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Flame Spread Along Free Edges of Thermally Thin Samples In Microgravity

W.E. Mell*, S.L. Olson**, and T. Kashiwagi***

*Chemical and Fuels Engineering Department
University of Utah, Salt Lake City, UT84112, USA
**Microgravity Combustion Science Branch
NASA Glenn Research Center, Cleveland, OH 44135, USA
***Building and Fire Research Laboratory
National Institute of Standards and Technology, Gaithersburg, MD20899, USA

Abstract

The effects of imposed flow velocity on flame spread along open edges of a thermally thin cellulosic sample in microgravity are studied experimentally and theoretically. In this study, the sample is ignited locally at the middle of the 4 cm wide sample and subsequent flame spread reaches both open edges of the sample. The following flame behaviors are observed in the experiments and predicted by the numerical calculation: in order of increased imposed flow velocity; (1) ignition but subsequent flame spread is not attained, (2) flame spreads upstream (opposed mode) without any downstream flame, and (3) the upstream flame and two separate downstream flames traveling along the two open edges (concurrent mode). Generally, the upstream and downstream edge flame spread rates are faster than the central flame spread rate for an imposed flow velocity of up to 5 cm/s. This is due to greater oxygen supply from the outer free stream to the edge flames than the central flames. For the upstream edge flame, the greater oxygen supply results in a flame spread rate that is nearly independent of, or decreases gradually, with the imposed flow velocity. The spread rate of the downstream edge, however, increases significantly with the imposed flow velocity.

Introduction

Fire safety precautions are especially vital for the longer duration and increasingly complex space missions in the future International Space Station and the planned manned flight mission to Mars (three years). For this reason, many flame spread experiments over combustible solid surfaces have been conducted in microgravity environments. For example, over a thermally thin cellulosic sample with external flows [1,2]; at various ambient pressures in a quiescent environment [3,4]; in a three-dimensional spread-pattern from a localized spot ignition [5]; and over a thermally thick polymethylmethacrylate, PMMA, sample in quiescent, high oxygen concentration environments [6,7]. All these experiments were conducted over the center part of the sample to avoid the effects of the sample edges as much as possible. However, limited published studies on flame spread along thin sample edges in normal gravity show that flame spread rate along free edges tends to be faster than that along the center of the sample [8,9]. Since faster flame spread rate means more rapid fire growth, measurements of spread rates along free edges in microgravity are needed. It has been observed that a slow external flow, which simulates ventilation flow in a spacecraft and the Space Station, has significant effects on flame spread in microgravity [1,2,10]. Thus, the focus of this paper is to determine the effects of a slow imposed flow on both flame spread about 1.5 cm (at a much later time than the 3.5 cm/s and 5 cm/s air flow cases). This delay was caused by the larger distance from the flame front to the free edges due to a smaller internal angle of the fan-shaped upstream flame at 2 cm/s compared to 3.5 cm/s and 5 cm/s air-flow velocities [11]. When the flame front reached the free edges, a sudden, rapid flame spread occurred. However, the edge flame spread rates were reasonably steady after the initial acceleration in both upstream and downstream directions. The edge flame spread rates, determined from the slopes of the nearly straight-line part of the plots in Figure 2, are shown in Figure 3 as a function of external air flow velocity. The upstream edge flame spread rate decreases slightly with an increase in external flow velocity. This trend is significantly different from that of the upstream central flame spread rate, which significantly increases with external flow velocity in this range of velocities [11]. However, these edge flames are propagating much faster than a normal-gravity, downward, free-edge flame over the same sample, which propagates at approximately 0.13 cm/s against buoyancy induced air flow. This suggests that edge flame spread rate would continue to decrease gradually with external flow velocity above 5 cm/s. However, downstream edge flame spread rate increases rapidly with an increase in external flow velocity.

In order to provide a perspective on edge flame spreading relative to central flame spreading, the edge flame spread rates are normalized by the central flame spread rates obtained from the samples without the free edges, which were determined during other series of RITSI tests [11]. The upstream and downstream central flame spread rates at each flow are used to normalize the upstream and downstream edge flame spread rates at the corresponding flow velocity, respectively. The normal gravity downward edge flame spread rate is also normalized by the normal gravity downward central flame spread rate. As is seen in the insert of Figure 3, at low velocities the upstream edge flames spread faster than the upstream central flame. However, as imposed flow velocity increases the oxygen supply to the central flame becomes sufficient and the upstream central flame spreads at the same rate as the upstream edge flame. This would be a minimum normalized upstream edge flame spread rate, because at normal gravity the normalized downward spreading edge flames are again faster than the central downward propagating flame. The downstream normalized edge flame spread rates increases rapidly with imposed flow, due to enhancements in both oxygen supply and convective heating.

