LAWS OF CONVECTIVE VORTEX FORMATION BEHIND A FLAME FRONT DURING ITS PROPAGATION IN A TUBE

S. A. Abrukov and V. P. Samsonov

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A broad range of combustion phenomena are typically strongly influenced by free-convective flows which develop in a gravitational field. These flows sometimes result in the formation of vortices and lead to significant changes in the combustion process [1-7]. There has not been sufficient study of vortex formation phenomena in combustion, particularly on an experimental basis. Even for the simplest object studied – a flame propagating in a tube – the hydrodynamics of the combustion products in a gravitational field have proven to be beyond the scope of both experimental and theoretical investigations.

Here we examine laws and conditions of convective vortex formation in combustion products during the propagation of a slow, stable flame in a vertical, half-open tube.

The main element of the experimental unit was the reaction tube, which was a half-open channel of square cross section. The opposite sides of the tube were made of optical glass, which made it possible to visualize the process with a polarization-type shift interferometer based on an IAB-451 shadowgraph. The process was recorded with an SKS-1M high-speed camera. A long narrow slit was made in one of the nontransparent walls. When a powerful light struck the slit, a light blade was created in the tube cavity and made it possible to visualize the velocity field in the flow of combustion products by the tracer particle method. To do this, finely dispersed MgO powder was poured into the gas mixture.

Weightless conditions were created in a freely falling container holding the reaction tube. The weightless state lasted 0.55 sec. The film camera was automatically activated and the electric spark which ignited the gas mixture was automatically generated at the moment the container was dropped. A more detailed description of the experimental unit is given in [8].

We used propane—air and CO—air mixtures in the experiments. The velocity of the flame relative to the still initial gas mixture was changed by changing the concentration of fuel in the mixture. Tests conducted on tubes of different diameters with a change in flame velocity in a broad range showed that the flow of combustion products behind the flame front is laminar for Froude numbers Fr greater than 0.04. Here, $Fr = u^2/gd$ is made up of the flame velocity u, acceleration due to gravity g, and cross-sectional dimension d. Laminar flow is maintained up to flame velocities at which its form becomes unstable for some reason. When $Fr > 0.04$, the flow of combustion products remains laminar even with a change in the orientation of the flame velocity vector relative to the gravitational acceleration vector and in weightlessness. A reduction in flame velocity ($Fr < 0.04$) from top to bottom under normal gravitational conditions showed that vortices are formed immediately behind the front. Here, the combustion products rotate downward toward the tube axis from the wall and upward along the tube. A further increase in flame velocity leads to an increase in the rate of vortex formation. The film frame shown in Fig. 1 illustrates the velocity field in the vortical flow of combustion products behind the front of a CO—air flame moving at 5 cm/sec in a tube with a channel having a cross-section width of 2.7 cm. The results of tests conducted under weightless and normal gravitational conditions when the mixture was ignited at the lower open end showed that no vortices were formed in the combustion products at any flame velocity.

The structure of the flow behind the flame front was also studied by the interferometric method. Figure 2 shows frames from an interference film illustrating the typical pattern of vortex formation behind the flame front when the flame propagates upward at a velocity of 7 cm/sec. The time indicated in the photographs is reckoned from the moment of ignition of the mixture. The interference bands which appear with the passage of the light wave through the optical discontinuity formed by the flame front and combustion products represent isolines of the phase difference of the light wave. The change in phase difference in this case is

