FLAME RADIATION IN INFRARED GAS RADIATORS

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A formula is obtained for calculating the amount of flame radiation present in infrared gas radiators.

In infrared gas radiators using the method of gas combustion in porous perforated media and in small volumes with highly convoluted contact surfaces the major radiation source is the solid firebed. However, on the firebed surfaces a flame exists, which acts as an additional radiation source. The question of the relative amount of flame radiation in flameless gas radiators is still under discussion at present.

According to [1], the flame radiation comprises 6-7% of the total thermal output of the radiator. However, in [1] the studies were performed for ceramic perforated fire nozzles, and so use of these results for metalloceramic and metallic fire nozzles may introduce error, since the fraction of flame radiation present may depend on the thermal load of the radiator. It is also necessary to consider that a supplemental grid installed above the fire surface will absorb a portion of the flux from the flame and, consequently, reduce the fraction of flame radiation in the total radiation flux. According to the data of [6], the fraction of flame radiation is of the order of 3%.

Gas combustion in infrared gas radiators occurs with an air excess coefficient $\alpha = 1.05$, i.e., complete combustion occurs; the gas combustion products consist of carbon dioxide gas, water vapor, and nitrogen. Dissociation of these products is significant at temperatures above 1500°C and so may be neglected, since under actual conditions of infrared gas-radiator operation the temperature is always below this value, mainly because of direct heat liberation.

The radiation of the nonluminous flame is taken equal to the radiation of the triatomic gases CO_2 and H_2O produced upon gas combustion.

The triatomic gases CO_2 and H_2O are among the selectively absorbing media. The transmission, absorption, and radiation spectra of CO_2 and H_2O are extremely complex, and so to simplify calculation their actual spectra will be replaced by simplified ones, containing only the three most significant bands [5]. In practical calculations of CO_2 and H_2O absorption capability, Hottel and Egbert diagrams are used. To determine absorption capability from these diagrams it is necessary to know the temperature of the gas combustion products, the partial pressures of carbon dioxide P_{CO_2} and water vapor P_{H_2O}, and the effective ray path length S_{ef}. For a thin planar layer of gas of thickness S

$$S_{ef} = 2S. \tag{1}$$

The partial pressures P_{CO_2} and P_{H_2O} may be determined from the gas combustion reaction equations using the volume content of the given gas in the combustion products.

Hottel and Egbert diagrams permit calculating the absorption capability of isothermal gas volumes. Nonuniformity of the temperature field may be considered by using the coefficient of radiation effectiveness, equal to the ratio of the actual radiant flux E to the radiant flux E*, calculated at a mean graphic medium temperature equal to the calorimetric temperature [4]. However, calculations performed with the graphs of [4] show that due to the low optical density of the radiation layer the radiation effectiveness coefficient is practically unity, and so further calculations will be performed for the mean graphic temperature.

In combustion of a gas–air mixture in perforated fire nozzles a planar flame front is formed near the nozzle surface. For stable combustion it is necessary that the velocity of the gas–air mixture be equal to

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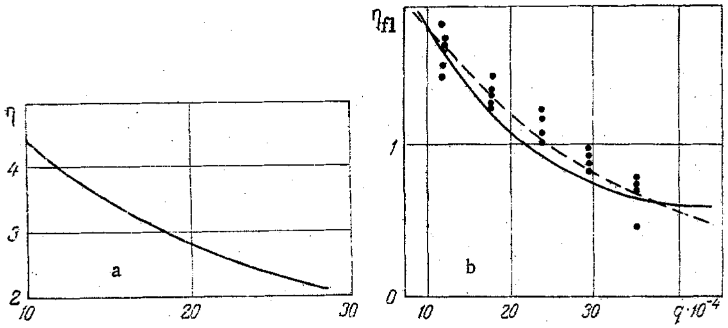

Fig. 1. Fraction of combustion product radiation of propane–air flame η (%) (a) and η_{fl} (%) (b) versus specific thermal load.

the normal flame-propagation velocity. Decrease in normal flame-propagation velocity is achieved by heat transfer from the gas–air mixture to the perforated nozzle. This effect of the surface on the value of normal flame-propagation rate, as was shown in [8], is equivalent to preliminary cooling of the gas–air mixture. This allows consideration of flame temperature with thermal theory formulas for an adiabatic flame. According to the thermal theory of Zel'dovich, Frank-Kamenetskii, and Semenov, the mass combustion velocity may be written as

$$G=\sqrt{\frac{2\lambda_c K_0 \rho_0^2}{c_p (T_c - T_0^*)^3}\left(\frac{T_0^*}{T_c}\right)^2 \frac{RT_c^2}{E}\exp\left(-\frac{E}{RT_c}\right)}. \tag{2}$$

