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Single Droplet Vaporization Including Thermal Radiation Absorption

P. L. C. Lage* and R. H. Rangel†
University of California, Irvine, Irvine, California 92717

Total hemispherical absorption distributions for *n*-decane and water droplets irradiated by a blackbody under spherically symmetric conditions are used in the calculation of transient droplet heating and vaporization. The gas model used is based on the extended film theory. Three liquid-phase models have been extended to include thermal radiation absorption. The results show that radiation absorption can be as important as, or more important than, the choice of liquid-phase model. Based on the effective-conductivity model, two dimensionless parameters expressing the ratios of radiation absorption and gas-liquid heat transfer to liquid conductive and convective heat transfer are defined. It is shown that the first parameter determines the droplet heating regime. Over 200 numerical calculations using the effective-conductivity model and various initial and ambient conditions have been performed for water and *n*-decane droplets. It is shown that the ratio of the two dimensionless parameters evaluated at the initial time can be used to correlate and predict the radiation absorption influence on the droplet lifetime. All cases investigated correspond to the slow heating regime. Under the conditions analyzed, the nonuniformity of the radiation absorption has little effect on the overall droplet heating and vaporization process.

Nomenclature

C_D = droplet drag coefficient
c_p = specific heat
F = dimensionless radiation to conduction parameter, $(R\alpha\mathcal{G})/[4k_l(T_\infty - T_r)]$
F_1 = dimensionless radiation parameter Eq. (4), $(3R\alpha\mathcal{G})/[4R_0\rho_l c_{pl} U_r(T_\infty - T_r)]$
$\mathcal{G}$ = total incident irradiance
k = thermal conductivity
$\dot{m}$ = mass vaporization rate
P = pressure
Q = total hemispherical absorption distribution
$\langle Q\rangle$ = mean volumetric absorption
Q_L = total heat transfer from the gas phase to the droplet
R = droplet radius
Re = Reynolds number, $2R|U_\infty - U|\rho_\infty/\bar{\mu}$
r = radial coordinate
S = dimensionless radiation absorption distribution, $Q/\langle Q\rangle$
T = temperature
U = velocity
U_r = reference quantity with units of velocity
u = dimensionless velocity, R_0U/α_l
u_1 = dimensionless velocity, U/U_r
V = droplet volume
X = coordinate along one-dimensional droplet trajectory
x = dimensionless droplet trajectory coordinate, X/R_0
α = absorptance or thermal diffusivity
β = dimensionless droplet radius, $R(t)/R_0$
Γ = dimensionless vaporization rate, $\dot{m}/2\pi\rho_l\alpha_l R$
Γ_1 = dimensionless vaporization rate, $\dot{m}/2\pi RR_0U_r\rho_l$
γ = density ratio, ρ_∞/ρ_l
δ = parameter in energy equation solution, Eqs. (8) and (10)
η = dimensionless radial coordinate, $r/R(t)$
Θ = dimensionless temperature, $(T - T_\infty)/(T_r - T_\infty)$
Λ = dimensionless liquid phase heat flux from the gas phase to conduction flux, $Q_L/[4\pi Rk_l(T_\infty - T_r)]$
Λ_1 = dimensionless liquid phase heat flux (Eq. 4), $(3Q_L)/[4\pi R_0^2\rho_l c_{pl} U_r(T_\infty - T_r)]\beta$
μ = dynamic viscosity
ρ = density
τ = dimensionless time, $\alpha_l t/R_0^2$
τ_1 = dimensionless time, $U_r t/R_0$
χ = effective-conductivity factor

Subscripts
b = blackbody
c = critical point
l = liquid
r = reference, also reduced conditions
s = droplet surface
∞ = freestream
0 = droplet initial conditions
1 = infinite-conductivity model

Superscript
$\bar{}$ = film conditions ($\frac{1}{3}$ rule)

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*Junior Specialist, currently Assistant Professor, Department of Chemical Engineering, COPPE/UFRJ, 21945 Rio de Janeiro, P.O. Box 68502, Brazil.
†Assistant Professor, Department of Mechanical and Aerospace Engineering. Senior Member AIAA.

Introduction

SPRAY heating and vaporization is a common feature in numerous processes, such as spray combustion and spray drying. In the first, temperatures are high enough to make radiative heat transfer important. However, the existing models for single-droplet vaporization and combustion do not consider radiation at all (Faeth,[1] Law,[2] Sirignano,[3] and Rangel[4]). In the framework of spray combustion modeling, the single-droplet vaporization model should include the radiation absorption inside the droplet, whereas, the whole combustor simulation should be responsible for taking into account the radiative heat exchange among surfaces and volume elements. The simplified single-droplet models used in global combustor simulations (e.g., Abramzon and Sirignano,[5] Tong and Sirignano[6]) should then be extended to include the internal radiation absorption by the liquid fuel.

