EXPERIMENTS ON DIFFUSION FLAME STRUCTURE OF A LAMINAR VORTEX RING

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Introduction

The study of flame-vortex interactions provides one of the means to better understand turbulent combustion, and allows for canonical configurations that contain the fundamental elements found in turbulent flames. These include concentrated vorticity, entrainment and mixing, strain and nonequilibrium phenomena, diffusion and differential diffusion, partial premixing and diluent effects, and heat release effects. In flame-vortex configurations, these fundamental elements can be studied under more controlled conditions than is possible in direct investigations of turbulent flames.

Since the paper of Marble [1], the problem of the flame-vortex interaction has received considerable attention theoretically, numerically and experimentally. Several configurations exist for study of the premixed flame/vortex ring interaction but more limited results have been obtained to date for the diffusion flame/vortex ring case [2-5]. The setup of Chen and Dahm [4,5], which is conceptually similar to that of Karagozian and Manda [6,7] and Karagozian, Suganuma and Strom [8] where the ring is composed of fuel and air and combustion begins during the ring formation process, is used in the current study. However, it is essential to conduct the experiments in microgravity to remove the asymmetries caused by buoyancy and thus obtain highly symmetric and repeatable interactions [4].

In previous studies [4,5] it was found that the flame structure of the vortex ring was similar to that obtained analytically by Karagozian and Manda [6,7]. Dilution of propane with nitrogen led mainly to a reduction in flame luminosities, flame burnout times were affacted by both fuel volumes and amount of dilution, and a simple model of the burnout times was developed. In this paper, a discussion on reacting ring displacement and flame burnout time will be given, and the flame structures of vortex rings containing ethane and air will be compared to those of propane reacting in air.

Experiment Description

The experiments were conducted under microgravity conditions at the NASA LeRC 2.2-sec drop tower, and the details of the experimental setup can be found in Chen and Dahm [5]. Gaseous fuel lies inside the nozzle and plenum, and air surrounds the outside of the nozzle which is enclosed in an open test section with transparent windows. A diffusion flame is first generated (using a spark ignitor) at the exit of an axisymmetrically contoured nozzle under normal gravity and flattens under microgravity. Gaseous fuel is then injected through the nozzle to form a laminar reacting vortex ring at the nozzle exit. The ring wraps the diffusion-reaction layer around itself in a complex interaction, and continues to burn until the fuel inside the ring is consumed. The ring circulation and fuel volume can be varied and hot-wire anemometry is used to measure these quantities. An on-board CCD camera records the visible luminosity of the flame-vortex interaction which is shown in inverse grayscale format throughout the paper.

Results and Discussion

Study of the ring displament allows the understanding of how combustion affects the circulation. Fig. 1 shows that a reacting vortex ring accelerates in the early (inviscid) stage of the interaction, then slows down (accumulation of product in the ring) and finally stops (near flame burnout). Existing inviscid and viscous models for nonreacting rings do not match the results, and it comes to no surprise since we are dealing with viscous and reacting vortex rings; but in the momentum dominated region, there is some agreement with theory. Theoretical models that incorporate combustion need to be developed.

Figure 2 shows that the simple model for the flame burnout time which was developed by Chen and Dahm [5] agrees reasonably with the experimental results, considering that the observed burnout times span by more than an order of magnitude. This model considers the ring filled with fuel and air as a spherical diffusion flame, and it assumes that the fuel and air is rapidly mixed.

For a given set of ring circulation (Γ in cm^2/sec) and fuel volume (V in cc), ethane cases (see Figs. 3 & 5) show reduced flame luminosity and shorter flame burnout times when compared to the propane cases (see Figs. 4 & 6). Furthermore, the formation and dissipation of the bright zones, which are associated with soot formation, in ethane cases differ somewhat to those of propane. Note that the fuel equivalence ratio and adiabatic flame temperature are 16.0 and 2260 K, respectively for ethane, and 15.6 and 2267 K, respectively for propane.

