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# Emulation of condensed fuel flames using a Burning Rate Emulator (BRE) in microgravity

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**Abstract:** The Burning Rate Emulator (BRE) is a gaseous fuel burner developed to emulate the burning of condensed phase fuels. The current study details several tests at the NASA Glenn 5-s drop facility to test the BRE technique in microgravity conditions. The tests are conducted for two burner diameters, 25 mm and 50 mm respectively, with methane and ethylene as the fuels. The ambient pressure, oxygen content and fuel flow rate are additional parameters.

The microgravity results exhibit a nominally hemispherical flame with decelerating growth and quasi-steady heat flux after about 5 seconds. The BRE burner was evaluated with a transient analysis to assess the extent of steady-state achieved. The burning rate and flame height recorded at the end of the drop are correlated using two steady-state purely diffusive models. A higher burning rate for the bigger burner as compared to theory indicates the significance of gas radiation. The effect of the ambient pressure and oxygen concentration on the heat of gasification are also examined.
***Keywords: condensed fuel flames, Burning Rate Emulator, microgravity***

## 1. Introduction

It is theorized that a condensed fuel flame having four characteristic properties: heat of combustion, surface temperature, smoke point and heat of gasification, can be modeled by a circular gas burner known as the Burning Rate Emulator (BRE) [1]. This concept has been previously demonstrated in normal gravity [2]. The present study verifies the BRE technique in a microgravity environment by performing drop tests at the NASA Glenn 5-s Zero Gravity Facility. Two burners, with diameters 25 mm and 50 mm respectively, are tested. The burner is installed in a quiescent chamber which undergoes free fall at the facility. The measurements during the test include heat flux from the flame to the burner surface, the heat flux sensor temperature, and the temperature of the perforated outlet plate at its center and the offset radius $R^*$. The fuel mass flow rate is measured and the flame height is determined by analyzing the image data.

The aforementioned key fuel properties are determined to emulate the burning of different condensed fuels. The heat of combustion and the smoke point are attained from literature [3-5]. The other properties, viz., the surface temperature and the heat of gasification are obtained from the experimental measurements. The measured temperature of the outlet plate gives the surface temperature. The determination of the heat of gasification is crucial to this study. For the steady burning of a condensed fuel, the heat of gasification L is given by the ratio of the net heat flux and the burning rate.

Methane, ethylene, and nitrogen-diluted ethylene are the three gaseous fuels studied during these tests. Pressure, oxygen content in the combustion chamber, and fuel flow rate are varied to ascertain their effect on the nature of the flame. A typical test for the 25 mm burner is shown Figure 1. Here, the sequence of images shows the flame growth during the 5s duration. The flames are ignited in normal gravity just before the drop begins. The flames during the drop transform from a 1-g diffusion flame to a microgravity hemispherical flame. The graph in Figure 1 shows the transient behavior of the heat flux signal and the flame height. The heat flux signal falls quickly as the drop starts and appears to reach quasi-steady state by the end of the drop. In contrast, the flame height rises slowly and doesn't appear to reach steady state after 5 seconds. Hence, the assumption that quasi-steady state has been achieved by the end of the drop is applied only to the heat flux data and not to the flame height.

