Flame-Vortex Studies to Quantify Markstein Numbers Needed to Model Flame Extinction Limits

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This has quantified a database of Markstein numbers [1-3] for unsteady flames; future work will quantify a database of flame extinction limits for unsteady conditions. Unsteady extinction limits have not been documented previously; both a stretch rate and a residence time must be measured, since extinction requires that the stretch rate be sufficiently large for a sufficiently long residence time. Ma was measured for an inwardly-propagating flame (IPF) that is negatively-stretched under microgravity conditions. Computations also were performed using RUN-1DL to explain the measurements. The Markstein number of an inwardly-propagating flame, for both the microgravity experiment and the computations, is significantly larger than that of an outwardy-propagating flame. The computed profiles of the various species within the flame suggest reasons. Computed hydrogen concentrations build up ahead of the IPF but not the OPF. Understanding was gained by running the computations for both simplified and full-chemistry conditions.

The drop tower experiment in Fig. 1 [4-6] was used to create a flat propane-air flame which interacts with a vortex, causing the flame to wrap around the vortex. The distorted flame surface eventually pinches off from the main surface, creating a pocket of reactants surrounded by an inwardly propagating spherical flame. An electrical connection is broken which signals the beginning of the drop; after a 500 ms wait time, exhaust ports are opened to prevent pressure buildup and the flame is ignited using a spark. After 200 ms the speaker is pulsed and the pocket formation occurs 300 – 400 ms later. Final pocket burnup occurs in another 150 ms, so the entire process takes less than 1.2 seconds. Flame speeds were measured by recording shadowgraph images of pocket at 500 frames/second using a Kodak RO digital camera. Figure 2 shows the digitized image of the flame boundary at five different times. For the IPF the velocity of the gas (**u**) inside the pocket is zero due to symmetry, so the stretch rate of an IPF is $K = S_u / R_c$.

Numerical Simulations. To explain the experimental findings, numerical simulations of both inwardly and outwardly propagating spherical flames (with complex chemistry) were generated using the RUN-1DL code [7], which includes 16 species and 46 reactions.

Figures 2 and 3 show some results of the microgravity IPF experiment, for which the propane-air equivalence ratio was 0.54. The slope of the curve in Fig. 3 is –Ma. Figures 4 and 5 show some numerical results for complex propane-air chemistry. The Markstein number is 11.5, which is within the range of values that were measured in the microgravity experiment. The Ma of the computed IPF is larger than that of the corresponding OPF. A difference between the IPF and OPF is that there is a buildup of hydrogen molecules ahead of the IPF that is caused by stretch, but no such buildup occurs for the OPF.

Conclusions

1. Markstein numbers of a inwardly-propagating flame were measured in microgravity using a unique experiment. This flame is of interest because it is subjected to negative stretch rates, and because curvature effect alone are present; the complications associated with strain are absent. The measured values of Ma for the IPF are significantly larger than previous measurements reported for the OPF case.
2. Computed Ma were obtained using the RUN-1DL code and complex chemistry. Results agreed with the experiment. Computed Ma for the IPF were significantly larger than computed for the OPF case, in agreement with the measurements.
3. When the heat release is artificially removed from the computations, both IPF and OPF cases are subjected to curvature effects alone, and strain effects are absent; the resulting computed Markstein numbers are identical. This indicates that the Markstein numbers associated with strain and curvature differ. The difference between Ma of IPFs and OPFs does not appear to be due to radicals and intermediate species.
4. The profiles of certain species concentrations, such as hydrogen molecules, has a significantly different shape for the IPF case than for an OPF. This is due to the boundary conditions for the IPF at the origin, which differ from those of the OPF.

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References

1. Sun, C.J., Sung, C.J., He, L.,Law, C.K., *Combust. Flame* 118:108-128 (1999).
2. Kwon, S., Tseng, L.K., and Faeth, G.M., *Combust. Flame* 90:230-246 (1992).
3. Tseng, L.K., Ismail, M.A., and Faeth, G.M., *Combust. Flame* 95: 410-426 (1993).
4. Ibarreta, A. and Driscoll, J.F., *Proc. Combust. Inst*. 28: 1783-1791 (2000).
5. Ibarreta, A., Driscoll, J.F., Feikema, D. *Proc. Combust. Inst*. 29 (2002).
6. Sinibaldi, J., Mueller, C., and Driscoll, J., *Proc. Combust. Inst*. 27: 827-832 (1998).
7. Rogg, B. and Wang, W., *RUN-1DL* - Ruhr-Universitat Bochum, 1997.