The heating and vaporization of a stagnant water droplet irradiated by a laser beam has been analyzed by Park and

Armstrong,[7] using electromagnetic theory. They have identified that there are two possible regimes of droplet heating: 1) the fast heating regime, and 2) the slow heating regime. In the former, the intensity of the incident beam is so large that the droplet heats up to the spinoidal temperature before any appreciable mass and heat transfer between the liquid and gas phases or liquid internal conduction take place. Therefore, the temperature profiles inside the liquid are similar to the absorption profiles, and the droplet explodes before any appreciable vaporization. However, the vaporization rates are so large that there is nonequilibrium at the droplet surface and kinetic boundary conditions must be used. This regime may be approximated as a source-dominated problem, without vaporization.[8] On the other hand, in the slow heating regime, the radiative energy absorbed is not enough to control the heating process. Conduction and vaporization are appreciable. It is also possible to admit a quasi-steady-state condition in which equilibrium at the droplet surface exists. The temperature profiles are almost symmetric, being similar to those obtained using a uniform source, and the maximum internal temperature occurs in the droplet center, being only a few degrees larger than the liquid boiling point. This rules out the possibility of explosive vaporization, at least through homogeneous nucleation.

Recently, Sitarski[9] has analyzed the vaporization of a coal-water slurry droplet irradiated by a black infinite plane. A simplified calculation was used to determine the total absorption distribution for slurry droplets using electromagnetic theory. The adequacy of this approximation has been recently analyzed by Lage and Rangel.[10] The axisymmetric heat conduction problem has been solved with kinetic heat and mass fluxes at the droplet interface, using finite-differences and a Monte-Carlo technique. The kinetics boundary conditions were used because the droplet sizes considered (20 μm, initially) were in the near-continuum and transition regimes of Knudsen numbers. Since the droplets are initially at the water boiling point, no droplet heating was considered. The results were characteristic of a slow heating regime; temperature profiles nearly symmetric, and maximum temperature only a few degrees above the boiling point.

In the present work, the role of internal radiation absorption in single-droplet vaporization is investigated for a simplified configuration where the incident radiation is assumed to be spherically symmetric and with blackbody spectral intensity distribution. Recently, Lage and Rangel[10] have calculated the total radiation absorption distribution for decane and water droplets irradiated by a blackbody in a nonparticipating medium under several axisymmetric configurations using electromagnetic theory. The spherically symmetric results, corresponding to isotropic blackbody radiation, are used here in the droplet vaporization analysis. The chosen configuration and the nonparticipating medium hypothesis impose some restrictions on the direct application of the present analysis in spray combustion situations. Nevertheless, the present work allows to quantify the radiation absorption effect in droplet vaporization. The results provide sufficient insight into this phenomenon, helping in future modeling attempts.

For the vaporization studies, the gas-phase model is based on the extended film theory developed by Abramzon and Sirignano,[5] and three liquid-phase heating models (infinite-conductivity,[2] conduction-limit,[11] and effective-conductivity[5]) are used in the calculations. All three liquid-phase models are extended by the inclusion of internal radiation absorption.

Vaporization Models with Radiation Absorption

The gas-phase model used is described by Abramzon and Sirignano,[5] and will not be discussed here. However, it should be noticed that it considers quasi-steady vaporization with quasi-steady phase equilibrium at the droplet surface, which implies the slow heating regime assumption. It also considers the dependence of the convective heat transfer on the Reynolds number. The gas phase is considered to be a mixture of air and the liquid vapor (n-decane or water) at a specific pressure. The liquid phase is considered to be pure n-decane or water, with constant physical properties, except for the dynamic viscosity, which is considered to be temperature-dependent. Special care is taken to use experiment-based correlations for the physical properties of the two phases with a small maximum deviation (usually better at 1%). Estimation techniques are used only for decane vapor[12] due to lack of experimental data. The equilibrium pressure is calculated by Wagner's equation for water, and a combination of Wagner and Antoine's equation for decane.[12] The data for the diffusion coefficient correlations, as well as most of the properties, are taken from Vargaftik.[13]

