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CANDLE FLAMES IN MICROGRAVITY

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Introduction

The candle flame is one of the oldest functional combustion systems, used primarily as a source of light. As a result, various practical aspects of candle burning have been understood for centuries (for a history of candle making and candles, see [1]). From a fundamental perspective, however, the candle flame is a complex combustion system. The fuel is a mixture of long chain hydrocarbon molecules whose oxidation chemistry is extremely complex. The flame interacts with a porous wick, the dynamics of which are complicated. Despite this, however, educators at all levels frequently use the candle as an introductory or example combustion problem. In addition, the candle flame occasionally serves as a model convective-diffusive flame in normal gravity theory and experiments. For example, candles were used to study flame flicker [2], spontaneous, near-extinction flame oscillations [3], electric field effects [4], enhanced gravitational effects [5], and magnetic field effects [6].

The candle flame in both normal and microgravity is non-propagating. In microgravity, however, the candle flame is also *non-convective* where (excepting Stefan flow) pure diffusion is the only transport mode. It also shares many characteristics with another classical problem, that of isolated droplet combustion. Given their qualitatively similar flame shapes and the required heat feedback to condensed-phase fuels, the gas-phase flow and temperature fields should be relatively similar for a droplet and a candle in reduced gravity (discussed later). Unless the droplet diameter is maintained somehow through non-intrusive replenishment of fuel, the quasi-steady burning characteristics of a droplet can be maintained for only a few seconds. In contrast, the candle flame in microgravity may achieve a nearly steady state over a much longer time and is therefore ideal for examining a number of combustion-related phenomena.

In this paper, we examine candle flame behavior in both short-duration and long-duration, quiescent, microgravity environments. Interest in this type of flame, especially "candle flames in weightlessness", is demonstrated by very frequent public inquiries. The question is usually posed as "will a candle flame burn in zero gravity," or, "will a candle burn indefinitely (or steadily) in zero gravity in a large volume of quiescent air." Intuitive speculation suggests to some that, in the absence of buoyancy, the accumulation of products in the vicinity of the flame will cause flame extinction [4]. The classical theory for droplet combustion with its spherically-shaped diffusion flame, however, shows that steady combustion is possible in the absence of buoyancy if the chemical kinetics are fast enough. Previous experimental studies of candle flames in reduced and microgravity environments [4,7] showed the flame could survive for at least 5 seconds, but did not reach a steady state in the available test time.

Experimental Apparatus

Candle flame experiments have utilized nearly all of the microgravity facilities available, i.e. the 2.2 and 5.2 sec drop towers and NASA Learjet at NASA Lewis, the 10 sec drop tower (JAMIC) in Hokkaido, Japan, and the Space Shuttle (Columbia) during the USML-1 mission in June, 1992.

In the drop towers' experimentation, large, sealed combustion chambers (to establish the desired

environmental conditions) enclosed the candle. Instrumentation was usually flame visualization by movie or video cameras. In the NASA Learjet, testing was in an unsealed chamber open to cabin pressure (estimated at about 0.8 atm). This provided an environment in which the effective gravity was reduced to 0.01 to 0.04 times that of normal gravity (g_0), with substantial variation in direction and magnitude. This is quite different from the reduction of 10^{-4} to $10^{-5} g_0$ without much variation provided by the drop towers or shuttle, respectively.

The principal difference between the shuttle test hardware and the basic drop tower hardware was (for safety purposes) the required use of a cubic perforated candlebox (11.5 cm on a side) for the shuttle tests. The box permitted fresh oxidizer to reach the candle but prevented a glove or other material from being accidentally ignited. The candlebox then fit inside a 25 liter sealed chamber called the glovebox working volume. The data was primarily black and white video obtained from orthogonally located video cameras. Color photographs of the flame were from a 35 mm SLR camera used in a few tests. Post-mission analysis of the video footage yielded the data presented below. In addition, data was also available from a 3-axis accelerometer sampling at 125 Hz mounted to the underside of the floor of the glovebox working volume. The Spacelab pressure and oxygen mole fraction were 1 atm and 0.217 at the time of each experiment.