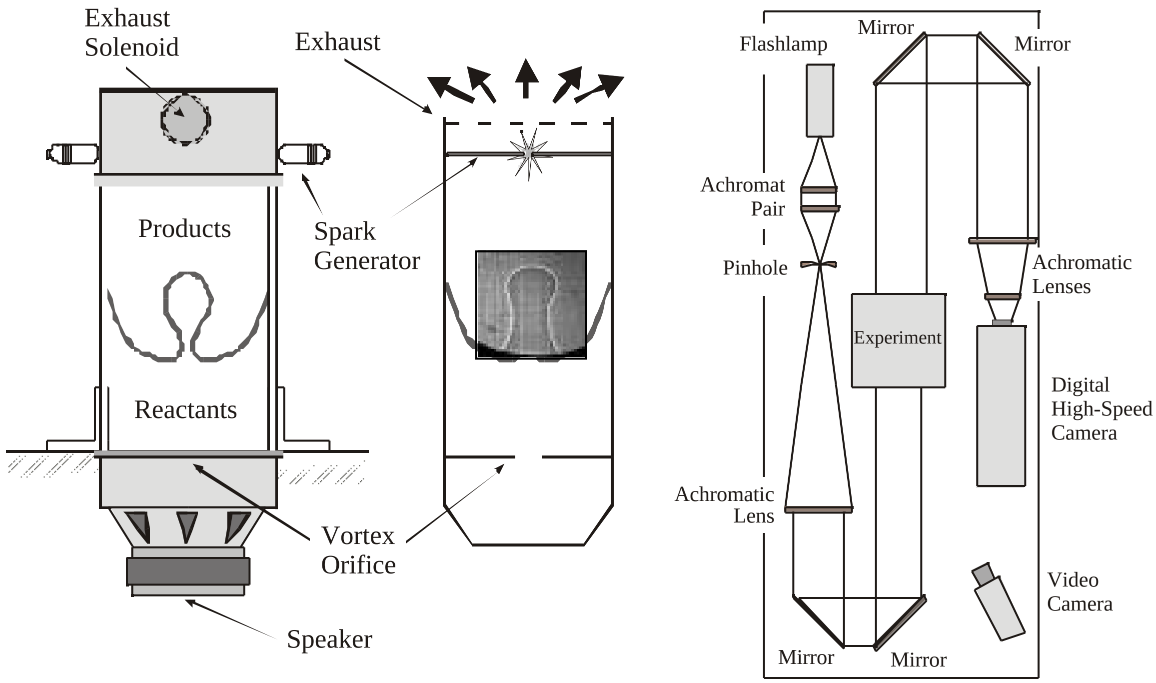


Figure 1. Michigan Microgravity Experiment to Create Unsteady Stretched Flames

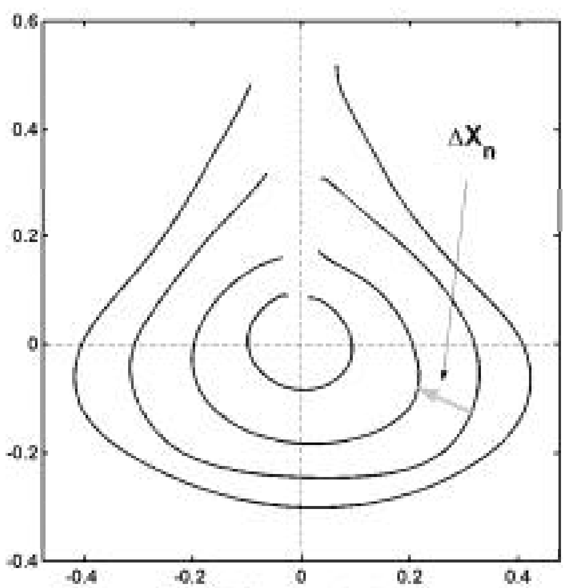


Fig. 2. Shadowgraph of Flame Positions

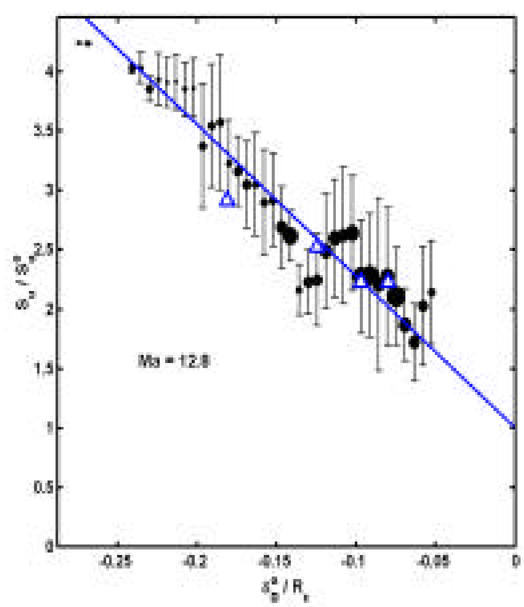
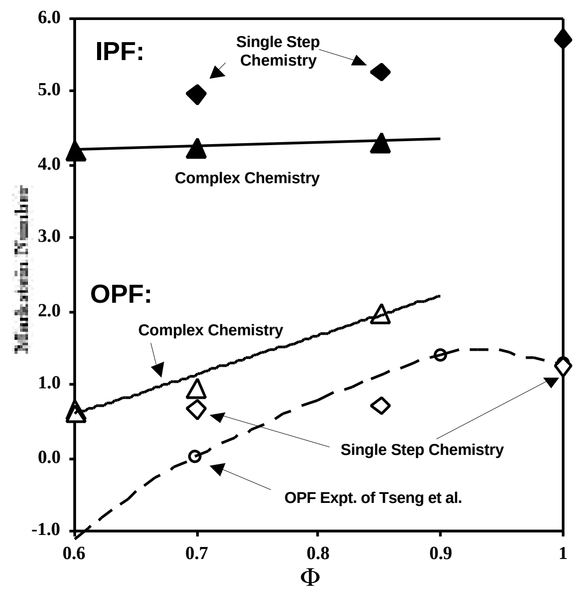
