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INTERACTION OF SPONTANEOUS VORTEX STRUCTURE WITH A FLAME FRONT

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Spontaneous vortex formation in combustion products near a flame front propagating in a combustible mixture down a vertical tube has been studied experimentally. It is shown that under certain conditions, free convection suppresses or stimulates vortex perturbations at the flame front. It is found that periodic changes in vortex intensity depend on oscillations of the flame front. This dependence is controlled by the rate of heat exchange among the flame front, combustion products, and pipe walls. The vortex flow structure depends on the shape of the closed trajectory along which the leading point of the flame moves in the coordinate system attached to the vortex.

Key words*: vortex structure, hydrodynamic instability, flame front, experiment.*

The problems of hydrodynamic flame instability, in particular, the influence of various factors (e.g., acceleration), are of major importance for the theory of flame propagation. Theoretical aspects of the problem were considered in detail by Zel'dovich [1] and Marckstein [2], who briefly discussed the role of the vortex component of perturbations. Marckstein [2], Gupta [3], and Raushenbakh [4] considered the main principles for controlling unsteady combustion, which, as a rule, amount to a periodic action on the combustion zone by forced vortex flows. Spontaneous formation of vortex structures in combustion products is due to an increase in entropy both at the flame front and on any discontinuity surface [5]. The vortex flow rate depends on flow acceleration on the flame surface and, thus, on the surface curvature [1]. At low flame propagation velocities in a tube, free convection also has an effect on vortex flow. Elucidating the mechanisms of interaction of a spontaneous vortex structure with a flame front is important to developing methods for controlling self-oscillating combustion regimes and increasing heat- and mass transfer rate in combustion chambers.

Abrukov and Samsonov [6] performed an experimental study of the development of Kármán's vortex street behind a flame front that had a large-radius surface curvature and propagated at a constant velocity down a vertical tube of rectangular cross section. The flame front symmetry was conserved throughout flame propagation. The fact that the vortex cells do not drift downstream, as in the case of flow around bodies, but follow the flame was neglected in [6]. The influence of periodic changes in gas rotation velocity in the vortex on flame front stability and propagation velocity was not analyzed. The goal of the present work was to study the relationship between vortex structure and flame front, which leads to a self-oscillating combustion regime and formation of a coherent vortex structure.

The experimental facility used in the experiments consisted of a container, which was free to fall from a height of 3.4 m. A rectangular reaction tube with a side length ratio of 1.5 was placed in the container. Since the cross-sectional dimensions were different, the vortex cells were shaped like cylinders, whose axes were directed along the largest wall in the tube cross section. In the experiments, we used reaction tubes with cross sections of 1×1.5 to 10×15 cm, which allowed us to control, over a wide range of Rayleigh numbers, both the rate of convective uprise of the combustion products and the time t_0 during which the free convective flow velocity reached its maximum, The tube length was 20 times the larger cross-sectional dimension.

After ignition of a combustible mixture, the upper end of the tube was opened automatically and the flame propagated downward at a constant velocity. Flame propagation was visualized by both the interference method using an IAB-451 shadow device and by the particle tracing method and was recorded by an SKS-1M

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high-speed movie camera and an AKS movie camera. Movie recording of the flame front and combustion products was performed through the transparent side walls of the container and the tube made from optical glass. To realize the particle tracing method, magnesium oxide particles were added to the combustible mixture before ignition. The particle size did not exceed 50 μm. The particles were illuminated with a "light knife" formed by a light beam from an DRSh mercury lamp which passed through a narrow slit on the tube wall. The experiments were carried out in normal and zero gravity to elucidate the role of free convection in the spontaneous formation of a vortex structure.

An analysis of the interference patterns of flame propagation obtained in [6] showed that the alteration of vortex cells on the opposite walls of the tube is accompanied by small-amplitude oscillations of the flame front. In this case, the flame surface rotates about the plane of the tube cross section. The rotation angle is 2–3°. The flame, in this case, is almost flat. Because of this, particular attention was given to the accuracy of the vertical orientation of the tube axis. It was established that departure of the tube axis from vertical by 2–3° led to a loss of flame front symmetry, development of flame oscillations, and formation of a vortex structure mainly near the tube wall at which the projection of the free fall acceleration vector onto the normal to the surface is positive.

Lean propane–air mixtures were used as the combustible gas. Rich mixtures were not employed because they lead to thermal diffusion instability and formation of cells on the flame surface. Propane concentration slightly exceeded the propagation limits, which allowed us to decrease the flame propagation velocity to 4–12 cm/sec. The velocity of combustion products varied from 15 to 45 cm/sec, which corresponded to Reynolds numbers Re $= vd/\nu =$ 50–300, where d is the larger dimension of the tube cross section, v is the velocity of combustion products, and ν is the kinematic viscosity. In zero gravity, the flow of the combustion products was laminar even with increase in flame propagation velocity to 25 cm/sec.

