

EXTINGUISHMENT OF A DIFFUSION FLAME OVER A PMMA CYLINDER BY DEPRESSURIZATION IN LOW-GRAVITY

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Introduction

The behavior of flames in low-speed flows in low-gravity is relevant to spacecraft fire safety [1]. Previous work [2-5] has shown that flames in the presence of low-speed forced flows in low-gravity may be more flammable than in a forced flow of the same magnitude in normal gravity. Additionally, fire suppression plans for the International Space Station include the use of venting (depressurization) as an emergency option for extinguishing fires [6]. This procedure would induce flows in the affected compartment that could temporarily intensify the fire, as was observed in flammability tests of solids conducted on board Skylab [7]. Despite a general understanding, current knowledge of the combined effects of reduced pressure and forced flow on a burning solid in low-gravity is inadequate for the design of a venting extinguishment system.

Previous studies in low-g have examined flammability limits for thermally thin solids [3-5]. However, there are differences when burning thick materials because the interior solid-phase temperature continuously changes, which affects the percentage of gas-phase heat feedback to the solid-phase. Changes in the heat feedback to the solid-phase can affect the flammability characteristics of the material [2]. In the current work, the extinction of a diffusion flame burning over PMMA (polymethyl methacrylate) cylinders during depressurization with a low-speed cross flow was examined experimentally and via numerical simulations.

Experimental Hardware & Procedures

Solid PMMA cylinders that were placed perpendicular to the forced flow were selected as the sample geometry as two distinct flow regions exist when a cylinder is placed in a cross-flow: a forward stagnation region and a wake region. The PMMA cylinders were 1.9 cm in diameter and 2.5 cm in length and steel washers were placed at the ends of the samples to limit burning along the ends of the cylinders. The experiments were conducted on board the NASA Lewis Research Center's reduced-gravity aircraft that provides twenty second periods of low-gravity (± 0.01 g's) [8]. The samples were ignited by a resistively heated wire before entering low-g at one atmosphere; the chamber pressure was reduced to the test condition during low-g. The samples were ignited during the normal-gravity portion of the flight trajectory because the time required to establish the flame was longer than the entire low-g period. To determine the low-pressure extinction limit the chamber pressure was reduced at a rate of 0.24 atm/minute from the initial low-g test pressure until the flame extinguished. During each experiment the acceleration levels, chamber pressure, solid-phase centerline temperature, and video images of the flame (both radial and axial views) were recorded.

Experimental Results

The experiments examined the low-pressure extinction limit in air as a function of pressure and solid-phase centerline temperature at a constant velocity of ten cm/s. The low-pressure limit could not be reached with flow velocities larger than ten cm/s due to limitations of the vacuum system. Limited extinction data was collected at five cm/s due to the effects of g-jitter, which is a perturbation of the acceleration level. In the cases in which extinction occurred, the acceleration data was examined to determine if extinction was caused by g-jitter or the reduction in pressure. In cases in which there was no g-jitter and the flame extinguished, extinction occurred by one of two modes: quench or blow-off. Quenching extinction was observed when the flame tips receded toward the forward stagnation point (FSP) and the flame continued to shrink until it extinguished. Quenching extinction occurred in tests with a centerline temperature less than 320 K. Blow-off extinction was attributed to cases in which the flame was carried downstream by the forced flow as illustrated by the time sequence of images shown in Figure 1. The white streaks at the bottom of each image are the ignitor wire heated by the flame.

A flammability map was created using the experimental extinction pressure and solid-phase centerline temperature data at extinction (Figure 2). Experimentally, the cylinders supported a flame to the right of the boundary. No flames were observed at conditions to the left of the extinction data. As expected, the experimental results indicate that a hotter material requires a lower pressure to

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extinguish. As the solid-phase centerline temperature increases, the extinction pressure decreases, and with a centerline temperature of 525 K, the flame is sustained to a pressure of 0.1 atm before extinguishing. At pressures above 0.3 atm the flame did not extinguish. The error bar on the boundary represents the scatter in the data that could have been caused by variations in the magnitude and duration of the high-gravity portion of the trajectory, or the transition from normal-gravity to low-gravity. One of the limitations of the experiments was the small size of the PMMA cylinders. The sample length and diameter were nearly equal, and because of this, the experimental configuration was not completely two-dimensional; there were axial heat losses from the sample, and the flame shape exhibited some three-dimensional effects.

