Low Stretch Solid-Fuel Flame Transient Response to a Step Change in Gravity

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Abstract

The effect of a step change in gravity level on the stability of low stretch diffusion flames over a solid fuel is studied both numerically and experimentally. Drop tower experiments have been conducted in NASA Glenn Research Center's 5.2 Zero Gravity Facility. In the experiments burning PMMA cylinders, a dynamic transition is observed when the steadily burning 1g flame is dropped and becomes a 0g flame. To understand the physics behind this dynamic transition, a transient stagnation point model has been developed which includes gas-phase radiation and solid phase coupling to describe this dynamic process. In this paper, the experimental results are compared with the model predictions. Both model and experiment show that the interior of the solid phase does not have time to change significantly in the few seconds of drop time, so the experimental results are pseudo-steady in the gas-phase, but the solid is inherently unsteady over long time scales. The model is also used to examine the importance of fractional heat losses on extinction, which clearly demonstrates that as the feedback from the flame decreases, the importance of the ongoing heat losses becomes greater, and extinction is observed when these losses represent 80% or more of the flame feedback.

Introduction

The stagnation point diffusion flame geometry is ideal for studying the complex coupling between the gas phase flame and the solid fuel. Previous research has utilized this geometry for steady-state flame studies [1-5], adding first surface radiative loss, buoyancy-induced stretch, solid-phase conductive loss, and gas-phase radiative loss. All of these features are included in this work, with the addition of both transient gas and solid phases.

Low stretch diffusion flame experiments (and steady modeling) have been conducted using gaseous burners in drop towers [6], but the coupling between gas and solid is not present in these experiments, so they do not capture important aspects of burning solids. In addition, no discussion of the normal to microgravity flame transition was provided for the "quasi-steady" test conditions which ignited in normal gravity, dropped into microgravity, then changed the fuel flow rate during the drop. Low stretch buoyant flame experiments have been conducted that use large scaling to obtain low stretch in normal gravity[7,8]]. The results of those tests show that flame standoff distance grows as flame stretch is reduced, and that the flame temperature reaches a maximum at stretch rates of 6-7 s^{-1}. In addition, the surface energy balance was shown to capture the increasing the fraction of heat feedback from the flame that is lost through radiation and conduction into the solid as stretch rate is reduced until extinction occurs.

Numerical Model

A transient two-phase numerical model with single step finite rate kinetics and temperature-dependent solid-phase properties has been developed to predict the transition behavior seen in drop tower experiments as well as to better understand the gas-solid coupling and time scales to reach steady-state after a change in gas-phase conditions [9] . The unsteady gas phase is modeled using a mixed-convection stagnation point flow below a cylinder[2]. Gas-phase radiation (CO_2 and H_2O only) is accounted for using a two-flux model using a calibrated absorption coefficient[9]. A one-dimensional transient solid model with surface radiative loss and fuel regression is used to describe the solid, with the surface energy balance coupling the two phases. The coupling between the gas-phase and solid-phase models was done in dimensional terms because the step change in stretch rate changes the gas-phase scaling. The physical location of the gas-phase grid is held constant throughout the computation, and the grid spacing definition is converted to account for the change in scaling at the start of the drop. In the computations, a steady normal gravity mixed convection flame is used for the initial conditions. The sample thickness was fixed in each case to be 3.125mm, which is similar to that obtained in the experiments after ignition and stabilization prior to the drop test. The forced flow part of the stretch rate remains fixed throughout the computation, but when the drop occurs, gravity goes to zero, eliminating the buoyancy-driven component of stretch. The flow decays to a purely forced stretch rate, as will be described in the results section.

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7th International Workshop on Microgravity Combustion and Chemically Reacting Systems

Experiment Description

Microgravity drop tower experiments were conducted in the 5.18 second Zero Gravity Facility at NASA Glenn Research Center[9]. The experiments were conducted in a droppable wind tunnel[10], that provides air flow from 0-20 cm/s through the 20 cm diameter test section. The sample holder consists of the cast PMMA fuel sample tube, 3.8 cm in diameter, 15 cm long, ~4mm initial wall thickness, mounted hanging from a cross-beam support. A thin kapton tape heater is mounted between the inner wall of the fuel tube and the hollow copper core, which carries cooling water to the apparatus. Between the heater and the cooling water, the backside temperature of the fuel can be adjusted prior to ignition to control in-depth heat loss.