The droplet dynamics equations are given by Abramzon and Sirignano[5] for a one-dimensional trajectory. They simply relate the acceleration to the drag force, neglecting the velocity history term. For the infinite-conductivity model, they can be written in the following dimensionless form:

$$\frac{dx}{d\tau_1} = u_1 \tag{1}$$

$$\frac{du_1}{d\tau_1} = \frac{3}{8}\frac{\gamma}{\beta}|1 - u_1|(1 - u_1)C_D(Re) \tag{2}$$

Using the quasisteady vaporization assumption, the droplet surface regression rate can be written in dimensionless form as

$$\frac{d\beta^2}{d\tau_1} = -\Gamma_1 \tag{3}$$

For the infinite-conductivity model, the droplet energy equation with radiation absorption, can be written in the following dimensionless form:

$$\frac{d\Theta}{d\tau_1} = -\frac{1}{\beta^2}(\Lambda_1 + F_1) \tag{4}$$

For the effective-conductivity model, the droplet dynamics equations and the droplet surface regression rate are, in dimensionless form

$$\frac{dx}{d\tau} = u \tag{5}$$

$$\frac{du}{d\tau} = \frac{3}{8}\frac{\gamma}{\beta}|u_\infty - u|(u_\infty - u)C_D(Re) \tag{6}$$

$$\frac{d\beta^2}{d\tau} = -\Gamma \tag{7}$$

The energy equation for the effective-conductivity model, including radiation absorption, can be written in dimensionless variables as

$$\frac{\partial\Theta}{\partial\tau} = \frac{1}{\beta^2}\left\{\chi\frac{\partial^2\Theta}{\partial\eta^2} + \left[\frac{2\chi}{\eta} - \frac{\eta}{2}\Gamma(\tau)\right]\frac{\partial\Theta}{\partial\eta} - (1 - \delta)3F(\tau)S(\eta, \tau)\right\} \tag{8}$$

$$\tau = 0, \qquad \Theta = \Theta_0 \tag{9}$$

$$\eta = 1, \qquad \frac{\partial\Theta}{\partial\eta} = -\frac{1}{\chi}(\Lambda + \delta F) \tag{10}$$

where δ is a parameter which enables one to consider radiation as volumetric absorption ($\delta = 0$), surface absorption ($\delta = 1$), or any intermediate case ($0 < \delta < 1$). The actual absorption corresponds to $\delta = 0$. $S(\eta, \tau)$ is the dimensionless absorption distribution, defined as[10]

$$S = (Q/\langle Q \rangle) \tag{11}$$

as a result, we have

$$\frac{1}{V}\int_V S \, dV = 1 \tag{12}$$

Note that $S = 1$ implies a uniform radiation absorption inside the droplet.

The effective-conductivity factor is calculated as the ratio of the liquid Nusselt number with and without internal combustion. A correlation in terms of the liquid Peclet number is given by Abramzon and Sirignano[5]:

$$\chi = 1.86 + 0.86 \tanh[2.245 \log_{10}(Pe_l/30)] \tag{13}$$

This correlation agrees with the Johns and Beckmann's simulation results[14] within $\pm 2\%$.[5] The liquid phase Reynolds number is determined by matching the tangential stress at the droplet surface and using a friction drag correlation.[5] This effective factor expresses the heat transfer enhancement due to internal circulation as an increase in the liquid thermal conductivity. Since internal radiation absorption provides an additional heat source inside the droplet, the effective-conductivity factor could also depend on F. Such dependence can be assessed through comparison between simulations using the two-dimensional circulating liquid model and the effective-conductivity model. Here, this dependence will be ignored and the effect of this approximation will be analyzed later. Equations (5–10), with $\chi = 1$, hold for the conduction-limit model.

The relative importance of radiation absorption to liquid heat transfer (conduction plus internal circulation) can be represented by the dimensionless ratio F/χ, which appears in the dimensionless energy equation [Eq. (8)]. Using the same kind of reasoning that Park and Armstrong[7] utilized for a pure conductive droplet irradiated by a laser beam, we can define the heating regime classification for a circulating droplet irradiated by nonspectral incident radiation as

$$F/\chi >> 1 \Rightarrow \text{fast heating regime}$$

$$F/\chi << 1 \Rightarrow \text{slow heating regime}$$

Since χ varies between 1–2.72, the F value largely determines the heating regime.

