Candle Flames in Microgravity

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Introduction

The goal of this work is to study both experimentally and numerically, the behavior of a candle flame burning in a microgravity environment. Two space experiments (Shuttle and Mir) have shown the candle flame in microgravity to be small (~ 1.5 cm diameter), dim blue and hemispherical. Near steady flames with very long flame lifetimes (up to 45 minutes in some tests) existed for many of the tests. Most of the flames spontaneously oscillated with a period of approximately 1 Hz just prior to extinction (summarized in ref. 1).

In a previous model of candle flame in microgravity, a porous sphere wetted with liquid fuel [1] simulated the evaporating wick. The sphere, with a temperature equal to the boiling temperature of the fuel, was at the end of an inert cone that had a prescribed temperature. This inert cone produces the quenching effect of the candle wax in the real configuration. Although the computed flame shape resembled that observed in the microgravity experiment, the model was not able to differentiate the effect of wick geometry, e.g., a long vs. a short wick. This paper presents recent developments in the numerical model of the candle flame. The primary focus has been to more realistically account for the actual shape of the candle.

Model Formulation

We have reformulated the candle flame problem in microgravity using cylindrical coordinates and transformed the set of governing partial differential equations using body-fitted coordinate transformation [2]. This transformation includes a better, more detailed wick and candle geometry description. Fig. 1 shows one of the candle configurations (wick length = 9.6 mm) and the numerical grid distribution.

The model is identical to the previous model [1] except that the current formulation uses an alternating direction implicit scheme for the unsteady terms (the original model used an explicit formulation). This increases the allowed time step and reduces the total amount of computer time required for the flame to reach steady state (by a factor of 70). With these changes, it is more practical to test the near-limit flame oscillation phenomena. The wick is coated with liquid fuel at a prescribed temperature. The model assumes finite-rate, one-step gas phase chemical reaction. The flow from the wick is treated by the potential flow formulation of Baum [3]. The model further assumes constant properties, and Lewis numbers, although each species can have a different (constant) Lewis number. Surface radiative loss is assumed to be black. Gas radiation from CO_2 and H_2O are computed using the local Planck-mean absorption coefficient multiplied by a factor of 0.4. This factor is based on previous one-dimensional comparisons and the anticipated flame thickness. This gas radiation is assumed to be a pure heat loss. Flame radiation heat feedback to the wick is not treated in this work (ref. 4 provides information on radiative heat feedback effects).

Model Results

<u>Effect of wick length</u>

Fig. 2 shows the temperature contours of three candle flames with different lengths (3.6, 6.6, and 9.6 mm) at an oxygen mass fraction Y_{Oe}=0.254. A longer wick produces a larger flame and a slightly larger aspect ratio; the flame standoff distance along the wick direction (y-axis) is larger and so is the lateral standoff distance. A longer wick produces a flame with a lower maximum flame temperature. This is due to the larger radiative loss for the larger flames. With no gas-phase radiative loss in the model, the opposite trend prevails (the longer wick produces a flame with a higher temperature).

Effect of ambient oxygen percentage

Fig. 3 shows the reaction-rate contours for three steady flames. Decreased oxygen increases the quenching distance at the base of the flame and decreases the flame aspect ratio. This trend is in agreement with previous experimental results [1], and was also predicted with the previous model. The more realistic cylindrical wick, however, appears to give a better quantitative comparison with the experiment.

Simulation of near-limit flame oscillation

The candle flame extinction in the space experiment occurs because of the gradual depletion of oxygen inside the closed volume of the glovebox. We used the numerical model to study both flame extinction and the oscillations that occur near extinction. For small containers, the boundary conditions at the outer edge of the domain change to a zero flux boundary condition. For outer boundaries greater than 8 cm, the computational time from a steady flame to extinction is too long, so we prescribe a rate of ambient oxygen mole fraction decrease at a fixed location from the flame. The starting oxygen mole fraction at the outer boundary for both computations is Y_{Oe}= 0.1813. At this oxygen mole fraction, a steady solution exists, but it is very close to the lowest ambient oxygen mole fraction that will support a steady flame. The steady profiles at this oxygen percentage are the initial condition for the transient calculations.

