Journal of Engineering Physics and Thermophysics, Vol. 69, No. 1, 1996

INITIATION OF DETONATION BY BURNING JETS

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UDC 621.374

We carried out an experimental investigation of the initiation of a detonation wave by burning jets at the orifice plate outlet.

Introduction. The study of the transition from combustion to detonation is important from both fundamental and practical points of view. The length of the transition depends on a large number of different parameters. The qualitative effect of these parameters on the length of transition is quite understandable. It includes two basic mechanisms of flame acceleration that are interrelated by turbulence and by interaction of the flame with a shock wave. In some cases, when various devices are designed that involve combustion and detonation as a working process, it is necessary to decrease the length of the predetonation flame prepagation region. This is especially true for combustible fuel-air mixtures in which the length of the transition from combustion to detonation can reach 100 diameters of the tube [1]. In [2-5] it is shown that the fast turbulent mixing of combustion products with a combustible mixture can lead to detonation. In the present article we give the results of an experimental investigation of the possibility of decreasing the length of the predetonation region in detonation initiation by burning jets.

Experimental Setup. We used a combustion chamber with a length of 143 mm and a cross-section of 10 × 10 mm. The object under observation was a region of the chamber with a length of 123.5 mm bounded on both sides by quartz windows. The beginning of the observation region was located at a distance of 10 mm from the rear endwall of the main channel. A combustible mixture was ignited by an electric spark from a keep-alive electrode, which was located at the rear endwall of the combustion chamber. In our experiments the ignition energy was equal to 0.7 mJ. As the combustible mixture, we used a stoichiometric mixture of acetylene and oxygen diluted with nitrogen. We investigated the mechasnism of the transition from combustion to detonation using streak photography of the process of flame propagation. Streak photographs were taken by a ZhLV-2 high-speed camera that was optically interfaced with an IAB-451 shadowgraph.

The dependence of the length of transition from combustion to detonation in a free channel on the overall concentration of nitrogen in the working mixture is presented in Fig. 1. The length of transition is expressed in the units of the main channel: $N = h/l$ (where h is the height of the channel and l is the distance from the place of the inception of a detonation wave to the place of ignition). As is seen from Fig. 1, the dilution of a stoichiometric acetylene-oxygen mixture with nitrogen begins to exert a strong effect on the length of transition when the overall concentration of nitrogen $\xi(N_2)$ in the working mixture becomes higher than 18.5%. A characteristic streak photograph of the process for $\xi(N_2) = 22\%$ is presented in Fig. 2. The transition to detonation for this mixture occurs at a distance of $N = 7.3$ units of the main channel, with the place of transition being located approximately in the middle of the region of observation. Therefore, in subsequent experiments the overall concentration of nitrogen in the working mixture was not smaller than 22%.

The burning jets entered the combustion chamber through an orifice plate. It was a steel plate with a working surface of 10 × 10 mm in which 0.62 mm-dia. holes were drilled. In the experiments, we used grids with permeabilities $\eta = S_h/S_{ch} = 0.077$ and 0.126 (where S_h is the total hole area; S_{ch} is the cross-sectional area of the main channel). During the experiments, we could change the distance from the place of ignition to the surface of the orifice plate.

Academic Scientific Complex "A. V. Luikov Heat and Mass Transfer Institute of the Academy of Sciences of Belarus," Minsk, Belarus. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 69, No. 1, pp. 26-32, January-February, 1996. Original article submitted March 24, 1995.

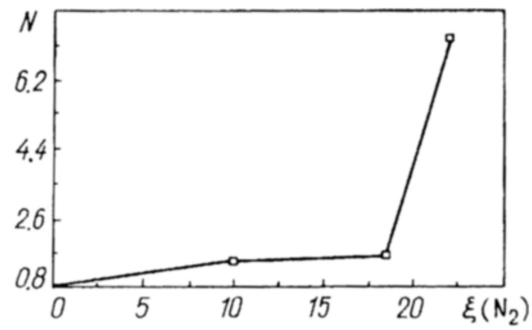

Fig. 1. Dependence of length of combustion-to-detonation transition in a stoichiometric mixture of acetylene and oxygen diluted with nitrogen on the total nitrogen concentration. The channel has a cross-section of 10 × 10 mm^2. The initial pressure P_0 = 0.1 MPa. $\xi(N_2)$, %.