The factor $c_p(T_c - T_0^*)$ has the sense of the reaction effect and is weakly dependent on T_0^*. The product $\overset{*}{\rho}_0 T_0^*$ is also practically constant. Therefore, assuming that $\lambda_c \sim T_c^{0.9}$ [9], Eq. (2) may be rewritten as

$$G=\mathrm{const}\sqrt{T^{4.9}\exp\left(-\frac{E}{RT_c}\right)}. \tag{3}$$

To avoid determining the constant, one can use tabular values of $T_{c_0}G_0$ under normal conditions; then

$$G=G_0\sqrt{\left(\frac{T_c}{T_{c_0}}\right)^{4.9}\exp\left[-\frac{E}{R}\left(\frac{1}{T_c}-\frac{1}{T_{c_0}}\right)\right]}. \tag{4}$$

Thus, knowing the velocity of the gas–air mixture, Eq. (4) may be used to calculate the initial temperature of the combustion products. Further, assuming the combustion product temperature to be constant over the entire volume, we calculate the amount of heat radiated from the decrease in heat content of the combustion products — the decrease in combustion product temperature ΔT. We then refine the value of the mean combustion product temperature and repeat the calculations.

Calculations were performed for a propane–air mixture with air excess coefficient of $\alpha = 1.05$. In the calculations the values $U_{c_0} = 0.39$ m/sec, $T_{c_0} = 2260$°K, and $E = 38$ kcal/mole [3] were used. Since in infrared gas radiators the distance between grid and fire surface comprises 8-10 mm, the effective layer thickness $S_{ef} = 0.02$. Combustion product radiation beyond the grid was not considered, since in passage through the grid the combustion products are cooled significantly by convective heat transfer.

Results of calculating fraction of flame radiation as a function of specific thermal load are shown in Fig. 1a. As is evident from the figure, the amount of flame radiation comprises 3-5% of the specific thermal load.

Experimental studies of the amount of propane–air flame radiation were performed with a grid-type radiator consisting of two metallic grids with cell diameter 0.4×0.4 mm^2, prepared from 0.2-mm-diameter wire, with one surface serving as the fire surface. The amount of heat radiated by the flame was determined as the difference between thermal flux obtained with gas combustion on the grids and the thermal flux obtained from the same grids heated by an electric current. Specific thermal load was calculated from gas expenditure with normal corrections for gas temperature and pressure. Grid temperature was monitored by Chromel–Alumel thermocouples. Thermal fluxes were measured with a bolometer, using the method described in [7]. To avoid heating of the bolometer by combustion products the burner plane was inclined at an angle of 60° to the horizontal.

Results are presented in Fig. 1b. The dashed curve represents data obtained by processing the experimental points by the method of least squares; the solid line is the calculated curve with consideration that a portion of the flame flux falls on the additional grid. As was shown in [2], upon irradiation of a solid surface through openings in a grid with a useful section coefficient of φ_0, a portion of the total flux passes through the grid equal to $\varphi_0^{3/2}$. As is evident from Fig. 1b, agreement of the experimental and calculated curves is completely satisfactory. The maximum deviation comprises 0.1% of the specific thermal load.

The decrease in relative amount of flame radiation upon increase in specific thermal load may be explained as follows. The specific thermal load q is proportional to the velocity of the gas–air mixture, and, consequently, considering Eq. (3),

$$q \sim T_c^{2.45} \exp\left(-\frac{E}{2RT_c}\right).$$

If we consider that the amount of heat radiated by the flame is proportional to T_c^4, then

$$\eta_{fl} = \frac{q_{fl}}{q} \sim T_c^{1.55} \exp\left(\frac{E}{2RT_c}\right).$$

In the temperature range concerning us ($T_c = 1500$–2000°K) the derivative $d\eta_{fl}/dT_c < 0$, and, consequently, with increase in specific thermal load the fraction of flame radiation decreases.

For practical calculations of flame radiation from metalloceramic and metallic grid gas radiators with a grid having a useful surface coefficient of φ_0, for the range $q = (10-30) \cdot 10^4$ W/m^2 the following formula is suggested:

$$Q_{fl} = (0.495 + 1.4 \cdot 10^{-2} q) F_0 \varphi_0^{3/2}. \tag{5}$$

The fraction of flame radiation in the same thermal load range may be calculated with the formula

$$\eta_{fl} = \left(\frac{0.495}{q} + 1.4 \cdot 10^{-2}\right) \varphi_0^{3/2}. \tag{6}$$

Thus, in calculating the fraction of flame radiation from perforated firebeds without an additional grid the former value of 6-7% of the specific thermal load may be used. With use of an additional grid in infrared gas radiators the fraction of flame radiation in the total flux from the heater decreases to 1-1.5% for grids with $\varphi_0 = 0.45$.

NOTATION

G, mass combustion velocity; K_0, preexponential factor; T_0, initial temperature of gas–air mixture; E, mean activation energy; T_c, flame temperature; c_p, mean heat capacity of combustion products; ρ_0^*, density of precooled mixture; T_0^*, temperature of precooled mixture; λ_c, thermal conductivity of gas–air mixture at $T = T_c$; T_{c_0}, adiabatic flame temperature; G_0, mass combustion velocity of adiabatic flame; q, specific thermal load; q_{fl}, amount of heat radiated by flame; η_{fl}, fraction of flame radiation; φ_0, useful section coefficient of grid; F_0, radiator surface area.

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