Conclusion

Existing models for vortex ring displacement do not match with the experimental data due to the lack of the combustion. An accurate model must take into account the reaction occuring inside the ring and how the fuel consumption and the product generation affect the ring circulation. With similar hydrodynamic conditions, rings containing ethane or propane display different flame structure and burnout time. The main discrepancy was the large reduction in the flame luminosity in the ethane cases. Varying the heat release will be of great interest by examining dilution of fuels or oxidizer with inert diluent, using other fuels such as methane and hydrogen, or oxygen enrichment of the fuel or oxidizer. These experimental results may be used for the verifcation and construction of models of turbulent flame and soot.

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References

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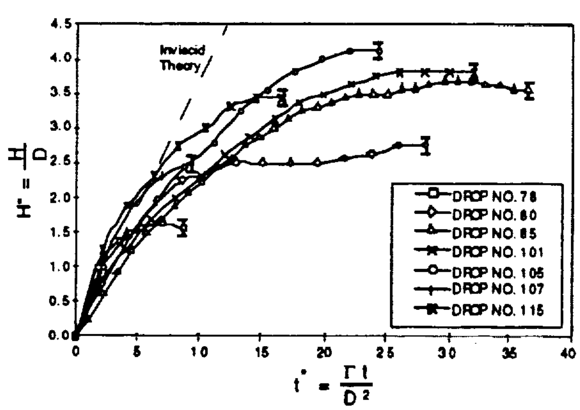

Fig. 1 Reacting vortex ring displacement curves compared to inviscid theory.

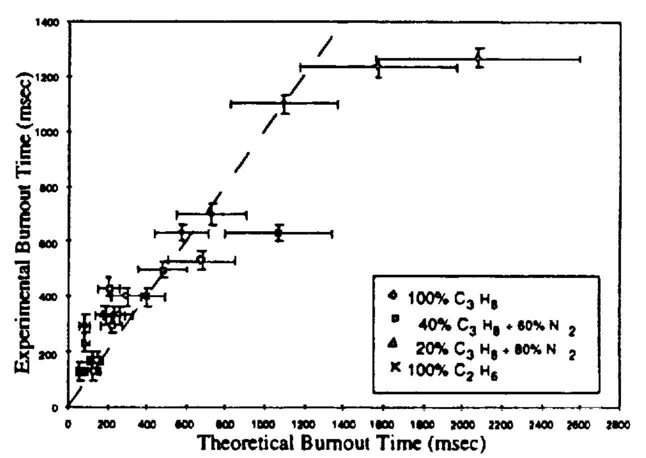

Fig. 2 Comparison of theoretical and experimental flame burnout times.

Fig. 3 Flame-vortex interaction for ethane burning in air, Γ=117 cm^2/sec and V=15 cc. The frame rate is 30 fps. Flame burnout time is 467 msec.