Theoretical Model

Since a more detailed description of the mathematical model has been given in Refs. [10,12], only a brief summary is given here. The gas phase is formulated with the conservation equations of mass, full Navier-Stokes form of the momentum (without gravity), energy, and species (fuel and oxygen) under the low-Mach-number limit. A global one-step reaction {Fuel Gas} + ν_{o2} {Oxygen} $\rightarrow$ Product with an Arrhenius rate is used. The pre-exponential factor in the reaction rate is 5.0 x 10^9 $cm^3/(g.s)$; the activation energy is 67 kJ/mol; the heat of combustion is 35kJ/g; the stoichiometric constant ν_{o2} is 3.57. These values were chosen to match roughly flame spread rates with the experiments of Olson [1]. In addition the same values have been used in our previous theoretical studies [5,10,12,13]. Ignition is initiated by an external radiant flux on the sample surface, and radiative emission and absorption in the gas are neglected.

with decreasing imposed flow velocity. There is an initial acceleration in the edge flame spread followed by a nearly steady (linear) spread for 2 cm/s and 3 cm/s imposed flows. For 1 cm/s imposed flow, the downstream edge flame spread rate does not reach a steady state with the sample size used in this study. For longer samples it is possible that this flame might extinguish. The steady edge flame spread rate is determined by the slope of the nearly linear part of the curves in Figure 5, and also from a similar plot for 29% oxygen concentration (not shown). The results are plotted with respect to the imposed flow velocity in Figure 6. This figure shows the same trends as observed in the experiments in Figure 3; downstream edge flame spread rate increases rapidly with an increase in the imposed flow velocity, but upstream edge flame spread rate is nearly independent or decreases slightly with the imposed flow velocity in the range used in this study.

Discussion

The spread rate of the upstream edge flame is greater than the upstream center flame due to improved oxygen supply along edges. The oxygen mass flux vectors clearly show this in Figure 4. Also, the lower half of Figure 7 shows that the amount of oxygen mass flux to the upstream edge flames is roughly two times higher than that to the central flame. Note that the upstream edge flame spread rate is nearly independent of, or decreases slightly, with imposed flow velocity. Since the upstream edge flame does not spread in quiescent conditions (for both 29% and 33% ambient oxygen concentrations) and blows out at sufficiently high velocities, it is expected that a maximum spread rate exists. In Figure 5 show that the upstream edge flame spread rate increases with oxygen concentration and tends to occur at a higher imposed velocity in lower oxygen concentration. This trend is similar to that observed for the center flame spread [1]. The calculated gas phase temperature of the upstream edge flame, as shown in Figure 7, does not increase with the flow velocity. This indicates that there is a sufficient oxygen supply to the edge flame, and further increase in the velocity gradually cools the flame. Thus, upstream edge flame spread rate starts to decrease with the imposed velocity at much lower velocity compared to the center flame spread [1]. However, oxygen supply to the downstream edge flames much exceeds that to the center part of the downstream flame spread, as shown in Figures 4 and 7. Because the supply continues to increase with the imposed flow velocity, the downstream edge flame spread rate increases significantly with the imposed flow velocity.

The next question is why the flame separates into upstream flame and downstream flame/flames as observed in the experiment and also in the calculation. When an upstream flame is present, the downstream flame can fail to spread because the upstream flame consumes too much oxygen [5,10,13]. This can be seen in Figures 4 and 7. When the imposed flow velocity is reduced, oxygen supply to the downstream flame becomes less but still a sufficient amount of oxygen can be supplied to the downstream edge flames from the outer free stream mainly by diffusion. This is seen in Figures 7 and 8. In Figure 8, the difference between the total oxygen mass flux vector (upper plot) and convective oxygen mass flux vector (lower plot) is the oxygen supply flux vector to the flames by diffusion. The convective oxygen mass flux to the downstream edge flame is very small as shown in the figure. Although the oxygen supply by diffusion to the flame

