HEAT TRANSFER BETWEEN A FLAME AND A HEAT-SUSCEPTIBLE SURFACE

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Results of an experimental study of heat transfer upon incidence of a direct-jet and swirled flame on a heat-susceptible surface are presented.

In a number of industrial devices use is made of jet application of a heat source to a heat-susceptible surface.

The analytic solution of problems involving interaction of a turbulent direct-jet, and especially a swirled, flame with heat-susceptible surfaces in a limited space presents significant difficulties.

It is known that heat transfer upon incidence of a flame on a boundary in a limited space depends on many factors, including the flow regime of the heat source, the degree of turbulence, the distance from the gas burner device to the surface, and the angle between the surface and incident flow [1, 2]. In particular, heat-exchange in transverse flow over planar surfaces was studied in [3-5]. In those studies a calculated formula for the heat-exchange coefficient upon formation of a turbulent boundary layer on the surface was presented:

$$\overline{\mathrm{Nu}}_0 = \frac{0.15\,\mathrm{Pr}^{0.33}\mathrm{Re}_0^{0.8}}{\bar{r}_*\bar{R}_\mathrm{k}^2}\left[\frac{0.29\,\mathrm{Pr}^{0.12}\mathrm{Re}_0^{0.38}+16}{\mathrm{Pr}^{0.17}\mathrm{Re}_0^{0.3}}+(\bar{R}_\mathrm{k}^{1.25}-2.38)^{0.8}\right]. \qquad (1)$$

Experimental data have generalized this expression to the range Pr = 0.72-8, $\mathrm{Re}_d > 9000$, and $\bar{R}_k > 2$. It should be noted that those studies were performed in an aerodynamic tube.

The present study is an experimental investigation of the dependence of heat-exchange between a flame and a susceptible surface upon the factors enumerated above. A semiindustrial apparatus, a diagram of which is shown in Fig. 1, was used. The heating chamber is in the form of a rectangular prism with working volume dimensions of length, 4000 mm; width, 800 mm; height, 750 mm. The heat-susceptible surface is located within this volume — a calorimeter 480 mm in diameter, which can be moved along the combustion chamber and set at various angles to the incident flow. A premix gas burner with removable fittings to produce either a direct-jet or swirled flame is attached to the front of the heating chamber. The attachment had an axial blade turbulizer with blades located at angles of 15 and 50° to the axis, which, according to the formulas of [6, 7], produce turbulizations of 0.3 and 1.2. During the experiments measurements were made of water flow rate through the calorimeter and prismatic chamber section (with measurement tanks), gas flow rate (with a GS-100 gas counter), air flow rate (with a Prandtl tube and MMN microanemometer), and water temperature (with TL-4 thermometers and Chromel—Copel thermocouples). Combustion-product composition at the exit of the heating chamber was analyzed by a GKhP-3 chemical gas analyzer. A Junkers calorimeter was used to determine the heat of gas combustion.

A stationary combustion and heat-exchange regime was established 3.5-4 h after turnon of the gas burner. Experiments for a given regime lasted 1.5-2 h. All measurements were performed every 5 min after establishment of a stationary regime, with the exception of temperature field measurements in the combustion chamber, which were made every 20 min.

Three series of experiments were performed: 1) for a direct-jet flame (turbulization $\Omega = 0$); 2) for a swirled flame, $\Omega = 0.3$; and 3) $\Omega = 1.2$. In each series of experiments the angle of incidence of the flame with the calorimeter surface was adjusted to 90, 60, 30, and 0°, and Reynolds numbers were increased from 1400 to 4500. Physical parameters were taken for the mean flame temperature near the calorimeter surface, and the calorimeter diameter was used as the defining dimension.

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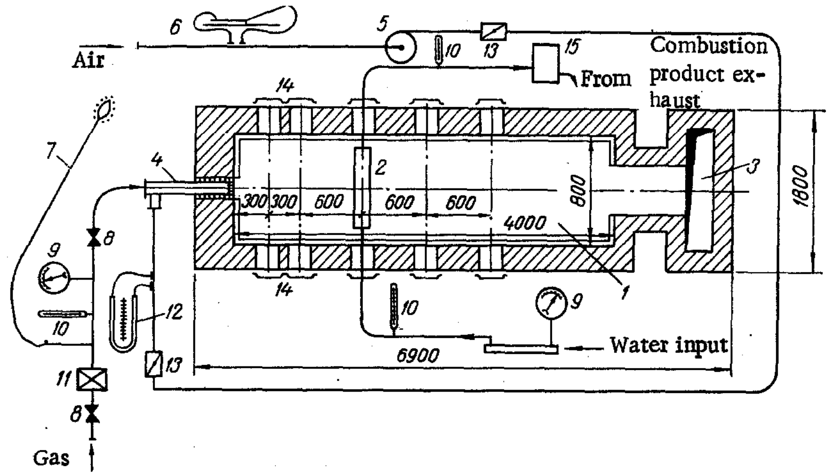

Fig. 1. Experimental apparatus: 1) heat chamber; 2) calorimeters; 3) combustion product exhaust; 4) burner; 5) ventilator; 6) microanemometer; 7) igniter; 8) stopcock; 9) manometers; 10) thermometers; 11) gas counter; 12) reference manometer; 13) gate valve; 14) viewports; 15) measuring tank.

