PROPERTIES OF THE DEVELOPMENT OF NONSTEADY THERMAL CONVECTION IN CYLINDRICAL LAYERS OF GASES

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Experimental investigations of nonsteady heat exchange in air at high rates of heating of a wire detector placed horizontally along the axis of a confining pipe are described.

In [1] a description is given of the procedure, installation, and experimental results of an investigation of nonsteady thermal convection in cylindrical air layers at low rates of heating of a wire filament. In this case the wire detector was placed horizontally along the axis of the confining pipes, and its heating rate was recorded by the acoustic frequency method [1, 2], based on the measurement of the frequency difference between emitted and received ultrasonic vibrations, which is proportional to the filament heating rate:

$$\Delta f(\tau) = A\frac{dT}{d\tau}\ . \tag{1}$$

As shown in [1], when the heat-transfer coefficient is constant, the dependence

$$\ln\frac{\Delta f(\tau)}{A_2} = -\alpha m\tau \tag{2}$$

should be satisfied, where A_2 is a constant and $m = 2/c\gamma r_1$ is a constant determined by the parameters of the detector.

It is interesting to study the properties of occurrence of nonsteady heat exchange at considerable rates of heating of the detector, i.e., with large amounts of thermal power applied. As the experiments showed, under these conditions the development of thermal convection acquires entirely new specific features. The heat-exchange process passes through several stages just before the start of established convection. Some time after the heater is turned on (less than one-tenth of a second) the heat transfer from the wire increases sharply. Then after 0.2-1.2 sec (depending on the applied power and the diameter of the pipe) sharp degradation of the heat-exchange conditions sets in (Fig. 1), which leads to an increase in the filament heating rate during some time segment (a fraction of a second). After this intense heat exchange again develops and for 0.5-1 sec (depending on the applied power when the inner diameter of the pipe is 8 mm), the value of the coefficient of heat exchange is about twice as large as the value of α under the conditions of established heat exchange (Fig. 1a and b). After this the heat exchange seems to slow again and the character of its occurrence described above can repeat (Fig. 1a). Then a period of established heat exchange sets in with a constant value of the heat-exchange (Fig. 1a, b, c) equal to about 100 W/m^2·deg for all the pipes.

The pattern described was observed for all the pipe diameters investigated (8, 14, 46 mm), but for pipes with a smaller diameter these properties were displayed more sharply and the number of inflections in the curve of the dependence $\ln\Delta f(\tau)$ was larger (up to four inflections, Fig. 1a). With an increase in the diameter of the confining cylinders, their number decreased and the established convection mode set in faster. In addition, the unstable convection mode was displayed more clearly with an increase in the thermal power applied to the detector (Fig. 1a and b). As the pipe diameter increases the convective heat exchange is stabilized faster and the character of its occurrence approaches that of heat exchange in an open space (Fig. 1c).

It should be noted that with heating in an open space (especially at high power) the established convection mode also does not set in immediately after the source of filament heating is turned on but after some time (0.2-1 sec).

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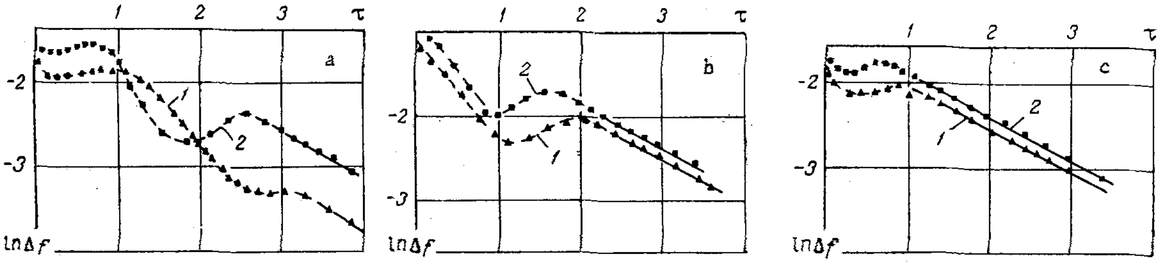

Fig. 1. Experimental dependence of ln Δf on τ, sec, for filament heating in a confining pipe with an inner diameter of 8 (a), 14 (b), or 46 mm (c): 1) P = 0.5 W; 2) P = 0.6 W.

