THE MECHANISM OF FLAME EXTINCTION IN A ROTATING CYLINDRICAL VESSEL

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INTRODUCTION

Laminar gas flame propagating in a field of increased gravity forces is quenched in the course of its propagation. In the field of centrifugal forces of a rotating vessel the flame surface takes the form of a cylinder. The quenching process always starts at the contact surface of the flame with the wall, and then extinction wave gradually spreads over the entire flame. Two factors play an important role in the reported phenomenon: cooling effect of the wall and centrifugal forces. The same factors are responsible for the extinction of downward propagating limit flame in a vertical tube. The mechanism of limit flame extinction triggered by the wall in the presence of buoyancy forces, produced by normal gravity, has been extensively studied in various laboratories both experimentally and numerically [1-5]. The extinction process was examined and the effect of various boundary and initial conditions on flames propagating near the lean limit composition was determined in these studies. In the few other experimental studies, the flame extinction has also been investigated under the action of increased gravity forces in the constant volume vessels [6-9].

In the present paper an experimental study of flame propagating in an open flat cylindrical vessel with a flow field of rigid-body rotation was carried out. The experiments were performed in a transparent vessel. The effect of the rotation rate on the flame propagation and extinction was investigated. During the experiments direct photographic observations of the extinction process were carried out. The radius of the expanding flame front cylinder was determined by photography of the luminous zone.

APPARATUS AND EXPERIMENTAL PROCEDURE

The experiments were conducted in a cylindrical combustion chamber of 90 mm inner diameter and 20 mm length, made of organic glass (Fig. 1). The chamber was horizontally mounted on the axis of an electric motor. Rotation rates of up to 6000 r.p.m. were used. The maximum tangential velocity at the edge of the cylinder was 28.3 m/s at 6000 r.p.m.

