FLAME PROPAGATION IN HYDROGEN—AIR MIXTURES IN A TUBE


The propagation of a hydrogen—air flame in a closed tube 76 mm in diameter and 2500 mm in length with and without a water film moving along the tube walls was studied experimentally and theoretically, it has been found that in a smooth-wall tube the maximum turbulization factor ranges between 10 and 30 for mixtures with the volume concentrations of hydrogen 15−30%. The presence of a moving water film on the tube walls intensifies the combustion process, which manifests itself in the essential acceleration of the detonation pressure rise. However, at the same time, the maximum explosion pressure for near-stoichiometric mixtures increases, while that for leaner compositions decreases. The results obtained are interpreted qualitatively.

Transportation of gas—vapor—air mixtures (including flammable ones) through tubes of different diameters d and length l is employed widely in various industrial processes. From the standpoint of explosion-proof technologies, of interest is the investigation of flame propagation in gas—air mixtures, including the explosion loads due to detonation-to-deflagration transition. Of special interest are mixtures with high burning velocities, wherein the explosion loads are maximum (i.e., hydrogen—air mixtures).

Among the publications concerned with this problem, worthy of mention is, first of all, the work of Lee et al. [1], wherein the turbulent deflagration of various H₂—air mixtures in the tube (0.05 m in diameter, 11 m long) was studied. It is established that the transition from deflagration to detonation in a blocked section of the tube corresponds to the volume concentration of hydrogen 12%. In [2, 3] it is shown that the combustion of hydrogen-containing mixtures can be substantially intensified by the addition of water droplets. A number of papers concerned with the combustion and detonation of hydrogen-containing mixtures in tubes are cited in [4]. In [5], the mechanism of flame propagation in gas—air mixtures in large cylindrical vessels was investigated.

The acceleration of flame propagation through a gas—air mixture in a tube with d = 76 mm and l = 1.64 m was studied in [6-8]. It has been shown that with obstacles absent, the flame propagation accelerates most significantly in the initial stage of detonation, after which the increase in the visible flame velocity slows down substantially. Rather different results were obtained by Abinov et al. [9], whose experiments were conducted in large stands with tube diameters up to 1.5 m and tube lengths up to 100 m. It has been observed that the flame velocity increases progressively as the flame propagates in the mixture; however, no transition to detonation occurs.

At the same time, the flame propagation in gas—air mixtures in tubes with nonflammable liquid (e.g., water) films moving on the inner tube walls has not been adequately described in the literature. Such a situation can take place in equipment with film cooling. The present work is concerned with the investigation of flame propagation in a hydrogen—air mixture in a vertical tube with a water film moving along the inner wall of the tube.

Experiments were carried out in a "Fragment" stand, the main part of which was an erected reaction tube (inner diameter 78 mm and height 2.5 m) made of stainless steel. Combustible mixtures were prepared in a special mixer and supplied to a pre-evacuated section of the tube. Combustion was initiated at the bottom or in the middle of the tube by flame propagation from a prechamber (a 200-mm-high cylindrical chamber 80 mm in diameter, installed below the reaction tube coaxially with it) or by an incandescent Ni—Cr wire heated by an electric discharge (duration 0.1 sec, energy ~ 10 J), respectively. The free space of the prechamber was filled with detonating gas (2H₂ + O₂). Combustion in the prechamber...
was initiated by an incandescent Ni–Cr wire. The detonating gas was separated from the reaction mixture with a polyethylene film. To intensify the combustion, metal spirals were placed chaotically in the free space of the prechamber so that ~30% of the tube cross section was blocked.

The water film on the walls of the tube was obtained with the help of a film-forming device located at the top of the tube. The average thickness of the film was ~1 mm, its velocity was ~1 m/sec.

In the course of flame propagation, the pressure in the tube was detected by three pressure transducers: two Sapfir-22 pressure gauges (time constant ~10^{-3} sec), installed at the top and at the bottom of the tube, and one Alga gauge (based on a piezocrystal, time constant ~10^{-5} sec) installed at the top of the tube. The signals of the Sapfir-22 gauges were fed to an N-115 light-beam oscillograph, and the signals of the Alga gauge were fed to a C9-8 storing oscillograph. The error was no more than 20% of the indication.