Analogous investigations for an open space were made by Ostroumov [3]. Nonsteady thermal convection from a thin horizontal filament in air and some liquids was investigated in that report. The temperature of the detector was measured from the variation of its electrical resistance. In the report it was established that in the investigated media an established convection mode sets in with some delay, equal to 0.6-0.8 sec for air. Thus, our experiments on the study of convective heat exchange in open air agree with the results of G. A. Ostroumov. The delay times in confined volumes are somewhat greater for our case and comprise 0.7-3 sec, depending on the applied power.

The most unexpected is the established fact of a sharp degradation of heat exchange in the period of the transition from heat conduction to established convection. In this case, as indicated above, the rate of heating of the wire starts to grow at certain times. This effect was observed systematically for all three pipe diameters investigated at applied powers exceeding 0.3 W.

One can attempt to explain this effect as follows. At the initial heating time the gas temperature near the wire grows sharply and a front with a large temperature gradient gradually propagates radially toward the inner wall of the pipe. Thermal expansion of the gas occurs simultaneously: the cold layers of gas are pressed against the wall and part of it is expelled from the pipe. The situation changes when the front with a large temperature gradient arrives at the wall. The wall makes it impossible for the gas to expand in the direction away from the heated filament, and it starts to expand in the opposite direction. As a result, a compression wave forms near the wall which starts to propagate toward the pipe axis, i.e., toward the heater, with the speed of sound. The amplitude of this converging wave (the pressure) will grow as it approaches the heater owing to the concentration of energy.

Therefore, strong adiabatic compression with a sharp increase in temperature can be observed near the surface of the wire heater. In the process, the temperature drop between the filament and the boundary layer of gas decreases and in principle it can change sign, which will correspond to a change in the sign of the coefficient of heat transfer. The effect evidently is the larger, the better the coaxiality of the wire filament and pipe and the thinner the filament. Then the process can repeat: the rate of heating of the filament grows, the temperature gradient near it increases again, and the heat-exchange intensity grows. An elastic wave also develops near the heater, but it is a diverging wave and its amplitude falls rapidly with greater distance from the axis.

The time when the temperature front with a large temperature gradient reaches the inner wall of the pipe evidently depends on the thermal diffusivity of the gas and the velocity of the convective flows (the velocities of gas movement), but at least it must not be greater than the time found from the condition

$$a\tau/r_2^2 \sim 1, \tag{3}$$

i.e.,

$$\tau \leqslant r_2^2/a. \tag{4}$$

For our conditions the time $\tau = r_2^2/a$ will be $\tau = 0.73$ sec for a pipe with $r_2 = 4$ mm and $\tau = 2.2$ sec for one with $r_2 = 7$ mm. As seen from Fig. 1a and b, the times of onset of the sharp slowing of heat transfer from the wire actually are of this order. Since the rate of convective mixing of the gas must grow with an increase in the applied power, it is natural to expect that this time will decrease. This is well seen from the experimental dependences shown in Fig. 1a and c.

Thus, nonsteady heat exchange in horizontal pipes containing heated filaments evidently represents a complex process including the combined occurrence of conductive and convective heat transfer and sonic phenomena, which also take part in the transfer of thermal energy. The elastic wave converging toward the axis of the cylinder transfers energy from less heated gas layers to more heated ones, which under certain conditions can lead to a negative value of the heat-transfer coefficient.

The amplitude of the elastic waves gradually decreases, after which the process of established convection begins with a constant value of the heat-transfer coefficient, approximately the same for all the pipes investigated. The very fact of the development of acoustic phenomena during convective heat exchange is possible and was established experimentally, by Righi [4, 5], for example.

The relative error in the determination of the heat-transfer coefficient did not exceed 4.3%. The accuracy attained is not ultimate and can be raised through an increase in the coefficient of multiplication of the carrier frequency and improved methods of treatment of the experimental oscillograms.

NOTATION

f	is the frequency of acoustic vibrations;
τ	is the time;
A	is the acoustic constant;
T	is the temperature of wire detector;
α	is the heat-transfer coefficient;
c, γ, and r_1	are the specific heat, density, and radius of wire;
a	is the coefficient of thermal diffusivity of gas;
r_2	is the inner radius of confining pipe;
P	is the electrical power going to heating of filament.

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