The candles for all of the testing reported here were 5 mm in diameter, 2 cm long with a 1-2 mm diameter cotton braided wick. The composition of the candle was 80 percent of an n-paraffin wax (typically C₁₉-C₃₅ hydrocarbon) with 20 percent stearic acid (C₁₈H₃₆O₂) to impart toughness. Ignition in all cases was by an electrically heated aluminum alloy hot-wire (approximately 3 amperes current) that was removed after ignition. In the drop tower tests the igniter was on for a preset time and then withdrawn, and for the shuttle experiments, the crew manually removed the igniter after ignition.

Initial and Quasi-Steady Flame Behavior

The results described in this section are from about 10 single-candle shuttle experiments. Immediately after ignition, the candle flame was spherical and bright yellow. After 8-10 seconds, the yellow, presumably from soot, disappeared, and the flame became blue and nearly hemispherical (Figure 1d, Figures 1a-c show for reference a normal gravity, drop tower and lear jet candle flame, respectively) with a diameter of approximately 1.5 cm. These behaviors are consistent with the earlier, short-duration studies in aircraft [4], the NASA Lewis Research Center 5.2 second drop tower [7] and the JAMIC 10-second drop tower (unpublished).

The visible flame in microgravity is different from that in normal gravity in a number of aspects: shape, size, color and flame structure. The microgravity candle flame has a large flame standoff distance from the wick, typically on the order of 7 mm (Figure 1d) as compared to 1-2 mm for normal gravity candle flames (at the base region). This large flame standoff distance implies a weaker heat feedback from the flame and a smaller wax mass burning rate. The nearly spherical nature of the microgravity flame implies that all of the flame provides heat feedback to the wick. This is unlike normal gravity where only a portion of the vaporized fuel reacts in the vicinity of the wick; the rest of the fuel vapor is swept downstream by buoyant convection and reacts in the plume region.

The different flame shapes and quench (thermal) distances imply that the flame structure of these of the normal and microgravity flames is different, as illustrated in Figure 2. In normal gravity, the gas-phase structure of the candle flame resembles that of a downward propagating diffusion flame over a thin solid [8,9]; models of the later system show that the highest fuel vapor reaction (consumption) rate (will be called reactivity for the rest of the text) is close to the bottom of the flame near the wick. This region stabilizes the flame and provides the heat feedback for fuel vaporization (Figure 2a). Note that the highest reactivity requires not only high temperature, but also high fuel and oxygen concentrations. Although the temperature is high in the upper part of the flame (downstream), the fuel supply rate is small and thus the reactivity decreases.

The structure of the microgravity candle flame is different (Figure 2b). Its nearly spherical shape resembles the droplet flame in microgravity. The visible candle flame, however, disappears at the bottom or base because of heat loss to the wax. Because of this quenching, the reactivity does not have the same spherical symmetry as a droplet flame. Contrary to normal gravity, the highest reactivity in

microgravity exists at the top of the wick and diminishes in strength toward the bottom because of the quenching by the wax. Experimentally measured luminous intensities (from the video tape) of the flames show that the top of the flame was always brighter than the sides, indicating that the reactivity was higher at the top of the flame.

Analysis of the video footage from the shuttle experiment yielded the flame radius and height (see Figure 2b) as a function of time. Only some flames reached steady-state with respect to both radius and height. For some the flame radius and height increased with time and for others decreased with time. This is probably due to variations in wick/liquid initial conditions resulting from the manual ignition process. The size of the flame is determined by not only the gas phase but by the size of the evaporating surface of the wick, and the magnitude of the heat loss to the solid/liquid wax. The last two parameters are determined to a large extent by the initial condition of the wick/liquid which varied from test to test. Normalizing H by R, however, provides more a measure of the flame shape than the absolute flame size. Figure 3 shows H/R as a function of time for a typical test. For nearly all flames this ratio was 1.8 early in the flame lifetime and gradually decreased to 1.3 at extinction.

The decrease in H/R throughout the flame lifetime occurs primarily from changes in H. Because the glovebox is a relatively small, sealed volume, the candle burns in an ambient of continuously decreasing oxygen content. As a result the local reactivity decreases everywhere in the flame as a function of time. The flame then retreats (H decreases) as the local reactivity falls below a critical value required for a luminous flame [10]. The reactivity at the base of the flame will decrease below this critical value first since the reactivity is always the lowest there.