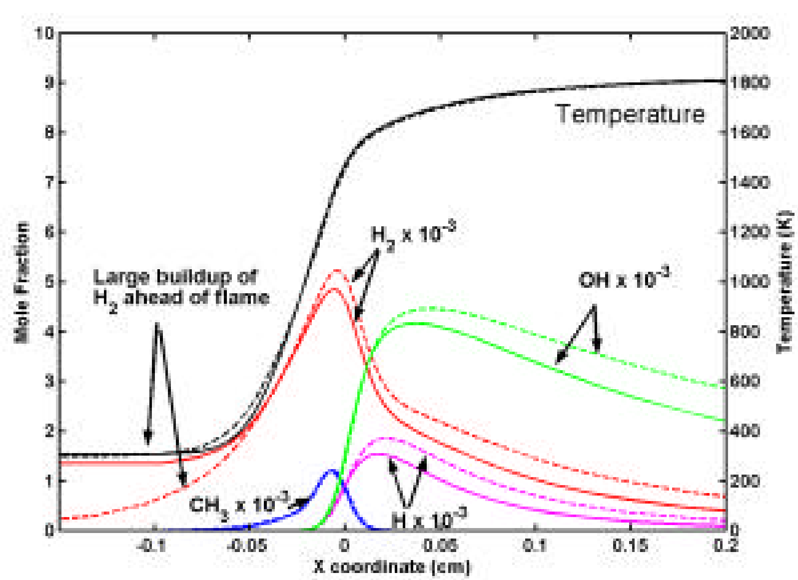


Fig. 3. Flame Speeds to Determine Ma





Figures 4 and 5. Computed and Measured Markstein Numbers Showing that Inward and Outward Propagating Flames (Negatively and Positively Stretched Flames) Have Different Ma. Computations show that H2 builds up ahead of IPFs but not OPFs.