During an experiment, the fuel is heated to a specified temperature (≈150°C), and then the flow is started. Uniform ignition of the PMMA is achieved, and then the experiment is then dropped. The primary variables in the experiments were the forced stretch rate and the gravity level. The gravity level changed from Earth-normal, or 1g, to 0g during each drop. In normal gravity, the mixed stretch rate was ≈ 20 s^{-1}. The forced stretch rate was varied between tests from 3-20 s^{-1}, but the set value was held constant during the drop.

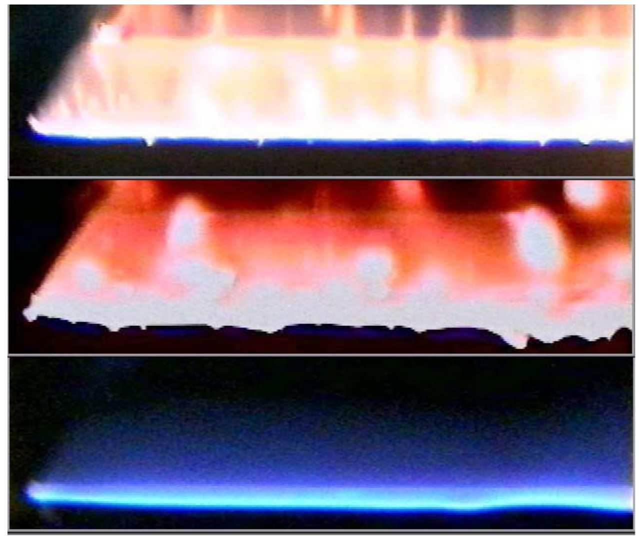

Figure 1: Sequence of images from drop. Initial 1g steady luminous flame with distinct blue outer flame, followed by sooty, pustular transition flame which evolves during the drop to a smooth blue 0g flame at a stretch rate of 5 s^{-1}. Sequence is side view of burning cylinder.

Results

Flame Standoff Distance

When the experiment is dropped, and the gravity step changes from normal gravity to zero gravity, the flame responds rapidly and non-monotically to the change in stretch rate. As shown in Fig. 1, at the drop start, the flame expands away from the fuel surface as the fuel vapor Stefan flow reaches further from the surface before encountering oxygen in the weakening stretch[9]. A maximum standoff distance is reached within a fraction of a second, and then the flame more slowly moves back toward the surface.

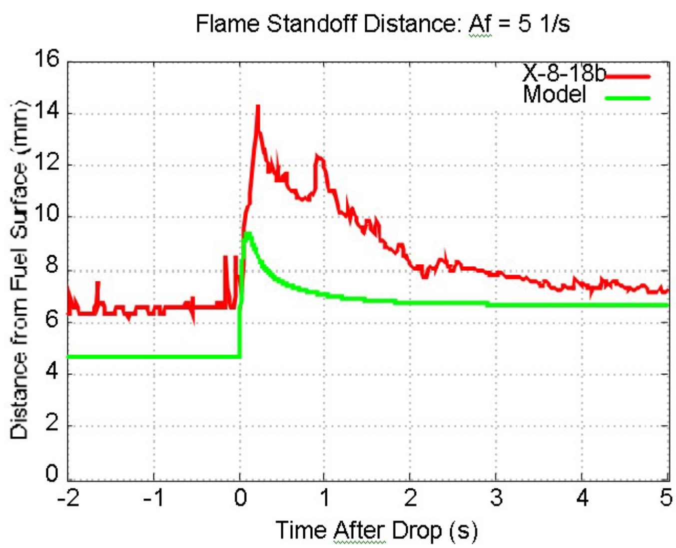

Figure 2: Experimental and computed flame standoff distances for a 1g flame transitioning to a 0g flame at a final stretch rate of 5 s^{-1}. Notice the overshoot in standoff distance at the drop start and the increase in flame standoff distance as stretch rate is reduced.