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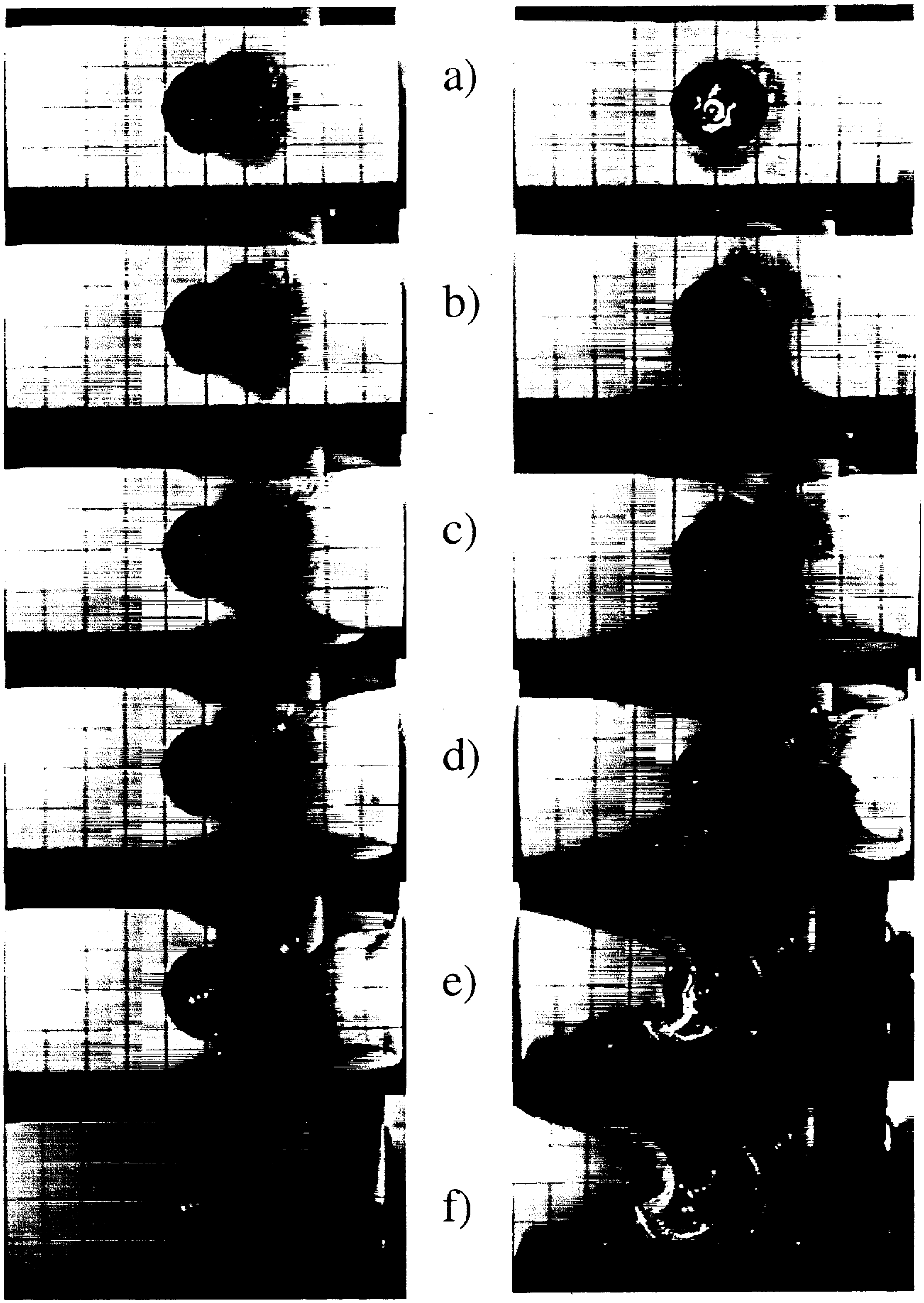
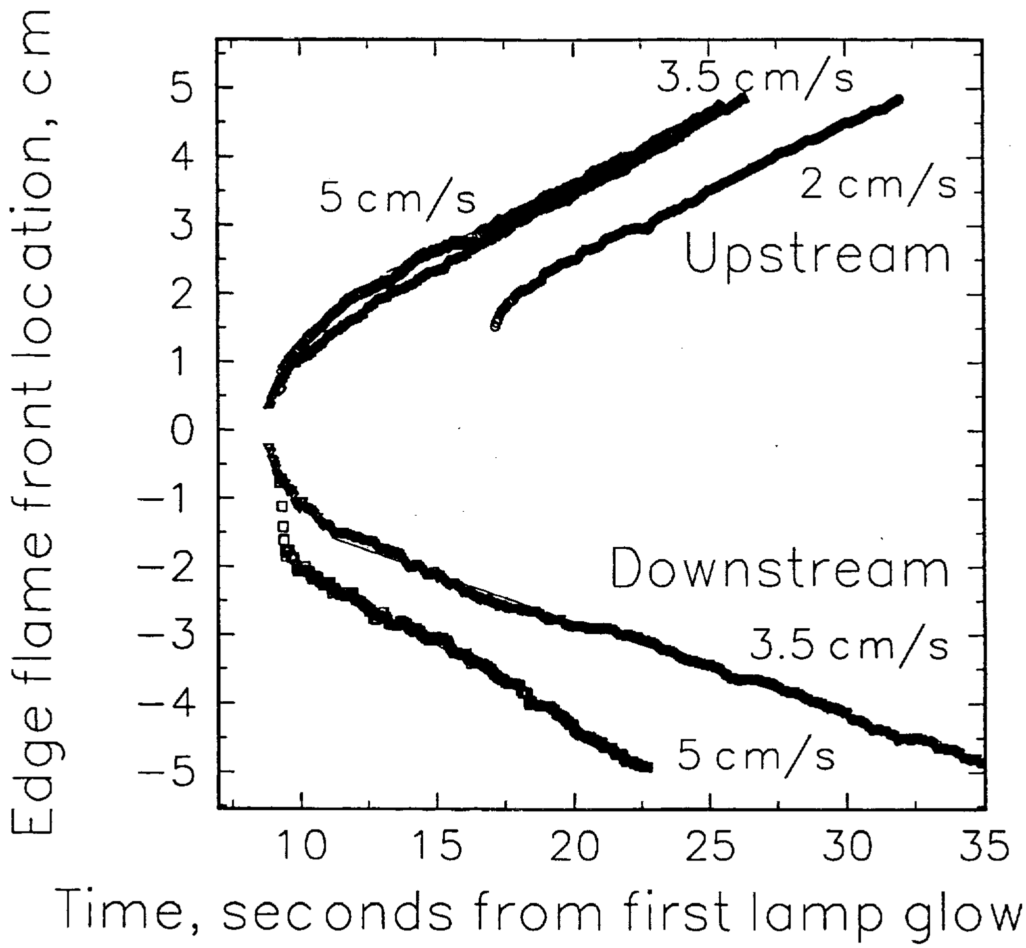