The experiments were carried out in the presence and absence of water films. Hydrogen–air compositions 1-3 with volume concentrations of hydrogen c = 15, 20, and 30%, respectively, were studied. Composition 4 containing 30% H\textsubscript{2}, 32% air, and 38% nitrogen was also investigated.

Typical oscillograms obtained during the combustion of hydrogen–air mixtures without a water film are shown in Fig. 1. One can see rather sharp maxima followed by a relatively slow decrease in pressure due to cooling of the combustion products as a result of heat exchange with the cool walls of the tube. Because of the heat losses, the maximum pressures are substantially lower than the corresponding thermodynamic values. As in [6], the most intense pressure rise is observed at the initial stage of the explosion. Later the acceleration of the pressure rise essentially decreases. Phylaktor et al. [6] explain this qualitatively by the fact that after initial acceleration the flame takes the form of a "tongue." The flame front touches the walls. Due to the cooling of the combustion products and increased heat losses by the reaction zone, the velocity of the latter decreases. At the same time, this effect is not observed in large stands (see [9]). This points to the important role of the tube dimensions in the mechanism of flame acceleration in the tube.

To determine the effective turbulization factors of the flame \( \chi \) for various mixtures, we performed a numerical simulation of the propagation of a hydrogen–air flame in a smooth tube, taking into account the flame turbulization and heat exchange with the tube walls. The simplified model described in [10] was used. The equations describing the flame propagation under nonadiabatic conditions are of the form [10]

\[
\frac{dI}{dt} - \chi S_u \left( \frac{L}{S_u} \right) \frac{dp}{dt},
\]

\[
B \frac{dP}{dt} = A \rho_u \chi S_u \left( E_u - E_b \right) + \int_0^l h_c (T_w - T_b (x)) \, dx,
\]

\[
\frac{dT_b}{dt} = \frac{T_b}{I} \gamma_b - \frac{1}{\gamma_b} \frac{dp}{dt} + \frac{1}{mc_p} h (T_w - T_b) c\Delta x,
\]

\[
B = \frac{c_p}{R} (M_b v_b + M_w v_w),
\]

where \( l \) is the flame coordinate counted off from the ignition point near the end of the closed tube; \( S_u \) is the burning velocity; \( L \) is the tube length; \( p \) is the pressure in the tube (assumed to be uniformly distributed over the volume, i.e., the burning velocity is equal to the sound velocity); \( A \) is the cross-sectional area of the tube; \( \rho_u \) is the density of the unburnt mixture; \( E_u \) and \( E_b \) are the specific formation heats of the initial mixture and the combustion products; \( h \) is the coefficient of heat transfer to the tube walls; \( c \) is the tube perimeter; \( T_w \) is the temperature of the tube walls, assumed constant during the process; \( T_b \) is the temperature of the combustion products at the point \( x \); \( \gamma_b \) is the adiabatic index of the combustion products; \( m \) is the mass of the combustion products in the tube section with coordinates from \( x \) to \( x + \Delta x \); and \( c_p \) is the specific heat coefficient of the combustion products.

In terms of the model, the tube length is divided into \( N \) parts (in our case \( N = 10 \)), and Eq. (3) is solved for each of the parts.

The calculated curves for the pressure dynamics in the reactor are shown in Fig. 1 for different \( \chi \) and \( h \). The calculations were performed on a PC/AT-286. It is seen that the initial stage of the explosion (before the decrease in the rate of pressure rise) can be described satisfactorily at \( \chi = 30 \) (hydrogen concentration \( c = 15\% \)), 15 (\( c = 20\% \)), and 10 (\( c = 30\% \)), i.e., the lower the burning velocity, the higher the flame front acceleration. A qualitatively similar result was obtained in [11], where the effect of fan turbulization of the flame on the velocity of flame propagation was studied.