Figure 2 shows the measured experimental standoff distance and the model's predicted standoff as a function of time during the drop. In the experiment, the standoff is defined as the distance from the fuel surface to the outermost visible part of the flame. In the simulations, the standoff distance is defined as the distance from the fuel surface to the location of the maximum flame temperature. Thus it is expected that the predicted standoff is less than the measured standoff distance. As shown in Figure 2, this is indeed the case. The model does a good job of capturing the transient behavior of the experimental flame, with the overshoot in the standoff distance predicted to occur within the first second of the drop, with a slower recovery to a larger standoff distance at the lower stretch rate in 0g. The experimental time to peak standoff distance appears to be consistent with the gas-phase relaxation time, estimated to be the inverse of the final stretch rate. The model predicts that the time to peak standoff distance is shorter than this estimate by a factor of two. The larger overshoot seen in the experiments is attributed to the vapor jetting from the bubble layer at the surface, which gives the transition flame its pustular appearance[9]. The simple solid-phase model does not include bubble layer effects and uses extrapolated properties at the highest temperatures, which may not be accurate for the molten viscous PMMA[11] . Lastly, the model does not account for the significant soot formation seen in the experiments. There is a second characteristic time noted in this work, which is the relaxation time to steady-state standoff distance under the new low gravity stretch conditions. The model predicts that the standoff distance stabilizes by approximately one second, whereas in the experiments, especially at lower stretch, the flame does not reach a steady standoff in the 5.2 s drop time. This is attributed to the solid-phase response.

Surface Temperature

Figure 3 shows the surface temperature measured in the experiment compared with the predicted surface temperature from the transient model. After the drop, the experiment shows a much longer transient which is still in the process of asymptoting to a lower surface temperature than the theory predicts. The transition to a steady temperature takes much longer than is predicted by the model, which is consistent with the slow transition noted above for the steady-state standoff distance. During a 5.18 s drop tower experiment, a thermal wave will penetrate only $L_{drop} \approx (\alpha t)^{1/2} \approx 0.07$ cm, less than 20% of the way through the sample. For any reasonable change in flame strength, clearly the flame at the end of the drop time will not have reached steady-state. The experimental temperature changes varied from 15-50K, with larger drops in temperature corresponding to lower stretch rate. This change is a significant change in Arrhenius fuel vaporization rate. Since the experimental temperatures remain higher for longer, the fuel vaporization rate will also remain higher for longer, resulting in a slower transition to a stable flame standoff distance.

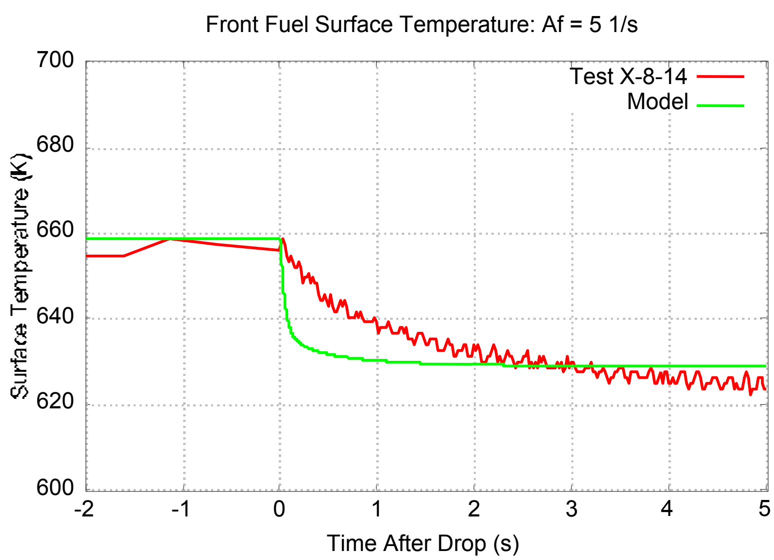

Figure 3: A surface temperature comparison between the experiment and the model. The surface temperature does not overshoot. Rather, the model shows a rapid decay in surface temperature. The experiments show a similar but more gradual decay.