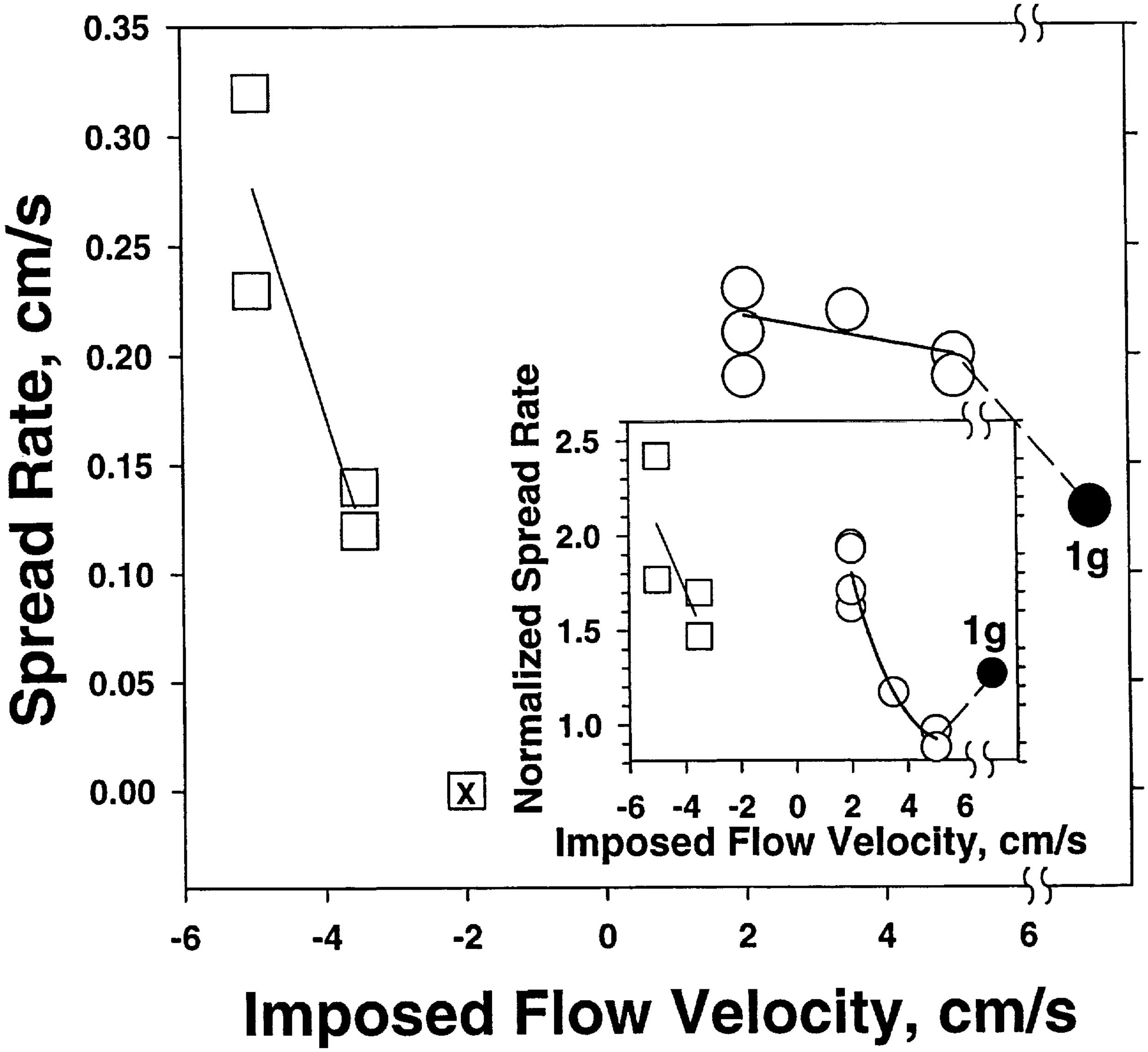
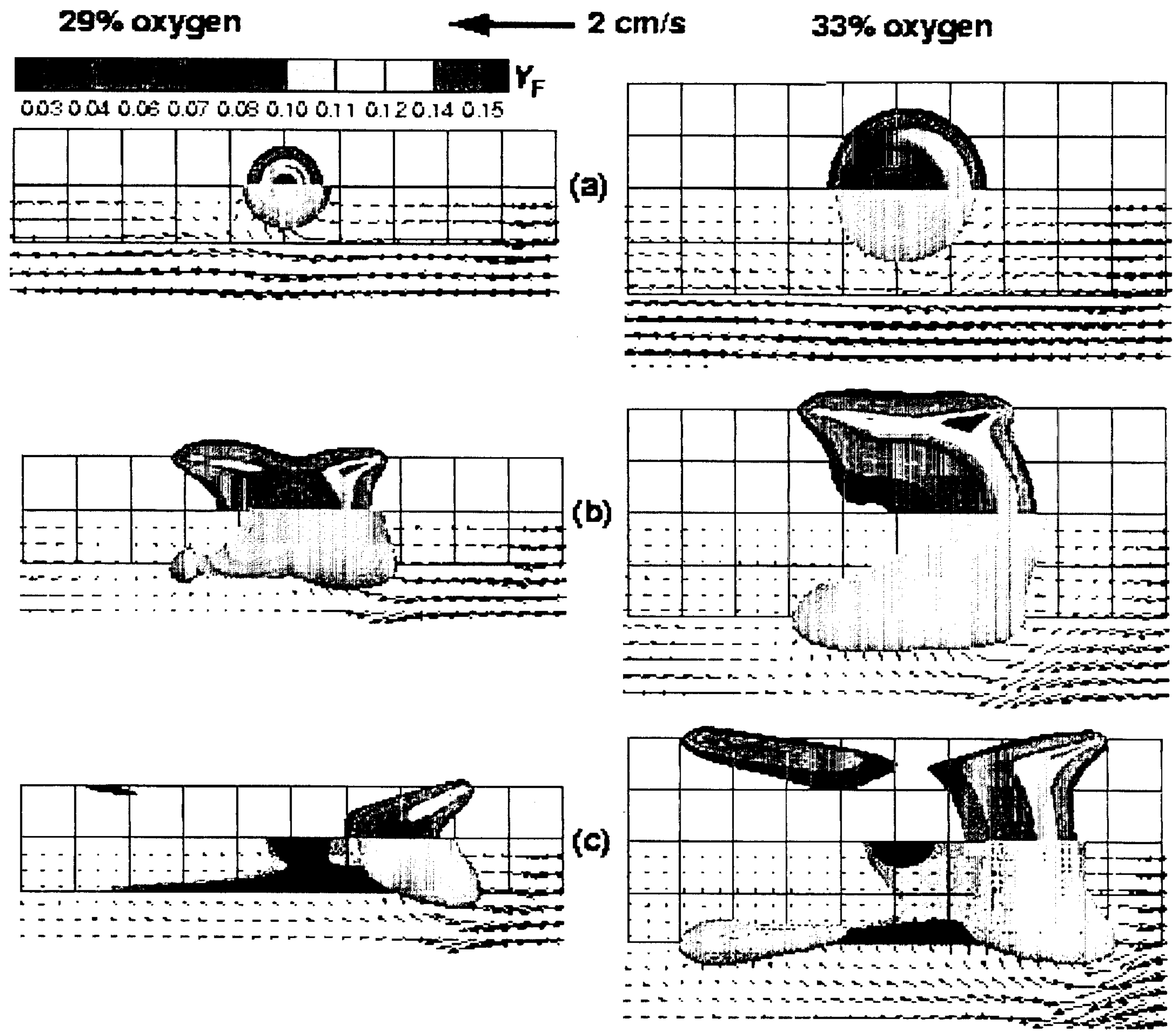