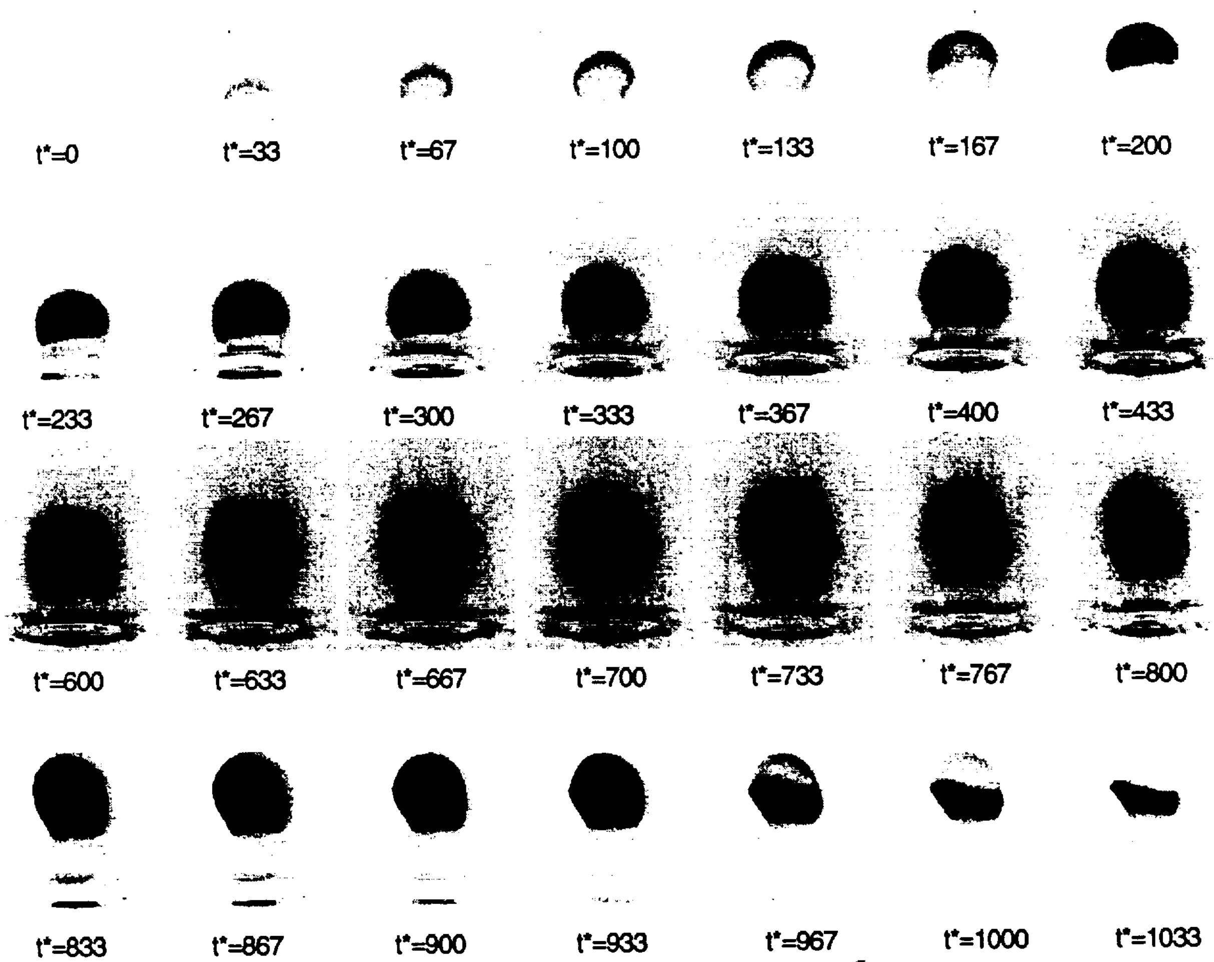

Fig. 4 Flame-vortex interaction for propane burning in air, Γ=117 cm^2/sec and V=17 cc. Compare to Fig. 3. The relative times shown are in millisecond. Flame burnout time is 1200 msec.