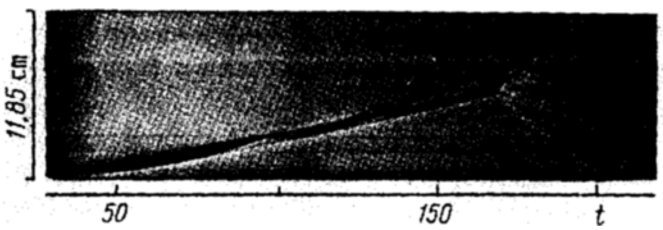

Fig. 2. Streak photograph of the process of combustion-to-detonation transition in a stoichiometric mixture of acetylene and oxygen diluted with nitrogen. The total nitrogen concentration is $\xi(N_2)$ = 22%. The channel has a cross-section of 10 × 10 mm^2. The initial pressure P_0 = 0.1 MPa. t, μsec;

Results and Discussion. To reduce the length of transition from combustion to detonation, for working mixtures with a high degree of nitrogen dilution we used an orifice plate with permeability η = 0.077. The plate was placed at a distance of 27 mm from the rear wall of the main channel; it divided the channel into two parts: the combustion and explosion chambers. In the process of the experiments, the total concentration was varied to obtain the critical composition of the working mixture at which the transition from combustion to detonation occurred in the zone of observation. A typical streak photograph of the combustion-to-detonation transition at the turbulizer outlet for a critical composition with $\xi(N_2)$ = 60% is presented in Fig.3a. In the region of the main channel behind the plate we can clearly see a fan of compression waves that propagate with velocity V_1 = 442 m/sec at the predicted speed of sound V_0 = 341 m/sec. In contrast to equilibrium conditions, the increase in the speed of sound is due to adiabatic heating of the working mixture for the time of flame propagation in the combustion chamber. At time t_2 = 339 μsec, the jets of burning gas are admitted with a supersonic velocity. The measured propagation velocity of the bow shock wave that accompanies the process of transition to the supersonic regime of outflow is V_2 = 603 m/sec. The explosion of the microvolumes of the working mixture in the region behind orifice plate occurs after the completion of its combustion in the preignition chamber at time $t \approx$ 367 μsec. It is accompanied by a series of shocks, the first of which has velocity V_3 = 1581 m/sec. Their enhancement leads to the formation of a stationary detonation wave at a distance of 2.8 units from the turbulizer outlet.

Starting from a total nitrogen concentration $\xi(N_2)$ = 62.5%, the transition from combustion to detonation at the turbulizer outlet did not appear any longer. Figure 3b presents a streak photograph of the process investigated for a working mixture with nitrogen content $\xi(N_2)$ = 70%. It is clearly seen that at the burn-up time of the working mixture in the space of the preignition chamber the burning products escape into the region of the free channel with a velocity smaller than the velocity of the fan of compression waves in front of them (V_2 = 467 m/sec), which move at the local speed of sound. Then, the turbulent front of the flame is gradually accelerated and begins to overtake the head of the fan of compression waves, which propagate at the speed of sound, V_1 = 449 m/sec. A local explosion of the unreacted portion of the working mixture is produced after the interaction of a complex of

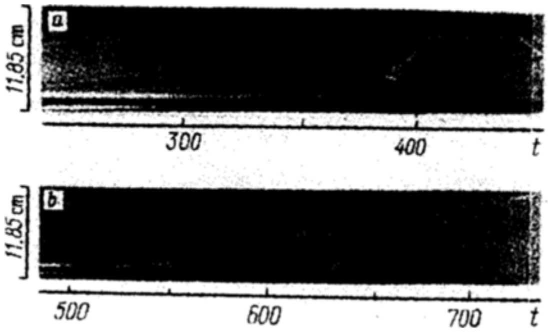

Fig. 3. Streak photograph of the process of combustion-to-detonation transition behind an orifice plate with permeability η = 0.077: a) $\xi(N_2)$ = 60%; b) 70%. The initial pressure P_0 = 0.1 MPa.

combustion waves and of the turbulent flame front with the forward wall of the main channel. The detonation wave produced by the explosion propagates in the opposite direction.

A similar series of experiments that were conducted with an orifice plate with η = 0.126 showed that as the permeability of the plate increased, the transition to detonation occurred in mixtures with a smaller total nitrogen concentration, $\xi(N_2)$ < 60%.

