MODELING CANDLE FLAME BEHAVIOR IN VARIABLE GRAVITY

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Introduction

The burning of a candle, as typical non-propagating diffusion flame, has been used by a number of researchers to study the effects of electric fields on flame, spontaneous flame oscillation and flickering phenomena, and flame extinction [1- 3]. In normal gravity, the heat released from combustion creates buoyant convection that draws oxygen into the flame. The strength of the buoyant flow depends on the gravitational level and it is expected that the flame shape, size and candle burning rate will vary with gravity. Experimentally, there exist studies of candle burning in enhanced gravity (i.e. higher than normal earth gravity, g_e) [4], and in microgravity in drop towers and space-based facilities [5-7]. There are, however, no reported experimental data on candle burning in partial gravity ($g < g_e$).

In a previous numerical model of the candle flame [7], buoyant forces were neglected. The treatment of momentum equation was simplified using a potential flow approximation. Although the predicted flame characteristics agreed well with the experimental results, the model cannot be extended to cases with buoyant flows. In addition, because of the use of potential flow, no-slip boundary condition is not satisfied on the wick surface. So there is some uncertainty on the accuracy of the predicted flow field.

In the present modeling effort, the full Navier-Stokes momentum equations with body force term is included. This enables us to study the effect of gravity on candle flames (with zero gravity as the limiting case). In addition, we consider radiation effects in more detail by solving the radiation transfer equation. In the previous study, flame radiation is treated as a simple loss term in the energy equation [7]. Emphasis of the present model is on the gas-phase processes. Therefore, the detailed heat and mass transfer phenomena inside the porous wick are not treated. Instead, it is assumed that *a thin layer of liquid fuel coated the entire wick surface* during the burning process. This is the limiting case that the mass transfer process in the wick is much faster than the evaporation process at the wick surface.

Model Formulation

The theoretical model considers a vertical candle with a 1*mm* wick diameter, an exposed wick length of 5*mm* and candle length (from candle base to wick tip) of 25*mm* burning in an infinite, air ambient (1 atm pressure). For most of the computation performed, the wick diameter will be 1*mm*. The main assumptions of the mathematical model are as follows. The flow is steady, laminar and axisymmetric (cylindrical coordinates). The gas-phase model assumes a single-step, second-order overall Arrhenius reaction, variable specific heats and thermal conductivity, constant Lewis number for each species (but different for each species), and ideal gas behavior. Full Navier-Stokes equations along with the conservation equation of mass, energy and species are solved. Flame radiation from CO_2 and H_2O is accounted for through the radiative divergence term in the energy equation. The radiative transfer equation is solved by the discrete ordinates method (DOM). For the application of DOM, the physical domain is assumed as a right cylindrical shaped enclosure containing an absorbing-emitting, non-scattering medium with mean absorption coefficients that vary from location to location. The mean absorption coefficient κ is $\kappa = 0.4[X_{CO_2} K_{P,CO_2} + X_{H_2O} K_{P,H_2O}]$ where the Planck mean absorption coefficients $K_{p,i}$ as a function of local temperature are taken from [9]. The multiplication factor 0.4 is used because of the non-optically thin nature of the flame [10]. The reason of this modification factor is that CO_2 and H_2O are not thin enough in the flame and self absorption in the spectral bands can be substantial. In other words, the use of the Planck Mean absorption coefficient would over-predict the gas radiation heat fluxes if not modified. The activation energy and the pre-exponential factor of the combustion reaction are selected such that the oxygen concentration at extinction for a candle with a 1mm wick diameter is 0.17 (mole fraction). This results in values of 30$kcal\ mole^{-1}$ and $3\text{x}10^{12} cm^3\ g^{-1}\ s^{-1}$, for the activation energy and the pre-exponential factor, respectively. For the boundary conditions, the entire wick is assumed to be coated with liquid fuel at boiling temperature 620K). The candle surface is assumed to be an inert solid with a prescribed temperature distribution. Complete details of the model and solution procedure are available elsewhere [8], along with complete listing of the results and discussion.