A common question is why the microgravity candle flame color is blue while normal gravity candle flames in the same atmosphere are sooty (yellow). There are three possibilities for this. The first is that the flame temperature is low enough (everywhere) such that soot cannot form [16]. The second is that soot exists but is cool and not luminous. The third is that the flame is partially premixed because oxygen can diffuse through the quenched base. The second possibility is unlikely since soot forms only at temperatures in excess of 1300 K at which yellow would be visible. Although the oxygen leakage can contribute to reduced soot formation in our candle experiment, it alone is probably not enough to eliminate soot. Near the top of the flame, the mixture should be non-premixed even with oxygen leakage.

The suppression of soot formation in the microgravity candle flames is most likely the result of the reduced flame temperature. The measured maximum flame temperature in a visually similar reduced pressure candle flame is around 1530 K [3]. This temperature is close to the soot formation threshold given by Glassman [11]. Other microgravity diffusion flames which have configurations not favoring oxygen leakage also are completely blue [12]. These near-limit flames, according to theory [10], should also have low flame temperatures. The reduced flame temperature results from the fact that the heat loss relative to the heat generation rate is larger in microgravity even though the heat loss in microgravity is smaller. Radiative heat loss which is considered negligibly small in normal gravity can also be significant in the microgravity candle flame, and can ultimately lead to quenched extinction. These radiative losses can be either from the surface [10], from gas-phase species such as CO₂ and H₂O [17] or from a combination of both [8,9].

Extinction

Extinction occurred between 40 and 60 seconds for all flames except one which had a lifetime of 105 seconds. This long-lived flame started and stayed smaller than normal (approximately 0.6 cm diameter) for most of its lifetime because it stabilized on only a portion of the wick. The cause of extinction for the shuttle experiments was oxygen depletion due to the finite glovebox/candlebox volume. This is different than a local accumulation of products around a diffusion flame that occur in any, even an infinite, ambient. In answer to the common question posed earlier, we assert that a steady-state candle flame would exist in an infinite ambient of air, i.e. the kinetics and diffusion rates are sufficiently fast and heat losses sufficiently small for the candle flame to be maintained until the wax is consumed.

A candle burning in a small sealed volume, such as the glovebox, will never reach a true steady state.

The flame characteristics will continue to change as the ambient oxygen is depleted. At best, then our flames would be quasi-steady. The candle burning in a sealed volume will be quasi-steady if the flame characteristics remain steady over a time scale on the order of a characteristic gas-phase transport time and further that this time is small compared to the time scale over which oxygen is depleted.

The question then comes to a comparison of these two time scales and the observed flame behavior. Over the flame lifetime, the flame shape as measured by H/R changes from 1.8 early in the flame lifetime to close to 1.3 at extinction. During this time the flame luminosity, as measured from the video tape, also decreases throughout the flame lifetime. The results show, however, that over a time period on the order of more than 5 seconds, the flame behavior as measured by the size (R and H), shape (H/R) and intensity (grayscale value from the video tape) does not change significantly.

The characteristic time scale over which oxygen is depleted in the glovebox is large (more than 1 minute). The glovebox contains about 0.25 gmol of oxygen and the estimated consumption rate is on the order of 10^{-5} gmol of oxygen per second. The candle, however, does not burn in the open glovebox. Oxygen transport to the flame is impeded by the safety-mandated candle box. While the candlebox causes extinction earlier than if the candle burned in the glovebox, the depletion timescale is over 30 seconds. Over a time period on the order of 5 seconds, the flame sees a near constant ambient even with the candle box, based on the consumption rate above.

The last time to estimate is the characteristic gas-phase transport time. A simple estimate of this time is $\tau_g = [(C \delta^2) / D]$, where δ is the *measured* flame standoff distance from the wick, D is the diffusion coefficient and the coefficient C is a geometric factor (approximately 1, 2 and 3 for planar, cylindrical and spherical geometries, respectively [13]). Using a D evaluated at a mean temp of 800 K, C=3 and $\delta = 6$ mm, τ_g will be on the order of 1 sec for the microgravity candle. Comparing this time to the oxygen depletion time shows that the candle flames in the Shuttle experiments were certainly quasi-steady.

