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# Low Pressure Flame Blowoff from the Forward Stagnation Region of a Blunt-nosed Cast PMMA Cylinder in Axial Mixed Convective Flow

*J. W. Marcum[1], P. Rachow[2], P. V. Ferkul[3], and S.L. Olson*[4],*

*[1]Purdue University, West Lafayette, IN, USA*
*[2]HX5 Sierra, LLC, Cleveland, OH, USA*
*[3]USRA, Cleveland, OH USA*
*[4]NASA Glenn Research Center, Cleveland, OH, USA*
*[*]Corresponding Author Email: sandra.olson@nasa.gov*

**Abstract:** Low-pressure blowoff experiments were conducted with a stagnation flame stabilized on the forward tip of cast PMMA rods in a vertical wind tunnel. Pressure, forced flow velocity, gravity, and ambient oxygen concentration were varied. Stagnation flame blowoff is determined from a time-stamped video recording of the test. The blowoff pressure is determined from test section pressure transducer data that is synchronized with the time stamp. The forced flow velocity is also determined from the choked flow orifice pressure. Most of the tests were performed in normal gravity, but a handful of microgravity tests were also conducted to determine the influence of buoyant flow velocity on the blowoff limits. The blowoff limits are found to have a linear dependence between the partial pressure of oxygen and the total pressure, regardless of forced flow velocity and gravity level. The flow velocity (forced and/or buoyant) affects the blowoff pressure through the critical Damkohler number residence time, which dictates the partial pressure of oxygen at blowoff. This is because the critical stretch rate increases linearly with increasing pressure at low pressure (sub-atmospheric pressures) since a second-order overall reaction rate with two-body reactions dominates in this pressure range.

***Keywords: blowoff, mixed convective flow, low pressure***

## 1. Introduction

The effect of reduced pressure on the blowoff flammability limits has been studied in a variety of geometries and with a variety of fuels. Flame spread over thin fuels was shown to follow a power law dependence on pressure and oxygen concentration away from the extinction limit, but near the extinction limit, the dependence breaks down. Extinction limits for thin cellulosic fuels burning downward [1] and both upward and downward [2] showed that the oxygen concentration at extinction increased as the pressure decreased. If the data is plotted as partial pressure of oxygen versus total pressure, a parallel linear relationship is found for the upward and downward limits. More recently, eleven practical aerospace materials [3] were tested at three pressures and the upward flammability limits show a linear dependence of partial pressure of oxygen with total pressure. A similar trend of partial pressure of oxygen versus total pressure boundary was found for Nomex-HT-9040 for concurrent-vertical, opposed-vertical, opposed-horizontal, and concurrent-horizontal extinction limits [4].

The objective of this work is to study the effect of oxygen concentration, forced flow velocity, and ambient pressure on the blowoff extinction limits of concurrent vertical PMMA rods with the intent to evaluate the effect of these variables on the blowoff limits.

## 2. Methods / Experimental

The blowoff experiments were performed in a low-pressure 20 cm diameter vertical blow down wind tunnel. The flow through the wind tunnel was controlled as well to provide an additional variable in addition to oxygen and pressure. The flow was set using a critical flow orifice and a set upstream pressure. The pressure in the test section was controlled using a digital backpressure control valve that can be manually adjusted in 0.007 atmosphere increments. The oxygen-nitrogen gases used were from premixed bottles.

The 0.3175 cm radius clear cast PMMA rods were sealed inside the test section and the test section was evacuated using a vacuum pump attached to the backpressure control valve. The control pressure for ignition was then set. The forced flow was initiated to fill the test section with the desired gas mixture, and the sample was ignited at a flammable pressure.

For normal gravity experiments, the igniter was retracted, and then the pressure was decreased in 0.1 PSIA increments every few seconds until the flame blew off. This decreasing pressure time history is shown in Figure 1.

