HEAT TRANSFER FROM COMBUSTION PRODUCTS TO THE WALLS OF A TUBE DURING PROPAGATION OF A FLAME

D. S. Kayumova

Inzhenerno-Fizicheskii Zhurnal, Vol. 11, No. 4, pp. 467–471, 1966

UDC 536.24

An experimental study has been made of heat transfer between the combustion products and the walls of a horizontal semi-closed tube during normal and vibratory propagation of a flame. The vibrations arose under conditions of self-excitation of oscillations in the combustion process. The temperature field in the combustion products was determined by an interferometric method.

The question of heat transfer from a pulsating stream has practical significance from the viewpoint of possible intensification of the heat transfer process. There have been very few published investigations of heat transfer during vibration of the heat transfer agent, in the case of forced motion in channels, especially when even the time-averaged process is unsteady. Such papers as exist are contradictory in their results. In some of them no influence of vibration on heat transfer was observed [1], in others an increase of heat transfer was observed [2–4], and in a third group—a decrease [5].

The tests were carried out with a horizontal tube of rectangular section, 28.5 × 12.5 mm, of length 60 cm. The tube was filled with a previously prepared mixture of CO and air of specific concentration. Then one end of the tube was opened and the hot mixture was ignited at the open end by an electric spark. The flame front propagated towards the closed end of the tube, while the combustion products moved in the opposite direction. The opposite end of the tube was connected to a gasmeter by means of a rubber hose. By pinching the hose with a clamp at various distances from the tube, we could obtain both a normal and a vibratory regime of flame front propagation, with various amplitudes of oscillation of the front. The tube in which combustion occurred was positioned perpendicular to the optic axis of a schlieren system. The working section of the tube, of length about 10 cm, was located approximately in the middle of the tube, and had plane-parallel glass side walls. To photograph the phenomena we used a high-speed SKS-1M camera capable of 5000 frames per second.

The specific heat flux was found by the enthalpy method, i.e.,

$$q = \frac{1}{S}\frac{Q}{\tau} = \frac{1}{S} V_s \Delta i. \qquad (1)$$

Assuming that combustion is complete [6], we may calculate the enthalpy from tables, knowing the percentage content of combustion products (it is known from the equation of the chemical reaction) and the temperature of the products at the inlet and exit sections of the part of the tube being examined. The volume flow rate of the combustion products was determined as follows. We shall write the general formula for a linear velocity

$$W = M/\rho F. \qquad (2)$$

Since the combustion products gradually cool, their density varies. For a second with density ρ_i we have

$$W_i = M/\rho_i F. \qquad (3)$$

We may determine M as the product of the volume of fresh gas burned in unit time, Fu, and its density ρ_0. Then

$$M = Fu\rho_0. \qquad (4)$$

The velocity of the combustion products relative to the walls of the tube is

$$w_i = W_i - u = u(\rho_0/\rho_i - 1). \qquad (5)$$

Then the volume flow rate of combustion products is

$$V = Fu(\rho_0/\rho_i - 1) = Fu(\eta_m\eta_T - 1). \qquad (6)$$

On the high-speed film it is easy to measure the frequency and amplitude of displacement of the flame front, the instantaneous and average velocity of propagation of the flame front relative to the tube walls, and the temperature in the combustion products. It is especially convenient in an unsteady regime to use optical methods, because of their lack of inertia, to determine the temperature field in the combustion products. In this work we used a diffraction interferometer [7], the interference picture and its interpretation being the same as for the Mach-Zehnder interferometer. Because of the nature of the nonuniformity, the process in the tube was considered to be two-dimensional, i.e., the medium was considered to be optically constant along the beam. This is valid near the flame front, where the boundary layer is comparatively thin. The concentration and the pressure in the combustion products do not vary. Under these conditions the relation

$$T = T_0(n_0 - 1)/(n - 1), \qquad (7)$$

obtained from simultaneous solution of the Lorentz-Lorenz and Mendeleev-Clapeyron equations, is valid. As T we took the experimental value of the combustion temperature from [8]. We found n from the displacement of the fringes:

$$n = n_0 + N\mu/2l. \qquad (8)$$

The absolute error of temperature measurement by this method is

$$\Delta T = T^2\mu\Delta N/2(n_0 - 1)T_0 l. \qquad (9)$$

Table 1

Specific Heat Flux q under Various Conditions

% CO	A/d	v/w	T_1, °K	T_2, °K	w, m/sec	$q \cdot 10^{-4}$, W/m^2
45	0	0	1940	1680	3.96	5.15
45	0.09	0.11	1760	1480	2.56	4.26
45	0.09	0.17	1780	1500	1.66	2.56
45	0.09	0.15	1880	1530	2.12	3.96
45	0.14	0.21	2000	1660	2.24	3.82
37	0	0	2090	1860	4.20	4.60
37	0.07	0.08	1990	1670	3.07	5.09
37	0.08	0.10	2270	1930	2.18	3.39
37	0.11	0.13	2110	1650	2.44	5.62
32	0	0	2250	1995	3.94	3.24
32	0	0	2130	1815	2.97	4.40
32	0.09	0.13	2100	1610	2.02	5.10
32	0.09	0.12	2230	1885	2.52	4.15
32	0.34	0.27	1890	1530	3.48	7.01
25	0	0	2080	1700	2.67	4.99
25	0.08	0.14	1935	1560	1.65	3.26
25	0.10	0.12	1975	1590	2.34	4.68
20	0	0	1975	1370	1.50	4.75
20	0	0	1960	1545	1.59	3.35

Since the displacement of the fringes may be determined with an accuracy up to $\Delta N = 1/20$ of a fringe, for example, for $T = 1500°$ K $\Delta T = 15°$ K.

High-speed films were taken of the processes occurring in the propagation of the flame front, for different A, v, mixture composition, etc., (see Table 1). The heat fluxes were calculated for the same instant of time, $\tau = 5.68 \cdot 10^{-2}$ sec. We took the beginning of the tube wall temperature tube as $\tau = 0$, i.e., the instant when the point on the front nearest to the tube wall passed through the mean section of the part of the tube being examined. The length of the working section was 24 mm.

It can be seen from Table 1 that, for normal propagation of the flame, the specific heat flux q is greater in some cases than q for vibratory propagation of the flame, while the contrary is true in other cases. Evidently, of all the above factors, that which has the greatest influence on q is the velocity of the combustion products. The latter is related to the apparent velocity of propagation of the flame front, which depends on the surface area of the front. This in turn depends on the type of oscillations. There are two types of oscillation of the flame in a semi-open tube: the so-called oscillations of type I and oscillations of type II [9]. During type I oscillations the area of the front is reduced, becoming almost planar, the velocity of displacement of the front decreases in comparison with the period of uniform propagation, and the motion of the combustion products is laminar. During oscillations of type II, on the other hand, the area of the front increases in comparison with normal flame propagation, the velocity of displacement of the front decreases sharply, and the motion of the combustion products becomes turbulent.

It may be said that Table 1 shows oscillations of type I, apart from film No. 14, for which w is larger than w without oscillations. The film speed in the SKS-1M camera was insufficient for investigation of the stronger type II oscillations, where the amplitude of oscillation as well as the mean velocity of displacement of the front increase strongly. In this case a comparision of the heat transfer with and without oscillations was made by an inverse shadow method. In this work we observed an increase of heat transfer with oscillations of type II in comparison with the flame propagation without oscillations. It may seen from Table 2 that the ratios η_q of the heat fluxes are larger in all cases than the velocity ratios η_w. This noteworthy fact indicates that there is a positive influence of vibration of the heat transfer agent on the heat transfer between the combustion products and the tube walls.

For comparison with the above-mentioned experimental data, we determined the heat fluxes with and without oscillations, with the aid of a platinum thin-film resistance thermometer mounted on glass, as described in [10]. The signal from the pickup was displayed on a S-1-19A oscillograph and photographed. From the known temperature of the substrate we calculated the heat flux according to the formula [11]

$$q = \frac{\lambda}{\sqrt{\pi a}} \int_0^{\tau} \frac{d\Phi(\tau)}{d\tau} \frac{d\tau}{(t-\tau)^{1/2}}. \qquad (10)$$

In calculating q, the integration was replaced by a summation. The oscillograph records show that, for the 45% mixture of CO with air, q_{max} with oscillations is larger than q_{max} without oscillations by a factor of 1.9, the mean heat fluxes over the whole time of the process are the same, and η_q with $\tau = 5.68 \cdot 10^{-2}$ sec $q = 14 \cdot 10^4$ W/m^2 is equal to 1.02. The mean velocities of displacement of the flame front, taken over the whole length of the tube, were roughly the same.