Visualizing the flow behind the flame front in reaction tubes with different cross sections, we determined conditions for the spontaneous formation of a vortex structure in combustion products. It is established that the alteration of vortex cells in Kármán's streets is due to flame front oscillations. Changes in the equilibrium position and shape of the flame causes distortions in the resulting velocity profiles of the free convective and forced flows. As a result, the conditions for vortex formation on the opposite walls of the tube were different and the Kármán's vortex street is destroyed. To verify this assumption, we placed the reaction tube at a small angle to the vertical. The slope varied from 1 to 10°. A further increase in slope caused substantial changes in flame shape and flame propagation characteristics near the concentration limits. Figure 1 shows interference patterns for the flame front and combustion product flow. The interval between frames 1–3 is 0.33 sec, which corresponds to 1/3 of the period of flame front oscillations. The tube with a cross section of 1.8×2.7 cm is inclined to the pattern surface at an angle of 3° to the right of the vertical. The flame propagation velocity is 7 cm/sec. Figure 1 shows that the flame front is asymmetric because of the departure of the tube from vertical. Flame propagation is accompanied by pronounced oscillations near a certain equilibrium position (frame 2 in Fig. 1). The interference lines above the flame front illustrate the development dynamics of a vortex cell in combustion products. Deviation of the tube from the vertical results in the disappearance of Kármán's street. Vortex cells form only at the wall to which heat transfer by free convection is most intense (in frames 1–3 on the left).

To interpret the interference pattern obtained under given experimental conditions, we estimate the effect of temperature, velocity, and geometric dimensions of the vortex cell on the order of magnitude of interference. The phase difference of the light wave is calculated by the formula $\delta = 2\pi(n - n_0)l/\lambda$, where λ is the light wavelength, $n - n_0$ is the difference in refractive indices on the path of interfering light waves, and l is the length of the light beam path. The effect of medium's parameters on the change in the phase difference (interference line number) is determined from the relation $\Delta\delta/\delta = \Delta(n - n_0)/(n - n_0) + \Delta l/l$, where $\Delta(n - n_0)$ -is the change in the refractive index due to the changes in temperature ΔT and pressure ΔP and due to the departure Δl of the vortex cell from a cylindrical shape. From the Gladstone–Dale relation $(n - 1)/\rho =$ const and the gas state equation $P = \rho RT$, where ρ is the density of combustion products and R is the universal gas constant, we derive the equation

$$\Delta\delta/\delta = \Delta(\rho v^2)/P + \Delta T/T + \Delta l/l. \quad (1)$$

In this case, v is the maximum velocity of the combustion products, which determines the gas pressure drop in the tube and near its open end. The first term in (1) contributes less than 0.001% to the value of $\Delta\delta/\delta$. The order of magnitude of $\Delta l/l$ is determined by the geometric similarity of the downstream flow and can be estimated from the ratio of the longitudinal to the transverse dimension of the flame. The flame front dimension measured by the photograph is $\Delta l/l \simeq 15$. Thus, the order of magnitude of the interference is determined predominantly by local temperature changes, and the interference lines can be approximately considered isotherms.