From an analysis of the foregoing experimental results it follows that a necessary condition for the occurrence of detonation at the orifice plate outlet is the implementation of a regime of supersonic outflow of combustion products. To check this statement, we conducted a series of experiments to determine the critical initial pressure at which the collapse of detonation combustion behind a turbulizer with permeability η = 0.077 occurs. As the working mixture we selected a mixture with $\xi(N_2)$ = 22%. Streak photographs of the investigated process for initial pressures P_0 = 24 kPa and 22.5 are presented in Figs. 4a and 4b, respectively. As is seen from the figures, for pressure P_0 = 22.5 kPa, a detonation wave does not appear at the turbulizer outlet. Let us consider in succession the velocities of the compression waves corresponding to both figures: V_1 is the velocity of the first fan of compression waves equal to 398 and 418 m/sec, respectively; V_2 is the velocity of the second fan of compression waves of 467 m/sec and 480 m/sec; V_3 is the velocity of the shock discontinuity that accompanies the process of outflow at 610 m/sec and 590 m/sec. It is seen that the intensity of the shock discontinuity for P_0 = 24 kPa is higher than the local speed of sound V_2 before its appearance. A thorough analysis of the streak photograph of the process for P_0 = 22.5 kPa reveals the presence of slight wakes of retonation waves in the region behind the turbulent flame front, indicating the occurrence of microexplosions of the unburned mixture portions. It seems, however, that their quantity, volume, and position turned out to be insufficient for the reinitiation of a detonation wave. When the initial pressure in the mixture decreases to P_0 = 20 kPa, the process of the flame outflow becomes subsonic.

From what has been said it follows that for a detonation wave to appear in the region at the orifice plate outlet the existence of the regime of supersonic outflow of combustion products is required, which is determined by the presence of a supercritical pressures difference $P/P_1 > 2$, where P is the pressure in the combustion chamber and P_1 is the pressure at the orifice plate outlet. Moreover, in all probability, for each mixture there is a minimum necessary value of the supercritical difference that is required for the inception of a stationary detonation wave in the region behind the plate.

The conclusions correlate with the results of [2, 3, 4], who considered the initiation of a detonation wave by burning jets during the emergence of combustion products from a tube into a space with various hydrocarbon fuels. Thus, it was shown in [2] that the regime of transition from combustion to detonation for working mixtures of acetylene with air on emergence of a turbulent flame front from a tube 0.66 mm in diameter and 11 m long tube into a space is possible only when the flow velocity becomes higher than 590 m/sec. The critical value of the flame front velocity (i.e., of the flow velocity at the tube exit) V = 590 m/sec fits the data obtained in our experiments.

For an orifice plate with η = 0.077 we investigated the effect of combustion chamber length on the transition to detonation behind it. We carried out the experiments at a critical total concentration of nitrogen in the working chamber $\xi(N_2)$ = 60%. The distance from the rear wall of the main channel to the plate surface was 12 and 48

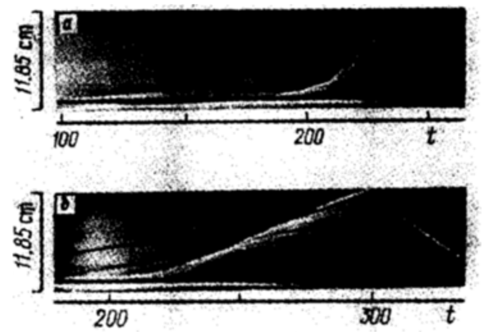

Fig. 4. Streak photograph of the process of combustion-to-detonation transition behind an orifice plate with permeability η = 0.077: a) initial pressure is P_0 = 24 kPa; b) initial pressure P_0 = 22.5 kPa. The total nitrogen concentration is $\xi(N_2)$ = 22%.

mm. In both cases, a detonation wave did not appear at the critical composition of the working mixture. Initiation was produced by subsonic jets of burning products. The absence of detonation can be explained by the effects of nonstationary interaction between the compression waves reflected from the combustion chamber walls and the expanding front of the flame. At a certain chamber length, this interaction expands the surface of the flame front and, as a result, leads to an increase in the rate of combustion. It is precisely this process that creates the supercritical pressure drop within the combustion chamber necessary for the transition to detonation.

To realize detonation combustion of working mixtures having a higher degree of dilution by nitrogen, $\xi(N_2)$ > 60%, we investigated the effect exerted on the transition process by additional barriers located at the outlet of an orifice plate with permeability factor η = 0.11. The orifice plate was placed at an optimum distance of 27 mm from the rear wall of the main channel.

In the first variant, as an additional barrier we used a second turbulizer with permeability factor η = 0.29 located at a distance of 40 mm from the first one. A streak photograph of the process of transition in a working mixture with total nitrogen concentration $\xi(N_2)$ = 60% is presented in Fig. 5a. It is clearly seen that, just as in the case if one orifice plate (see Fig. 3), the emergence of combustion products begins prior to complete burning of the working mixture in the preignition chamber. However, the fan of combustion waves reflected from the surface of the second turbulizer leads to choking of the flow and to transition to a subsonic regime of outflow. The measured velocity of the compression wave head that outstrips the turbulent flame front is equal to V_1 = 431 m/sec. In the streak photograph (Fig. 5a) we clearly discern the process of flame front deceleration, which leads to a situation in which the velocity of some portions of the turbulent flame front becomes on the order of 100 m/sec. When the compression wave head arrives at the surface of the second plate and reflects from it, a regime of supersonic escape to the region of the free channel occurs. The velocity of the bow shock wave that accompanies the start of supersonic jets is equal to V_3 = 788 m/sec.

