STUDY OF LAMINAR FLAME QUENCHING IN A ROTATING CYLINDRICAL VESSEL

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Introduction

To burn lean mixture in a swirling flow effectively it is necessary to understand the behavior of the flame front during its propagation in a field of increasing radial acceleration. In the past, in a few experimental pieces of work, flame propagation in a solid body rotating mixture was studied, mostly however with qualitative results. The autors revealed the existence of centripetal forces for flames ignited off-axis and subsequent flame propagation from the center to the cylinder wall (Margolin and Karpov 1974), quenching of the cylindrical flame at the end plates of the cylinder in case of a high rotation rate (Babkin et al. 1982), elongation of the flame shape in the axial direction even for relatively small rotation rates (Hanson and Thomas 1984), laminarization of turbulent flow (Zawadzki and Jarosinski 1983), and different flame behavior depending on mixture composition and rotation rate (Gorczakowski et al. 2000). Some new quantitative results were also obtained during flame propagation in a open "disk" cylindrical vessel (Gorczakowski and Jarosinski 2000). It was found in this study that flame propagating in a mixture of a certain composition is quenched at different radial acceleration rates and different diameters, but at the same tangential velocity. Ishizuka in 2000 studied some other aspects of combustion in swirling flow (predominantly the flame velocity along the swirl axis). In spite of those research efforts, the physical mechanism of flame extinction is still not understood. A flame extinction mechanism based on the Coriolis' accelerations, as suggested in several discussion groups, cannot be accepted because these accelerations are significantly smaller than accompanying flame extinction the radial ones and because they do not depend on the radius: extinction at constant tangential velocity as found here indicates that it should depend on it.

Experimental

To reveal the physical mechanism of flame extinction under the action of centrifugal forces a set of experiments with a propagating flame front in a vented cylindrical rotating vessel was carried out with different mixture compositions and with flame extinction records at different rotation rates (equivalent to different radii of flame extinction). Additionally, an instant temperature was measured in two points at the same radius: one point located near to the plate wall (at a distance of 6mm from it) and the other at equidistant point (15mm) relative to both plate walls. The experiments were carried out in a constant volume vessel. This method makes it possible to measure at the same time the temperature of a propagating flame and of expanding hot combustion gases near the wall after local flame extinction.

Results of measurements

An example of the history of flame propagation in a vented vessel is shown in Fig. 1. The successive frames of a film taken side-on are used to determine graphs of functions $r=f(\tau)$ and $L=\varphi(\tau)$, where r is the radius attained by the flame front, L the flame width and τ the time after ignition.

Similar graphs performed for different concentrations of propane and different rotation rates made it possible to collect a comprehensive graph shown in Fig. 2.

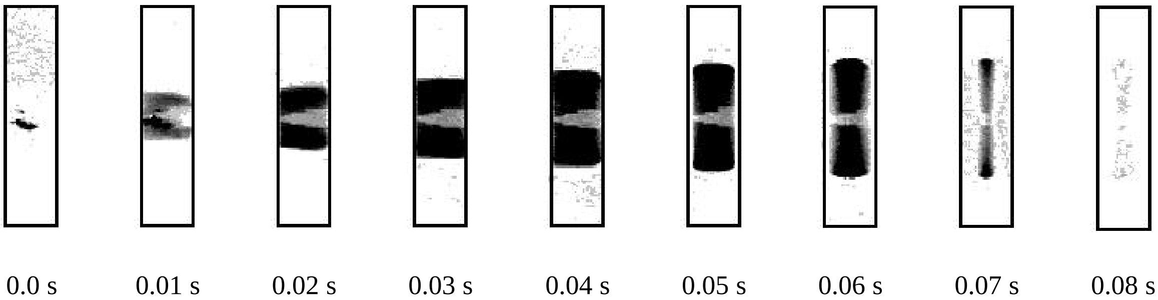

Fig. 1. Flame propagation and extinction patterns in a propane-air mixture with concentration of 3.75% C_3H_8 in a rotating vented cylindrical vessel (90mm inner diameter and 30mm height). Rotation rate ω=628 s^{-1}. Shatter speed: 1/50.

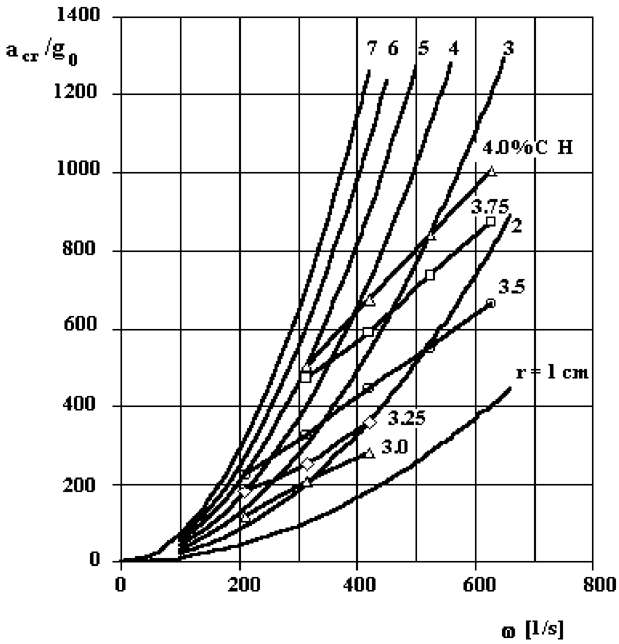

Fig. 2. Dimensionless radial acceleration a_{cr}/g_0 at the extinction radius r_{cr} for different mixture concentration as a function of the rotation rate ω.

