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TRANSLATION

VARIATION IN THE LENGTH OF THE COMBUSTION ZONE OF A HOMOGENEOUS MIXTURE IN A TURBULENT FLOW AS A FUNCTION OF PRESSURE

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VARIATION IN THE LENGTH OF THE COMBUSTION ZONE OF A HOMOGENEOUS MIXTURE IN A TURBULENT FLOW AS A FUNCTION OF PRESSURE

V. S. Pelevin

In the article the results of an experimental investigation of the length of the combustion zone as a function of pressure (below atmospheric) during the burning of a homogeneous mixture in a turbulent flow are set forth. The investigation was conducted with the aid of a burner using an air mixture of grade B-70 gasoline.

In Ref. [1] it is shown that "in any fuel-burning process there are a number of common basic phenomena, which are related to the nature of the process, regardless of the type of apparatus." They include auto-ignition, forced ignition, the conditions of normal flame propagation, turbulent combustion, and detonation.

If a stationary gaseous fuel mixture (contained in a vessel, for example) is slowly heated, it is impossible, before the beginning of a chemical reaction, to establish a relationship between the temperature of this mixture and its concentration. It is noted that if the heating of the mixture proceeds infinitely slowly, then up to the moment of ignition the distribution of the temperature and concentration of the mixture at any point in the volume will be homogeneous for any moment of time. The relationship between the temperature and the concentration of the mixture is established only after the beginning of a chemical reaction, since the quantity of heat released during a reaction depends upon the amount of fuel burned. When the mixture is heated rapidly, it is impossible to establish the distribution of temperature and concentration just mentioned.

Let us now turn our attention to the processes occurring in turbulent flows. When the components of the pulsation velocities in a medium at rest or in a laminar flow become so great that a physical change takes place in an infinitely small volume, the transition to turbulent flow begins. In this case it is impossible to achieve a homogeneous distribution of temperatures and concentrations throughout the entire volume. As A. S. Predvoditelev points out, the state of the flow will also have a substantial effect on the kinetics of the chemical reaction. Existing methods for the measurement of the rate of a chemical reaction in a turbulent flow inevitably involve a fixed length of time and take into consideration a certain region of the flow. The instruments are unable to measure locally the rate of a chemical reaction under observation, while the measurements themselves are always accompanied by errors. This is why the kinetic equations of chemical reactions in turbulent flows have to appear in averaged form, and this averaging must be carried out with the aid of methods of mathematical statistics.

The problem in the present investigation was the study of an over-all, visually observed effect, viz., the variation in the length of the combustion zone as a function of pressure under conditions of turbulent flame propagation [2].

When we examine the process of combustion of a homogeneous mixture in a turbulent flow, we can see that chemical conversion of the material does not occur instantaneously, but propagates in time and forms a certain combustion zone, over the length of which a change in the components and the state of the entire system takes place.

If we know the over-all or statistical effect involved in the change of state of the system and its dependence on other parameters, it is possible to establish dependences which can obviously be used to explain the fundamental phenomenon of the chemical conversion and to use them for practical purposes.

For the experiments we used a previously prepared and well mixed homogeneous air mixture of grade B-70 gasoline, which was fed through a tubular burner 16 mm in diameter with an annular peripheral ignition source. It is known that when a turbulent stream of a homogeneous fuel mixture flows forth from a tube of circular cross section with an annular peripheral ignition source and is burned, there appears beyond the exit of the tube a straight flame cone with the visible boundaries of its inner and outer luminous surfaces.

The length of the combustion zone L_c was determined along the axis of the tongue by determining the combustion efficiency of the fuel, i.e., from the CO_2 content. As experiments have shown, the vertex of the flame cone formed by the inner luminous surface is always pulsating. Because of the pulsation of the vertex of the flame cone, the measurement of the length of the combustion zone L_c was made in our experiments from the place where the CO_2 content is equal to 1%, in order to obtain more reliable data. The end of the combustion zone was determined as the place of maximum CO_2 content. A sampling of the gas for subsequent analysis was performed at various distances from the end of the burner with the aid of a specially constructed water-cooled gas-sampling tube. The temperatures were measured at these same points by the method of X-ray reversal of spectral lines. Two series of experiments were performed.