a)
b)
c)
d)
e)
f)

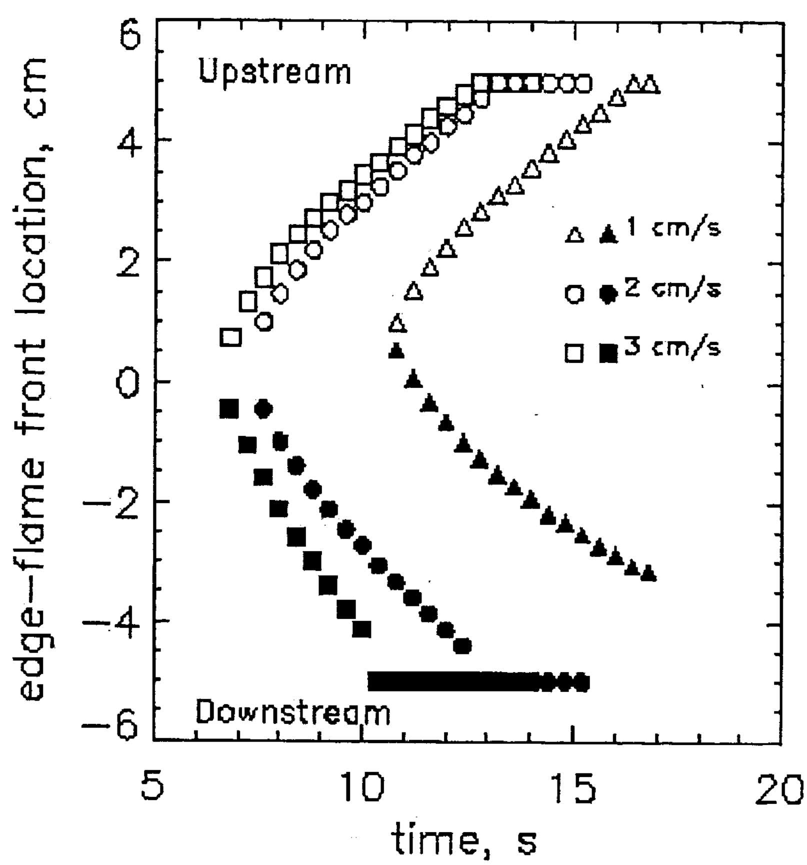


Edge flame front location, cm
Time, seconds from first lamp glow
3.5 cm/s
5 cm/s
2 cm/s
Upstream
Downstream
3.5 cm/s
5 cm/s
5
4
3
2
1
0
−1
−2
−3
−4
−5
10
15
20
25
30
35

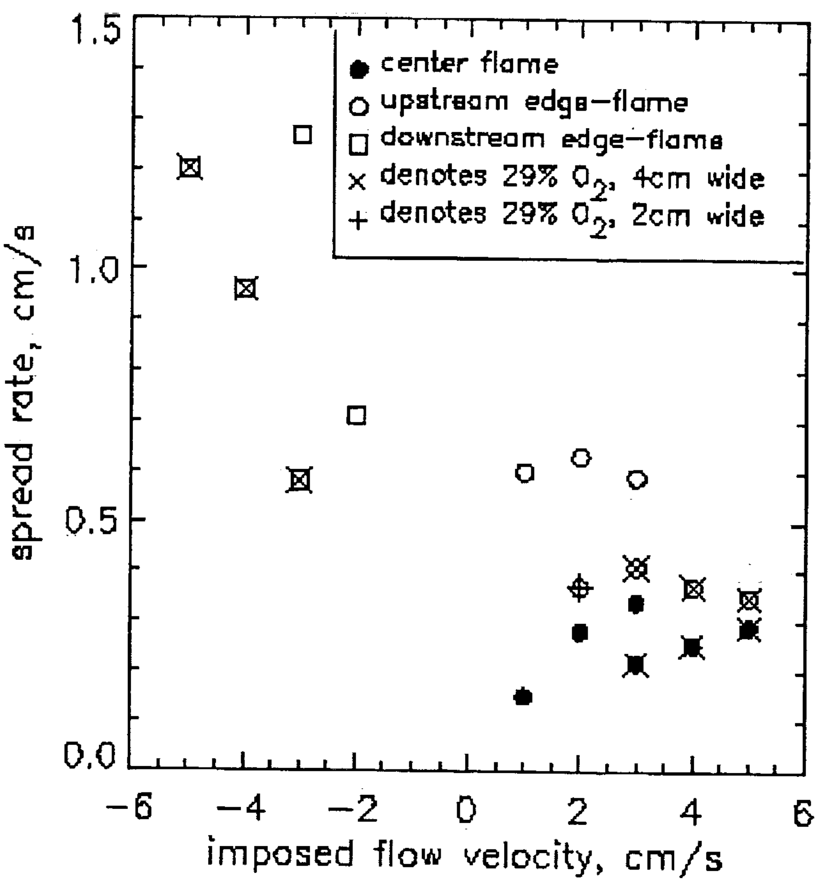


Spread Rate, cm/s
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
-6
-4
-2
0
2
4
6
Imposed Flow Velocity, cm/s
x
1g
Normalized Spread Rate
2.5
2.0
1.5
1.0
-6 -4 -2 0 2 4 6
Imposed Flow Velocity, cm/s
1g