Numerical Procedure

During heating, the droplet temperature increases from its initial value to close to the substance boiling point near the droplet surface. This temperature variation affects the thermophysical properties (mainly the dynamic viscosity) as well as the optical properties. For water, the variation of the optical properties with temperature has already been investigated by Hale et al.[15] and by Pinkley et al.[16] Their results show that the optical properties of water do not vary significantly over the 1–70°C range. Accordingly, Pendleton[17] provided an explanation for explosive vaporization patterns of water droplets irradiated by lasers, without considering the variation of the optical properties with temperature. There are no similar studies available for decane optical properties. For the droplet vaporization simulations, the total hemispherical absorption distributions obtained by Lage and Rangel,[10] assuming temperature-independent optical constants, were used.

The infinite-conductivity model consists of a system of four differential equations [Eqs. (1–4)]. This system of ordinary differential equations has been solved by an ODE solver based on a third-order semi-implicit Runge-Kutta method with step selection. This ODE solver has been implemented using the development given by Villadsen and Michelsen,[18] but with the possibility of calculating the system Jacobian numerically by finite differences. The finite-difference approximation for the Jacobian has been taken from DASSL.[19] Standard "stiff" problems (Van der Pol's equation, Robertson problem, and exponential systems with eigenvalues ratio up to 1000) have been used to test the ODE solver, which has been able to integrate them efficiently.

The effective-conductivity model has been solved by the orthogonal collocation method.[18] The set of ordinary differential equations which results from the discretization, plus Eqs. (5–7), has been solved using the same ODE solver described above. The results have been checked by increasing the number of collocation points. Accuracy always better than 0.1% could be achieved in the dimensionless surface temperature and radius for all times, with a number of collocation points in η^2 varying from 4 to 20, depending on the case considered.

In the numerical solution of the liquid phase models, the radiation absorption distribution and/or the total absorptance previously calculated,[10] are used as input and linearly interpolated in droplet size and radial position during the droplet vaporization calculation. A number between 9–24 droplet sizes has been used, making the linear interpolation between sizes a good approximation for the absorption distributions.

Results

A large number of droplet vaporization simulations have been performed with the liquid phase models cited above, over a wide range of initial and ambient conditions. The pressure has been set to 1 and 10 bar, the ambient temperature has been varied from 500 to 1800 K, the droplet initial radius has been varied from 25 to 100 μm, and the droplet initial Reynolds number has assumed values from 0 to 322. The blackbody temperature, in the cases where radiation absorption was considered, was set at 1050, 1450, and 2000 K for water, and 1000 and 1500 K for decane. In typical situations involving spray flames, the radiation-source temperature is equal to, or larger than, the temperature of the gas surrounding the droplet. Thus, the temperature of the radiation source is chosen accordingly. In all cases, the initial droplet temperature was 300 K. Representative results for the vaporization models, including the nonuniform radiation absorption, are shown in Figs. 1–4. The dimensionless radius and the dimensionless surface temperature vs time are shown in Figs. 1 and 2 for water irradiated by blackbody radiation at 1450 K, and in Figs. 3 and 4 for decane irradiated by blackbody

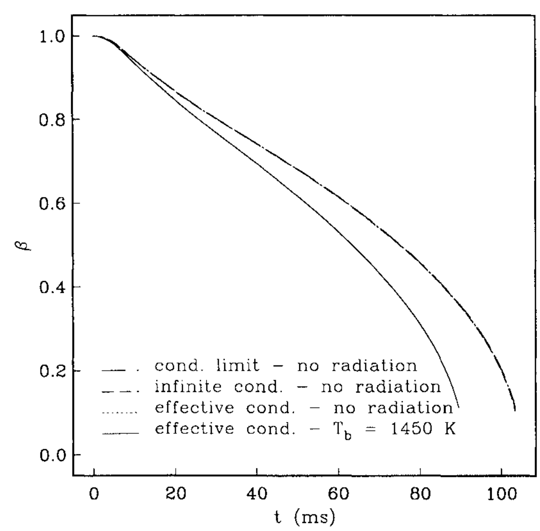

Fig. 1 Dimensionless radius variation for a water droplet, initially at 300 K and 50 μm in radius, irradiated by a blackbody at 1450 K, in a medium at 1000 K and 10 bar.

