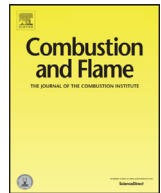




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Unsteady droplet combustion with fuel thermal expansion

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ABSTRACT

Millimeter-size fuel droplets burning in microgravity show substantial thermal expansion at earlier times in their burning history. Here, we develop a simple model that accounts for thermal expansion of the liquid fuel and compare it against experimental measurements. The results show that excellent agreement with measured droplet-diameter histories throughout the hot-flame period of combustion is obtained when the effect of thermal expansion is included.

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1. Introduction

The senior author of this contribution (FAW) is especially grateful for this opportunity to honor C. K. Law for his many important contributions in combustion, by offering here one small further advance in the theory of droplet combustion, a topic included in Law's Ph.D. thesis with this author.

The classical theory of droplet combustion [1] predicts that the square of the droplet diameter decreases linearly with time, a result that is widely used, for example in spray-combustion applications, to this day for estimating burning rates. This theory, however, neglects many of the unsteady effects associated with droplet combustion which could become important under certain conditions [2]. For example, recent droplet-combustion experiments carried out in the International Space Station [3,4] show that a large *n*-alkane droplet, initially at room temperature, following hot-wire ignition, burns with a hot flame for a short duration and then extinguishes through excessive radiative heat loss, only to be followed by a low-temperature cool flame that supports continued droplet vaporization. A major portion of the hot-flame burning occurs during the unsteady droplet heat-up period in these experiments, while the cool-flame combustion is primarily quasi-steady. Experimental results also show that the square of the droplet diameter actually increases after ignition and becomes a linearly decreasing function of time only later, just prior to hot-flame extinction. This observation points to the fact that, during the droplet heat-up period, thermal expansion could play a significant role.

Unsteady effects caused by liquid-phase heating during droplet combustion were examined by Law [5] and Law and Sirignano [6] under two limiting conditions, a rapid-mixing limit [5], in which the droplet temperature becomes spatially uniform but temporally varying, and a heat-conduction limit [6], where it varies both radially and temporally. In these studies, the effect of thermal expansion of the liquid droplet was not considered, and the liquid-phase density was assumed to be constant. Such thermal expansion effects have been addressed previously, both theoretically [7] and experimentally [8], but they have not yet been studied for droplet combustion. Here we consider the rapid-mixing limit, and, unlike [5], include liquid thermal-expansion effects. The results are compared with predictions of the constant-density model of Law [5] and with experimental data obtained from the recent space-based droplet-combustion experiments [9], to assess the importance of thermal expansion of the liquid fuel.

2. Formulation

Consider a fuel droplet with an initial radius r_{s0} , and a uniform initial temperature T_{s0} , which is below its boiling point T_b corresponding to the ambient pressure p_∞ . When this droplet is ignited in a microgravity environment, a spherical flame surrounds the droplet, and it is heated from its initial temperature, approaching a quasi-steady equilibrium temperature. During this heat-up period the droplet density ρ_ℓ (the initial value of which is $\rho_{\ell 0}$) decreases, leading to droplet swelling. The gas-phase combustion processes are much faster than the liquid-phase thermal evolution, whence, as before [5,6] we can assume the gas phase to be quasi-steady. The gas-phase conservation equations are then readily solved once the droplet radius r_s , its surface temperature T_s , and

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an effective heat of vaporization per unit mass of fuel consumed L_e are specified, for example by employing a mixture-fraction coordinate, as earlier [10], an approach that applies under suitable additional approximations discussed in that publication and that will be adopted here.

The gas-phase results that are needed to address the unsteady liquid-phase thermal-evolution problem are the droplet mass burning rate \dot{m} and the surface fuel mass fraction Y_{Fs} , which are expressed in dimensionless form as

$$\dot{m}/(4\pi\rho Dr_s) = \ln(1+B), \tag{1}$$

where the transfer number is

$$B = (\tilde{T}_\infty - \tilde{T}_s + \tilde{Y}_{O_\infty})/\tilde{L}_e, \tag{2}$$

and as

$$Y_{Fs} = \frac{(\tilde{T}_\infty - \tilde{T}_s + \tilde{Y}_{O_\infty}) - \tilde{L}_e \tilde{Y}_{O_\infty}}{\tilde{T}_\infty - \tilde{T}_s + \tilde{L}_e + \tilde{Y}_{O_\infty}}, \tag{3}$$

where the oxygen mass fraction Y_O , the temperature T , and the effective heat of vaporization L_e are normalized as $\tilde{Y}_O = Y_O/\nu$, $\tilde{T} = c_p T/Q$, and $\tilde{L}_e = L_e/Q$, where Q is the heat of combustion per unit mass of fuel consumed, c_p is the specific heat of the gas, and ν is the stoichiometric oxygen-to-fuel mass ratio. In Eq. (1) ρ is the gas density and D is the mass diffusivity, both approximated as constants, Lewis numbers have been set equal to unity. In addition to these results, an independent relationship between the fuel surface temperature and its mass fraction can be specified from the Clausius–Clapeyron equation:

$$Y_{Fs} = \exp\left[\frac{\tilde{L}_e c_p}{R_g} \left(\frac{1}{\tilde{T}_b} - \frac{1}{\tilde{T}_s}\right)\right], \tag{4}$$

where \tilde{L} is the latent heat of vaporization L , also normalized by Q , and R_g is the gas constant per unit mass, the molecular weights of the gas-phase species at the droplet surface having all been set equal, for simplicity.