For the first series of experiments (Fig. 1) the amount of air supplied was constant and independent of the rarefaction in the pressure chamber. The concentration of fuel in the air mixture remained constant and was equal to 1.72%.

For the second series of experiments (Fig. 3) the amount of air supplied varied according to the variation in pressure. The fuel concentration remained constant and was the same as in the first series of experiments.

It has been established experimentally that a rise in CO_2 content in a range up to 0.5% begins long in advance of the start of the visible luminous combustion zone. The shape of the curves of the fuel burnup or of the CO_2 content and the shape of the curves of the temperature variation are the same [3], while the location of the maximum CO_2 values corresponds to the location of the maximum temperature values. This attests to the fact that the boundaries of the thermal and chemical combustion zones coincide and that the shape of both curves correctly reflects the course of the process in the combustion zone.

The method used for taking measurements along the axis of the burning tongue relieved us of having to take into account the variation in the direction of the flow lines and the possible penetration of air from the surrounding medium into the combustion zone. The latter was observed only in the case of an appreciable tongue length, in the zone where final combustion takes place.

In all cases, where the pressure in the pressure chamber was reduced, the flow velocity of the fuel mixture at the burner outlet was increased (Fig. 2). This led to a decrease in the time the fuel remained in the combustion zone and, consequently, to an increase in the length of the zone. As is apparent from the graphs, for any range of measurements the length of the combustion zone increases rapidly with a decrease in pressure. In logarithmic coordinates the averaged values of the length of the combustion zone fit nicely on slanted straight lines. Thus over the whole range of variation of CO_2 content from 1% to maximum the functional relationship mentioned above may be represented in the form:

$$L_c = A/p^{0.75}. \quad (1)$$

The theoretical values of the combustion zone length, according to formula (1), for various pressures coincide well with the experimental data.

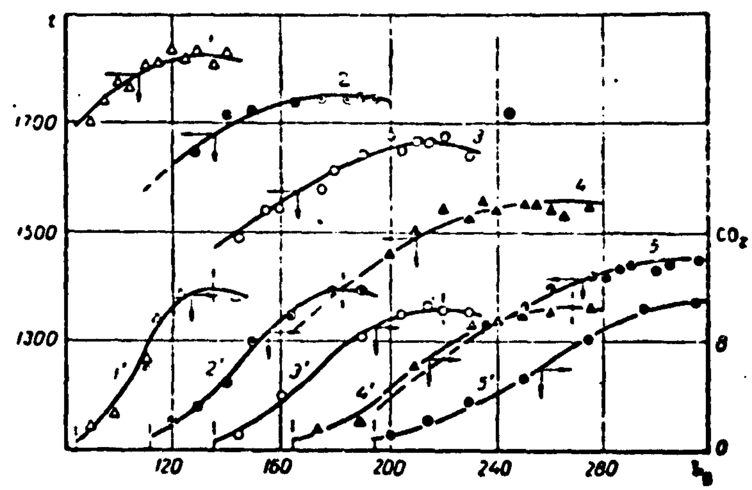

Fig. 1. The relationship between the length of the combustion zone L_c (mm), the temperature t (°C), and the CO_2 content (%) for pressures in a pressure chamber at Re = 8000: 1,1') 760; 2,2') 500; 3,3') 400; 4,4') 304; 5,5') 235 mm Hg.

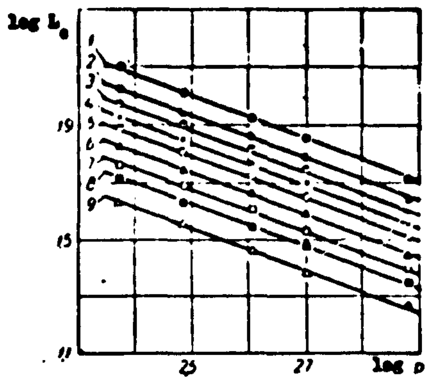

Fig. 2. The dependence of the averaged values of the length of the combustion zone L_c (mm) on the pressure p (mm Hg) in logarithmic coordinates for various ranges of variation of CO_2 content (%): 1) from 1 to max.; 2) from 2 to max; 3) from 3 to max.;... (Slope of straight lines n = -0.75; Re = 8000)