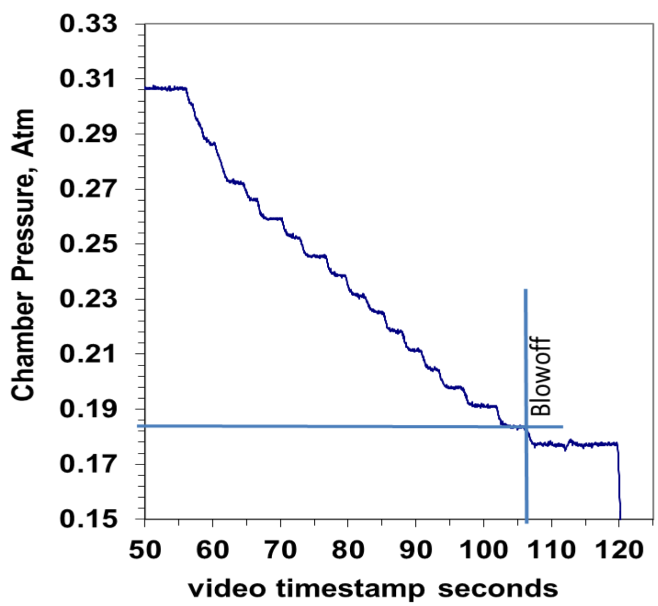


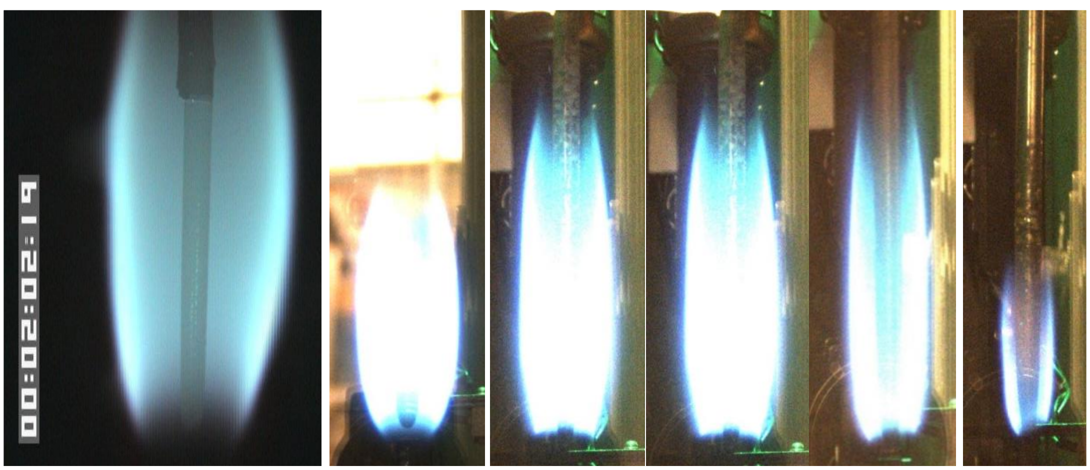

**Figure 1: Pressure history for a typical normal gravity blowoff test. Blowoff is determined from the video and the video timestamp is used to determine the pressure at blowoff.**

For Zero Gravity Research Facility drop tests, the flame was ignited at a flammable oxygen concentration. After the igniter was retracted, the flame was allowed to stabilize, and then the oxygen concentration was switched at a prescribed time before the drop start based on the flow time for the oxygen to reach the flame. During the drop, the flame adjusts to the new oxygen concentration at the fixed forced flow velocity and pressure, and the flame either blows off or survives the 5.18 second drop.

Blowoff is determined from the video images. The video image has a timestamp that was also recorded in the digital file with the pressure data. The pressure and forced flow velocity at blowoff are determined for each test from the digital pressure readings at blowoff.