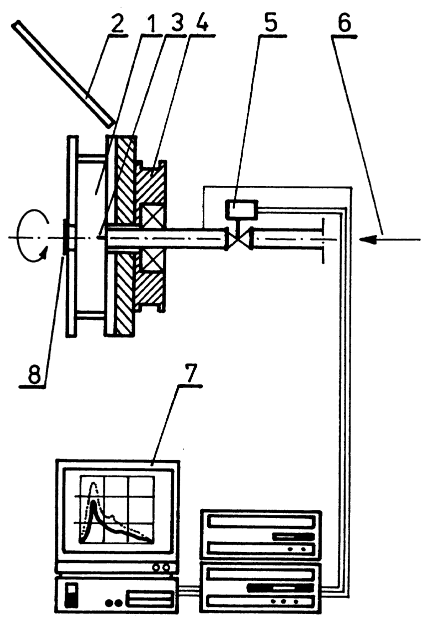


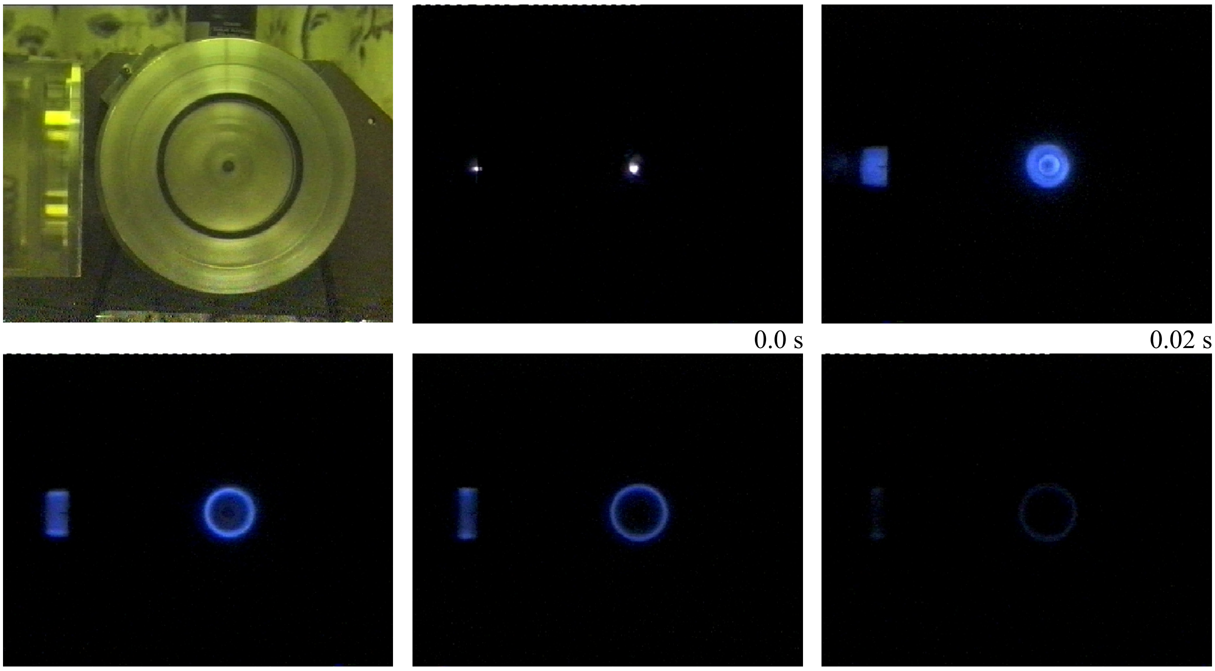
Fig. 1. Simplified schematic of the apparatus: 1- combustion chamber, 2- mirror, 3- igniter, 4- V-belt wheel, 5- solenoid valve, 6- mixture supply, 7- PC computer, 8- self-stick paper covering the outflow orifice.

The methane-air mixture was used in the experiments. It was made by blending methane and air with rotameter-type flow meters. The combustible mixture was conveyed to peripheral part of the vessel by a mixing tube and a central venting orifice with 15 mm diameter. The vessel was filled by displacement. The experimental procedure consisted in supplying the vented vessel for a few minutes with the mixture of the required composition at appropriate flow rates. After shutting off the flow, and closing the venting orifice of the vessel with a self-stick piece of paper, the tube was rotated at a desired speed for about one minute to establish rigid-body rotation of the mixture. Rigid-body rotation of the gas was confirmed by the recorded trajectories of radiant particles moving radially in the section perpendicular to the axis of rotation of the cylindrical vessel. Finally, the mixture was ignited at the center of the tube by a spark, the venting orifice was automatically open and a run was recorded. In such conditions the flame could propagate freely in the direction of increased centrifugal forces to the moment of extinction.

The photographic records of the combustion process were made with a conventional Panasonic S-VHS video camera. The camera observed a front view of the flame. To have an additional side-view of the same flame, a mirror set up at 45 degrees was used.

RESULTS AND DISCUSSION

A typical history of the flame propagation and quenching process, recorded by a video camera, is shown in Fig. 2. The behavior of the flame at the quenching conditions is highly reproducible. Figure 2 shows a typical sequence of frames.



0.0 s 0.02 s 0.04 s 0.06 s 0.08 s

Fig. 2. History of flame propagation in 8.45% methane-air mixture in an open rotating vessel at rotation rate $\omega = 524\ s^{-1}$. Shatter speed: 1/50 s.

Figure 3 shows the time history of radial flame propagation for different rotation rates. After ignition the flame almost instantly becomes cylindrical. At the start it has some minimum radius which exceeds 10-12 mm. The self–stick paper (see Fig. 1) is taken away from the central orifice by the hot combustion gases and the central part of the combustion vessel communicates with the surroundings. From this moment the flame propagates freely in radial direction, preserving its regular cylindrical surface parallel to the rotation axis. The higher the rotation rate is the lower is the flame propagation velocity (expressed by the slope of the curves) and the smaller is the radius of flame extinction r_{cr}. During flame propagation in a field of increasing radial acceleration burning velocity gradually decreases until, finally, the flame is quenched (Fig. 4). The quenching of the flame starts always at the walls normal to the rotation axis. It is shown in Fig. 4 that the burning velocity strongly depends on the rotation rate ω, and that the limit burning velocity at the quenching conditions is about 5 cm/s.