Numerical Model & Simulations Procedures

The numerical simulation used in this research iteratively couples a two-dimensional quasi-steady gas-phase model [2] with a two-dimensional transient solid-phase model [9]. The gas-phase model includes Navier-Stokes, continuity, energy and species equations with a one-step second order overall chemical reaction and Arrhenius kinetics. This model does not include gas-phase radiation; it assumes an infinite cylinder, and the computational domain has a streamwise symmetry boundary condition two diameters from the centerline. The solid-phase model includes conductive heat transfer within the solid and surface regression due to vaporization. The energy balance at the gas/solid phase interface is given by:

$$\lambda_G \frac{\partial T}{\partial n}|_G = \lambda_S \frac{\partial T}{\partial n}|_S + \dot{m} L + Q_{RAD} \quad (1)$$

in which λ_S and λ_G are the solid-phase and the gas-phase thermal conductivities, n is the surface normal, $\dot{m}$ is the vaporization rate, L is the heat of vaporization, and Q_{RAD} is surface radiation. The ratio of the solid-phase and gas-phase conduction terms in the energy balance is defined as Φ , which can be written as:

$$\Phi = \frac{\lambda_S (\partial T / \partial n)_S}{\lambda_G (\partial T / \partial n)_G} = 1 - \frac{\dot{m} L + Q_{RAD}}{\lambda_G (\partial T / \partial n)_G} \quad (2)$$

This ratio varies in time and along the circumference of the cylinder. Experimentally, the status of the flame at the forward stagnation point (FSP) was critical to sustained combustion. In quenching extinction the flame at the FSP was the last to extinguish; if the flame at the FSP was locally extinguished, the remaining portions of the flame followed quickly (blow-off). No wake flames were observed in the present low-g experiments. Thus, the value of Φ at the forward stagnation point (Φ_{FSP}) is used in evaluating the simulation results. The computed Φ_{FSP} and the centerline temperature as a function of time are shown in Figure 3 together with the experimentally measured centerline temperatures. (The different symbols for the experimental centerline temperature represent different cases with different final pressures.) Since there is a one-to-one correspondence between Φ_{FSP} and the centerline temperature, the measured centerline temperature can be used to infer Φ_{FSP} , which is an important parameter in the quasi-steady gas flame model. High values of Φ_{FSP} (near 0.9) occur at ignition and Φ_{FSP} decreases as the gas-phase heats the solid-phase (Figure 3). The small discrepancy between the experimental temperature data and the model's predictions may be due to experimental axial heat losses that are not included in the model.

The simulations start with the solid-phase model mimicking the transient heat-up process during ignition and flame spread [9]. Using the experimental data as a guide, the solid-phase simulation generates the surface boundary condition needed to couple with the gas-phase flame equations. The coupled system of unsteady solid equations and quasi-steady gas-phase equations are then used to model the flame behavior as the pressure is reduced. Two sets of simulations have been made; in the first set, the simulation parameters are selected to mimic the experimental conditions. In the second set, parameter values that could not be examined experimentally were simulated. The coupled model is run until the flame extinguishes.

Numerical Results

Initial simulations examined conditions similar to the present low-gravity experiments. The predicted flame behavior during depressurization and extinction, which is similar to the experimental flame behavior, can be visualized with fuel reaction rate contours from a single case (Figures 4 and 5). The images in Figure 4 are predicted quasi-steady flames during depressurization. The stand-off distance, which is defined as the distance from the surface of the cylinder to the middle of the maximum fuel reaction rate contour, is predicted to increase as the pressure decreases; this effect was also observed in the low-g experiments. The predicted blow-off extinction process for this case is shown in Figure 5; image (A) is at the identical conditions as image (F) in Figure 4 and images (B) - (E) are at the next step in the model's coupling process that occurs with a lower pressure and a decrease in Φ_{FSP} . Images (A) and (E) in Figure 5 are quasi-steady predictions while images (B) - (D) are intermediate gas-phase steps. The ability to use the intermediate steps from the gas-phase model as representations of a transient process is possible because the convergence routine uses a fictitious time marching term [9]. During the extinction process, the predicted reaction rate contours behave similarly to the experimental flame extinction process (Figure 1); the experimental flame and the predicted contours detach from the forward stagnation point and are carried downstream by the forced flow. Table 1 summarizes model parameters and outputs for the simulation case illustrated in Figures 4 and 5.