We note that the velocity of the shock wave reflected from the plane of the second turbulizer attains the value V_2 = 1267 m/sec. This testifies to the presence of explosions of unburned microvolumes of the working mixture in the region between the two plates. This is evidenced indirectly by the existence of slightly visible wakes of retonation waves. They lead to acceleration of the flame front at the additional barrier outlet. The velocity of the front at the moment of arrival at the forward endwall of the main channel attains the value V_4 = 1140 m/sec. Thus, we may state that the use of an additional barrier having the form of an orifice plate with η = 0.29 does not lead to the formation of a stationary detonation wave for a critical composition of the working mixture.

Next we considered the effect of two steps with a height of 1.7 and a length of 3 mm located at a distance of 40 mm from the main turbulizer outlet. A characteristic streak photograph for $\xi(N_2)$ = 60% is presented in Fig. 5b. It is clearly seen that in this case, too, the dynamics of the process remains virtually unchanged, though flow choking occurs less intensely, since the penetrability of the additional barrier is small. However, this turns out to be sufficient for the formation of a stationary detonation wave. After the start of outflow of combustion products from the preignition chamber the velocity of the turbulent flame front is V_1 = 476 m/sec. The velocity of the shock

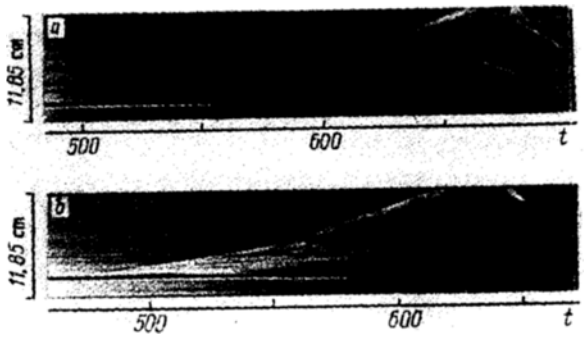

Fig. 5. Streak photograph of the process of combustion-to-detonation transition behind an orifice plate with permeability $\eta = 0.077$ in the presence of an additional barrier in the form of: a) a second orifice plate; b) a double step. The initial pressure $P_0 = 0.1$ MPa.

wave that reflects from the step is $V_2 = 1643$ m/sec. It is formed from microexplosions of unburned fragments of the working mixture directly at the orifice plate outlet. In all probability, the quantity and dimensions of these fragments are insufficient for the formation of a stationary detonation wave, which is associated with more complete burning of the working mixture due to its retardation. The velocity of flame front propagation behind the step is $V_3 = 1194$ m/sec. Detonation appears after interaction with the forward endwall. The velocity of the retonation wave formed is $V_4 = 2045$ m/sec.

Naturally, the class of additional barriers is not limited to those two considered in the present work. Therefore, on the basis of this part of the research, in which we investigated the effect of additional barriers on acceleration of the transition from combustion to detonation behind an orifice plate, we may conclude that in many cases a barrier causes retardation of the flow of a reacting mixture and the transition to a subsonic regime of escape leading to collapse of the regime of transition from combustion to detonation at the plate outlet. Consequently, one should be very careful in selecting the type of a barrier and its position behind the turbulizer outlet.

Conclusion. We carried out an experimental investigation of the transition from combustion to detonation behind orifice plates in a stoichiometric mixture of acetylene and oxygen diluted with nitrogen. We showed that a transition to detonation turns out to be possible only on initiation by supersonic burning jets. The use of an orifice plate with permeability $\eta = 0.077$ made it possible to reduce the length of the combustion-to-detonation transition to 58 mm for a mixture with a total nitrogen concentration of 60%

We investigated the influence of additional barriers on the process of transition from combustion to detonation. The barriers were installed at a distance of 40 mm downstream from the orifice plate outlet. It is shown that for a critical composition of the working mixture with $\xi(N_2) = 60\%$ the compression waves reflected from the barrier surface lead to retardation of the flow behind the turbulizer and to collapse of the regime of detonation initiation.

The work was carried out with the partial financial support of the Fundamental Research Fund of the Republic of Belarus.

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