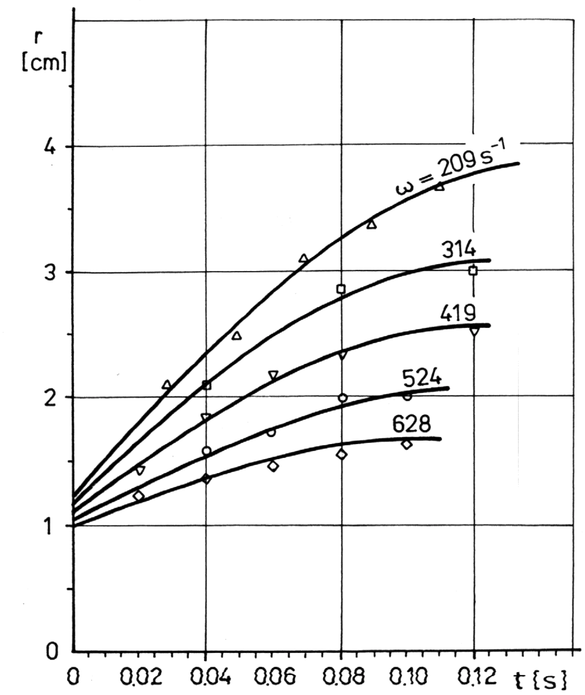


Fig. 3. Flame radius r as a function of time t for 8.45% methane-air mixture and for different rotation rates ω.

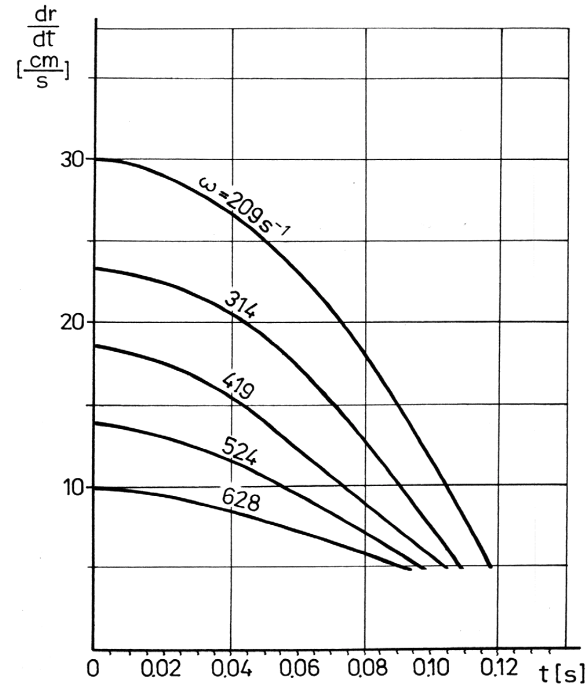


Fig. 4. Burning velocity as a function of time t for 8.45% methane-air mixture and for different rotation rates ω.

The experimental curve representing the influence of the rotation rate, ω, on the radius of flame extinction, r_{cr}, is shown in Fig. 5.

Relationship of the radius of flame extinction with radial acceleration and the rotating rate is shown in Figs. 6 and 7. The analysis of experimental results presented in these figures reveals that radial acceleration g at the extinction radius r_{cr} depends linearly on the rotation rate ω

