INVESTIGATION OF BOUNDARY LAYER STABILITY IN THE PRESENCE OF INTENSE HEAT TRANSFER

Yu. A. Polyakov

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The results of an investigation of the transition of a laminar boundary layer to turbulent in the air behind a shock wave by the thin-film thermometry method are presented. Stabilization of transition Reynolds number is observed with an increase of the intensity of heat transfer.

The problem of transition of a laminar boundary layer to turbulent in the presence of intense heat transfer has important applications in physical gas dynamics, since the character of flow in the boundary layer determines the magnitude of tangential stress on the surface.

A number of theoretical and experimental studies have been devoted to this problem recently ([1, 2] et al.). The organization of such an experiment under steady-state conditions is difficult, since it is necessary to create considerable heat abstraction from the model. In a shock tube it is possible to study the dynamics of the boundary layer in a wide range of parameters by the thin-film resistance thermometry method.

The problem of investigating the boundary layer on a flat plate differs from the problem of the development of a boundary layer on the wall of a shock tube by the boundary conditions, but on the basis of experiments in a shock tube it is possible to make qualitative conclusions on the effect of heat transfer on the transition. The problem of the development of a laminar layer behind a shock wave was investigated theoretically in a number of studies [3, 4].

If a thin-film thermometer is mounted flush with the surface of the tube channel, it is possible to record the transition of the boundary layer during movement of the gas dynamic "plug" over the sensing element owing to the small magnitude of the time constant ($\tau_1 \simeq 1$-$3\ \mu$sec).

The fact of the occurrence of the laminar layer behind the shock wave over the sensor was determined by the stepped form of the temperature of the substrate surface recorded by a thin-film resistance thermometer [5, 6]. The change of heat transfer conditions at the time of transition and development of the turbulent layer is recorded by the marked change in the thermogram of the surface temperature. The clarity of the recording of the temperature of the sensor's film permits evaluation of heat fluxes in the laminar and turbulent parts of the layer.

An evaluation of the length of the laminar zone in the tube is of considerable importance for methodological investigations. The presence of a turbulent layer on the optical walls of the tube channel can interfere with visual observations conducted in the flow core. This is important when studying the mechanism of detonation and when determining the delay of ignition of combustible mixtures. In thermodynamic investigations the spectral lines can be distorted due to considerable absorption by a cold turbulent layer.

The purpose of the present study was to determine the effect of the magnitude of the heat flux on boundary layer stability and the possibility of the effect of dissociation processes in the flow core on the transition of a laminary layer to turbulent.

The experimental device was a diaphragm-type shock tube of rectangular section 55×72 mm with a total length of the low-pressure chamber of more than 10 m. The tube consisted of two copper waveguide

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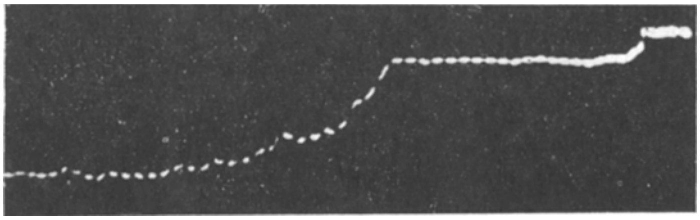

Fig. 1. Photooscillogram of the heat pulse of the surface temperature behind the shock wave (the transition of the laminar layer to turbulent is seen). Markers are 1 μsec each ($p_1 = 5 \cdot 10^{-2}$ atm, M = 5).

sections lined for strength with shaped steel plates uniformly bolted over the entire length. The size of the measuring section was selected on the basis of the length of the laminar zone of the boundary layer on the side wall of the section. A pressure chamber made from a welded cylinder with flanges for a vacuum line was mounted in the measuring section at the end of the tube to prevent destruction of the boundary layer by the reflected wave.

To determine the duration of the gas dynamic plug, we used a thermal probe in the form of an 8-mm-diam. quartz tube with a thin-film thermometer applied about its generatrix. The probe was located after the measuring section and recorded the size of the plug from the wave front to the contact zone on the basis of the change of the parabolic form of the surface temperate at the stagnation point of a cylinder. The thin-film thermometers were manufactured according to the technology presented in [7] and represented 5-mm-diam. glass cylinders with a platinum film brazed on the polished surface of the substrate. To eliminate the shunting effect of the gas and other interferences the sensing element was coated with silicon monoxide with subsequent annealing to convert SiO to SiO_2. The sensors had a resolution time of not worse than 2-3 μsec.

Calibration of the thermometers was done by the method in [8] by a rectangular current pulse having a specific duration.

The velocity of the shock wave was measured by recording the time of passage of the shock wave of a fixed base between the thermal sensor triggering the driven sweep of the oscillograph and the start of the temperature jump, which was recorded by another sensor. Thus the wave velocity can be referred with sufficient grounds to the channel section where the transition was investigated.

In calculating the thermodynamic and gas dynamic properties of the flow behind the shock wave we used the tables for air [9], and the experimental results in [1] were taken into account for calculating the transition, Reynolds number Re_T. The experiments were conducted in air in the range of shock-wave Mach numbers from 2 to 10 at initial pressures in the low-pressure chamber of 10^{-2}, $5 \cdot 10^{-2}$, and 10^{-1} atm. Owing to the absence of glass sections, unlike in [2], the permissible level of initial pressures was considerably higher.