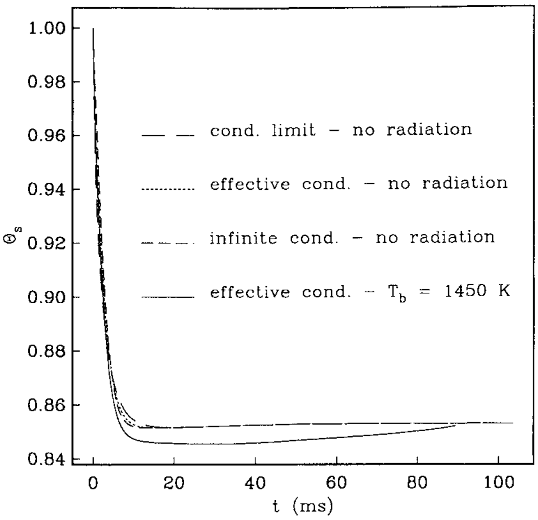

Fig. 2 Dimensionless surface temperature variation for a water droplet, initially at 300 K and 50 μm in radius, irradiated by a blackbody at 1450 K, in a medium at 1000 K and 10 bar.

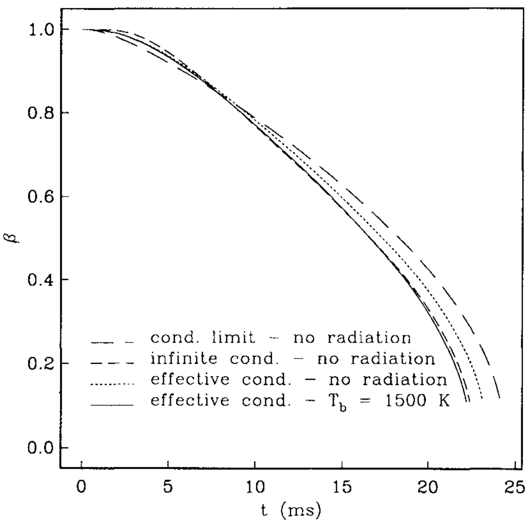

Fig. 3 Dimensionless radius variation for a *n*-decane droplet, initially at 300 K and 50 μm in radius, irradiated by a blackbody at 1500 K, in a medium at 1000 K and 10 bar.

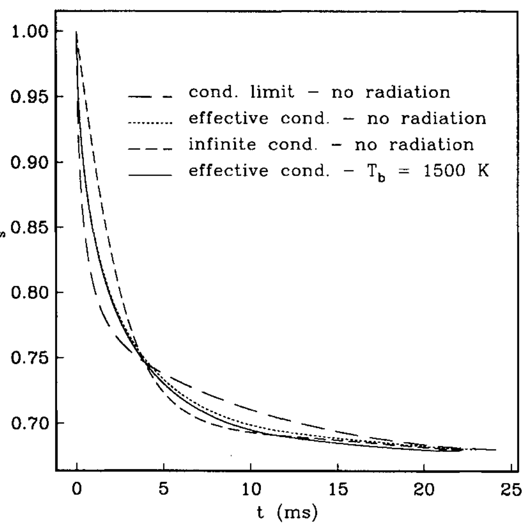

Fig. 4 Dimensionless surface temperature variation for a *n*-decane droplet, initially at 300 K and 50 μm in radius, irradiated by a blackbody at 1500 K, in a medium at 1000 K and 10 bar.

radiation at 1500 K. In both base cases, the initial radius is 50 μm, the initial Reynolds number is 98.5, the ambient pressure is 10 bar, and the ambient temperature is 1000 K. The reference temperature is the liquid initial temperature. It can be seen that radiation absorption can be as important as, or more important than, the choice of liquid-phase model.

Figure 5 shows the transient temperature profile inside a water droplet, with initial radius of 50 μm, irradiated by a blackbody at 2000 K in a stagnant environment at 500 K and 1 bar. These conditions have been chosen in order to achieve a large superheating, because low temperature and pressure decreases the gas-liquid transfer processes, and a large water droplet irradiated by a blackbody at 2000 K absorbs a large amount of radiative energy. From Fig. 5, it is clear that the relative temperature difference caused by radiation aborption is quite appreciable in this case. Since the surface gas concentration cannot increase without limit (the equilibrium concentration), there is a limit in the rate of heat removal through vaporization. Thus, if radiation is absorbed in the droplet at a rate that cannot be removed by the gas heat transfer processes, there is a temperature buildup inside the droplet. Accordingly, Fig. 5 shows that the temperature reaches a maximum during the droplet lifetime and then decreases. This figure presents temperature profiles throughout this maximum temperature, which can be calculated to be around 353 K, below the water boiling point at 1 bar. Therefore, there is not enough radiative energy, even for high-temperature blackbody irradiation, to produce explosive vaporization through homogeneous or heterogeneous nucleation. For even higher blackbody temperature, higher initial droplet temperature, and nonhomogeneous water droplets, the water boiling point could be surpassed, which would lead to explosive vaporization through heterogeneous nucleation. This seems to agree with the microexplosion of a coal-water slurry droplet predicted by Sitarski.[9] However, the occurrence of microexplosions in low-absorbing substances, such as hydrocarbons, is extremely unlikely, even through heterogeneous nucleation. In these cases, the droplet temperature increase due to radiation absorption is quite small. The radiative energy is mostly absorbed near the surface and used to enhance droplet vaporization rather than droplet heating. However, due to the nonlinear characteristics of the vapor-liquid equilibrium, even a small surface temperature variation indeed results in an appreciable difference in droplet lifetime. Figures 6 and 7 show the mass vaporization rate for the base water and decane cases, respectively.