This gas-phase transport time is valid where the region of interest is in the immediate vicinity of the flame. This area reaches steady-state relatively quickly because of the balance between the convective and diffusive transport. Outside the flame, however, where the convective transport is small, the characteristic gas-phase transport time is much longer. The estimate of this time is more difficult, because of the selection of an appropriate length scale. Using a somewhat arbitrary length scale of ten times the flame radius, we find the radial combustion product profile will reach approximately 90% of its steady state value in a time on the order of 8 seconds. This estimate is based on the theoretical solution [14] of the spherically symmetric transient-diffusion equation with a source at the flame radius.

Based on the latter estimate of the gas-phase diffusion time, the assertion of a quasi-steady gas-phase is not as clear. This latter time is in all likelihood, however, an overestimate. Theoretical treatments of droplet burning show that the assumption of a quasi-steady gas-phase yields accurate results [15,16] as long as the flame lies in a radius $r_f < r_D (\rho_l / \rho_g)^{1/2}$. If we use the wick diameter as the droplet size, this condition is met for the candle flame. This condition, however, is more appropriate for the transient droplet problem.

Near-extinction flame oscillations

Each candle flame on the space shuttle oscillated (spontaneously) in the final 5 seconds. The flame symmetrically traced back and forth along the candle axis in each cycle. The oscillation had a frequency of about 1 Hz with an amplitude that started small and grew until extinction (Figure 3). This type of oscillation is fundamentally different than the well-known flame flicker, owed to hydrodynamic instability [2], as will be explained below.

As the ambient oxygen concentration decreases, the flame oscillations initiate when the flame base extinguishes, i.e. it visibly begins to retreat. The liquefied wax and wick are still hot, so fuel vaporizes, and the fuel vapor and oxygen diffuse toward each other in the base region. Eventually a combustible mixture exists and a flashback of the flame base occurs. This further depletes the ambient oxygen concentration, so that more of the base or weakest part of the flame (compared to the previous cycle)

extinguishes, and the cycle repeats. The oscillations continue, increasing in amplitude as the ambient oxygen is continuously depleted, until the ambient oxygen concentration becomes too low to sustain any part of the flame.

Chan and T'ien [3] observed this type of oscillation at 6-9 Hz in normal gravity, low pressure (0.14 atm) candle flames that were visually similar to the shuttle candle flames. Scaling analysis of the experimental conditions of Chan and T'ien show that a buoyant flow existed even at reduced pressure. Analysis of the acceleration data shows that oscillations for the shuttle tests occurred at acceleration levels of 10^{-5} to $10^{-6} g_0$ where buoyant convection is much smaller than diffusive transport rates. Therefore buoyant convective flow is not required for the oscillation .

The different frequencies are due to the different diffusive transport time scales in the two environments. The time for fuel vapor transport from the wick to the flame surface provides a comparative measure of these characteristic times. τ_g for the microgravity candle flame was shown above to be approximately 1 second. Using the same equation with the experimentally measured δ , and an appropriate D yields a reduced pressure τ_g of 0.12 sec. The magnitude and the ratio (about 9) of the characteristic times in the two environments are in the range of the experimentally measured frequencies. Since the flame radii for the two cases are sufficiently close, the difference in transport times comes mainly from the pressure dependence of the diffusion coefficient. The identification of time scales, however, does not necessarily explain why oscillations have to occur; this requires a proper phase relationship between the involved processes.

Future Plans

The work on candle flames is continuing with three distinct phases. The most significant part is the development of a comprehensive model of the candle flame. An initial model that is comprehensive in the gas-phase is being developed. Next, the model will be coupled with a model of the wick/liquid phase. Another glovebox experiment is currently planned for operation in the MIR space station. The experiment is an enhanced version of the USML-1 experiment with a larger candle box with more free area. In addition to videography of the flames, thermocouple measurements, point measurement of the far-field oxygen concentration and radiometric measurements of the flame are planned. Ground-based work in the drop towers and normal gravity is also continuing.