The recording apparatus consisted of a measuring circuit with a ballast resistor, pulse amplifier, and IO-4 oscillograph. The duration of the "plug" was recorded simultaneously by the thermal probe and the results for which τ of the plug > τ_l (where τ_l is the temporal length of the laminar part of the boundary layer) were used in the calculations.

A typical pulse of the surface temperature is shown in the photograph, where we see a recording of the heat transfer intensities in the laminar and turbulent parts (Fig. 1).

The results of the investigation were treated by a method which gives, in our opinion, a clear and more physical concept of the effect of the heat factor on the transition. The stay time of the laminar layer over the sensing element was determined from the length of the pulse area from the thermal sensor to the instant of a marked change of the temperature curve recording the loss of stability and start of development of the turbulent layer. The modified heat flux $q\sqrt{\tau}/\sqrt{p_2}$ is determined uniquely by the Mach number. The magnitude of the heat flux was determined on the basis of the temperature jump by the formulas of a semi-bounded body. The transition number was determined by the formula used in [2]:

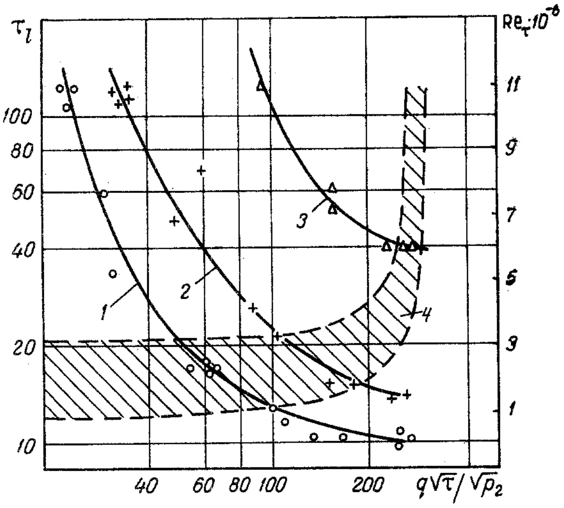

Fig. 2. Transition time vs heat transfer intensity ($q\sqrt{\tau_l},/\sqrt{p_2}$ kcal$^{1/2}$/$l^{1/2}$; τ_l, μsec): 1) $p_1 = 10^{-1}$ atm; 2) $5 \cdot 10^{-2}$; 3) 10^{-2}; 4) zone of Re_T variation depending on heat transfer intensity.

$$\mathrm{Re}_\tau = \frac{\rho_2}{\mu_2} \cdot \frac{u_2 V_s}{(V_s - u_2)} \tau_l.$$

The experimental results are presented in Fig. 2. For analysis the transition Reynolds number Re_T is shown as a function of the modified heat flux on the wall. As a result we can make the following conclusion:

1. The transition time τ_l increases nonlinearly with decrease of p_1. Thus, $\tau_l = 10$ μsec when $p_1 = 10^{-1}$ atm, $\tau_l \simeq 15$ μsec when $p_1 = 5 \cdot 10^{-2}$ atm, and $\tau_l = 10$ μsec when $p_1 = 10^{-2}$ atm (for example, for $q\sqrt{\tau_l}/\sqrt{P_2'} = 200$). Naturally the average time values are indicated. Consequently, it is easy to show by extrapolation that when $p_1 \leq 1$ mm Hg the transition time is much greater than the stay of the hot gas near the wall, and therefore it is impossible to record the transition up to the appearance of the contact zone.

2. For high Mach numbers ($M \geq 10$), when dissociation of the air in the flow core is of considerable significance, no anomalies were observed in the behavior of the temperature curve, which indicates the small effect of processes of diffusion of atoms with their subsequent recombination in the cold layer on the temperature gradient near the wall under conditions of partial dissociation of air.

Thus, the effect of physicochemical processes occurring at the upper "limit" of the boundary layer on transition is ruled out, at least in the range of gas dynamic parameters considered.

3. The weak effect of the initial pressure p_1 (in the range $p_1 \simeq 5$–100 mm Hg) on the temperature factor T_W/T_2, which is mainly a function of the Mach number, was confirmed experimentally.

4. Beginning with $q\sqrt{\tau_l}/\sqrt{p_2} \simeq 150$ ($M \simeq 7$), there is a considerable stabilizing effect, which is determined mainly by the intensity of heat transfer. The zone of variation of Re_T when $q\sqrt{\tau_l}/\sqrt{p_2} < 150$ for a concrete value of the intensity of heat transfer is explained by the effect of the unit Reynolds number $Re = \rho_2 u_2/\mu_2$.

NOTATION

M	is the Mach number of shock wave;
V_s	is the shock wave velocity;
u_2	is the velocity of gas behind shock wave;
q	is the heat flux;
τ	is the time;
T_W	is the temperature of wall surface;
T_2, ρ_2, μ_2	are the temperature, density, and viscosity of gas behind shock wave;
p_1	is the initial pressure in low-pressure chamber;
τ_l	is the time during which the laminar layer is over the sensor.

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