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Fig. 1

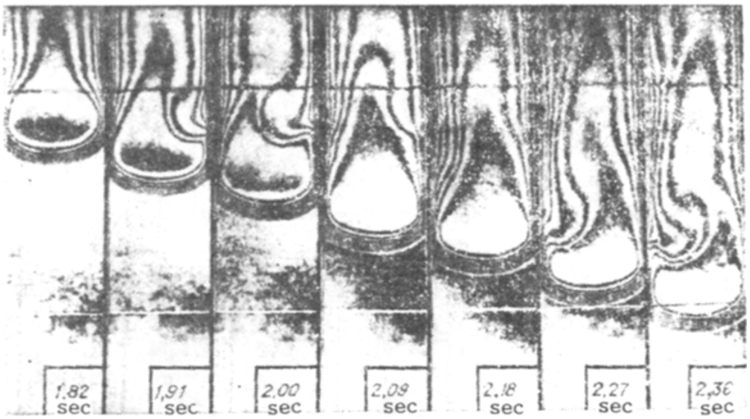

Fig. 2

determined mainly by the change in temperature. It is evident from the photographs that the phase difference changes near the flame front only right next to the tube walls. This provides grounds for concluding that the optical discontinuity is two-dimensional and that the interference bands can be regarded as isotherms.

Analysis of the interferograms shows that the flame is stable before the vortices appear and that the flow of combustion products is laminar. Here, the interference bands are typically bent toward the center of the tube, which is evidence of gradual expansion of the boundary layer. The vortices which appear in the interference pattern are manifest as a sudden curvature of the interference bands and shifting of the bands from the wall of the tube. The vortex is gradually entrained by the flow toward the open end of the tube and decays. After a certain amount of time, a similar vortex is created on the opposite wall of the tube. Thus, a series of vortices is created on opposite walls of the tube, these vortices rotating alternately to the right and to the left, and down and up the tube axis. The vortices increase in size to equal the width of the channel with a decrease in flame velocity to the limiting value, and flow behind the flame front becomes chaotic. The experimental findings provide evidence of the free-convective nature of the vortex formation mechanism in the combustion products. The physical essence of this phenomenon is similar to vortex formation in a flow of heated gas undergoing cooling on the cold walls of a vertical tube in the viscous-gravitational regime, when the directions of forced (due to thermal expansion of the combustion products) and natural (free-convective) motion are opposite.

The following are necessary and sufficient conditions of vortex formation near the flame front: the convection induction period should be sufficiently small, and the condition of flow separation on the wall should be satisfied in the region of initiation of the vortex.

As was done in [9], we will evaluate the first of these conditions by introducing the parameter $\sigma = \tau/t$, where τ is the characteristic time of flame propagation; t is the convection induction period. According to [10], at $Pr \approx 1$, $t = 70d^2/aRa^{2/3}$, where a is the diffusivity of the combustion products; Ra = PrGr is the Rayleigh number; Gr is the Grashof number; Pr is the Prandtl number. Since $\tau = d/u$,

$$\sigma = 70\mathrm{Pe}/\mathrm{Ra}^{2/3}, \quad (1.1)$$

where Pe = ud/a is the Peclet number. At $\sigma > 1$, the necessary condition for vortex formation near the flame front is satisfied. Equation (1.1) makes it possible to determine the value of flame velocity at which the necessary condition of vortex formation is satisfied. For example, the flame velocity $u \lesssim 10$ cm/sec for a tube 2.7 cm in diameter.

According to [1], a sufficient condition of vortex formation is triviality of the velocity gradient in the y direction perpendicular to the wall at the separation point, i.e., $(\partial v/\partial y) = 0$. In a vertical tube, this condition can be realized only when the flame is propagating downward. In this case, the rate of outward flow of the expanding combustion products is compensated for by the equal (in magnitude) rate of return flow of descending combustion products undergoing cooling on the wall. Using the formula