The time-dependent behavior of the dimensionless numbers, F and Λ, has also been investigated. It has been verified that both numbers decrease during the vaporization process.

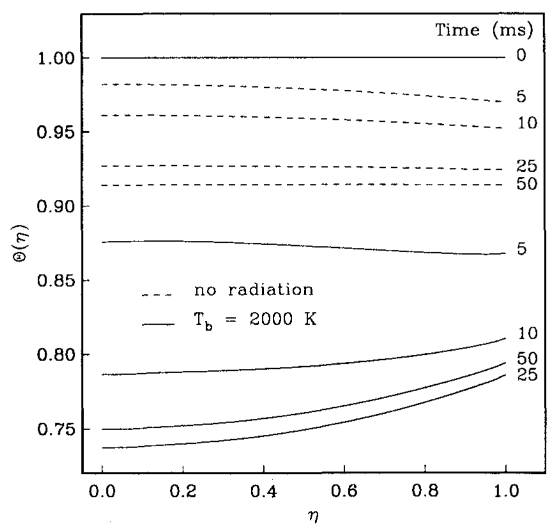

Fig. 5 Dimensionless temperature variation in water droplets, initially at 300 K and 50 μm in radius, with and without radiation from a blackbody at 2000 K, in a medium at 500 K and 1 bar.

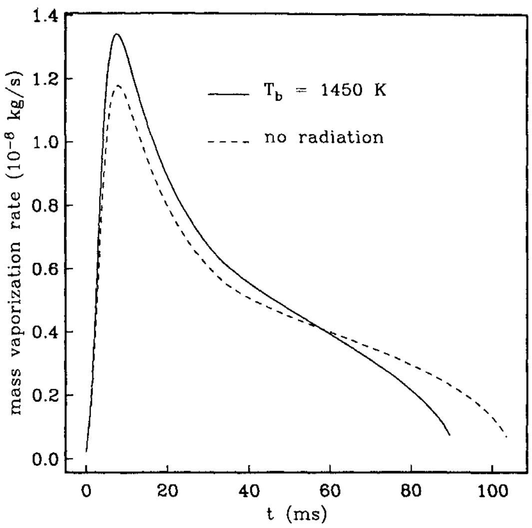

Fig. 6 Mass vaporization rate variation for a water droplet, initially at 300 K and 50 μm in radius, irradiated by a blackbody at 1450 K, in a medium at 1000 K and 10 bar.

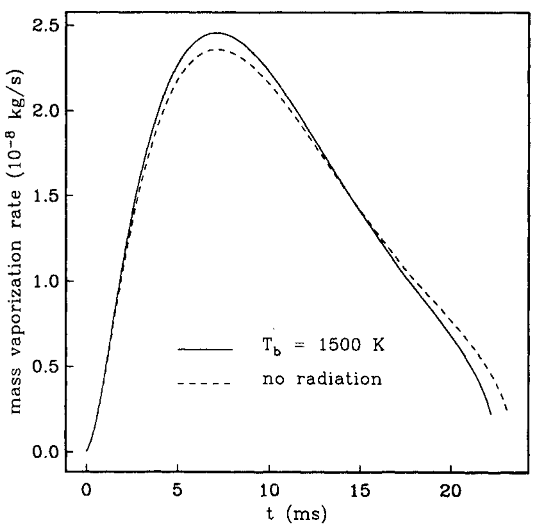

Fig. 7 Mass vaporization rate variation for a *n*-decane droplet, initially at 300 K and 50 μm in radius, irradiated by a blackbody at 1500 K, in a medium at 1000 K and 10 bar.