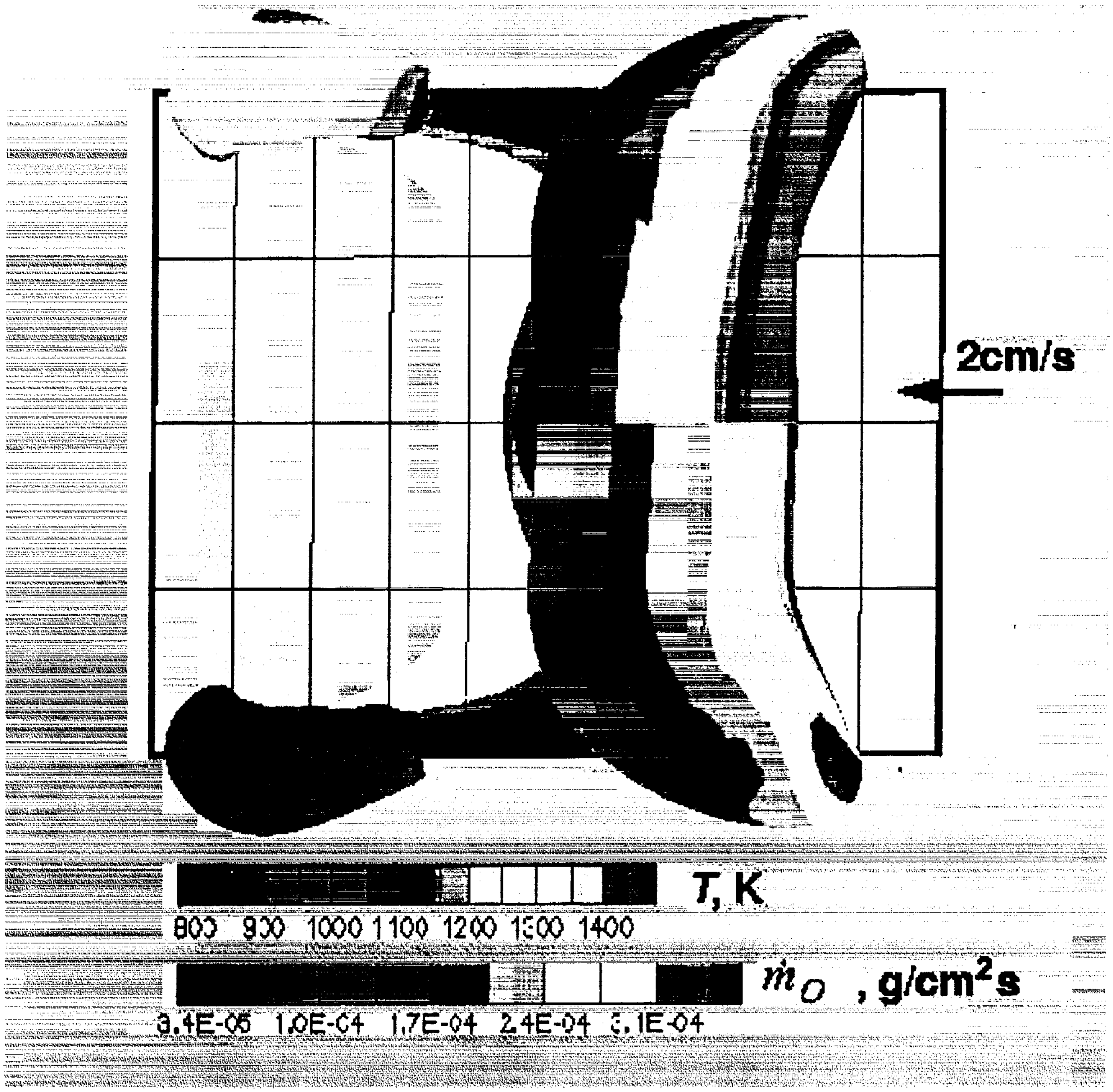

29% oxygen
2 cm/s
33% oxygen
Y_F
0.03 0.04 0.06 0.07 0.08 0.10 0.11 0.12 0.14 0.15
(a)
(b)
(c)



