The Effect of Velocity on the Extinction Behavior of a Diffusion Flame during Transient Depressurization

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INTRODUCTION

Current fire suppression plans for the International Space Station include the use of venting (depressurization) as a method for extinguishing a fire [1]. Until recently this process had only been examined as part of a material flammability experiment performed on Skylab in the early 1970's [2]. Due to the low initial pressure (0.35 Atm) and high oxygen concentration (65%), the Skylab experimental results are not applicable for understanding the effects of venting on a fire in a space station environment (21% O_2, 1 Atm). Recent research by Goldmeer, Urban and T'ien [3] examined the extinction behavior of a diffusion flame over a polymethyl methacrylate (PMMA) cylinder during a transient depressurization in low-gravity. This study utilized low-gravity experiments performed on NASA's Reduced-gravity Research Aircraft Laboratory and numerical simulations to examine conditions applicable to the Space Station environment. The numerical model, based upon the work of Yang and T'ien [4], was used to examine extinction limits as a function of depressurization rate, forced flow velocity, and initial solid phase temperature. The experimental and numerically predicted extinction data indicated that as the solid phase temperature increased the pressure required to extinguish the flame decreased. The numerical model was also used to examine conditions not obtainable in the low-gravity experiments. From these simulations, a series of extinction boundaries were generated that showed a region of increased flammability existed at a forced flow of 10 cm/s. Analysis of these extinction boundaries indicated that they were quasi-steady in nature, and that the final extinction conditions were independent of the transient process. The velocity range in the previous study was limited and thus the results did not examine the effects of velocities less than 1 cm/s or greater than 20 cm/s.

This paper extends the analysis of the previous study [3] to a comprehensive examination of the effect of increased velocity on extinction behavior and extinction limits during a transient depressurization in low-gravity. This is achieved by examining extinction data from buoyant (normal-gravity) and low-buoyant (low-gravity) depressurization experiments, as well as from numerical predictions of flame behavior during depressurization in a non-buoyant (zero-gravity) environment.

EXPERIMENTAL SETUP

The fuel samples were solid circular PMMA cylinders with a 1.9 cm diameter and a length of 2.5 cm. Steel disks were placed at the ends of the cylinders to limit three-dimensional effects. A type K thermocouple inserted along the axis of the PMMA cylinders measured the solid phase centerline temperature to ±0.75%. The fuel samples were mounted in a combustion chamber in which a constant forced air flow velocity was maintained during each experiment; the fuel cylinder's axis was mounted perpendicular to this forced flow. The low-gravity experiments were performed on the NASA Reduced-gravity Aircraft Laboratory (DC-9) [5]. During each test the sample was ignited at a pressure of 1.0 Atm and the chamber pressure was reduced until the flame extinguished. Acceleration levels, chamber pressure, air flow rates, solid phase centerline temperature, and video images of the flame (both radial and axial views) were recorded. A more detailed description of the experimental hardware and procedures can be found in References [3] and [6].

NUMERICAL MODEL

A transient two-dimensional numerical model that consisted of a quasi-steady gas phase coupled to an unsteady solid phase was used to examine a diffusion flame over a solid PMMA cylinder in a constant, low-speed

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flow during depressurization in a non-buoyant (zero-gravity) environment. The quasi-steady gas formulation was adopted from Yang and T'ien [4]. The gas phase was assumed to be quasi-steady based on a short gas residence time (~ 1 sec) as compared with the depressurization time scale (~ 60 sec) and the solid phase thermal conduction time (~ 350 sec). The gas phase model employed two-dimensional continuity, momentum, energy and species equations, assumed constant Lewis and Prandlt numbers, and assumed that the gas phase chemical reaction was single step and second order. A two-dimensional heat conduction model that included the effects of surface regression was used to model the solid phase [3,6]. The coupled gas/solid phase system employed an energy balance at the gas/solid interface that included conductive heat transfer to the solid (from the gas phase), surface radiation, fuel vaporization, and the conductive flux into the solid. The model was validated by comparing numerical and experimental extinction data. A full description of the model can be found in References [3] and [6].

EFFECT OF VELOCITY ON THE EXTINCTION LIMITS

To provide a comprehensive examination of the effect of velocity on extinction behavior and extinction limits during depressurization in zero-gravity, the velocity range of the parametric study in Ref. [3] is extended to lower (0.5 cm/s) and higher (50 cm/s) values. The extinction predictions from the previous study are combined with the new predictions (Figure 1). In these plots, the extinction conditions are defined by the solid phase centerline temperature and chamber pressure at extinction. A typical solid phase centerline temperature - pressure trajectory is shown in the plot for a 40 cm/s forced flow. (During the transient simulation, the chamber pressure decreases to simulate the depressurization process and the solid phase temperature increases as it is heated by the flame.)