It is interesting to note that, although the order of magnitude of the quantity η_q is the same as in the experiments with the interferometer, the numerical values of the heat fluxes here are far greater. For example, for $\tau = 5.68 \cdot 10^{-2}$ sec $q = 14 \cdot 10^4$ W/m^2. Thermal radiation contributes a definite portion here. But, in the main, it is expressed in the dependence of q on the material of the wall.

In order to estimate the role of thermal radiation, we calculated the ratio of the heat transfer by radiation to that by direct contact. For our conditions the

Table 2

Comparison of the Ratios of the Heat Fluxes and of the Velocities With Oscillations to the Corresponding Values Without Oscillations

Film no.	η_q	η_w	Film no.	η_q	η_w
2/1	0.83	0.65	13/10	1.28	0.64
3/1	0.50	0.42	14/10	2.16	0.88
4/1	0.77	0.53	12/11	1.16	0.68
5/1	0.75	0.56	13/11	0.94	0.63
7/6	1.10	0.73	14/11	1.59	1.17
8/6	0.74	0.52	16/15	0.65	0.62
9/6	1.22	0.58	17/15	0.94	0.88
12/10	1.57	0.51			

heat flux by radiation was 10–20% of the heat flux by direct contact.

NOTATION

q is the specific heat flux; S is the lateral surface area of section of tube under examination; t, T are the temperature in °C and °K, respectively; Q/τ is the heat flux; τ is the time; V_S is the volume flow rate of combustion products adjusted to standard conditions; Δi is the change in volume enthalpy; W is the linear velocity of combustion products relative to flame front; M is the mass gas flow per second; ρ is the gas density; F is the area of tube cross section; u is the velocity of displacement of flame front relative to tube walls (during vibratory propagation of the flame u is the mean velocity over one period); η is the ratio of some quantities (see corresponding subscripts); n is the refractive index of gas; N is the number of fringes by which interference picture is displaced; μ is the wavelength of light; l is the length of a nonuniformity (in our case tube width); A is the amplitude of displacement of flame front; d is the tube diameter; v is the amplitude of oscillatory velocity of flame front; $w = V/F$ is the mean velocity of combustion products averaged over flow rate; λ is the thermal conductivity of glass substrate of sensor; a is the thermal diffusivity; $f(\tau)$ is the function describing variation of substrate temperature with time. Subscripts: 0 and i with ρ are the fresh mixture and combustion products; m and T with η are the ratio of number of moles and of temperatures in combustion products to corresponding quantities in fresh mixture; 1 and 2 with T are the inlet and outlet of test section of tube; q and w with η are the ratios of heat fluxes and velocities in the presence of vibrations to the corresponding quantities without vibrations.

REFERENCES

1. G. B. Darling, Petroleum, 22, May 1959.
2. G. G. Agadzhanyan, in collection: Theory of Similarity and Simulation [in Russian], 1951.
3. S. I. Kosterin, I. A. Kozhinov, and A. I. Leont'ev, Teploenergetika, no. 3, 1959.
4. R. Marchal, Journess internationales transmission chaleur, 19–24 juin 1961. Paris, 1962.
5. Yu. A. Sozin, Aviatsionnaya tekhnika, no. 3, 4, 1963.
6. L. N. Khitrain, Physics of Combustion and Detonation [in Russian], Izd. MGU, p. 174, 1957.
7. D. S. Kayumova, Final Scientific Conference of the Kazan State University, 1962 [in Russian], Izd. Kazanskogo Un-ta, 1963.
8. B. Lewis and G. Elbe, Combustion, Flames, and Explosions of Gases [Russian translation], IL, 1948.
9. S. A. Abrukov, Third All-Union Congress on Combustion Theory, 1. [in Russian], Izd. AN SSSR, 1960.
10. Yu. A. Polyakov and E. A. Mit'kina, Pribory i tekhnika eksperimenta, no. 4, 1961.
11. W. H. Giedt, Jet Propulsion, 25, no. 4, 158, 1955.

26 May 1966

Kazan Construction Engineering Institute