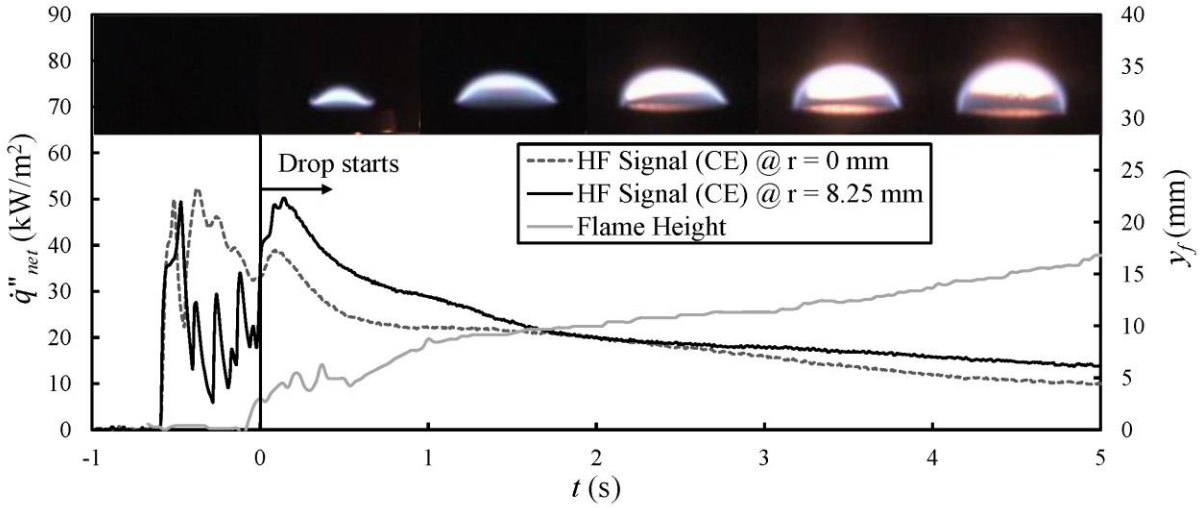



Figure 1: A typical drop test for the 25 mm burner

## 2. Transient Analysis

To establish the extent of steady state achieved during the 5-s drop, the results are compared to a simple transient analysis. The model considers a heated sphere at temperature $T_s$ immersed in a cool environment with ambient temperature $T_\infty$. The sphere has a radius $R$ and the environment has a specific heat $c_p$, density $\rho$ and thermal conductivity $k$. There is no flow through the sphere and it loses heat to the surroundings only through conduction. The solution for the unsteady temperature $T$ and surface heat flux $\dot{q}''_{surface}$ is available in literature [6] and is given below.

$$T = T_\infty + \frac{R(T_s - T_\infty)}{r} erfc\left(\frac{r - R}{2\sqrt{kt/\rho c_p}}\right) \quad (1)$$

$$\dot{q}''_{surface} = \frac{k(T_s - T_\infty)}{R} + \frac{k(T_s - T_\infty)}{\sqrt{\pi k t/\rho c_p}} \quad (2)$$

The above problem could be compared to a flame on a burner surface with the surface of the burner at temperature $T_s$ and the ambient temperature at $T_\infty$. To get an estimate of the flame height, a reasonable assumption is made that the thin flame sheet is at a dimensionless temperature $\left(\frac{T-T_\infty}{T_s-T_\infty}\right)$ of 0.2. The flame height and heat flux can be calculated for the same test shown in Figure 1 so that they could be easily compared. Figure 2 shows the comparison of flame height and heat flux with the experimental readings. It is evident from the figures that the heat flux approaches quasi-steady state at the end of 5 seconds whereas the flame height is far from steady state. For the particular case shown in Figure 2a, the flame height reaches only about 37% of steady state after 5 seconds. Hence, to get a better idea about flame behavior in microgravity, longer duration tests need to be conducted aboard the International Space Station.