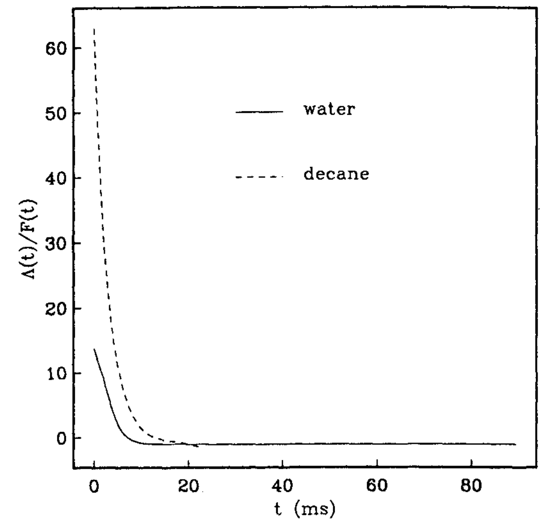

Fig. 8 Time variation of F/Λ for decane and water droplets, initially at 300 K and 50 μm in radius, irradiated by a blackbody at 1500 and 1450 K, respectively, in a medium at 1000 K and 10 bar.

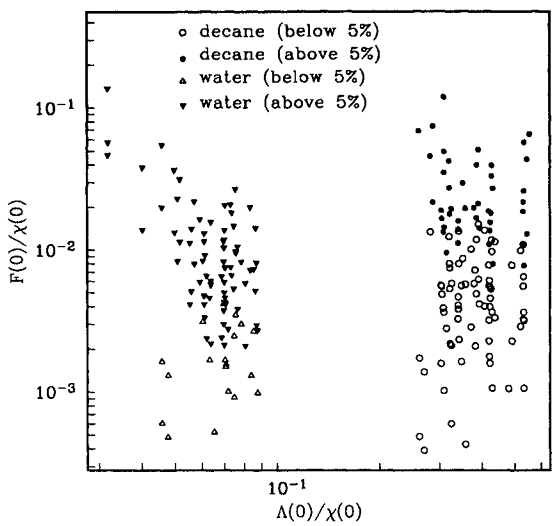

Fig. 9 Two-dimensional parameter space $F(0)/\chi(0) \times \Lambda(0)/\chi(0)$ generated by the vaporization simulations with radiation absorption of *n*-decane and water droplets.

F decreases due to the decrease of α and droplet radius. The latter contribution is more pronounced, because from the Lage and Rangel computations,[10] α decreases only 30–40% when the radius varies from 50 to 10 μm. On the other hand, the parameter Λ depends primarily on the heat transfer between the gas and liquid phases, assuming values far from zero only during the fast surface heating time. It should be noticed that when radiation absorption is considered, Λ can assume negative values, which indicate heat transfer from the liquid bulk to the interface. Since radiation absorption can result in an internal droplet temperature larger than the surface temperature, heat can be transferred from the droplet interior to its surface, where it is used to vaporize the liquid. Typically, Λ varies from about 1 to almost 0 during the droplet lifetime, while F varies from 10^{-2} to 10^{-3}. Thus, the gas-liquid heat transfer is dominant during the surface transient heating, and the importance of radiation absorption increases towards the end of the droplet lifetime. Also of interest is the ratio F/Λ, which expresses the relative importance of radiation absorption to gas-liquid heat transfer. The time variation of $(F/\Lambda)^{-1}$ is shown in Fig. 8 for the water and decane base cases. This figure shows that the initial value of this ratio is dominant in the whole process, due to the rapid transient surface heating.

In order to determine the importance of radiation absorption, 214 vaporization cases have been calculated (95 for water, 119 for decane) using the effective-conductivity model, with and without radiation absorption. These cases cover the ranges of ambient and initial conditions described above. All these calculations, including radiation, generate data points in the $F(0) - \Lambda(0)$ parameter space. Since internal circulation has been taken into account through the effective-conductivity factor, more representative dimensionless numbers should be given by F/χ and Λ/χ, which appear in the energy equation and its boundary condition [Eqs. (8) and (10)]. They represent the ratios of radiation absorption and gas-liquid heat transfer to liquid heat transfer (conduction plus internal circulation), respectively. The data points are presented in Fig. 9, in terms of the initial value of these dimensionless numbers. The difference in the droplet lifetime, defined as the time necessary for vaporization of 95% of the initial droplet mass between the calculations with and without radiation, has been used as a criterion to determine the importance of radiation absorption. In Fig. 9, a distinction of the data points is made depending on whether or not the error in predicting the lifetime is larger than 5%. The other parameters appearing in the dimensionless energy equation (Γ and S) do not have much importance in determining the influence of radiation absorption in the vaporization process. Thus, the F/χ vs Λ/χ parameter space can be used to characterize the main heat transfer ratios of the process of vaporization with internal radiation absorption. Moreover, from Fig. 9, it can be seen that F/χ varies between 4×10^{-3} to 0.15. These low values all correspond to the slow heating regime and validate the quasi-steady vaporization hypothesis. Since the ratio F/Λ represents the radiation absorption to gas-liquid heat transfer, it may give a direct means of correlating the radiation absorption effect. Moreover, $(F/\Lambda)^{-1}$ decreases so quickly that its initial value should be representative enough to correlate the radiation absorption effect. The percent lifetime error that occurs if radiation absorption is neglected in the analysis is plotted in Fig. 10 vs the ratio F/Λ evaluated at the initial time. It can be seen that there is a correlation between the droplet lifetime error and this quantity. A straight line, given by regression, has also been plotted in Fig. 10. Although the data deviate slightly from the straight line at the upper and lower limits, a higher order correlation is not worthwhile due to the large data scattering. This plot enables one to readily determine if radiation could be neglected in the analysis, without solving the vaporization model, provided that the total absorptance is known.