## 3. Results and Discussion

Blowoff images for each oxygen concentration tested are shown in Figure 2. The forced flow is up in these images, in the same direction as buoyant flow. The flames near blowoff are generally blue, and blowoff occurs as the stagnation region opens up and the flame blows downstream. The downstream flame will often exhibit large oscillations at 2-3 Hz forward and back along the rod multiple times before the final retreat and complete extinction. As the ambient oxygen increases from 15% to 21% by volume, the extinction pressure decreases, causing the flame to expand. No flame could be stabilized at 14% oxygen at one atmosphere pressure.




$O_2$ % by volume: 21 19 18 17 16 15

**Figure 2: flame blowoff images just as the stagnation region opens up. First image is using a different camera, showing the timecode used to synchronize the video of blowoff with the digital pressure data.**

### 3.1 Blowoff pressure as a function of forced flow velocity

The effect of forced flow on the normal gravity blowoff pressure is shown for four oxygen concentrations in Figure 3. At each oxygen concentration, a linear relationship is found between the blowoff pressure and the forced flow velocity, consistent with previous results with methane opposed jet blowoff tests [5]. Linear fits are shown for each oxygen concentration.

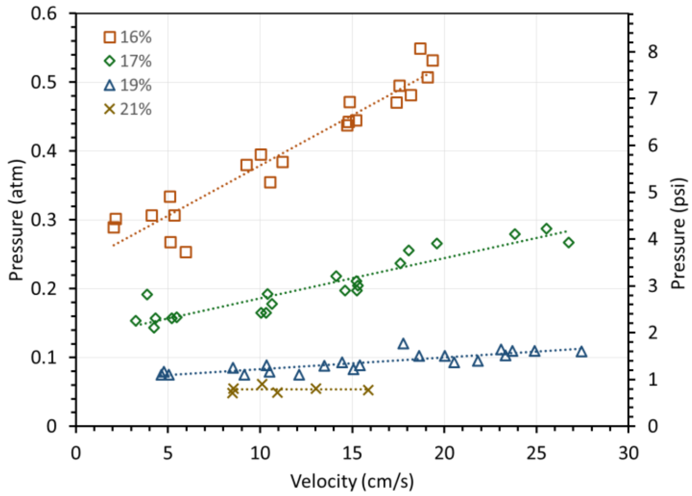



**Figure 3: Blowoff pressures as a function of forced flow velocity for four oxygen concentrations for normal gravity experiments.**

For 16% oxygen, drop test results are shown in Figure 4 with the normal gravity test results. The drop tower results are labeled stable if the flame survives the 5.18 s drop test, and blowoff if the flame blows off during the drop. The normal gravity blowoffs occur at a significantly lower forced flow velocity for a given pressure, indicating that a normal gravity buoyant flow is a significant contribution to the mixed convective flow effect on the blowoff pressure. If we shift the normal gravity data by linear superposition of flows $V_{forced} + V_{buoyant}$, where $V_{buoyant} = 27$ cm/s, the normal gravity data overlaps the drop tower test results. Surprisingly, a constant buoyant flow appears to be adequate, so buoyant flow is not a strong function of pressure. As was noted in [1], the flame temperatures are reduced only slightly near the extinction limits as pressure is reduced. The buoyant velocity varies with $\Delta\rho/\rho$ which for a given constant pressure test varies as $\Delta T/T$ and which does not change much with pressure near extinction. This buoyant flow shift agrees with an estimated buoyant velocity $V_{buoyant} \sim \Delta\rho/\rho\ (gd)^{1/2} \sim 25$ cm/s for $g=981$ cm/s$^2$, $d=0.635$ cm, and $\Delta\rho/\rho \sim 1$. Also notice that because of the inherent buoyant flow, the lowest total pressures at blowoff are lower in the microgravity tests since the achievable flows are lower in microgravity.