$$g = \omega^2 r_{cr} = \text{const.}\ \omega$$

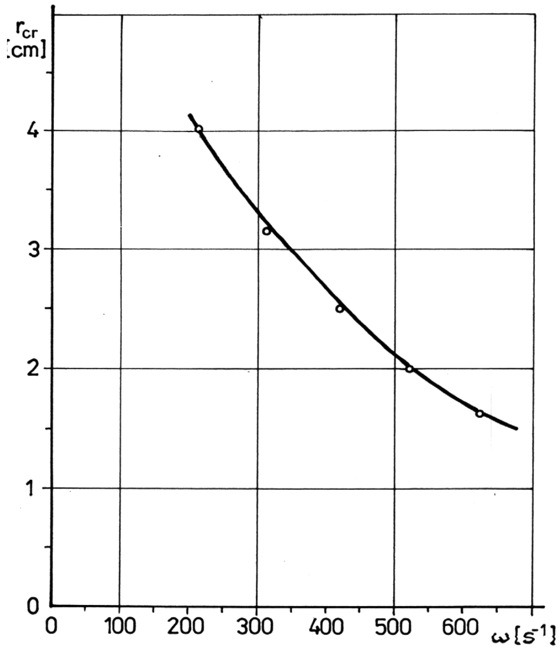


Fig. 5. Variation of the radius of flame extinction r_{cr} as a function of the rotation rate ω for 8.45%

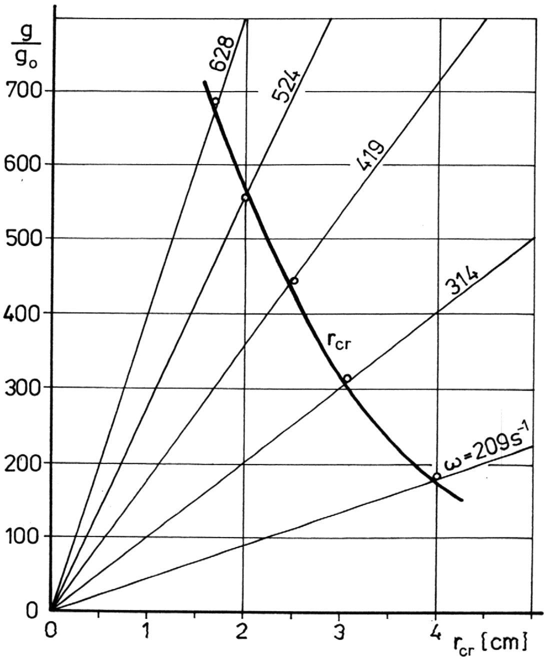


Fig. 6. Radial acceleration g related to gravity acceleration g_0 as a function of the extinction

methane-air mixture.

radius r_{cr} for different rotation rate ω.

This relation shows that the product of the rotation rate and the extinction radius ωr_{cr} is constant, i. e. for 8.45% methane-air mixture the flame is always quenched at the same tangential velocity $v = \omega r_{cr} \cong 10\text{-}11$ m/s.

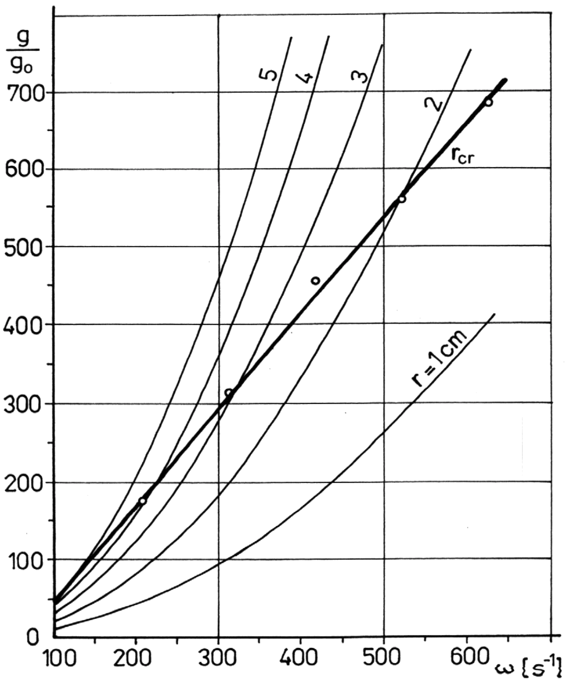


Fig. 7. Radial acceleration g related to gravity acceleration g_0 at the extinction radius r_{cr} as a function of the rotation rate ω.

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