# UPWARD AND DOWNWARD FLAME SPREADING AND EXTINCTION IN PARTIAL GRAVITY ENVIRONMENTS

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## INTRODUCTION

The premise of this research effort has been to begin exploring the gap in the literature between studies of material flammability and flame spread phenomena in normal-gravity and those conducted in the microgravity environment, with or without forced flows. From a fundamental point of view, flame spreading in upward (concurrent) buoyant flow is considerably different from concurrent forced flow. The flow accelerates throughout the length of the buoyant flame bringing the streamlines and the flame closer to the fuel surface and strengthening the interaction between the flame and fuel. Forced flows are diverted around the flame and away from the fuel surface, except where the flow might be constrained by a finite duct. The differences may be most clearly felt as the atmospheric conditions, viz. pressure or oxygen content, approach the flammability limit. From a more practical point of view, flame spreading and material flammability behavior have not been studied under the partial gravity conditions that are the natural state in space exploration destinations such as the Moon and Mars. This effort constitutes the beginning of the research needed to engineer fire safety provisions for such future missions.

In this program we have performed partial-gravity experiments (from 0.1 to 1 $g/g_{Earth}$) considering both upward and downward flame spread over thin solid fuels aboard the NASA KC-135 aircraft. In those tests, the atmospheric pressure and the fuel sample width were varied. Steady flame spread rates and approximate extinction boundaries were determined. Flame images were recorded using video cameras and two-dimensional fuel surface temperature distributions were determined using an IR camera. These results are available in [1 – 3], and complement our earlier work in downward spread in partial gravity varying oxygen content [4].

In conjunction with the experiment, three-dimensional models of flame spreading in buoyant flow have been developed. Some of the computed results on upward spreading have been presented in [3]. A derivative three-dimensional model of downward spreading has been developed [5]. It is currently being used to evaluate the standard limiting oxygen index (LOI) measuring device and its potential performance in different gravity levels.

Since radiation plays an important role in flames at low gravity, considerable effort has been spent on flame and surface radiation on spreading flames. A theoretical study using a two-dimensional model with gas-phase radiation compared flame spread in concurrent and opposed flows and clarified a number of questions in low-speed flows. In forced flow, concurrent flame spread rate is approximately proportional to upstream velocity (similar to the gravity dependence

in buoyant case) but opposed flame spread rate is non-monotonic. While at most forced flow velocities, spread rates are generally higher in concurrent flow than in opposed flow, the curves can cross at very low forced velocity. However, the lowest flammable oxygen percentage is always in the concurrent flow case. [6]

In this paper we wish to show a comparison of upward and downward flame spread in partial gravity tests, show some numerical simulation results from opposed flow spreading in mixed convection flow and indicate some conclusions with respect to flame spread behavior in the partial gravity environment.

## EXPERIMENTS

Upward and downward flame spreading was observed in reduced-pressure air environments in normal-gravity and in partial-gravity environments using the GIFFTS test apparatus [1-4] with slight modifications. Fuel samples were a thin cellulosic tissue, trade name "Kimwipes." A repeatable pre-test sample-drying procedure was developed using a hot-air gun. Test pressures between 0.2-0.4 atmospheres were established using primary standard, precision mixtures of 21% $O_2$, balance $N_2$. Flight tests were performed onboard the NASA KC-135 aircraft providing partial-gravity environments of 0.1, 0.16, and 0.38 $g/g_{Earth}$. Limited tests were conducted at greater than 1.0 $g/g_{Earth}$. Chamber pressure and 3-axis accelerations were recorded by the GIFFTS computer. Conventional video and a FSI Inc. Prism DS infra-red camera with a flame filter at 3.8μm (to reject emissions from excited $H_2O$, $CO_2$) were used to image the solid surface. The IR camera signal is calibrated to a black body emission; quantitative temperature measurements require the surface emissivity properties within the filter pass band. We have been developing methods for determining surface emittance from a burning surface [7, 8].

