varkappa} = \varkappa/\varkappa_0$ may be used, the limits of variation of which are independent of the composition of the gas and the fuel-air ratio $0 \le \bar{\varkappa} \le 1$ ($\varkappa = 0$—homogeneous mixture, $\bar{\varkappa} = 1$—complete lack of mixing).

For a tube with $w\gamma = w_m\gamma_m$

$$\varkappa = \int_0^1 \left| \frac{c - c_m}{c_m} \right| \bar{r}\, d\bar{r} =$$

$$= \frac{4}{\bar{r}_2^2 - \bar{r}_1^2} \sum_{n=1}^{n=\infty} \frac{|\bar{r}_2 I_1(\mu_n \bar{r}_2) - \bar{r}_1 I_1(\mu_n \bar{r}_1)|}{\mu_n I_0^2(\mu_n)} \times \tag{6}$$

$$\times \exp\left[\left(\frac{1}{\bar{D}} - \sqrt{\frac{1}{\bar{D}^2} + 4\mu_n^2}\right)\bar{x}\right] \int_0^1 |I_0(\mu_n \bar{r})|\, \bar{r}\, d\bar{r}.$$

Computation of the integral

$$T_n = \int_0^1 |I_0(\mu_n \bar{r})|\, \bar{r}\, d\bar{r}$$

requires clarification. As the argument z increases from 0 to ∞ the zeroth-order Bessel function $I_0(z)$ changes sign to the opposite of that when $z = \zeta_k$, where ζ_k are roots of the equation $I_0(\zeta_k) = 0$.

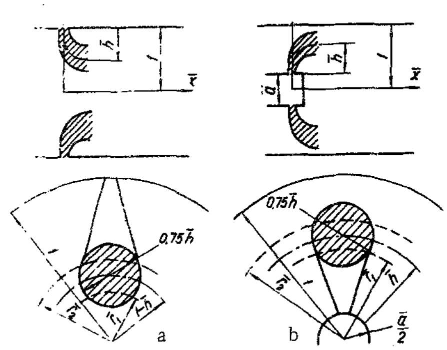

Fig. 1. Schematic gas distribution in embrasures with a) central and b) peripheral burners.

Carrying out the substitution, we write T_n in the form of a number of absolute values of definite integrals:

$$T_n = \frac{1}{\mu_n^2} \int_0^{\mu_n} |I_0(z_n)|\, z_n\, dz_n = \frac{1}{\mu_n^2}\left[\left|\int_0^{\zeta_1} I_0(z_n)\, z_n\, dz_n\right| + \right.$$

$$\left. + \left|\int_{\zeta_1}^{\zeta_2} I_0(z_n)\, z_n\, dz_n\right| + \ldots + \left|\int_{\zeta_k}^{\mu_n} I_0(z_n)\, z_n\, dz_n\right|\right] = \frac{1}{\mu_n^2} F_n(\mu_n).$$

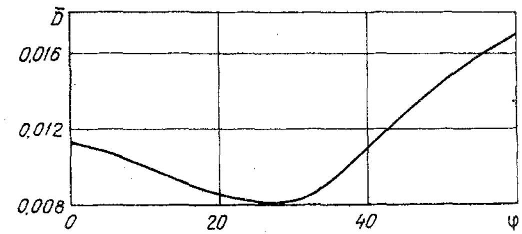

Fig. 2. The dependence $\bar{D} = \bar{D}(\varphi)$ in a cylindrical embrasure.

Putting $B_n(\mu_n) = 4F_n(\mu_n)/\mu_n^3 I_0^2(\mu_n)$, we have

$$\varkappa = \frac{1}{\bar{r}_2^2 - \bar{r}_1^2} \sum_{n=1}^{n=\infty} |\bar{r}_2 I_1(\mu_n \bar{r}_2) - \bar{r}_1 I_1(\mu_n \bar{r}_1)|\, B_n(\mu_n) \times$$

$$\times \exp\left[\left(\frac{1}{\bar{D}} - \sqrt{\frac{1}{\bar{D}^2} + 4\mu_n^2}\right)\bar{x}\right]. \tag{7}$$

The series (7) converges satisfactorily, the number of terms applicable to the calculation being determined by the two parameters $\bar{D}$ and $\bar{x}$, and not exceeding four in any case of practical interest, when $\bar{x} > 0.2$.

The values of B_n are equal, respectively, to 1.105; 0.864; 0.678; 0.588 for n = 1; 2; 3; 4.

The data in the literature on turbulent transfer coefficients in tubes, which are, moreover, very limited, cannot be used for practical calculation of mixture quality.