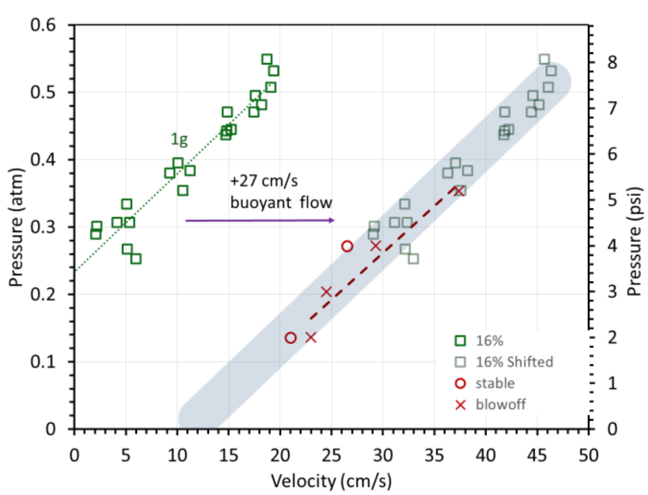



**Figure 4: Normal gravity blowoff tests at 16% oxygen compared to drop tower tests, showing the need for a buoyant flow shift of ~ 27 cm/s.**

### 3.2 Blowoff pressures as a function of partial pressure of oxygen

The partial pressure of oxygen at which normal gravity blowoff occurs for each % $O_2$ is plotted in Figure 5 as a function of the total pressure at blowoff. The flammability limit was found experimentally to be between 14% and 15% oxygen in normal gravity, and the curve fit finds the partial pressure oxygen at one atmosphere pressure is 0.1486 atmospheres, or 14.86% O2 by volume, as shown in Figure 5. The $R^2$= 0.9988 for the fit to all the normal gravity data.

Also shown in Fig. 5 are the lines of constant oxygen mole fraction plotted as $ppO_2$ versus total pressure. Of course, each data point falls on its corresponding mole fraction line. However, the linear trend to the blowoff data is an independent linear fit. The forced flow velocity for each test is reflected in the symbol size, as shown by the scale on the right axis.

In addition to the normal gravity data, the zero gravity drop tower results are plotted, and are found to follow the same trend despite the velocity shift as shown in Figure 4.

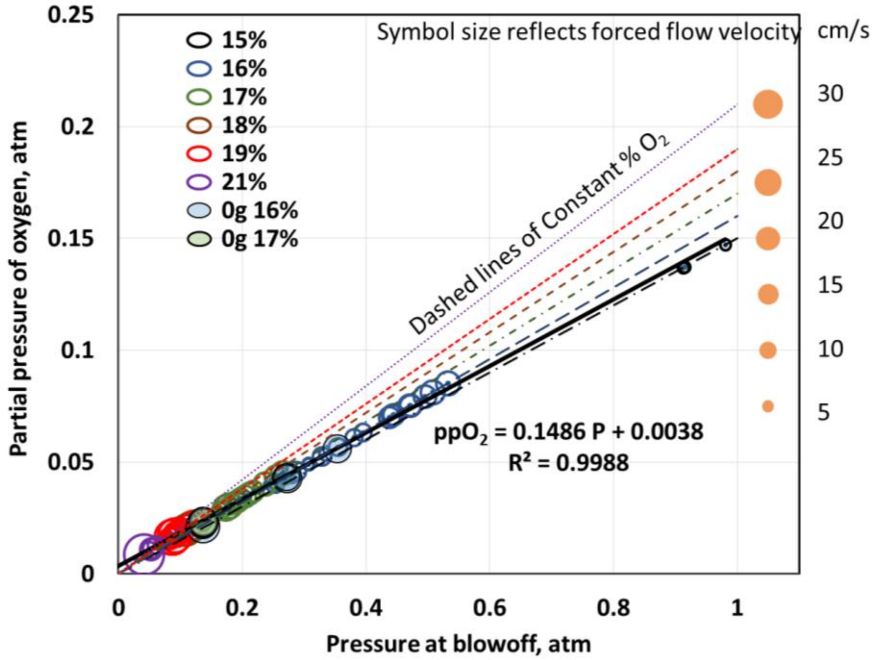



**Figure 5: Partial pressure of oxygen at blowoff versus total pressure at blowoff. The trend in the data is independent of the mole fraction of oxygen lines for each oxygen mole fraction.**