Figure 1 shows an example of flame spread rates versus the local gravity level for 2 cm wide Kimwipes burning in air at a reduced pressure of 27.6 kPa. The upward burning spread rate varied linearly with gravity level for all pressure environments and sample widths tested (the inset shows data or 1 cm sample width), which has been predicted in scaling analysis [9]. The primary heat transfer mechanism for upward spread is buoyant convection, which increases with gravity. The measured pyrolysis lengths also increase proportionally with gravity. The three dimensional model predicts nearly linear spread rate dependence on gravity, as shown, for example, by the open symbols in the figure.

The downward spread rate is non-monotonic and peaks near the Martian gravity levels of 0.38 $g/g_{Earth}$. The reductions from the peak are attributed to finite kinetic effects: a short residence time at high gravity, and
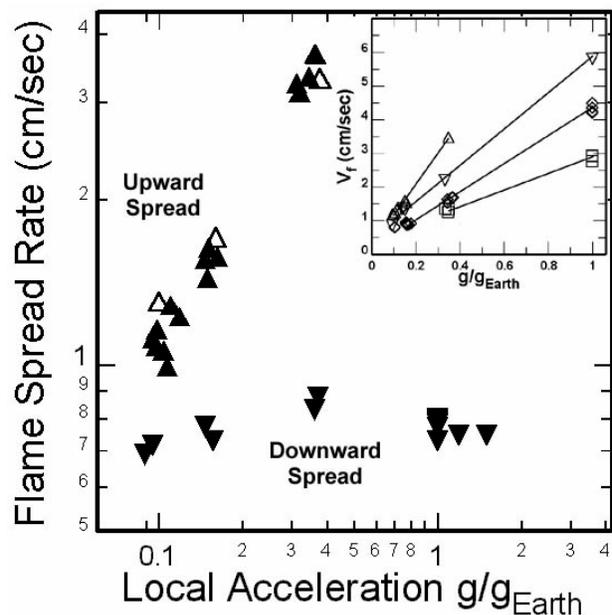


Figure 1. Upward and downward flame spread rates for 2 cm wide samples burned in 27.6 kPa (4.0 psia) air at various gravity levels. Upward pointing symbols indicate upward spread; downward pointing symbols, downward spread. Open symbols indicate results of numerical simulations of flame spread. The inset shows results for 1 cm wide samples.

radiative loss at low gravity. This spread rate behavior is qualitatively similar to composite observations of forced flow spreading. Here a single fuel, test apparatus and testing environment provide an unambiguous demonstration of the behavior.

Within the gravity levels tested, the upward spread rates are everywhere larger than the downward rates. If the upward and downward spread rates were extrapolated to lower gravity levels, a merging or crossover would occur. While this possibility has not been confirmed by experiment, the forced flow analog has been predicted [6].

Figure 2 shows flammability boundaries for flame spreading upward or downward over 2 cm wide Kimwipes burning in air. Elevated gravity levels ($>1g/g_{Earth}$) were obtained by testing during the aircraft pull-up maneuver. The downward spreading boundary is U-shaped showing the dual extinction limits (insufficient residence time in high g, radiative loss in low g) now predicted by several diffusion flame models.
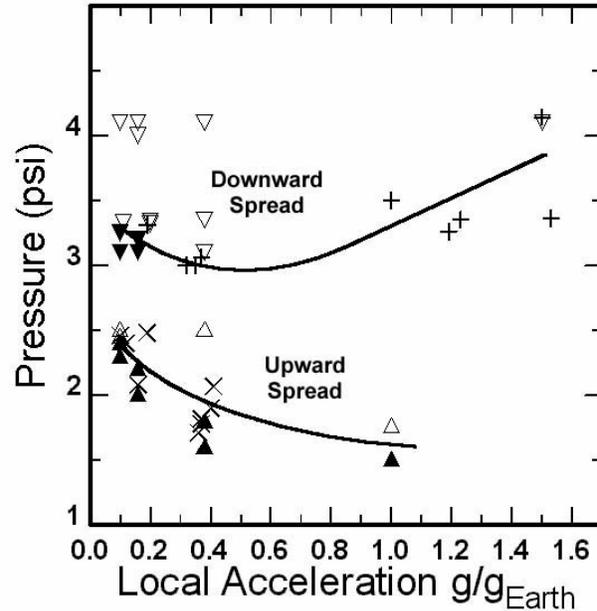


Figure 2. Flammability boundaries for upward and downward spreading flames over 2 cm wide samples. Open and closed symbols indicate flammable and non-flammable conditions respectively. Crosses indicate observed extinctions occurring well after ignition. Downward pointing symbols indicate downward spread, upward pointing indicates upward spread.

