COMBUSTION OF GASES IN THIN-WALLED SMALL-DIAMETER TUBES

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The possibility of a combustion wave propagating in a tube with inner diameter less than critical has been studied experimentally. It is shown that a steady-state combustion wave can occur in a thin-walled tube at certain flow rates of the fuel gas. The flame stabilizes due to warming up of the tube walls.

It is well known [1] that a flame does not propagate in a tube whose inner diameter is less than critical. The limitation on the diameter is determined by the conductive heat transfer from the flame front to the tube wall [1]. However, it has been shown in [2] that a combustion wave can occur during gas filtration through an inert porous medium in a channel with subcritical diameter. According to the models proposed in [2-4], one of the main differences of this wave from that propagating in a gas is that the heat required for warming up and igniting fresh gas is transferred mainly via the porous medium. Thus, the presence of a porous medium is a necessary condition for the filtration combustion wave to occur. This work is aimed at searching for conditions that would allow the combustion wave to propagate through a tube of inner diameter less than critical.

The experiments were carried out in a steel tube of outer diameter 3 mm and inner diameter 2.5 mm. A stoichiometric methane-air mixture was used. The gas flow rate was adjusted by gas pressure regulators and was determined by the pressure difference measured by an oil manometer.

The critical tube diameter for the methane-air stoichiometric mixture is 3.5 mm [5]. Hence, the flame should not propagate along the tube with inner diameter 2.5 mm. In fact, when the steady-state flame is set in the tube outlet section, a decrease in the gas flow rate results in extinction rather than in the flame propagating into the tube. However, if the tube end with the flame is heated by an external heat source (in this work we used an alcohol burner), the flame enters the tube. Moving the external heat source slowly along the tube, one can move the flame from the inlet section toward the center of the tube. Now the flame can exist without the external source, propagating downstream of the gas flow. A narrow red-hot ring on the tube surface indicates the position of the flame zone. However, the lifetime of the flame is limited. It has been established that extinction occurs due to plugging of the tube with the condensed water, which is one of the combustion products.

The process described differs from the filtration combustion of gases in porous media as follows. In the porous medium, according to the models proposed by Babkin et al. [2-4], the combustible mixture is ignited due to heat transfer from the solid lattice. In our case, fresh gas is heated up to the ignition temperature not by the tube wall, but by the heat transferred through the gas. This statement can be proved by the following observations. At the location of the combustion wave front the tube changes its color from dark red (seen only in the dark) to bright red, depending on the gas flow rate, i.e., the combustion waves occurs at tube wall temperatures lower than the ignition temperature. In the experiments, the combustion wave can be induced in the tube only by moving the flame slowly from the tube end. Our attempts to induce a combustion wave far from the tube end by heating a small section of the tube by an open flame, with the width of this section being larger and the temperature being essentially higher than the corresponding values for the in-tube combustion wave, failed. In our case, the combustion wave seems to exist due to the heating of the tube wall by the flame, which decreases the critical diameter to a value that allows combustion to occur.

To study the dynamic characteristics of the flame jet in the tube section heated by this flame, we should prevent its extinction. For this purpose the tube section wherein the steam condensed was heated by an electric current. The temperature
of the electrically heated section of the tube was essentially lower than that of the section with the flame. The time dependences of the flame coordinate were measured at various gas flow rates. The experiments were carried out as follows. A required flow rate of the fuel was established. The electrical heating was switched on. One electrode was fixed at the tube end, with the other one (movable) being attached as far from the tube end as the flame should be moved with the external heat source. Then the alcohol burner was used to move the flame at the given location. After that the movable electrode was carried out downstream (toward the combustion products). From this point the coordinate of the glowing zone was measured. As the flame approached the electrode, the latter was moved downstream (the heating electric current was maintained constant).

The characteristic time dependences of the glowing zone coordinate are shown in Fig. 1. It is seen that the flame propagation is almost steady-state. The flame velocity was determined from the slopes of the straight lines drawn through the experimental points. Figure 2 shows the velocity of flame propagation as a function of the gas flow rate $Q$. As one might expect, the flame velocity increases with the gas flow rate. At gas flow rates higher than 2.0 and lower than 1.1 cm$^3$/s, the flame dies. It should be noted that the intensity of the glow in the tube section wherein the flame resides increases with $Q$. The glowing zone shows a tendency to broadening with increasing gas flow rate.

Thus, it has been shown that a combustion wave can occur in a thin-walled tube of diameter less than critical at certain flow rates of combustible gas. In this case the combustion wave is the flame stabilized inside the tube due to heating of the tube wall by the flame. The flame propagates downstream at a constant rate which depends on the average gas flow velocity.

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