The simulation predicts low-pressure extinction limits consistent with the experimental limits (Figure 6). In this figure, the extinction pressure is expressed as a function of Φ_{FSP} . The experimental value of Φ_{FSP} is deduced from the centerline temperature data (Figure 3). The error bars in Figure 6 represent the possible range of Φ_{FSP} due to the difference between the predicted centerline temperature and the experimental data.

Additional simulations examine conditions that could not be investigated experimentally due to limitations of the hardware and test facilities. These simulations examine the effects of flow velocities, ranging from one to twenty cm/s, which is important as the induced velocity in the space station module would be a function of location relative to the vent valve. These additional simulations also examine the effects of increases in the solid-phase temperatures (decreases in Φ) before depressurization, which is relevant to the space station procedure as the elapsed time between the detection of a fire and the start of depressurization cannot be predetermined. Thirdly, the additional simulations examine depressurization rates lower than the present experimental rate (slower depressurization), which includes the proposed space station venting scenario, which is an order of magnitude slower than that of the present experiments.

The effect of velocity on the extinction limit is not monotonic. At values of constant Φ_{FSP} , flames are sustained to lower pressures at ten cm/s than at one or twenty cm/s (Figure 7); the region above each constant velocity curve is the flammable domain. At constant velocity, flames are sustained as the pressure decreases if Φ_{FSP} decreases, which is equivalent to increases in the solid-phase temperature (Figure 8). A negative value of Φ_{FSP} indicates that the temperature gradient within the solid is reversed; the hot solid conducts heat to the surface to compensate for the decrease in heat feedback from the flame that occurs because the reaction rate decreases with pressure [9]. This reversal in Φ_{FSP} occurs in simulations in with a long depressurization time, or a long period of burning before depressurization.

Increasing the solid-phase temperature (decreasing Φ) by either a longer period of burning before depressurization, or an increase in the depressurization time, decreases the extinction pressure. The model predicts blow-off extinction at velocities greater than fifteen cm/s and quenching at velocities less than eight cm/s. Additionally, the simulations predict that the path taken to the extinction boundary is not critical; extinction will occur at the boundary whatever the path taken (assuming a quasi-steady gas-phase process).

Conclusions

The degree of heat up in a thick solid material affects the low-pressure extinction limits in low-gravity. The relevant solid-phase parameter is Φ , which is the ratio of solid-phase to gas-phase conduction at the gas-solid interface. The solid-phase temperature increases during combustion, Φ decreases and the extinction pressure decreases. The low-pressure limit is also affected by the presence of a forced flow; a condition of increased flammability occurs at velocities of eight to ten cm/s. This is also the critical velocity dividing two different extinction modes: quenching extinction occurs at lower velocities and blow-off at higher velocities.

The results of this research could be used to refine the International Space Station's venting specifications, which state that the affected module would be depressurized from 1.0 atm to 0.3 atm within a period of ten minutes [4]. This research suggests that an effective venting procedure would be to quickly depressurize the module to a pressure of 0.1 atm, which would probably extinguish the fire. Rapid venting to the final pressure would limit additional heating of the solid-phase that would otherwise cause a decrease in the extinction pressure. The disadvantage to rapid venting is that it could cause the flame to intensify, as documented in the Skylab experiments [7]. The current simulations indicate that the flame might temporarily intensify if there was an increase in the forced flow, but the increases in the gas-phase temperatures and reaction rates quickly disappear as the pressure decreases.

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Time (sec)	Caption legend	Pressure (atm)	Re_D	Φ_{FSP}	Maximum T_{GAS} (K)	Solid-phase Centerline Temperature (K)	Stand-off distance (cm)
6	Fig 4 - (A)	0.880	3.84	0.290	2194	406	0.61
24	Fig 4 - (B)	0.610	2.68	0.256	2194	431	0.73
42	Fig 4 - (C)	0.430	1.87	0.238	2155	453	0.95
60	Fig 4 - (D)	0.300	1.30	0.221	2161	474	1.14
78	Fig 4 - (E)	0.210	0.20	0.204	2114	494	1.24
102	Fig 4 - (F) Fig 5 - (A)	0.130	0.56	0.175	1981	517	1.32
108	Fig 5 - (E)	0.115	0.50	0.150	513	522	No Flame

Table 1
Summary of predicted flame behavior during depressurization ($U_{FORCED} = 10$ cm/s)