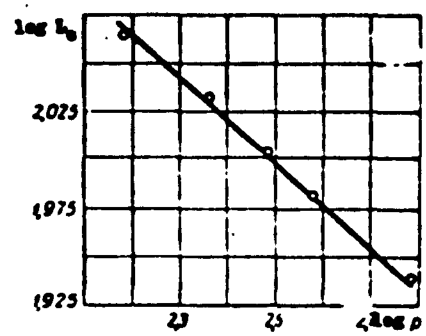

Fig. 3. The dependence of the length of the combustion zone L_c (mm) on the pressure p (mm Hg) when W = constant, p varies from 610 to 152.2 mm Hg, Re varies from 16,000 to 4000, CO_2 varies from 1% to maximum, n = -0.25.

The length of the combustion zone changes slightly with a decrease in pressure (Fig. 3). The slope of the straight line in Fig. 3 is n = -0.25. The dependence of the length of the combustion zone on pressure in this case has the following form:

$$L_c = B/p^{0.25}. \qquad (2)$$

Thus it has been established that in a flow with a constant Reynolds number the length of the combustion zone varies extremely rapidly, when the pressure is lowered below atmospheric. In flows with constant velocity, on the other hand, the length of the combustion zone varies insignificantly, when the pressure is reduced. Note that for one and the same fuel mixture the values of the coefficients A and B in the measurement of the length of the combustion zone within the same set of limits remain practically constant for different pressures. A check of the obtained relationships using the experimental data of other authors [4] shows that the obtained formulas may be employed in calculations for various homogeneous fuel air mixtures on burners of various diameters.

An evaluation of the width of the combustion zone as one of the basic parameters characterizing the process of turbulent combustion is an extremely important question in designing combustion chambers of air-breathing jet engines. As is known, in those cases where the pressure in the combustion chamber proves to be below atmospheric, an impairment in the characteristics of the combustion process is observed. In Ref. [1] it was stressed that "the state of the flow has a substantial effect on the kinetics of the chemical reaction," and thus on the size of the combustion zone.

There are no reliable experimental data concerning the effect of pressure on the characteristics of turbulent flow (pulsation velocity v', scale of turbulence $\underline{l}$).

In order to estimate the effect of the hydrodynamic flow factors on the length of the combustion zone, let us make use of a relationship from Ref. [5].

$$L_c \sim u_t \tau_t \sim W\, \tau_t,$$

where $\tau_t \sim 1/u_h$. Then

$$L_c \sim W\, 1/u_h.$$

According to the data of Refs. [2, 6] $u_h \sim p^{-0.25}$. For an approximate evaluation we shall use the theoretical relationship [7] $l \sim \nu^{0.5} \sim p^{-0.5}$.

For homogeneous fuel-mixture flows with constant discharge rates we obtain

$$L_c \sim p^{-0.25}.$$

Thus the relationship which we have found experimentally agrees with an existing theoretical assertion [7], where one of the characteristics of the turbulent flow, the scale of turbulence, $l \sim p^{-0.5}$.

If we arbitrarily take as the characteristic of the rate of chemical conversion the time (τ) during which the change from the initial fuel concentration to the maximum CO_2 content in the combustion products takes place, then the length of the combustion zone

$$L_c \sim \tau u_c.$$

In the case of a constant flow velocity a decrease in pressure causes only a decrease in the pulsation velocity (v') due to an increase in the viscosity of the medium (ν). Therefore the intensity of the turbulence ($\varepsilon = v'/W$) decreases, and this leads to a decrease in the rate of flame propagation and thus to a change in the dimensions of the combustion zone.

Notations

A — coefficient of proportionality determined experimentally for given limits of measurement of the length of the combustion zone for any pressure. The value of the coefficient A is different for different fuels; u_t — rate of flame propagation in turbulent flow; u_h — rate of flame propagation in laminar flow; τ_t — combustion time; W — flow velocity; n — slope of curve.

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