### 4 Constant critical Damkohler number

A critical Damkohler number ($Da_{crit}$) is defined as

$$Da_{crit} = \frac{flow\ time}{reaction\ time} \sim \frac{reaction\ rate}{flow\ rate} = \frac{\beta\rho\ (X_f)(X_{O2})e^{(-E/R\,T_{crit})}}{a} \sim \frac{ppO_2}{P}$$

The critical Damkohler is assumed to be constant along the blowoff boundary [6]. In the numerator, the density and oxygen mole fraction are proportional to $ppO_2$. In addition, there is a pressure dependence as part of the stretch rate $a=a_{forced}+a_{buoyant}=(3/2)U/R + a_{buoyant}$, where theoretically, the critical stretch rate increases linearly with increasing pressure [7] at low pressure where a second order overall reaction rate with two-body reactions dominates. This agrees with the observed linear dependence of blowoff pressure with forced flow velocity as shown in Fig. 3. The flame temperatures are reduced only slightly near the extinction limits as pressure is reduced [1]. Therefore, for a constant critical Damkohler number, ppO2 should be approximately proportional to total pressure, as is observed in Fig. 5.

## 5. Conclusions

Low-pressure blowoff experiments were conducted with a stagnation flame stabilized on the forward tip of cast PMMA rods in a vertical wind tunnel. Pressure, forced flow velocity, gravity, and ambient oxygen concentration were varied. The blowoff pressure is found to be linearly dependent on the forced flow velocity. The microgravity blowoff pressure for a given oxygen concentration occurs at a higher forced flow velocity, implying that a buoyant flow contribution in normal gravity is not negligible. The partial pressure of oxygen at blowoff is linearly dependent on the total pressure regardless of forced flow velocity and gravity level. The flow velocity (forced and/or buoyant) affects the blowoff pressure through the constant critical Damkohler number residence time, which dictates the partial pressure of oxygen at blowoff. This is because the critical stretch rate increases linearly with increasing pressure at low pressure (sub-atmospheric pressures) since a second-order overall reaction rate with two-body reactions dominates in this pressure range.

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## References

[1] Frey, A. E. JR. and T’ien." JS, “A theory of Flame Spread over a Solid Fuel Including Finite-Rate Chemical Kinetics,” Combust. and Flame 36 (1979): 263-289.
[2] Chu, L., C. H. Chen, and J. S. T'ien. "Upward propagation over paper samples." Proceedings of the ASME Paper 81 (1981).
[3] Hirsch, D.B, Williams, J., and Beeson, H.; “Pressure Effects on Oxygen Concentration Flammability Thresholds of Polymeric Materials for Aerospace Applications” J. Testing & Evaluation, V.36, Issue 1, (pp. 69-72). NASA Document ID 20070018178, (2008).
[4] Osorio, Andres Felipe. "Effect of Environmental Variables on the Flammability of Fire Resistant Materials." Dissertation, Univ. Cal. Berkeley (2014).
[5] H.K. Chelliah, C.K. Law, T. Ueda; An experimental and theoretical investigation of the dilution, pressure and flow-field effects on the extinction condition of methane-air-nitrogen diffusion flames, Proc. Intl. Comb. Symp. 23(1) (1991) 503-511.
[6] A. Alkidas, and P. Durbetaki. Stagnation-point heat transfer: the effect of the first Damkohler similarity parameter, *Journal of Heat Transfer* 94.4 (1972): 410-414.
[7] C.H Sohn, S.H Chung, Effect of pressure on the extinction, acoustic pressure response, and NO formation in diluted hydrogen–air diffusion flames, Combustion and Flame 121 (1–2)(2000) 288–300.