Flame Propagation in a Rotating Cylindrical Vessel and Conditions of its Quenching

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1 Introduction

Combustion in a swirling flow most frequently is applied in piston engines and in different industrial burners. Recently it is used in some combustion systems of spark ignition engines supplied with lean mixtures. To burn lean mixture effectively in a swirling flow it is necessary to know well the behavior of flame during its propagation in a field of increasing radial acceleration. To study this problem a flame propagating in a flammable mixture inside a rotating cylindrical vessel was observed and its parameters were measured. It was found experimentally that in a short time from the beginning of rotation the rotating mixture started to have properties of a solid body. It was also found that every flame, even that propagating in a stoichiometric mixture, was quenched in such vessel if a radius of the cylinder and the rotation rate were high enough [1]. Flame propagation in a rotating mixture was studied in the past but mostly with qualitative results. Better understanding of the fundamental mechanism of flame propagation and extinction in a field of centrifugal forces is the main objective of the present study.

2 Experimental apparatus

The experiments were conducted in a cylindrical combustion chamber of 90mm or 140mm inner diameter and 30mm height made of Plexiglas with horizontal axis of rotation (Fig. 1).

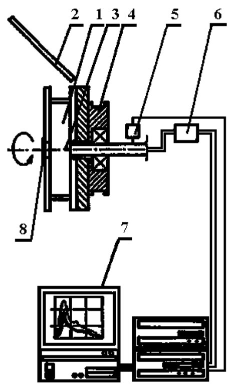

Fig. 1. Simplified schematic of the apparatus: 1 – combustion chamber, 2 – mirror for observation of the side-view of the flame, 3 – igniter, 4 - V-belt wheel, 5 – solenoid valve, 6 – mixture supply, 7 – PC, 8 – stopper or tissue paper covering the outflow orifice.

Venting orifice with diameter of 15mm was located at the axis of rotation. Homogeneous propane-air mixtures were employed in experiments. Spark ignition at the center of the vessel was applied. The photographic records of the combustion process were made with a conventional S-VHS video camera.

In a vented vessel experiments the following propane concentrations and rotation velocities were used to record flame propagation and extinction:

i - 3.00%, 3.25%, 3.50%, 3.75% and 4.00%C_3H_8,

ii -1000, 2000, 3000, 4000, 5000 and 6000rpm

Side view of the combustion chamber with freely propagating laminar flame is shown in Fig. 2.

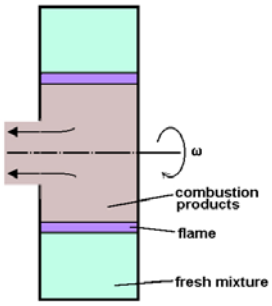

Fig. 2. Side View of Cylindrical Combustion Chamber for Study of Laminar Burning Velocity.

3 Results and discussion

Example of flame propagation in a vented vessel is shown in Fig. 3. The successive frames of film are used to determine burning velocity and the moment of the beginning of flame extinction near the front wall.

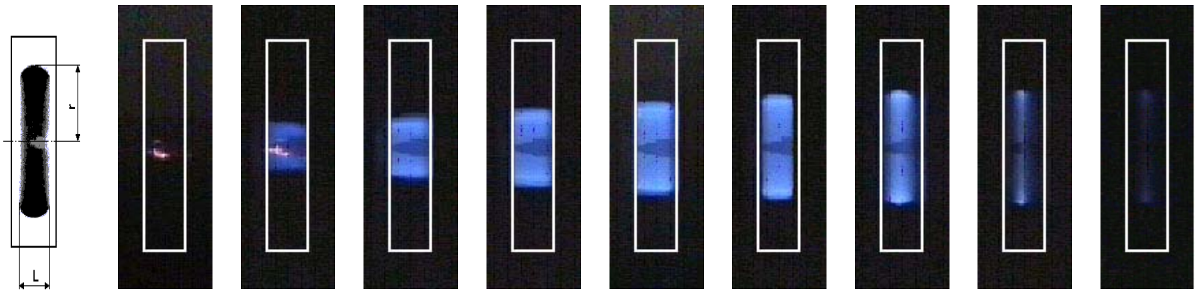

Fig. 3. Pictures of flame propagation and extinction in propane-air mixture with concentration of 3.75% C_3H_8 in rotating vented cylindrical vessel (90mm inner diameter and 30mm height). Rotation rate ω=628 s^{-1}. Shatter speed: 1/50. First frame on the left side of this Figure contains definitions of flame radius and flame width.