The upward spreading case has a wider flammable domain that the downward case. In the upward case, tests at elevated gravity were not feasible in the current apparatus because of size limitations. The flammable domain shrinks as the sample width is reduced from 2 cm to 1 cm as expected. For both the concurrent flow (upward spread) and opposed flow (downward spread) cases, the stabilization of the flame, and therefore the flammability of the material, is established at the base of the flame where it first encounters the fresh oxidizer flow. In the upward case the flame is stabilized where the fuel burnout occurs while in the downward case the flame is stabilized where the fuel is preheated to the pyrolysis temperature. Differing thermal demands on the flame stabilization zone lead to different limiting conditions.

## THREE-DIMENSIONAL MODELING OF DOWNWARD SPREADING FLAMES

In additional to the 3-D model of steady upward spreading flames, 3-D downward spread in a mixed forced and buoyant flow was recently simulated numerically for a flow in a duct that resembles the standard limiting oxygen index (LOI) apparatus [5]. In this study, the limiting oxygen mole fractions were determined as functions of sample width, tunnel width, sample holder configuration, forced velocity and gravity level. A cotton fiberglass composite fuel was simulated. The detailed flame structure and the flow field in the duct were resolved. Fig. 3 shows a computed LOI as a function of forced flow velocity at normal and zero gravity. The normal gravity boundary is monotonic with respect to the forced velocity while the LOI at zero gravity is non-monotonic and has a minimum around 5 cm/s. The LOI at normal gravity are higher than those at zero gravity for the range of forced velocity computed.
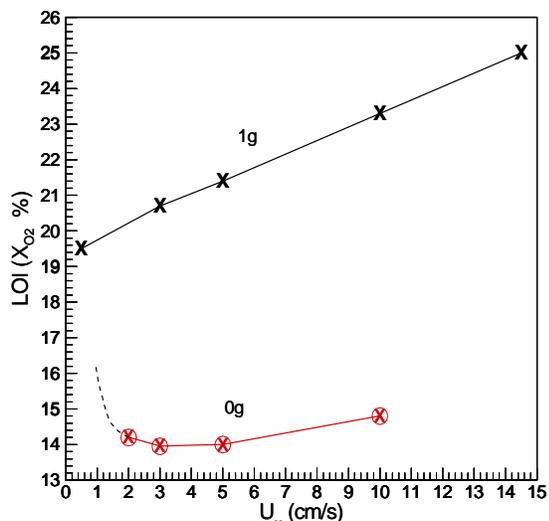
Figure 3. Limiting Oxygen Index (LOI) prediction for cotton/ fiberglass fuel in a mixed-convection environment, computed using a three dimensional model with as-yet uncalibrated kinetic constants. Fuel samples are 5 cm wide by 15 cm long burning in a vertical flow tunnel with a 10cm by 10cm cross section and 50 cm length. The flame location is fixed at the middle of the tunnel. A uniform forced flow is introduced from the tunnel bottom. The upper end of the tunnel is open to 21% air. The sample has inert side stripes 6 mm wide on each side. The symbols are the computed LOI. The last point in the 1g data (i.e. at 0.5 cm/s) is affected by the flow entrained from the atmosphere at the top of the tunnel. The dotted line in the zero-gravity result is what we expect from future computations at lower velocities (based on 2-D results).

## CONCLUSIONS

This exploratory study of flame spreading and material flammability in partial gravity environments provides some practical results that require further study. Upward flame spread rates are proportional to gravity level, the downward case is non-monotonic. Over the partial gravity range accessible to testing, flames spread more quickly in the upward than the downward direction, and the flammable domain of upward spreading is wider than for downward spreading.

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