In this analysis, we assume that the droplet temperature is uniform as a result of vigorous internal mixing, the so-called “Law-limit” [5]. In the microgravity experiments [9], the opposed-needle deployment technique, in which the droplet is stretched between two hypodermic needles that are suddenly withdrawn to freely deploy the droplet in microgravity, enhances internal liquid mixing, as does the thermo-capillary flow generated by the hot-wire igniters (see [9] for details). The droplet density ρ_ℓ as a function of its temperature T_s can be expressed in a linearized form around a reference temperature T_r . With T_r taken to be the equilibrium vaporization temperature, as is done here, this linear approximation remains accurate over the entire range of temperatures, for the moderate pressures of these experiments, so that

$$\rho_\ell(T_s) = \rho_{\ell r}[1 - \beta(T_s - T_r)], \tag{5}$$

where $\rho_{\ell r} = \rho_\ell(T_r)$ is the reference droplet density, and $\beta = (d\rho_\ell/dT)/\rho_{\ell r}$ is the coefficient of thermal expansion. The value of T_r is determined by putting \tilde{L}_e equal to \tilde{L} in Eq. (3) and employing that in Eq. (4), thereby requiring an iterative computation when the properties of the atmosphere are specified. In the Law limit,

$$L_e = L + \frac{m_\ell c_{p\ell} d(T_s)/dt}{\dot{m}} \tag{6}$$

where $c_{p\ell}$ is the liquid specific heat (assumed constant), and $m_\ell = (4/3)\pi\rho_\ell r_s^3$ is the instantaneous droplet mass. The difference between L and L_e is of critical importance, the former applying in the Clausius–Clapeyron equation but the latter in the transfer number.

3. Analysis

With $X = (r_s/r_{s0})^2$, Eq. (1) may be used in Eq. (6) to yield, after rearrangement,

$$\frac{d\tilde{T}_s}{d\tau} = (\tilde{L}_e - \tilde{L}) \frac{\ln(1+B)}{(\tilde{\rho}_\ell \tilde{c} X)}, \tag{7}$$

in which

$$\tilde{\rho}_\ell = 1 - \tilde{\beta}(\tilde{T}_s - \tilde{T}_r), \tag{8}$$

where $\tilde{\rho}_\ell = \rho_\ell/\rho_{\ell r}$, $\tilde{c} = c_{p\ell}/c_p$, $\tilde{\beta} = \beta Q/c_p$, and the non-dimensional time has been defined as $\tau = 3\rho Dt/(\rho_{\ell r} r_{s0}^2)$. Eq. (3) can be solved explicitly for \tilde{L}_e , giving

$$\tilde{L}_e = \frac{(1 - Y_{Fs})(\tilde{T}_\infty - \tilde{T}_s + \tilde{Y}_{O_\infty})}{Y_{Fs} + \tilde{Y}_{O_\infty}}, \tag{9}$$

which, in view of Eq. (4), serves to express \tilde{L}_e as a function of droplet temperature alone for use in Eq. (6), when conditions in the ambient atmosphere are fixed.

An additional expression for X , which is a function of time, is needed before Eq. (7) can be solved. The definition of \dot{m} provides such a relationship, namely

$$\dot{m} = -\frac{4}{3}\pi \frac{d}{dt}(\rho_\ell r_s^3) = 4\pi\rho Dr_{s0} X^{1/2} \ln(1+B). \tag{10}$$

Use of Eqs. (6) and (7) in this expression results in

$$\frac{3}{2}\tilde{\rho}_\ell \frac{dX}{d\tau} = -[1 - (\tilde{L}_e - \tilde{L})\tilde{\beta}/(\tilde{\rho}_\ell \tilde{c})] \ln(1+B). \tag{11}$$

With Eqs. (2), (4), (8), and (9) providing necessary functions of \tilde{T}_s , Eqs. (7) and (11) are two coupled nonlinear ordinary differential equations for $\tilde{T}_s(\tau)$ and $X(\tau)$, which are to be solved with the initial conditions $\tilde{T}_s(0) = \tilde{T}_{s0}$ and $X(0) = 1$. These equations are readily integrated numerically to obtain X and \tilde{T}_s as functions of time.

4. Results and comparisons

In this analysis the initial droplet diameter d_0 , which is equal to $2r_{s0}$, appears only as a scaling parameter for X and the dimensionless time τ . Figure 1 shows a representative comparison the predicted dependence of both X and the droplet temperature on τ , for three different sets of assumptions. Property values selected for the three fuels considered are listed in Table 1; the values of the parameters chosen for Fig. 1 correspond to *n*-decane in air at one atmosphere pressure, initially at a droplet temperature of 300 K. The calculated equilibrium liquid temperature under those conditions is 442.5 K, a little less than the normal boiling point of 447 K.

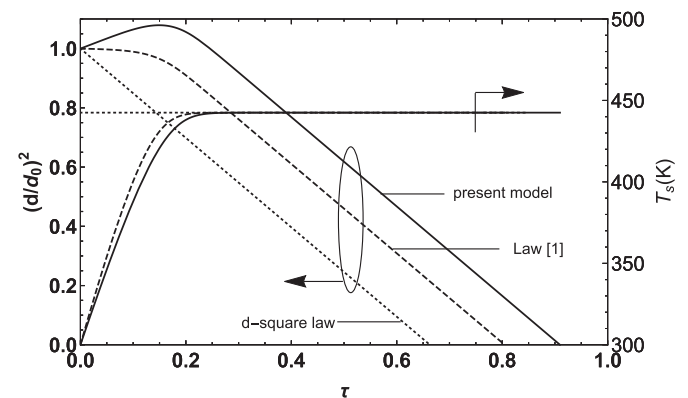


Fig. 1. Normalized droplet diameter squared and droplet temperature as functions of dimensionless time, with (solid lines) and without (dashed lines) thermal expansion; results for the d-square law are shown as dotted lines.

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