These extinction plots show that at constant velocity, the extinction pressure decreases as the solid phase temperature increases. As illustrated in the figure, the lowest extinction pressure occurs at a forced velocity of 10 cm/s. Thus, a velocity of 10 cm/s is a condition of increased flammability. The numerical predictions also show that the mode of extinction changes with velocity. At velocities less than 30 cm/s only two modes are shown: the envelope flame or complete extinction. At velocities greater than, or equal to 30 cm/s, the flame transitions from an envelope flame to a wake flame and then completely extinguishes as the pressure decreases. The predicted flame shapes, as visualized by the reaction rate contours, and the flow streamlines for the envelope and wake flames are shown in Figure 2. Figure 2A shows the flow vortex in the cylinder's wake; although not shown by the streamlines in Figure 2B, there is a local region with a low velocity (nearing separation) directly behind the cylinder.

Wake flames were not observed in the low-gravity experiments at a forced velocity of 10 cm/s forced flow. In these experiments the envelope flame extinguishes as the pressure decreases as shown in Figure 3. This extinction behavior is predicted by the numerical model and shown by the extinction boundary in Figure 1. How-

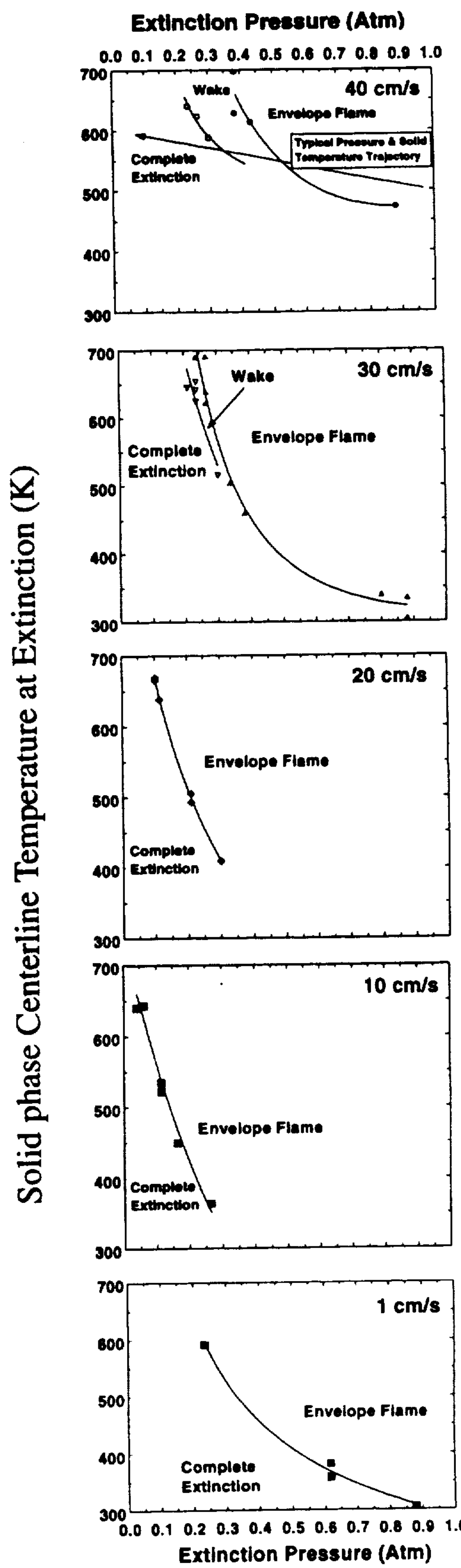

Figure 1
Numerically Predicted Extinction Boundaries at Constant Forced Velocity

ever, wake flames were observed in similar normal-gravity (mixed convective) experiments. In these experiments the envelope flame transitions into a wake flame as the pressure decreases (Figure 4). As the pressure continues to decrease the wake flame extinguishes. The extinction boundary for the normal-gravity experiments, as shown in Figure 5, has the same form as the higher velocity numerical predictions (Figure 1).

The new numerical predictions also indicate that combustion is not sustainable at velocities ≤ 0.5 cm/s, or ≥ 50 cm/s. This prediction of no sustained combustion even occurs with a highly elevated solid phase temperature profile, as indicated by a solid centerline temperature (595 K), at the start of depressurization.