Transient computations were performed on spherical containers with radii of 6.5, 7.0, 7.5, and 8.0 cm. The wick is near the center of the sphere. For all the cases, the flame temperature decreases monotonically to extinction without any detectable oscillation. The largest container (8.0 cm) is larger than the perforated candle box but is substantially smaller than the glovebox. The equivalent volume of the candle box – glovebox combination is difficult to estimate.

To better approximate the experimental situation, while making the problem computationally tractable, the rate of oxygen decrease is prescribed at r = 6.5 cm, the outer radius of the computation domain. Large values of dY_{oe}/dt correspond to smaller containers, and smaller values correspond to larger containers. Qualitatively, large values of dY_{oe}/dt give a monotonic decrease of flame temperature, similar to the closed container cases investigated. When dY_{oe}/dt becomes small enough, a near-limit oscillation occurs prior to extinction. Figure 4 shows that the number of cycles before extinction increases as dY_{oe}/dt decreases. The period of oscillation is essentially independent of dY_{oe}/dt, but the amplification rate decreases with decreasing dY_{oe}/dt. The numerical experiments indicate that near-limit oscillations require a very gradual approach to extinction.

References

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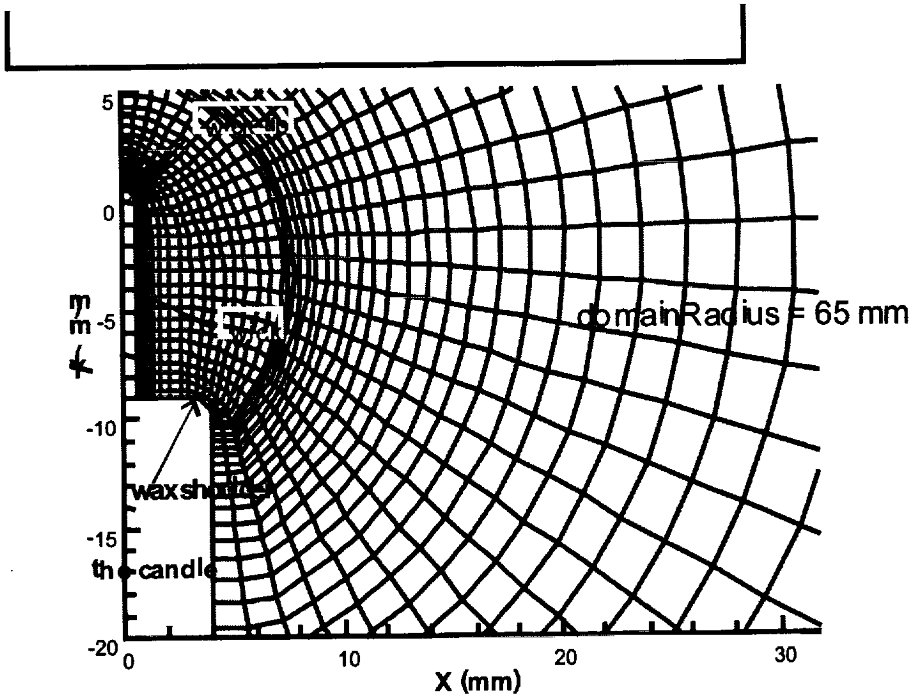


Figure 1. Candle configuration and grid distribution.