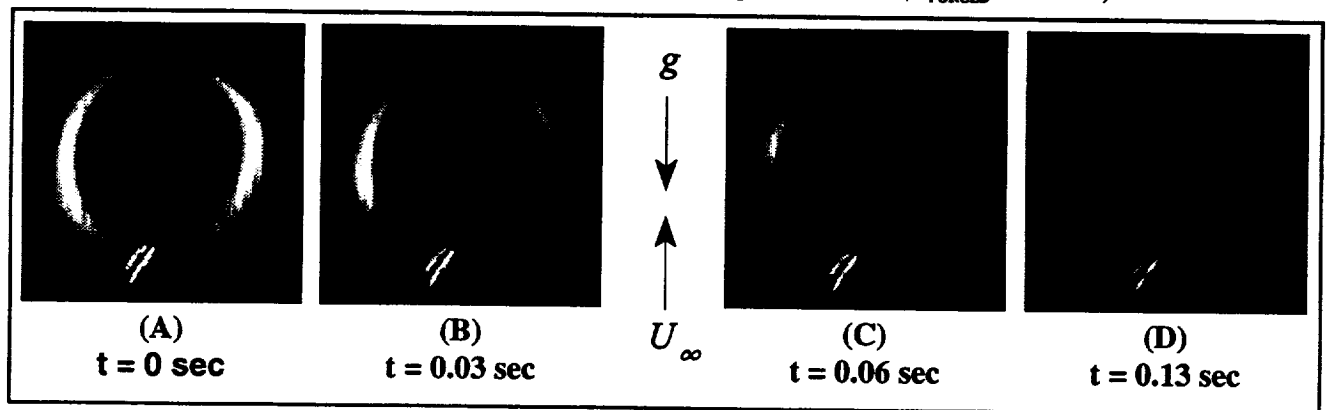


Figure 1
Blow-off extinction in low-gravity
($P = 0.242$ Atm; $U_{FORCED} = 10$ cm/sec; $T(r=0) = 326$ K)
Z-Axis acceleration was approximately zero-g (± 5 milli-g's)

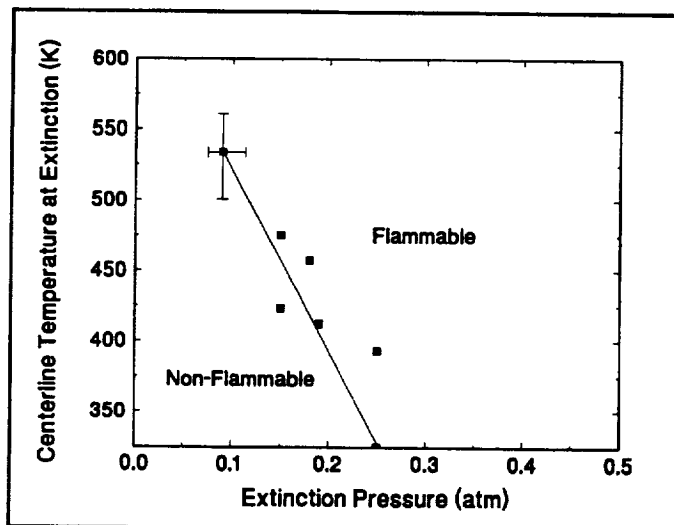


Figure 2
Experimental extinction boundary at constant velocity
($U_{FORCED} = 10$ cm/s)

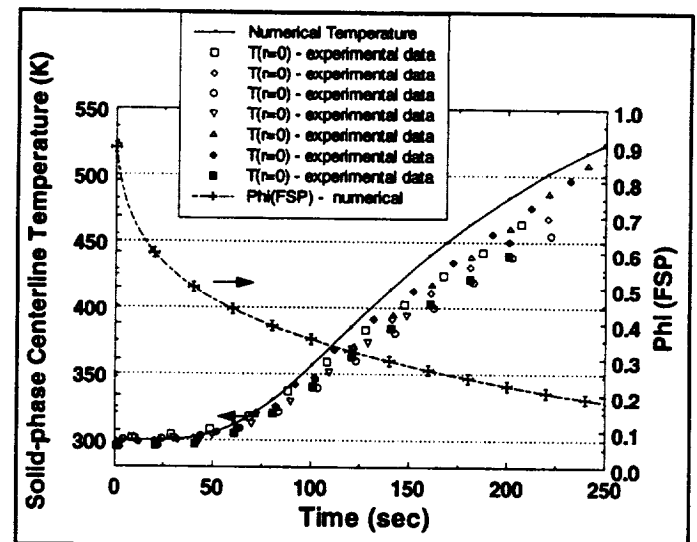


Figure 3
Comparison of experimental and numerical solid-phase centerline temperature and computed values of Φ_{FSP}