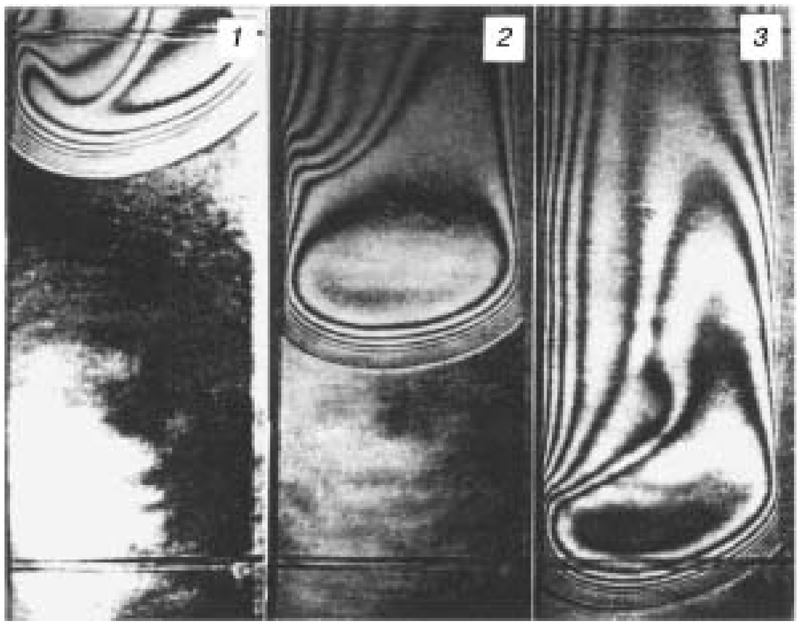

Fig. 1

In addition, Fig. 1 shows the effect of the vortex flow on the temperature distribution near the tube wall and in the flame front (frame 1). In frames 1 and 2, the maximum orders of magnitude of the interference in the flame front differ by 10–15%. A decrease in temperature in a certain segment of the flame front causes a decrease in normal flame propagation velocity in this region, a decrease in surface curvature, and return of the flame front to the equilibrium position. The amplitude of the vortex perturbations generated by the flame front decreases, leading to a decrease in rotation velocity in the vortex cell. The vortex cell core (frame 2) is shifted downstream of the flame front by a distance of the order of the tube cross section width. After a lapse of time equal to the oscillation period, the temperature equalizes in all regions of the flame front, the free convection velocity increases again, and the process is repeated. Frame 3 shows the formation of a new vortex cell. The vortex cell core is observed to shift toward the flame front. An analysis of individual frames shows that the fluctuations in the vortex cell core coordinate and gas temperature in the cell lag behind the temperature and coordinate fluctuations in the flame front region adjacent to the tube wall by $\pi/2$ in phase.

The photographs in Fig. 2 supplement the pattern of spontaneous vortex formation in the tube. Frames 1–3 were obtained by shooting flame luminescence and the combustion-product flow visualized by the particle tracing method. The dimensions of the tube cross section are 5.0×7.5 cm, and the flame propagation velocity is 10 cm/sec. The tube is set upright. In our experiments, the oscillation amplitude of the symmetric flame front is larger than that obtained in [6], because at the higher velocity of the free convective flow, the flame front becomes less stable due to an increase in curvature radius. In frame 3, the direction of rotation of the combustion products in the vortex cell is clockwise, which corresponds to gas descent with lower temperature near the tube wall.

The vortex position and the gas rotation velocity in the vortex cell can be described in terms of the flame leading point. In [1], the leading point of a flame is regarded as a point of the flame that is most advanced toward the flame propagation velocity. In the present work, the trajectories of the leading point were studied using interference films and records of flame luminescence. It appeared that for the strictly vertical position of the tube, these trajectories are circles. The vortex is formed near the tube wall at which the flame leading point is situated. The tube is inclined at a small angle to the vertical, the trajectory of the leading point is an ellipse. Its major axis is perpendicular to the tube axis, and the center is shifted to the wall at which the vortex cell is formed. As the amplitude of oscillations increases, the lengths of the major and minor axes of the ellipse change. The major axis becomes vertical, after which the flame front loses stability.

The photographs in Figs. 1 and 2 show that the vortex cell core forms spontaneously in the region in which the combustion-product flow has been hitherto laminar and there are no conditions for transition to turbulence of the flow because $\mathrm{Re} < 300$. The coordinates of the vortex cell are determined exactly. In the frame of reference