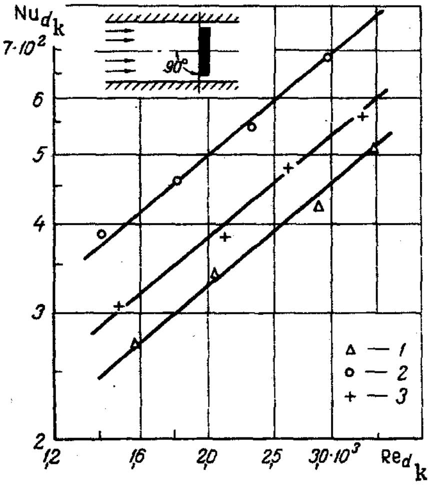

Fig. 2

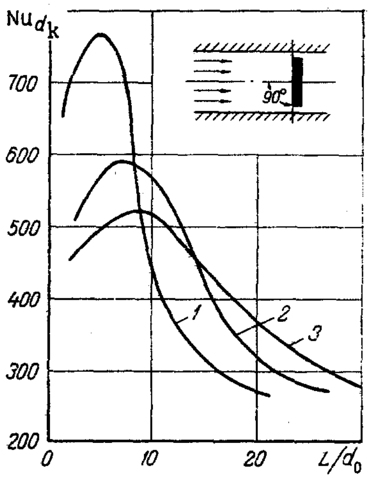

Fig. 3

Fig. 2. Function Nu = f(Re) in combustion chamber for direct-jet and swirled flames ($L/d_0 = 5.6$; $\varphi = 90°$): 1) direct-jet flame, $\Omega = 0$; 2) swirled flame, $\Omega = 1.2$; 3) swirled, $\Omega = 0.3$.

Fig. 3. Function Nu = f(L/d_0) in combustion chamber for direct-jet and swirled flames: 1) $\Omega = 1.2$; 2) 0.3; 3) 0.

Figure 2 presents curves of $Nu_{d_k} = f(Re_{d_k})$ for direct-jet and swirled flames incident on the heat-susceptible surface at an angle $\varphi = 90°$, with distance from burner mouth to calorimeter $L/d_0 = 5.6$. It is evident from the figure that with increase in flame turbulence the heat-exchange increases in comparison to the direct-jet case by 19% at $\Omega = 0.3$ and by 49% at $\Omega = 1.2$. This relationship is preserved for $Re_{d_k} = 3500$, $Pr = 0.57$ within the limits $5.6 L/d_0 \leqslant 8$, and may be approximated by the following expressions:

for direct-jet flame,

$$Nu_{d_k} = 0.590\, Re_{d_k}^{0.83}, \tag{2}$$

for flame with turbulization $\Omega = 0.2$,

$$Nu_{d_k} = 0.693\, Re_{d_k}^{0.83}, \tag{3}$$

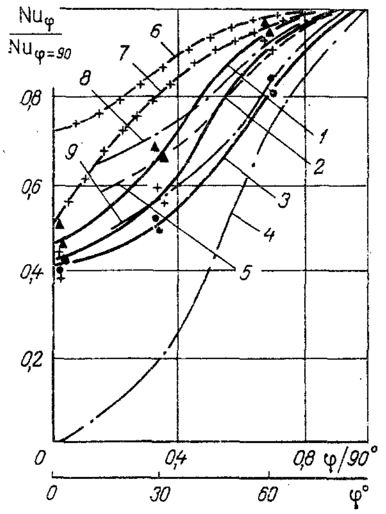

Fig. 4. Function $Nu_\varphi/Nu_{\varphi 90°} = f(\varphi/90°)$: 1-3) experimental data of present authors (1, for direct-jet flame; 2, for swirled flame, $\Omega = 0.3$; 3, for swirled flame, $\Omega = 1.2$); 4) data of [11] (for four-section calorimeter 980 × 760 mm in limited space with $L/d_0 = 22.8$); 5) data of [10] (for disk 344 mm in diameter in unbounded flow); 6, 7) data of [12] (for plate 300 × 300 mm in aerodynamic tube, Re = 85,000 and 30,000, respectively); 8, 9) data of [2] (for 176-mm-diameter disk in unbounded space, Re = 12,000 and 4500, respectively, $L/d_0 \leqslant 2$).

and for $\Omega = 1.2$,

$$Nu_{d_k} = 0.890\, Re_{d_k}^{0.83}. \tag{4}$$

It should be noted that change in L/d_0 from 8 to 10 for $\Omega = 1.2$ leads to a significant decrease in heat transfer from the flame to the surface. For $L/d_0 > 15$ heat transfer becomes greater for the direct-jet flame than for the swirled flame. As is evident from Fig. 3, the degree of turbulence ceases to have an effect on heat transfer for $L/d_0 > 18$. This may be explained by the peculiarity of a swirled flame that its long-distance effect is reduced by its more intense mass exchange with the surrounding medium [8], and also by the strong degeneration of aerostructure and form for a flame of this caliber [9].

Analysis of the curves of Fig. 4 shows that for direct-jet flames (curves 3, 8, 9), swirled flames [1, 2, 4), and also for nonisothermal jets (5, 6, 7) heat transfer increases with increase in the angle of incidence of the working substance with the heat-susceptible surface. The divergence in these curves can be explained by the various aerodynamic conditions occurring in bounded and unbounded spaces, the differing nozzle flow rates, nonisothermal conditions in the flow, and slight variations of L/d_0 (in 4, 5, 8, and 9).

The experimental study performed herein has permitted obtaining formulas for the dependence of heat transfer on the parameters cited above.

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