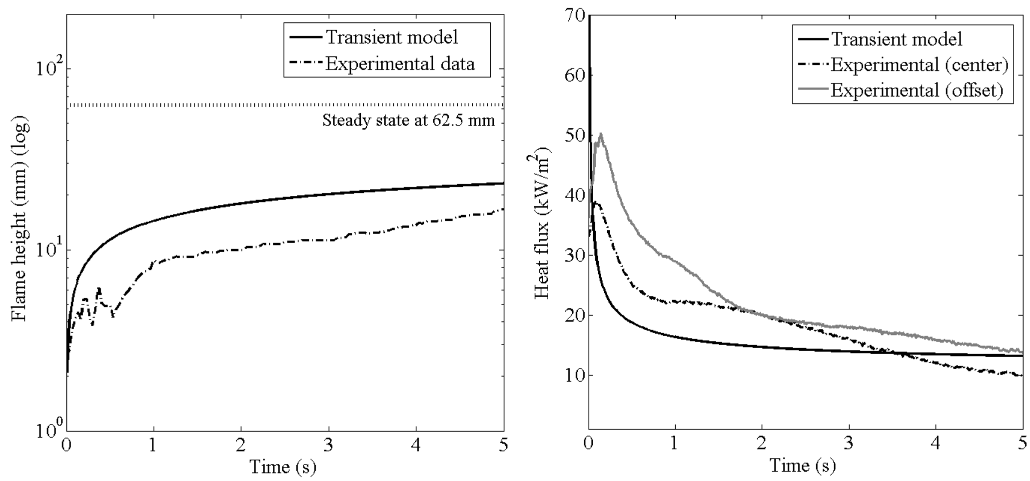



Figure 2a (left): Flame height vs. time for a typical 25 mm burner test,
Figure 2b (right): Surface heat flux vs time for a typical 25 mm burner test

## 3. Theory

Two models are suggested to correlate the results of the drop experiments. The first model compares the BRE tests to the burning of a stagnant layer of liquid pool [7,8]. The model is one-dimensional and steady in nature. The heat transfer at the liquid-gas interface is only due to diffusion from the flame and the flow is assumed to be laminar. The other model [9] analyzes quasi-steady burning of small particles with shapes ranging from a needle to a circular disc. This model is two-dimensional and works with ellipsoidal coordinates to condense the problem into a one-dimensional solution. The objective of these models is to obtain expressions for the burning rate and flame height to verify the experimental results. According to both models, the burning rate of the fuel is identically expressed as:

$$\dot{m}'' = \left(\frac{8k}{\pi c_p D}\right)\ln(1+B) \tag{3}$$

The flame height is derived using the one-dimensional model and is given as:

$$\frac{y_f}{D} \equiv \left(\frac{\pi}{8}\right)\frac{\ln\left[(1+B)/(Y_{O_2,\infty}/(rY_{F,o})+1)\right]}{ln(1+B)}\left[\frac{B}{\ln(1+B)}\right] \tag{4}$$

## 4. Correlation of Results

It is hypothesized that the BRE burner could emulate the burning of any condensed phase fuel. This can be visualized by examining the mass burning rate as a function of heat of gasification as shown in Figure 3. The burning rate decreases with heat of gasification but the burning perseveres even at high values of the heat of gasification $L$. Figure 3 also shows that the BRE burner could emulate fuels with heat of gasification in the range of 0.4 – 4 kJ/g which corresponds to a number of solid and liquid fuels [7].

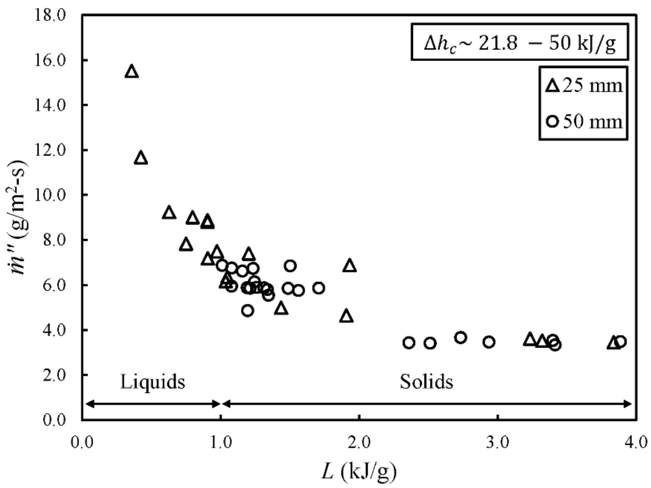



Figure 3: Microgravity burning rate as a function of the derived heat of gasification