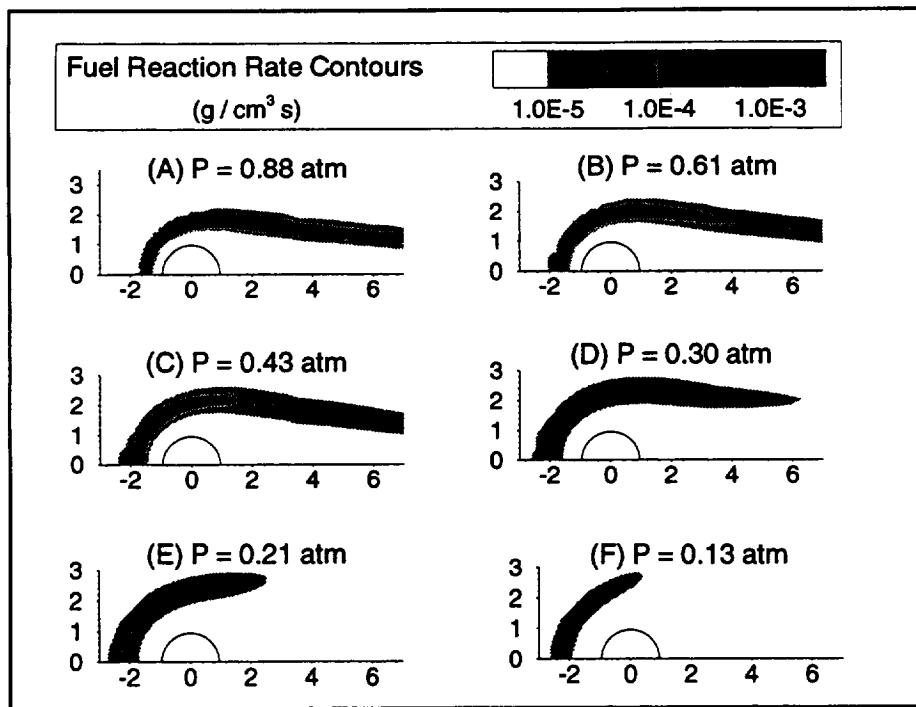


Figure 4

Predicted fuel reaction rate contours during depressurization with $U_{\infty} = 10$ cm/s
(dimensions in cm)

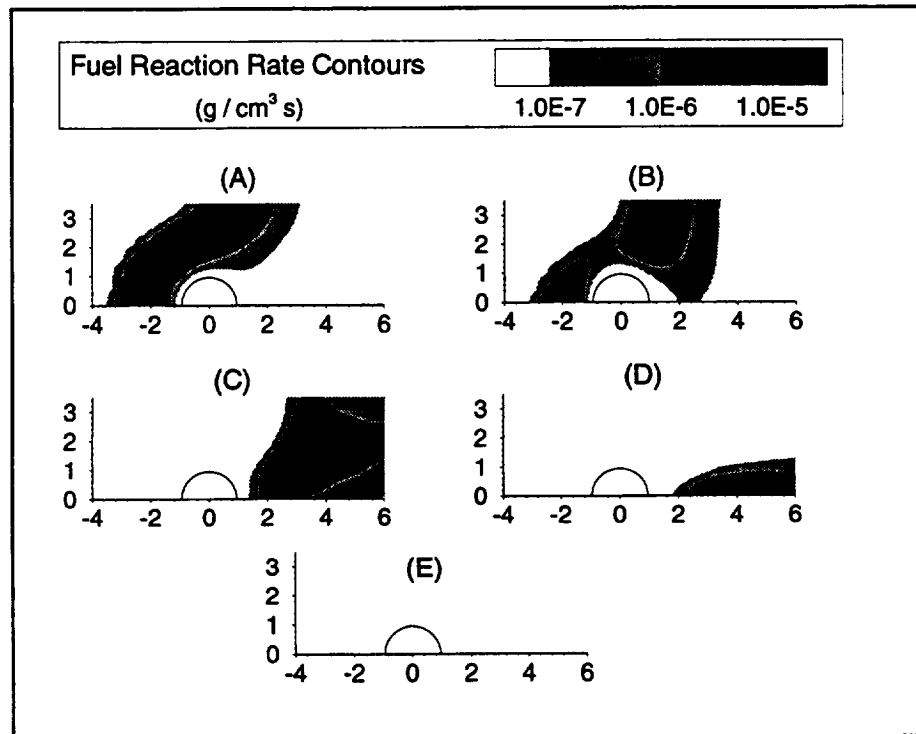


Figure 5

Predicted reaction rate contours during blow-off extinction with $U_{\infty} = 10$ cm/s