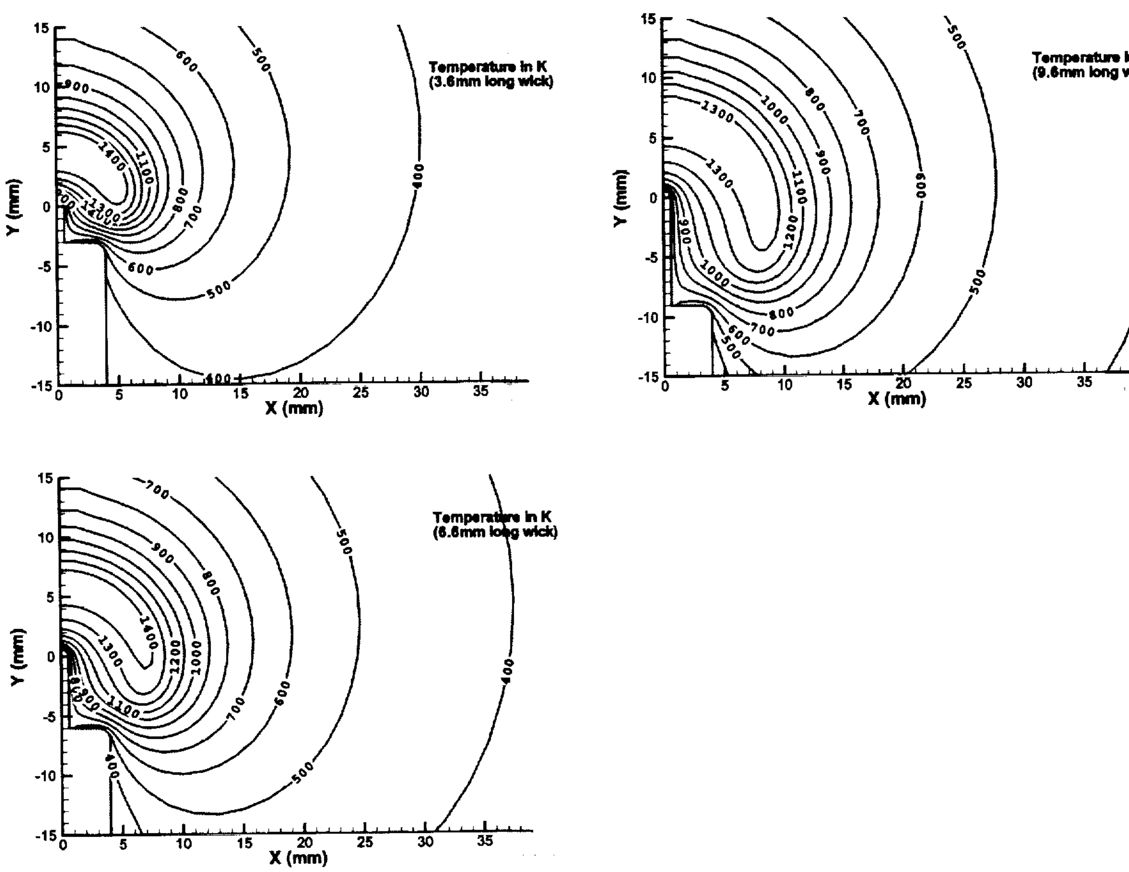
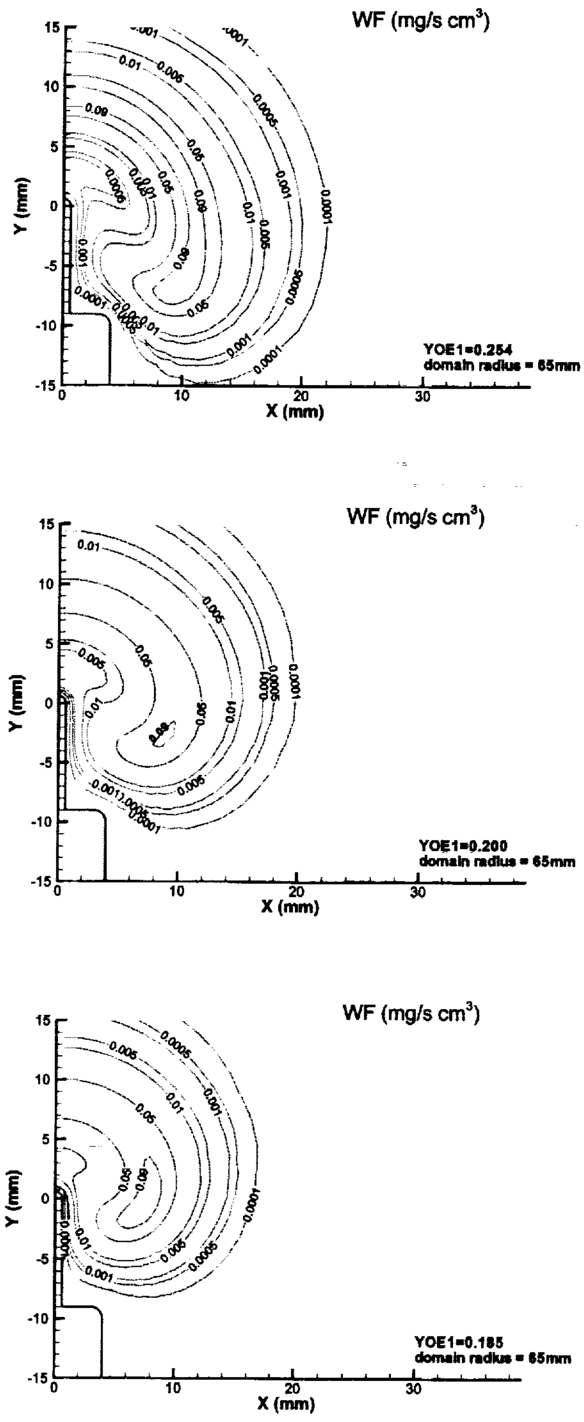