The steady state theory discussed in the previous section is utilized to predict the burning rate and flame height for the BRE experiments. Eqs. (3) and (4) give the dimensionless mass flux and flame height respectively. These are compared to the experimental results in Figures 4 and 5b. The dimensionless burning rate in Figure 4 follows two distinct curves corresponding to the two burner diameters. This different trend for the two burners may be due to a possible higher rate of gas phase radiation relative to total heat release for the bigger burner. The steady state theory assumes negligible radiation which might be the reason for over-prediction.

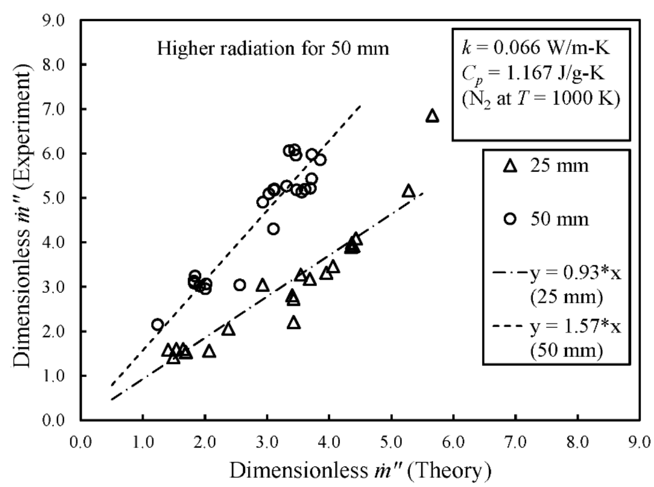
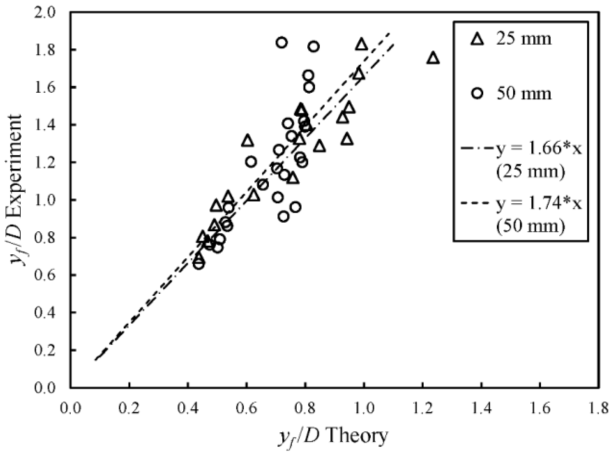



Figure 4: Comparison of theoretical and experimental dimensionless burning rate (left)

To further inspect the influence of radiation, it is interesting to look at the net heat flux as a function of flame height for the two burners. Figure 5a demonstrates that the heat flux is higher for the 50 mm burner at the same flame height. It can be suspected that the greater gas volume for the 50 mm burner radiates at a higher rate which increases the net heat flux. This reinforces the claim of higher radiation for the 50 mm burner.

Figure 5b shows that the predicted flame height is lower than the experimental reading. However, according to the transient analysis and experimental data, steady state is not achieved during these tests. Preliminary analysis using the 2D combustion model yielded positive results for the flame height. Hence, we need to look at the 2D model to predict the flame height.