Surface Energy Balance

The surface energy balance (Eqn. 1) is used to evaluate the coupling between the gas and solid phases during the transition process. The surface energy balance includes conduction from the flame, radiation from the flame zone, in-depth conduction, energy needed to vaporize the fuel, and surface radiation to the environment. The left side represents the net heat flux from the gas to the surface. Each term can be evaluated as a function of time using predicted burning rate data and temperature measurements (gas and solid-phase).

$$\lambda_g \frac{\partial T}{\partial x}\Big|_g + q_{rad,g} = \lambda_s \frac{\partial T}{\partial x}\Big|_s + \dot{m}L + q_{rad,s} \qquad Eqn(1)$$

The gas conduction to the solid drops dramatically at the start of the drop, due to increase in flame standoff distance. The gas-phase radiation, (CO_2 and H_2O only), increases slightly during the transition but returns to almost the same value after a few seconds. As was shown in Fig. 2, because of the drop in the flame feedback via conduction, the surface temperature drops. Because of this drop, the surface radiation drops slightly. The in-depth conduction loss also drops during transition before rebounding to nearly the same levels, as the in-depth solid gradients take time to react to the reduced surface temperature. The most dramatic effect of the reduced flame feedback is in the pyrolysis rate. Burning rates are significantly lower at low stretch [7,8].

To determine overall trends, the terms of the surface balance are compared as ratios. The ratio $F_{reutilization}$, is the fraction of gas-to-surface net heat flux used to vaporize more fuel, and the other ratio, F_{loss}, is the fraction of gas-to-surface net heat flux that is lost to the solid interior and radiated from the surface. In this way, $F_{loss}+F_{reutilization}=1$.

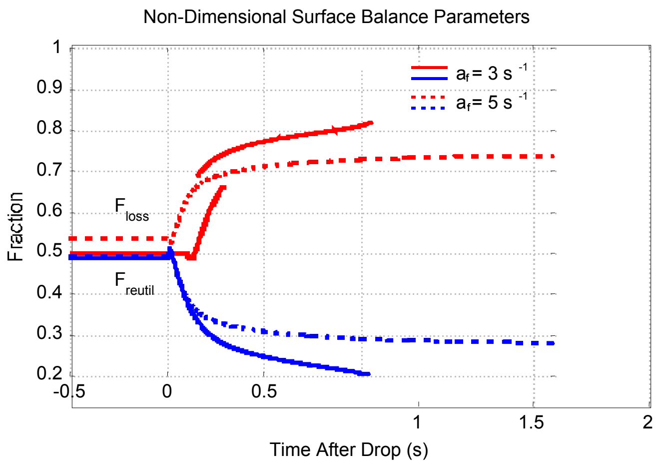

Figure 4: Loss and Reutilization Ratios as a function of time during a drop. At a stretch rate of 3 s^{-1}, the flame extinguishes, whereas as 5 s^{-1}, the flame is steady.

These two ratios are plotted as a function of time in Figure 4 for an extinction case and a stable flame case. The model predicts that the surface energy balance changes abruptly after the start of the drop. At a stretch rate of 3 s^{-1}, the flame extinguishes as the F_{loss} exceeds 0.8. At a stretch rate of 5 s^{-1}, the losses asymptote to a maximum of 0.75 within a few seconds, but hold steady there. In the extinction case, the net heat flux denominator in the ratio becomes too small, whereas the losses reflected in the numerator change only slightly prior to extinction. The primary difference in the two cases is the gas-phase conductive feedback, which is 1.5 W/m^2 for 5 s^{-1}, whereas it is only 1.2 W/m^2 for 3 s^{-1} prior to extinction. Thus extinction is attributable to insufficient heat feedback to the surface under low stretch conditions to compensate for existing heat losses. The model predictions thus agree very well with previous experimental results [7,8] at the 1D flame extinction limits.

Conclusions

The effect of a step change in gravity level on the stability of low stretch diffusion flames over a solid fuel is studied both numerically and experimentally. Both model and experiment show a rapid overshoot in flame standoff distance due to the rapid reduction in stretch rate while fuel blowing changes more slowly. Both model and experiment show that the interior of the solid phase does not have time to change significantly in the few seconds of drop time, so the experimental results are pseudo-steady in the gas-phase, but the solid is inherently unsteady over long time scales. The model is also used to examine the importance of fractional heat losses on extinction, which clearly demonstrates that as the feedback from the flame decreases, the importance of the ongoing heat losses becomes greater, and extinction is observed when these losses represent 80% or more of the flame feedback.

Acknowledgements: This work was supported by NASA Office of Biological and Physical Research, and the Ohio Space Grant Consortium.

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