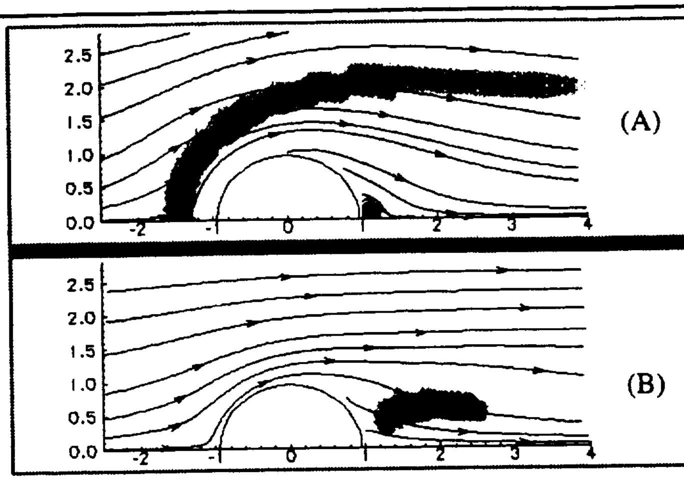

Figure 2
Numerically Predicted Fuel Reaction Rate Contours and Flow Streamlines During Depressurization

Forced flow velocity = 30 cm/s

(A) P = 0.267 Atm; Envelope Flame (with vortex flow)

(B) P = 0.23 Atm; Wake Flame

DISCUSSION

The numerical model predicts the formation of a wake flame at higher velocities during the extinction process. The presence (or absence) of a wake flame results from a coupling of hydrodynamic and combustion effects. As the forced velocity increases a recirculating region forms downstream of the cylinder (Figure 2A). Additionally, as the magnitude of the forced flow increases, the forward stagnation point flame stand-off distance and width decrease [6], increasing the conductive heat transport to the condensed phase. This results in higher surface temperatures and higher mass burning rates at the rear of the cylinder in comparison to the lower velocity cases as shown in Figure 6. In this plot the predicted surface temperatures and mass burning rates for two cases (U = 10 and 30 cm/s) are shown as a function of the angular position along the surface of the cylinder. The burning rates are computed from the surface temperature using an Arrhenius expression. An angular position of 0 degrees is at the forward stagnation point (FSP) of the cylinder. The predicted data in both cases is from a quasi-steady numerical gas phase step with an envelope flame just prior to reaching the local (forward stagnation point) extinction limit. This figure shows that at the higher velocity the surface temperatures, and hence the burning rates, are larger than at the lower velocity. This increase in the mass burning rate is critical for the presence of a wake flame.

This study also has implications for fire suppression procedures on the International Space Station. Once the

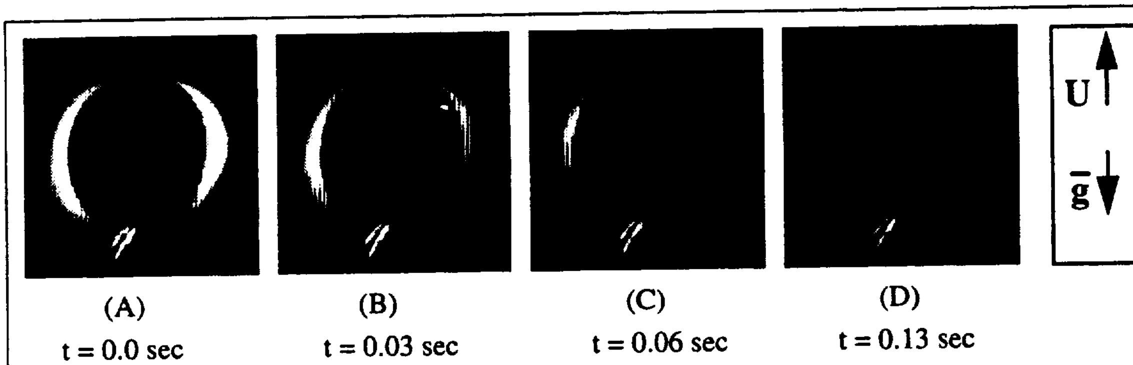

Figure 3
Extinction in low-gravity with a forced flow of 10 cm/s
P = 0.242 Atm; solid phase centerline temperature = 326 K

(The glow at the bottom of each image is the ignitor wire that is heated by the flame.)

decision has been made to depressurize, the pressure in the affected module should be decreased quickly. Flames in high velocity regions will be extinguished, even if the material has been heated. Flames in low flow areas, or in recirculating flow regions present a more important suppression problem. If the module is depressurized too slowly, the fuel material(s) will be allowed to heat up, further decreasing the required extinction pressure. If the final pressure is not low enough, the flames will continue to burn (after depressurization) until near quiescent flow conditions are obtained. Thus, depressurization should be done rapidly and to a low pressure to avoid additional increases in the solid temperature, and to ensure that the flame will be extinguished.