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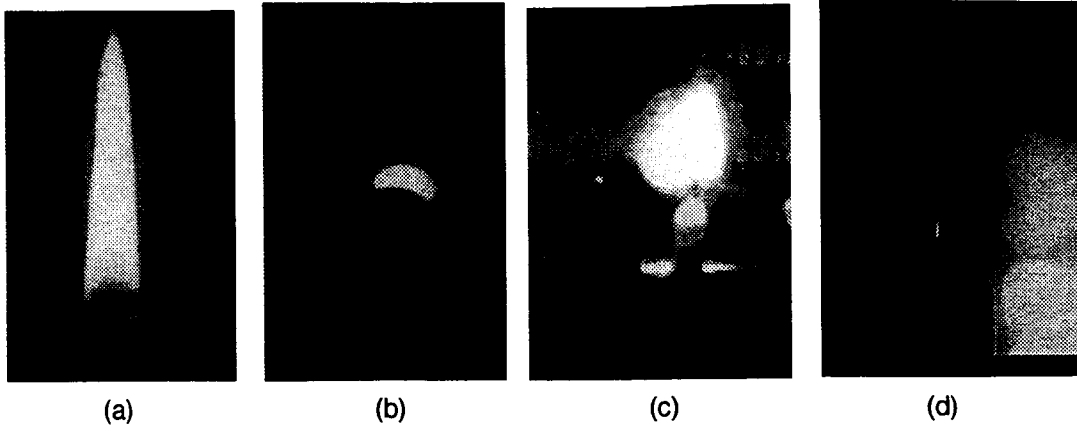


Figure 1. Pictures of candle flames in a. normal gravity, b. 5.2 second drop tower, c. Lear jet, and d. Space Shuttle.

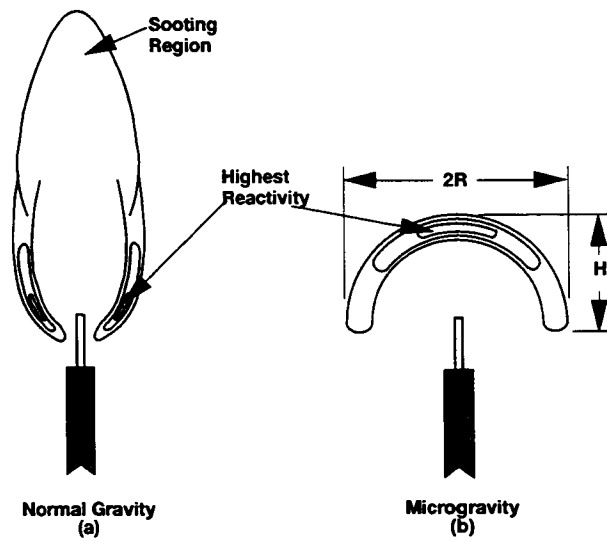


Figure 2. Schematic representation of the difference of the reactivity contour between a (a) normal gravity candle flame and (b) microgravity candle flame.

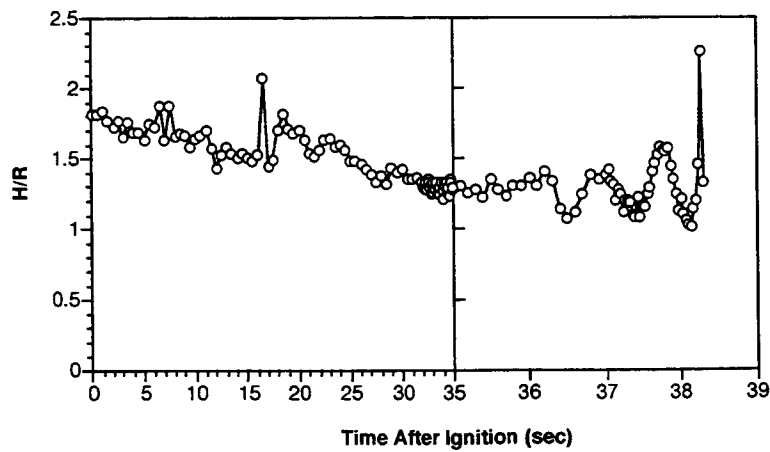


Figure 3. Flame shape, shown as H/R, as a function of time for a typical Space Shuttle test.