Results and Discussions

Effect of gravity

Figure 1 shows the influence of gravity (up to 5g_e) on candle flame shape and size. The reaction rate contour of w_f=5x10^{-5}$g\ cm^{-3}\ s^{-1}$ represents the boundary of the visible flame. The flame length increases as the gravity level increases from 0g_e to 3g_e, decreases from 3g_e to 60g_e and blows off at higher gravity levels. The stand-off distance (the distance from the line of symmetry to the maximum width of flame) decreases with increasing gravity level. Figure 1 also shows that there is a sudden downstream retreat of the flame base position from 3g_e to 5g_e. At 10g_e and above (not shown in Fig. 1), the flame base is downstream of the flat wick top surface. In this model we have assumed that the liquid fuel is coated over the entire wick surface including the top. The solutions for 10g_e and above show that the fuel vapors that support the flame come entirely form the wick top surface. In other words, above 10g_e the candle flame is a wake flame.

If the top surface of the wick is made inert, the model predicts that the flame blows off at 6g_e, instead of at approximately 60g_e. Villermaux and co-workers [10] gave a blow-off limit of approximately 7g_e. It seems very possible that no liquid wax reaches the wick tip in the experiments. In normal candle burning, the wick adjusts its length by the self-trimming process. If the wick is too long, it is unable to draw enough liquid to the top portion. The lack of evaporative cooling in this dry portion increases its temperature and burns off the excess length. The result of this process is that for a self- trimmed candle, the wick length is where the wick tip fails to have enough liquid fuel. Also, in increasingly high gravity levels the gravitational force on the liquid in the wick becomes more significant [4]. It is reasonable to believe therefore that the inert wick top results are applicable and the numerical model and existing experimental data are in good agreement.

Figure 2 shows the total wax burning rate and maximum flame temperature as a function of gravity level. The burning rate increases with gravity and reaches a maximum at 3g_e. At higher gravity levels, the flame retreats (Fig. 1), and the burning rate drops quickly (Fig. 2).

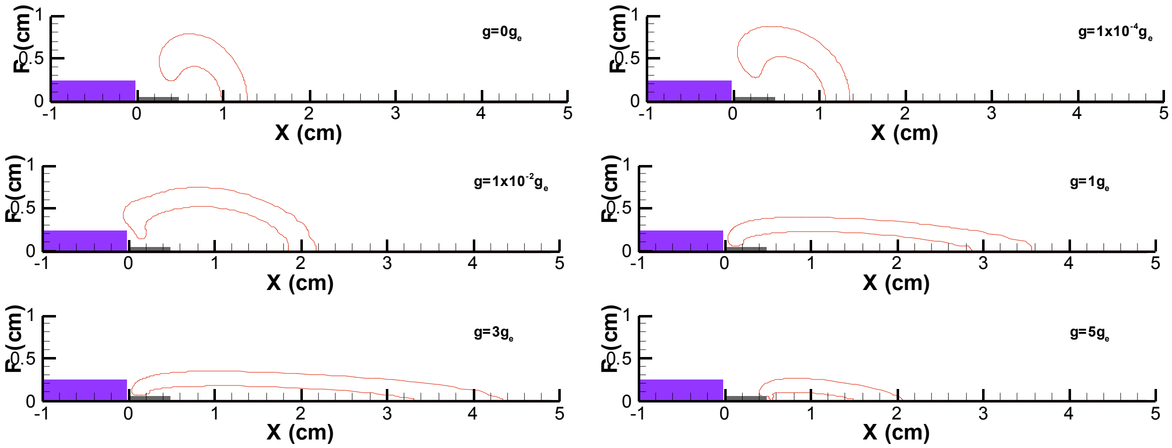


Figure 1: Fuel reaction rate contours at various gravity levels (each contour has a value of $5x10^{-5} g\ cm^{-3}\ s^{-1}$).

At high g_e's, the maximum temperature is close to the adiabatic temperature, but it decreases as g decreases and reaches 1130K at zero g_e. The low flame temperatures at the reduced gravity levels suggest the influence of heat losses (radiation and conduction).