Future work with the numerical model will include a more detailed examination of the structure and behavior of the wake flame including the coupling of the hydrodynamic and combustion processes.

ACKNOWLEDGMENTS

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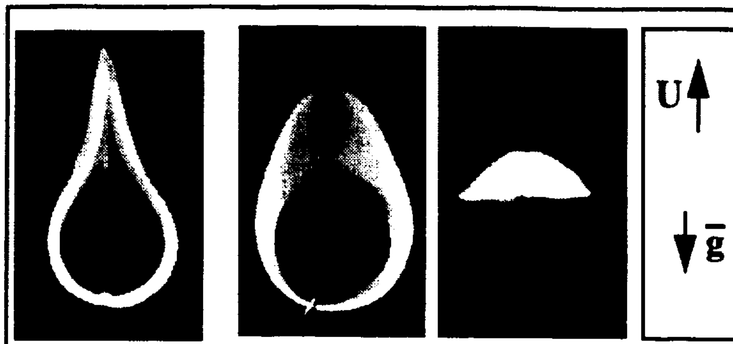

(A) P = 0.98 Atm T(r=0) = 307 K

(B) P = 0.11 Atm T(r=0) = 510 K

(C) P = 0.07 Atm T(r=0) = 526 K

Figure 4
Normal-gravity extinction process with a forced flow of flow of 10 cm/s.
(The white glow at the forward stagnation point is the ignitor wire which is heated by the flame.)

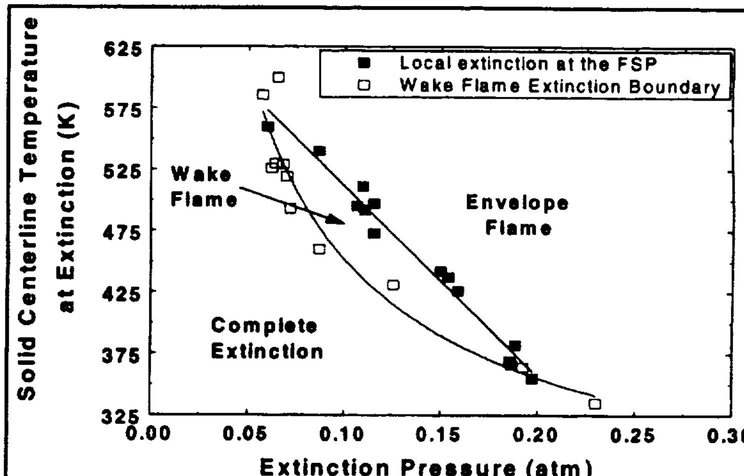

Figure 5
Normal-gravity Experimental Extinction Boundary with a forced flow of 10 cm/s

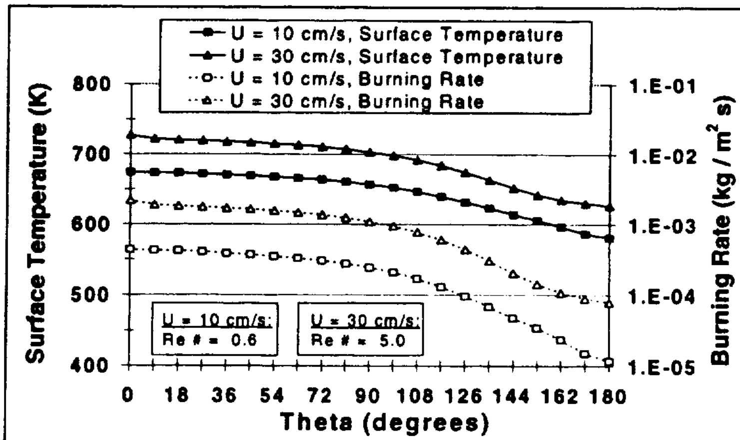

Figure 6
Effect of Forced Velocity on the Surface Temperature and Burning Rate Distribution