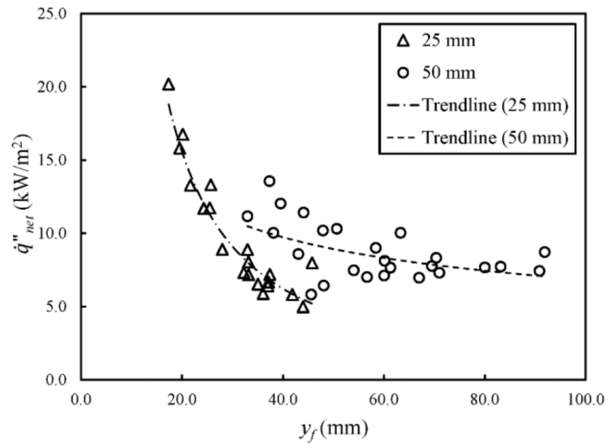




Figure 5a: Net het flux as a function of flame height for 25 mm and 50 mm burners (left)

Figure 5b: Comparison of theoretical and experimental dimensionless flame height (right)

**Effect of ambient pressure and oxygen content**

The analysis in the previous subsection could not fully capture the effect of changes in ambient pressure and the oxygen content in air. The pressure of the ambient air is varied in the current study from 0.5 – 1.0 atm whereas the oxygen mole fraction in air ranges from 0.21 – 0.30. To comprehend the effect of parameters such as pressure and oxygen content, the tests with similar mass flow rates are inspected for the same burner and fuel. Two sets of tests with 30% oxygen content are chosen to study the influence of ambient pressure on heat of gasification as can be seen in Figure 6a. The heat of gasification follows an upward trend with an increase in ambient pressure. Figure 6b correspondingly shows the effect of oxygen mole fraction on heat of gasification. The two sets of tests selected for this analysis have the same mass flow rate and 1 atm pressure. The heat of gasification shows a monotonic rise with the oxygen content. The theoretical models employed for the present work show a dependence of results on the oxygen mole fraction. However, there is no dependence on ambient pressure.

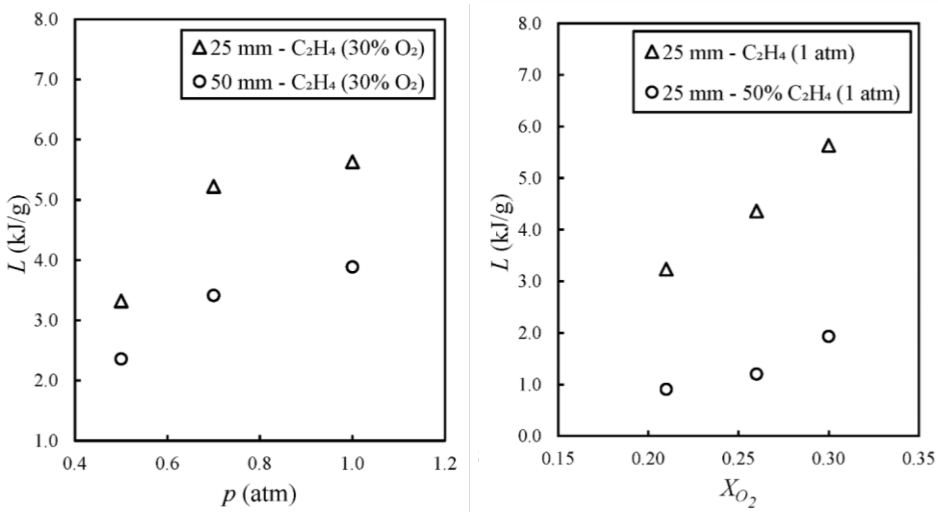



Figure 6a: Effect of ambient pressure on heat of gasification
Figure 6b: Effect of oxygen mole fraction on heat of gasification

## 5. Conclusions

Tests were conducted at the NASA 5-s Zero Gravity Facility using the BRE burners. A simplistic transient model was applied which demonstrated that the experimental flame height is not steady whereas the surface heat flux could be assumed to approach quasi-steady state. The 1D purely diffusive model gives reasonable results. However, for analysis of flame height, it is necessary to look at the 2D combustion model. It appears that the ratio of radiation loss to total heat release becomes significant as the burner diameter increases. Hence, there is also a need for an inclusive model which considers the effect of radiation.

## 6. Acknowledgements

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## 7. References

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