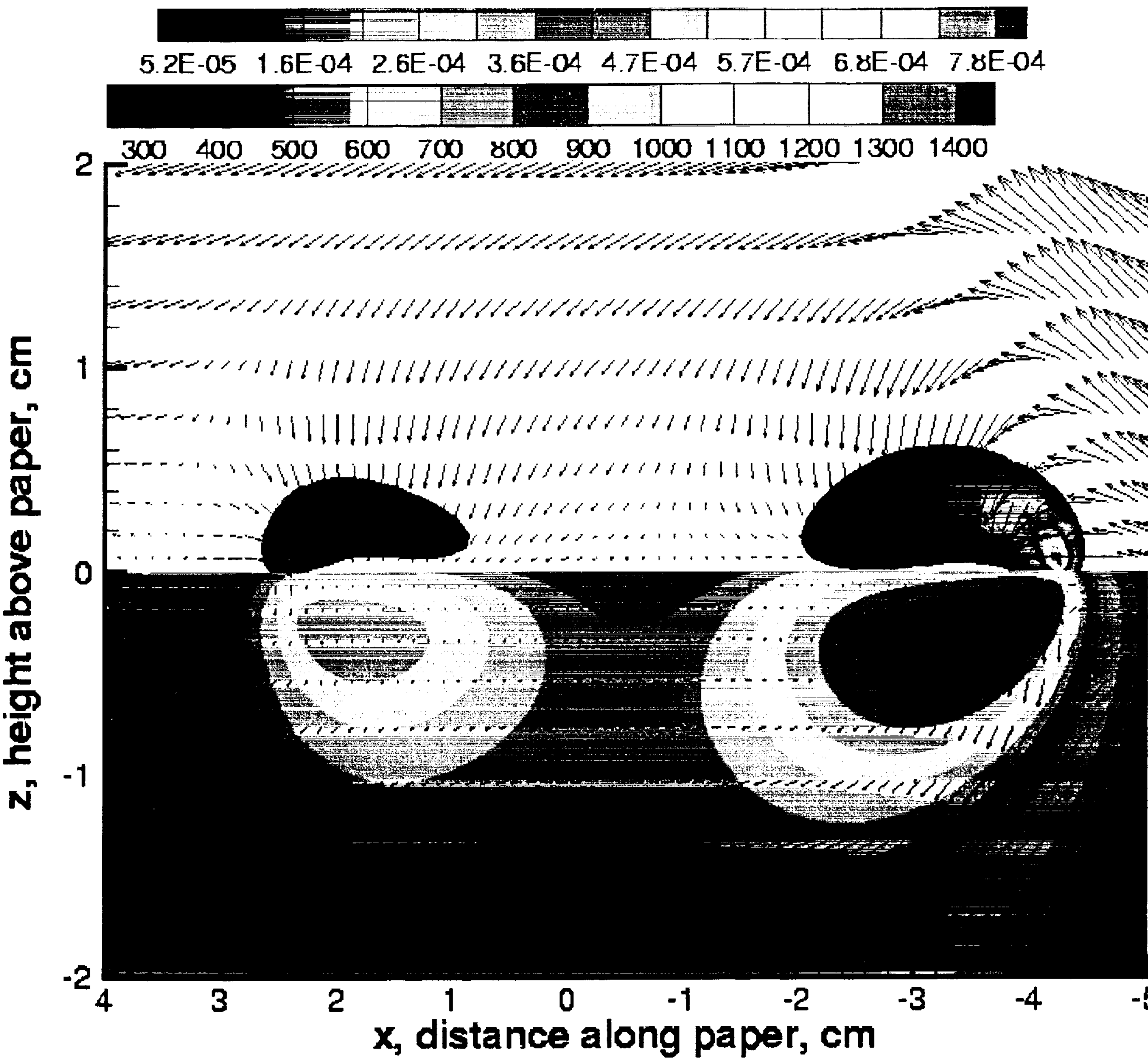
Upstream
Downstream
1 cm/s
2 cm/s
3 cm/s
edge–flame front location, cm
time, s
6
4
2
0
−2
−4
−6
5
10
15
20



center flame
upstream edge-flame
downstream edge-flame
denotes 29% O_2, 4cm wide
denotes 29% O_2, 2cm wide
spread rate, cm/s
imposed flow velocity, cm/s
1.5
1.0
0.5
0.0
-6
-4
-2
0
2
4
6



2cm/s
T, K
800 900 1000 1100 1200 1300 1400
ṁ_O , g/cm²s
3.4E-05 1.0E-04 1.7E-04 2.4E-04 3.1E-04



5.2E-05 1.6E-04 2.6E-04 3.6E-04 4.7E-04 5.7E-04 6.8E-04 7.8E-04
300 400 500 600 700 800 900 1000 1100 1200 1300 1400
z, height above paper, cm
2
1
0
-1
-2
4 3 2 1 0 -1 -2 -3 -4 -5
x, distance along paper, cm