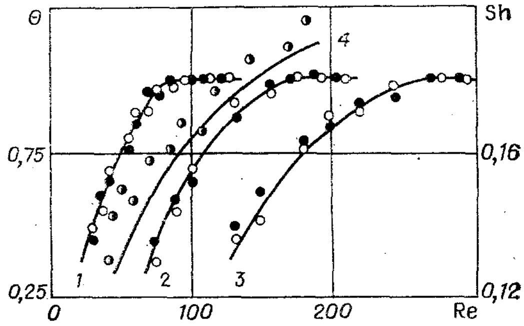

Fig. 3

$$v_+ = 0.328\sqrt{gd} \tag{1.2}$$

and considering that

$$v_- = u^0(T/T_0 - 1), \tag{1.3}$$

we can evaluate the flame velocity at which boundary-layer separation and vortex formation should occur. In Eqs. (1.2) and (1.3), v_+ is the rate of free-convective motion of the combustion products; v_- is the rate of flow of the combustion products out of the tube due to thermal expansion; v is the resulting velocity; u^0 is the normal flame velocity; g is acceleration due to gravity; T_0 and T are the initial temperature of the gas mixture and the combustion temperature. Equation (1.2) was taken from [11] and describes the rise of an air bubble in vertical tubes filled with liquid. It must be noted that Eq. (1.3) is generally valid only for flat flames. However, measurements of the velocity of the tracer particles in the flow of combustion products using the photographs showed that this formula gives velocity values sufficiently close to the actual values for the above-described tests with slightly curved flames. Since $u^0 = uS^0/S$, where S^0 and S are the cross-sectional area of the tube and the surface area of the flame front, and since $S^0 \approx S$, then we set $u^0 \approx u$ in (1.3). As indicated above, $\partial v = 0$; if $v_+ = v_-$ we can write $0.328\sqrt{gd} \approx u(T/T_0 - 1)$, from which

$$u \approx 0.328\sqrt{gd}/(T/T_0 - 1). \tag{1.4}$$

For a tube with the cross-sectional dimension d = 2.7 cm, estimation of flame velocity from Eq. (1.4) gives a value of about 5 cm/sec. Thus, flame velocities corresponding to the actual values are obtained from Eqs. (1.1) and (1.4).

The sequence of vortices shown in Fig. 2 is externally similar to the Karman vortex street which is created, for example, in the flow of a liquid about a cylinder. Since flame velocity in our tests ranged from 5 to 25 cm/sec and tube diameter ranged from 2.7 to 6 cm, it was possible to graph the dependence of the frequency of vortex formation on the Reynolds number, shown in the form of the function Sh(Re) by curve 4 in Fig. 3. Here, Sh = nd/v is the Stouhal number; n is the frequency of vortex formation; Re = vd/ν is the Reynolds number; ν is the kinematic viscosity. The solid line shows the dependence constructed for a Karman vortex street in [1]. The half-darkened circles denote the results obtained in the present study. It is evident that the frequencies obtained here are somewhat higher than those obtained in [1]. Nevertheless, the values are fairly close and show the same dependence on the Reynolds number.

Vortex formation and separation of the boundary layer from the tube wall are accompanied by a drop in temperature on the wall in the region of the vortex. Temperature was monitored during the experiments with a thermocouple built into the side wall so that its junction, about 50 μm in diameter, projected 0.5 mm over the plane of the wall. The signal from the thermocouple was sent to an N041U4.2 loop oscillograph. The temperature drop on the wall in the vortex region was also calculated from the interferogram using the following formula for a planar discontinuity

$$\Theta = \frac{T}{T_*} = \frac{(n_0 - 1) - N\lambda/2d}{(n_0 - 1) - N_*\lambda/2d},$$

where T and T_* are the temperature of the combustion products on the tube axis and on the wall; N and N_* are the orders of interference on the tube axis in the region not occupied by the vortex and on the tube wall in the vortex region; λ is the wavelength of the light; n_0 is the refractive index of the light of the gas mixture. The results of the interferometer and thermocouple measurements are shown by curves 1-3 in Fig. 3 in the form of dependences of the dimensionless temperature $\theta = T/T_*$ on the Reynolds number. Curves 1-3 were constructed for conditions when the Reynolds number takes values of 10^4, $5 \cdot 10^4$, and 10^5, respectively. The values of the Reynolds number at which $\theta = 1$ correspond to conditions when no vortices are formed. The path of the curves in the figure shows that at certain Reynolds numbers the temperature on the wall differs little from the temperature on the tube axis, which is equal to the combustion temperature. The range of values of the Reynolds number at which vortex formation occurs typically broadens with an increase in the Reynolds number.

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