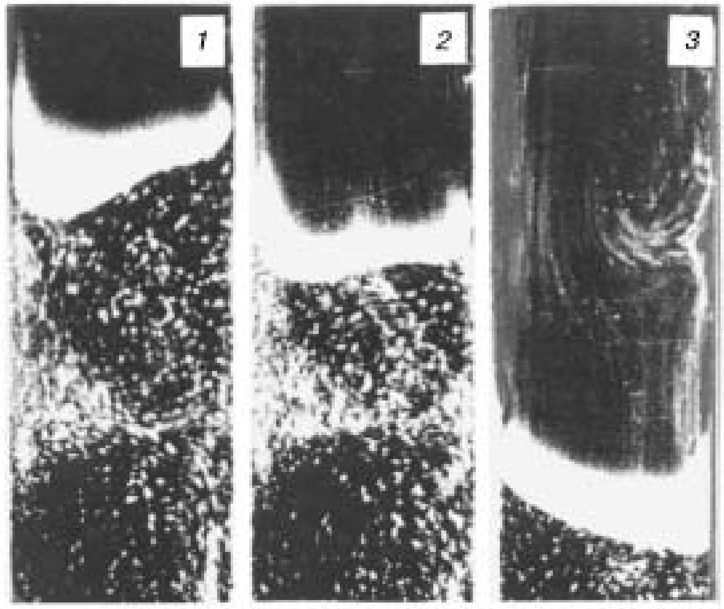

Fig. 2

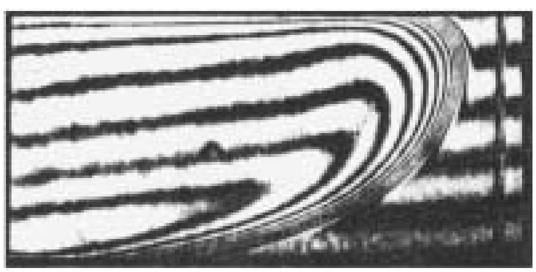

Fig. 3

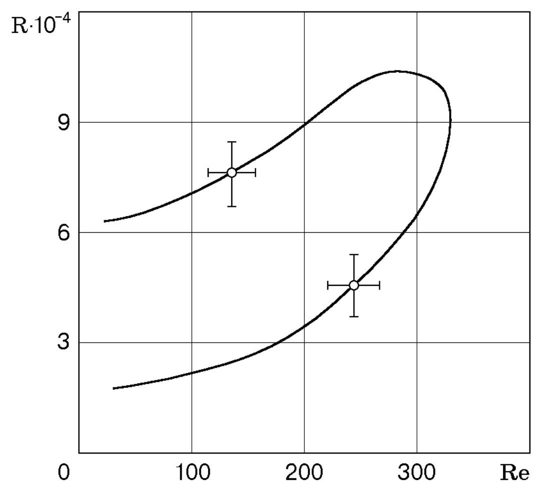

Fig. 4

attached to the flame front, the vertical coordinate is equal to the product of flame propagation velocity by the time t_0. The horizontal coordinate is determined by the flame front curvature (frame 3 in Fig. 2). The presumed mechanism of formation of flame self-oscillations and Kármán's vortex street is supported by the fact in zero gravity, that the vortex structure does not form at any velocity.

For flame propagation in a vertical tube, the leading point is located in the upper part of the flame front and its position does not change. Figure 3 gives an interference pattern of flame propagation in a horizontal tube with cross-sectional dimensions of 5.0×7.5 cm for combustion of an air–propane mixture containing 2.7% propane. The flame propagation velocity increases to 21 cm/sec due to an increase in flame surface. From Fig. 3 it follows that a vortex is not formed in the combustion products. This is probably due to the fact that the free convection flow has no time to develop because of a decrease in the characteristic time of residence of the combustion products near the flame front. An increase in flame front curvature with other things being equal also does not result in vortex formation.

Figure 4 shows the region of existence of the spontaneous vortex structure behind the flame front, which is limited by the curve of the Rayleigh number versus the Reynolds number. The Rayleigh number was calculated from the relation $R = g\beta T d^3/(a\nu)$, where g is the acceleration of gravity, β and a are the volumetric thermal expansion coefficient and thermal diffusivity of the gas, and T is the flame temperature. The interior region limited by the curve of R(Re) is filled with the experimental points corresponding to the R and Re values for which vortices are formed behind the flame front. On the opposite boundaries of the region, two experimental points are given to indicate the limits of errors in determining these points. At a low flame propagation velocity, the time t_0 is shorter than the characteristic time of flame propagation equal to u/d (u is the velocity of visible flame propagation). In the combustion products, free convective flow develops, which propagates downstream near the tube walls and upstream at the center of the tube. The resulting velocity profile is a superposition of the velocity distributions of the free convective flow and the combustion-product flow expanding at the flame front where the streamlines refract. The bend of the resulting velocity profile corresponds to separation of the boundary layer and to energy transfer from the main flow to the vortex flow, according to [7]. Since the change in the transferred kinetic flow energy is proportional to the transverse gradient of the combustion-product velocity $\partial u/\partial y$, the maximum vortex intensity can be found at the instant the vortex cell occupies most of the tube cross section. A comparison between the velocity profiles of the free convective and forced flows makes sense only at a small (of the order of the tube cross section) distance from the flame front. With distance from the flame front, the streamlines become parallel, which indicates damping of the vortex perturbations generated by the flame front. To produce a vortex structure at a higher flame propagation velocity, it is necessary to increase the cross-sectional dimensions of the tube. This is explained by the fact that a decrease in the time t_0 is achieved by increasing the Rayleigh number, which is proportional to the cross-sectional dimensions of the tube to the third power. From Fig. 4 it follows that in tubes with large cross section, the spontaneous vortex structure can be obtained at considerable flame propagation velocities. An increase in cross-sectional dimensions to the values determining the upper boundary of the region of spontaneous vortex structure leads to transition to turbulence and destruction of the vortex structure.

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