Analysis of the experimental results showed that, for a given mixture composition, the critical dimension less radial acceleration a_{cr}/g_0 at the extinction radius is a linear function of the rotation rate ω with coefficient of proportionality in a form of tangential velocity at the extinction radius r_{cr}. Finally the relation between a_{cr} and ω could be expressed as:

$$a_{cr} = (v_t)_{cr}\,\omega$$

This relation shows that the product of the rotation rate ω and the extinction radius r_{cr} for each mixture composition is constant. It means that the flame propagating in a mixture of specified mixture composition is always quenched at the same tangential velocity $(v_t)_{cr}=\omega r_{cr}$.

Experimentally determined numerical values of tangential velocity responsible for flame extinction near the front walls as a function of propane concentration are shown in Fig. 4.

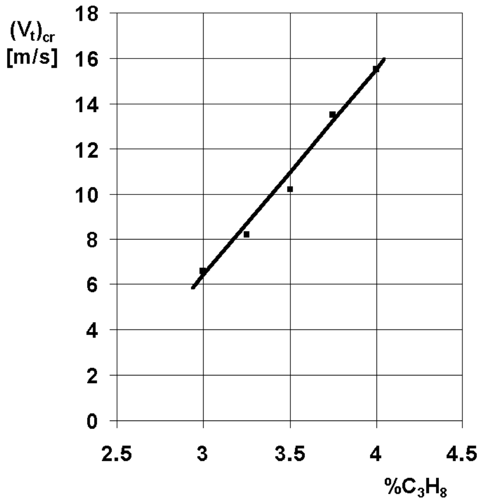

Fig. 4. Tangential velocity $(v_t)_{cr}$ at extinction radius r_{cr} as a function of concentration of propane in a mixture.

It was observed that a flame propagating in a mixture of the same composition in a rotating vessel changed its shape from a barrel-like to a cylindrical one in a field of increasing centrifugal forces. The cylindrical shape is attained at a certain ration between inertial and buoyancy forces. Dimensional analysis can be used to draw up general conditions of flame extinction. Observation showed that flame quenching depends on the property of the mixture (expressed by the laminar burning velocity u_L), critical radius of flame extinction and critical centripetal acceleration a_{cr}.

From these three parameters we can create nondimensional number which is the Froude number:

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

In the past the Froude number was used many times as a similarity number in modeling of the physical processes influenced by buoyancy forces [2-4]. Values of the Froude number as a function of mixture composition as calculated based on experimental data are shown in Table 1.

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

%C3H8	3.00	3.25	3.50	3.75	4.00
u_L [m/s]	0.16	0.21	0.25	0.31	0.35
$(v_t)_{cr}$ [m/s]	6.48	8.28	10.30	13.90	15.70
Fr^{-1}	1640.3	1544.6	1697.4	2010.5	2012.2

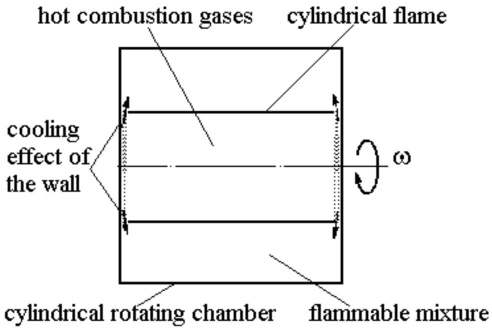

Fig. 5. Schematic diagram of flame extinction under the action of centrifugal forces during its propagation in rotating cylindrical vessel.

When the cylindrical flame is locally quenched at the front walls of the vessel the cold combustion gases are collected at the contact area and the Ekman layer is created. This layer moves with high velocity along the flame surface [5]. The mechanism of flame extinction under the action of centrifugal forces can be explained by means of a schematic diagram shown in Fig. 5.

5 Conclusions

- Convex barrel-like flame under the action of centrifugal forces on some radius becomes cylindrical with a right angle to the wall.
- Froude number is a proper criterion of flame “flattening”.
- Heat loss causes the cylindrical flame to extinguish locally near the front walls.
- The combustion gases, which are in contact with the front walls are cooled and displaced radially under the action of centrifugal forces.
- They move ahead of the flame in a form of Ekman layer.
- The flame is then extinguished because it is now propagating into partially diluted nonflammable mixture.

Acknowledgements

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