(A): $P = 0.13$ atm, and $\Phi_{FSP} = 0.175$

(B) - (E): $P = 0.115$ atm, and $\Phi_{FSP} = 0.15$

Images (A) and (E) are quasi-steady solutions to the gas-phase model

Images (B) - (D) are intermediate gas-phase steps

(all dimensions in cm)

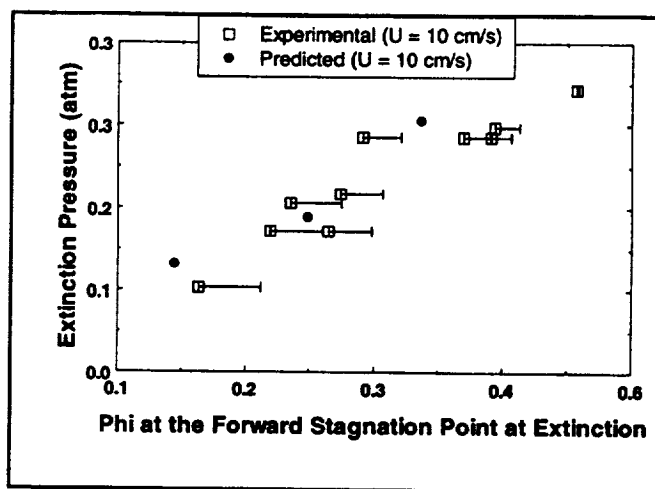


Figure 6
Comparison of experimental and predicted extinction boundaries at 10 cm/s

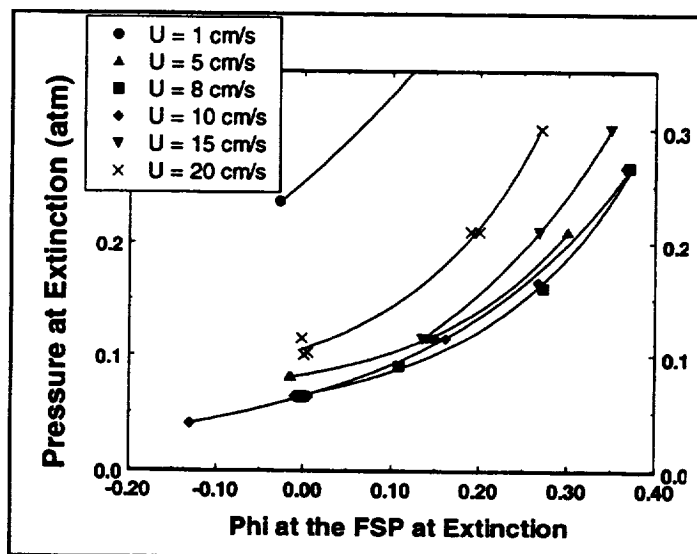


Figure 7
Predicted extinction boundaries at constant velocity

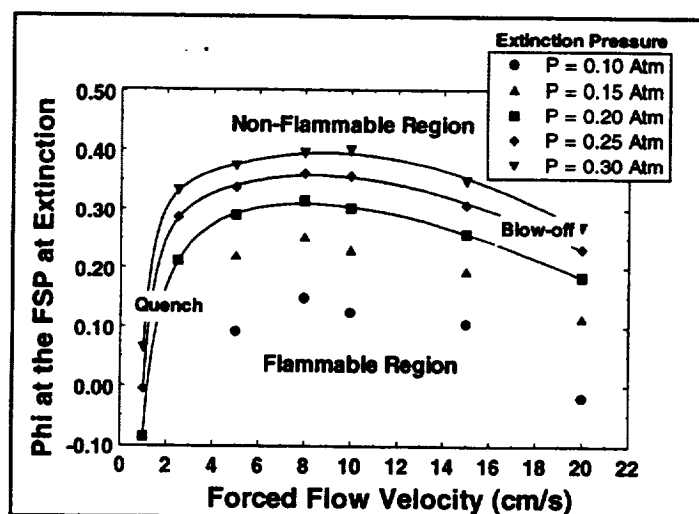


Figure 8
Predicted extinction boundaries at constant pressure