Figure 2. Temperature contours for three candles with different wick lengths.



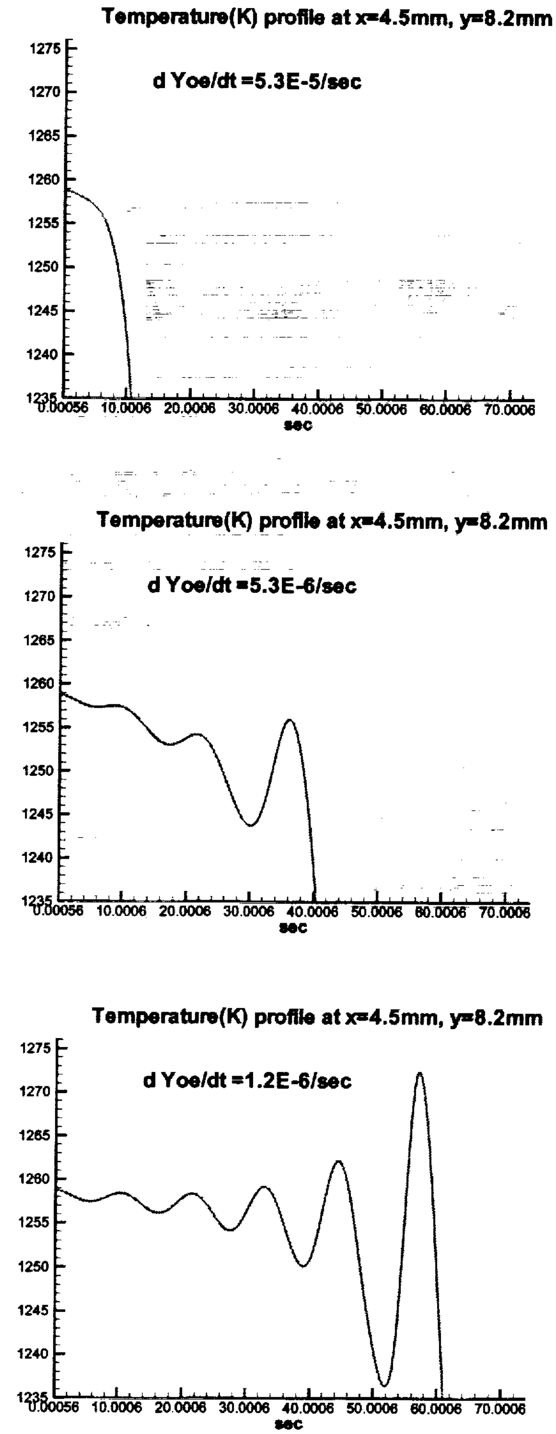


Figure 3. Reaction rate contours for three steady candle flames in different oxygen mole fraction ambients.

Figure 4. Near-limit flame oscillations for three candle flames with different rates of oxygen depletion.