The presence and variation of flow swirl, the embrasure configuration, and the turbulence-promoting influence of the gas jets may be taken into account by introducing an effective mass transfer coefficient $\bar{D}$, obtained by reducing the experimental data according to (7) and allowing for the peculiarities of embrasure aerodynamics.

The reduction of test data on mixing in cylindrical embrasure models [2, 3] has allowed evaluation of $\bar{D}$ for these cases as a function of flow swirl. The graph of $\bar{D} = \bar{D}(\varphi)$ shown in Fig. 2 may be used with least reliability when $\bar{h} \le 0.4$ and $\bar{x} = 0.4$–0.6, i.e., in the most interesting practical cases.

Figure 3 shows the curve $\bar{\varkappa} = \varkappa(\bar{x})$, obtained by calculation when $\bar{D} = 0.05$. The satisfactory agreement between the calculated curved and the test points is evidence that (7) quite accurately describes the behavior of the process in the embrasure.

Increase of $\bar{D}$ in the last case proves to have a substantial influence on mass transfer in the tube of the channel configuration.

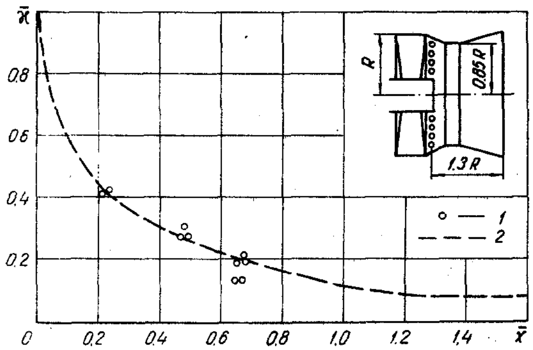

Fig. 3. Construction of the peripheral burner embrasure of the BKZ-160-100 GM boiler, and a graph of the variation of $\bar{\varkappa}$ along its length (φ = 45°): 1) test; 2) theory.

Evaluation of the mixing quality for a peripheral burner reduces, according to [1], after determination of the range of the gas jets, to computation of the quantity $\bar{\varkappa}$ from (7), using (3) and the graph of Fig. 2. With a central gas supply to the burner, it is sufficient to replace the difference $1 - \bar{h}$ in (3) by $\bar{h} + \bar{a}/2$, the method of calculation otherwise remaining as before.

The effect of having multi-row and multi-caliber gas orifices could be calculated, by complicating condition (4) with the introduction of a group of rings, each of which would correspond to the range of a definite number of orifices. It is more convenient in that case to introduce effective values of range, diameter, and number of orifices according to the formulas

$$\bar{h}_{\text{eff}} = \sum_{i=1}^{i=j} \bar{h}_i b_i \bar{d}_i^2 \Big/ \sum_{i=1}^{i=j} b_i \bar{d}_i^2; \qquad d_{\text{eff}} = \frac{\bar{h}_{\text{eff}}}{k\sqrt{\gamma_g \bar{w}_g^2}};$$

$$b_{\text{eff}} = \sum_{i=1}^{i=j} b_i \left(\frac{\bar{d}_i}{\bar{d}_{\text{eff}}}\right)^2.$$

From test data on two boilers equipped with burners similar in construction to those considered in Fig. 3, the quantity $\bar{\varkappa}$ should not exceed 0.2 in a case where it is necessary to compress the gas at thermal stresses of the furnace volume on the order of 300×10^3 W/m^3 and air-fuel ratios $\alpha \sim 1.05$. Use of the method of calculating mixing quality in burner installations, but, when test data have been accumulated, also allows the relation between the degree of preparation of the fuel-air mixture and the direct output of the flame to be explained.

NOTATION

R—embrasure radius; $\bar{x} = x/R$—relative length; $\bar{r} = r/R$—relative radius; c—gas concentration; c_m—mean gas concentration over section; $\bar{D} = D/wR$—relative turbulent transfer coefficient; w—flow velocity in embrasure; $\bar{h} = h/R$—relative range of gas jets; $\bar{d} = d/R$—relative diameter of gas orifices; k—coefficient, taking account of orifice pitch; $\gamma_g w_g^2$—ratio of velocity heads of gas and air; b—number of gas orifices; c_g—gas concentration in conventional ring; $\bar{a} = a/R$—diameter of central gas supply tube; $\overline{w\gamma}$—ratio of local mass flow velocity in embrasure to mean mass velocity over section; $\bar{f} = f/F$—relative area; F—cross-sectional area of embrasure; α—air-fuel ratio; L—stoichiometric coefficient; φ—axial register blade angle setting; j—number of rows of gas orifices; $\bar{h}_i$, d_i, b_i—range, diameter, and number of orifices in i-th row.

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