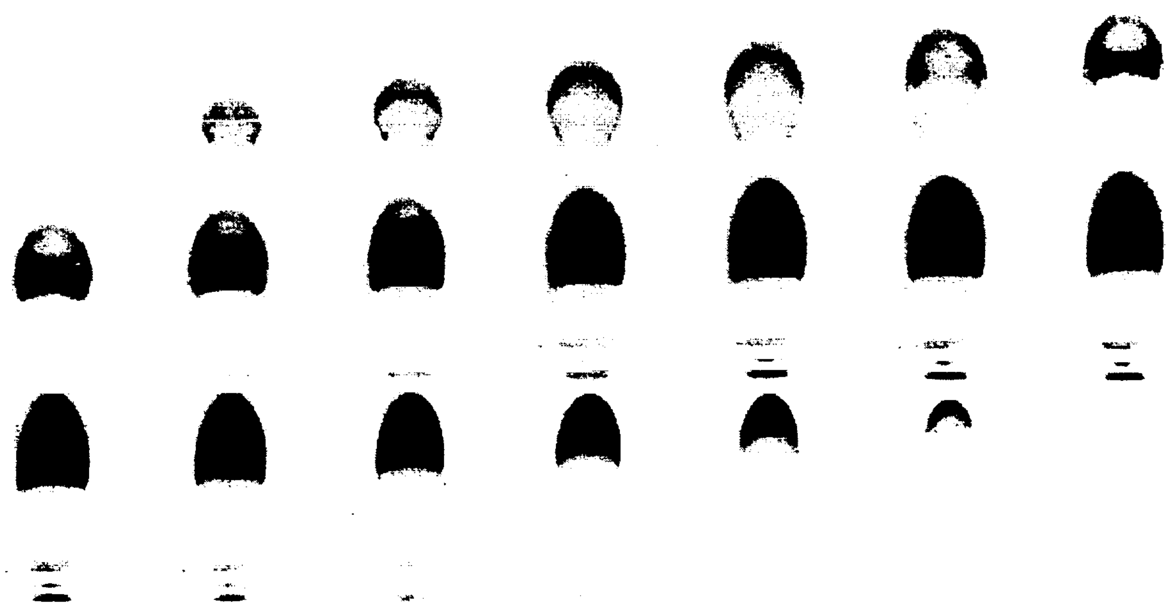

Fig. 5 Flame-vortex interaction for ethane burning in air, Γ=282 cm^2/sec and V=26 ccms. The frame rate is 30 fps. Flame burnout time is 667 msec.

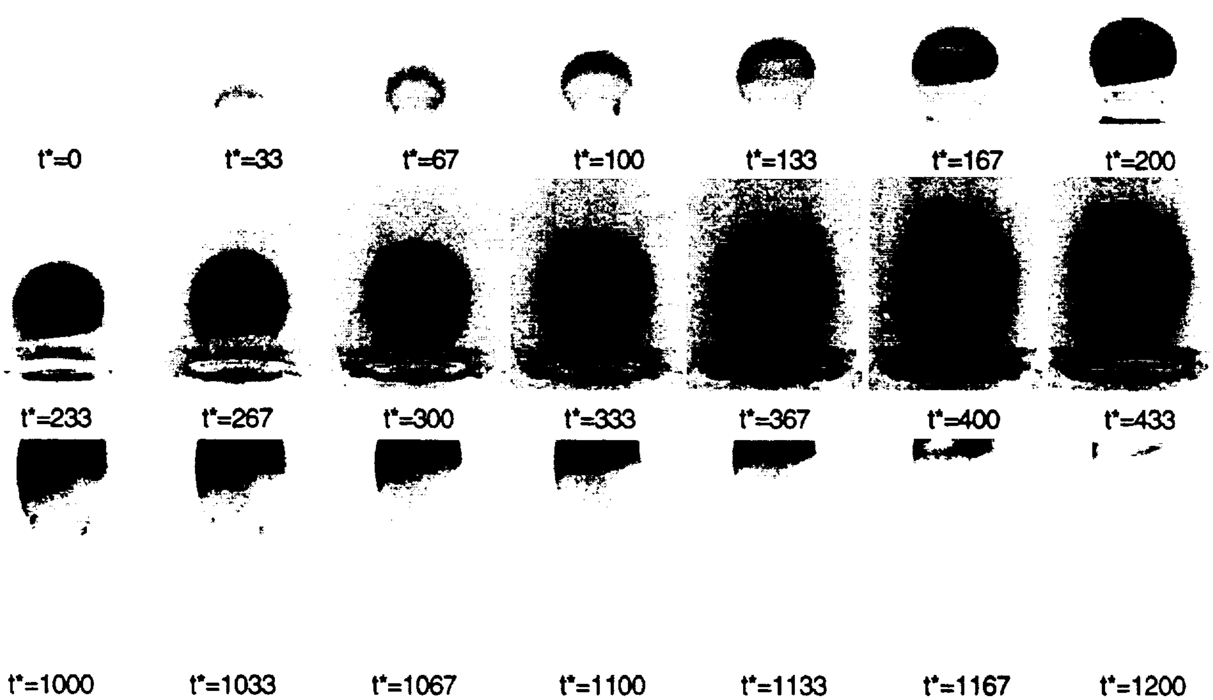

Fig. 6 Flame-vortex interaction for propane burning in air, Γ=273 cm^2/sec and V=26 cc. Compare to Fig. 5. The relative times shown are in millisecond. Flame burnout time is 1233 msec.