Comparison of Flame Structure Between $0g_e$ and $1g_e$ Flames

Figure 1 shows that there is a large difference between candle flame shapes at high and low gravity levels. The shape difference is a manifestation of the different transport processes important in these flames. Figure 3 presents the fuel vapor reaction rate contours and the temperature contours for (a) $0g_e$ and (b) $1g_e$. At $0g_e$, both the reaction rate and the temperature contours are hemispheric shaped with a thermal-diffusive length about $6mm$. The model predicts a steady flame diameter, D, and flame height, H, of $14.9mm$ and $9.45mm$, respectively, which compares quite well with the experimental values of $14.5mm$ and $11.2mm$ [7]. At $1g_e$, the flame is elongated and narrow. The flame base stabilization zone, located at the wick base, is small compared with the wick length. The thermal-diffusional distance is of the order of $1mm$.

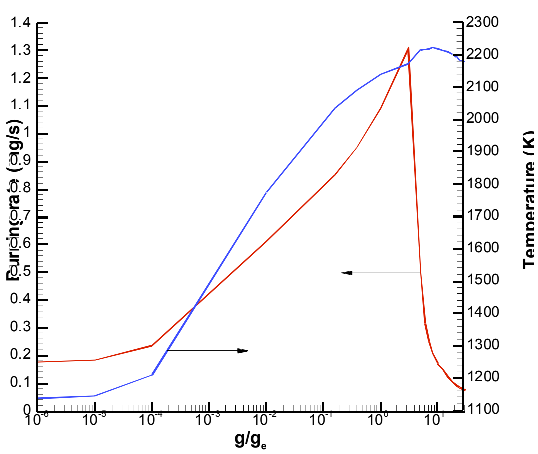
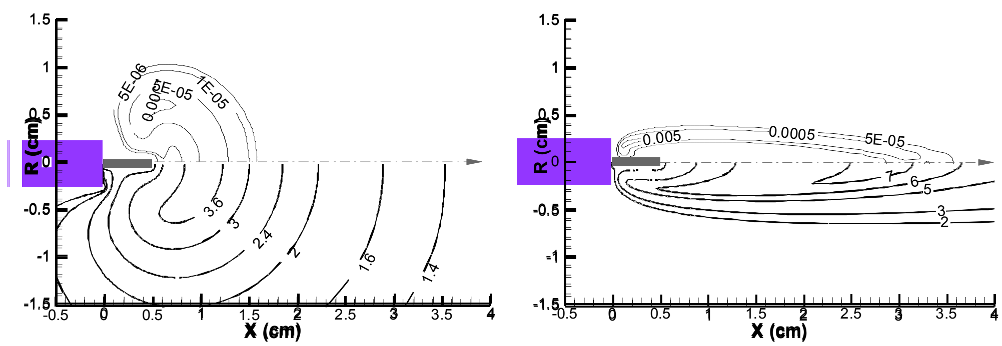


Figure 2: Candle burning rate and maximum gas temperature at various gravity levels.

Effect of Radiation

Radiative heat loss has been attributed to the occurrence of low-stretch one-dimensional diffusion flame extinction [11] and has also been suggested to contribute to the observation of blue colored microgravity candle flame [7]. In $0g_e$ candle flame, the ratio of radiation loss/heat generation is 37.6% and the ratio of conduction loss/heat generation is 29%. We performed computations to determine the relative contributions of the different types of radiation sources (gas vs. surface). The three computations were: (1) with flame and surface radiation (flame temperature 1130.5K), (2) without flame but with surface radiation and (1435.8K) (3) without both flame and surface radiation (1452.2K). From this, we can deduce that surface radiative loss is not important and radiative and conductive losses are both important. Furthermore, there is substantial unburnt fuel vapor leaking through the quenched base that contributes to the low flame temperature. We note in computing the heat generation rate, the total evaporation rate has been used.

The small loss from surface radiation seems surprising since in other solid burning problems with similar surface temperatures [12] it is a major contributor to total heat loss. The difference is that in the microgravity candle flame, the total surface area of the wick is small so the majority of radiative loss comes from the gas phase. The conductive loss in this example is even bigger than the radiative loss. The exact amount of radiative and conductive losses will depend on the wick (or flame) diameter and the surface temperature boundary conditions but suffice to say that both types of losses are important in the candle low burning rate regime.



(a) (b)

Figure 3: Flame temperature (lower half, normalized by 300K) and fuel vapor reaction rate (upper half) contours for 1mm diameter candle (a) microgravity ($0g_e$) and (b) normal gravity ($1g_e$).

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