Measurements of instant temperature during flame extinction were carried out in a special set of experiments. The temperature probes were located at the edge of extinguishing flame (Fig. 3).

Discussion

To understand the mechanism of flame extinction let us remind first some properties of a flame propagating in a vertical channel from the open top end to the closed bottom end. The shape of such a flame front is usually convex. The convex flame surface can be considered as one cell of a disturbed cellular flame. This cell can be interpreted as a wave grown up according to Landau-Darieus instability mechanism to the limit shape caused by nonlinearity

(Zeldovich Ya. B.1979). Locally, the flame front propagates in the direction normal to the flame surface. Displacement of points over any curved flame front surface is identical with stretching. Flame stretch increases with an increase of flame curvature.

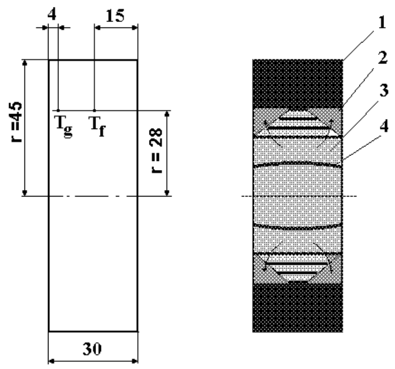

Fig. 3. Location of temperature probes in the vessel.

The convex flame front is stable. Large-scale disturbance developed on such flame prevent evolution of the small-scale disturbances. In case of their appearance they drift to the walls and decay. Convexity of a laminar flame is being controlled by several factors, which depend on the type of the apparatus: fuel/air equivalence ratio of the mixture in a tube, distance between the walls in a quenching channel, and centrifugal forces in a rotating vessel (or any other forces influencing the flame).

A flat flame is exposed to much less favourable conditions for its propagation near the channel walls. A contact area of such flame (and adjacent to it of the zone of combustion products) with the wall is very large in comparison with a convex flame, and, as a consequence, the flame near to the wall is effectively cooled. In case of flat flame the stretch mechanism does not supply its edges with chemically active species. At the same time the decreased temperature near the wall quenches chemical reactions at a distance with order of magnitude of the flame thickness and, hence local flame extinction occurs. Thus extinction of the flat flame front propagating at the right angle to the wall is triggered by heat loss to the wall and the flame is finally driven to extinction by buoyancy effects, in the centrifugal field which forces cooler product gases radially outwards ahead of the flame. The flame is extinguished because it is now propagating into partially diluted mixture. The extinction process initiated at the wall is continued because more and more relatively cold combustion products are being transported by buoyancy effects to flame edges.

In the way described, a flame propagating in a mixture of the same composition in a rotating vessel can change its shape from a barrel-like to a cylindrical one in a field of increasing centrifugal forces. The cylindrical shape can be attained at a certain ratio between inertial and buoyancy forces. A Froude number may be applied to describe the relationship between these two quantities. The Froude number should take into account a property of the mixture (laminar burning velocity u_L) as well as critical parameters at flame quenching conditions (critical centripetal acceleration a_{cr} and critical radius r_{cr}):

$$Fr = \frac{u_L^{\,2}}{a_{cr} r_{cr}} = \frac{u_L^{\,2}}{\omega^2 r_{cr}^{\,2}} = \frac{u_L^{\,2}}{(v_t)_{cr}^{\,2}}$$

Values of the Froude number as a function of mixture composition as calculated based on experimental data are shown in Table 1. For a given mixture composition, different values of

u_L were found experimentally, depending on the value of rotation rate ω. In calculations the average experimental values of u_L were used.

The same order of magnitude of the calculated Froude numbers indicates that this number is an adequate criterion to describe flame-quenching conditions under the action of centrifugal forces.

Table 1. Froude number as a function of mixture composition, calculated from parameters measured under flame quenching conditions.

C_3H_8%	3.00	3.25	3.50	3.75	4.00
u_L	0.16	0.21	0.25	0.31	0.35
$(v_t)_{cr}$	6.48	8.28	10.3	13.9	15.7
Fr	0.000648	0.000646	0.000589	0.000497	0.000497

Conclusions

The behavior flame propagation and extinction in a flammable gas mixture with solid body rotation was studied in detail. Propagating flame is convex as a result of Landau-Darieus instability, but under the influence of radially increasing centrifugal forces its shape reveals the asymptotic tendency to become cylindrical. The flame is quenched at the position situated at a certain maximum angle with the wall. The quenching radius depends on mixture composition and rotation rate. Flame extinction always occurs at the radius corresponding to a specified constant tangential velocity, which is a function of mixture composition. It was found experimentally that the critical radial acceleration a_{cr} determined at the critical radius of flame extinction r_{cr} is a linear function of the rotation rate ω with a tangential velocity as a coefficient of proportionality. Physical analysis of flame extinction phenomena leads to the definition of a Froude number, which stands for the ratio between buoyancy and inertial forces, and seems to be adequate criterion for describing flame quenching conditions under the action of centrifugal forces.

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