In order to verify the importance of considering the nonuniform radiation absorption in vaporization studies, some calculations have been made using uniform radiation absorption $[\delta = 0, S(\eta) = 1]$ and surface absorption $(\delta = 1)$. Results are presented for the water base case in Figs. 11 and 12. These figures show the transient behavior of the dimensionless droplet radius and the dimensionless surface temperature, respectively. It can be seen that, although radiation absorption is important, its radial nonuniform distribution does not appreciably affect the results. The lines representing the results for the three different ways of considering radiation absorption are almost indistinguishable from each other. However, careful comparison indicates that the uniform-absorption assumption usually gives better results than those obtained by assuming surface absorption, even though the radiation absorption is highly surface-concentrated, for most of the cases analyzed. This is a direct result from the prevailing slow heating regime, where liquid conduction and convection are able to transfer part of the absorbed energy to the droplet interior before it is used in the vaporization process. Since the radiation absorption distribution is not relevant in the global droplet vaporization behavior, a uniform absorption model can be used, provided only that the absorptance is known, without introducing any appreciable error in the analysis. These results agree with the findings of Park and Armstrong[7] for the slow heating regime, and with Sitarski results.[9] This is remarkable, because the first results are for directional laser irradiation, and the latter ones for black plane irradiation.

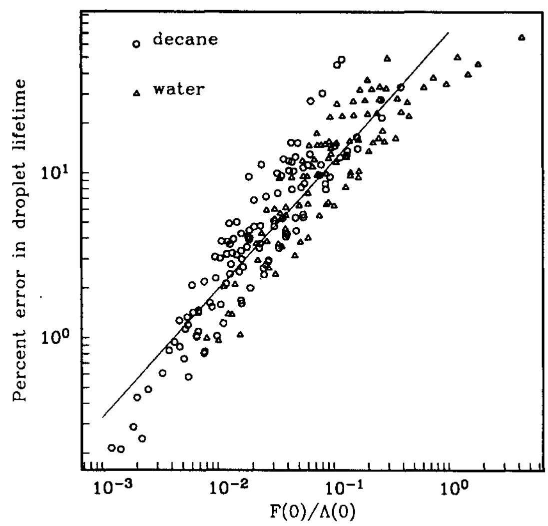

Fig. 10 Percent error in predicting droplet lifetime as a function of the radiation absorption to gas-liquid heat transfer ratio, $F(0)/\Lambda(0)$.

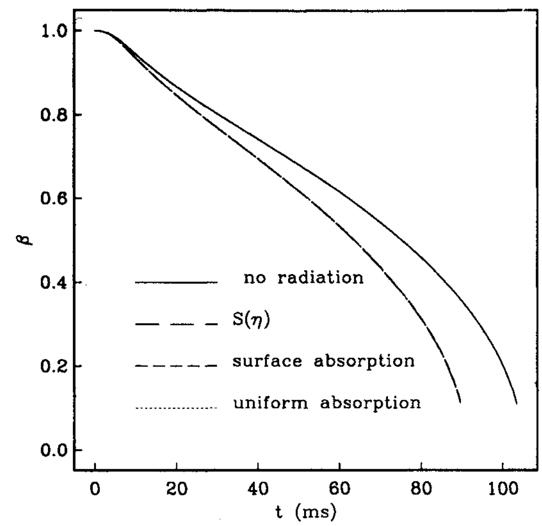

Fig. 11 Dimensionless radius variation for a water droplet, initially at 300 K and 50 μm in radius, irradiated by a blackbody at 1450 K, in a medium at 1000 K and 10 bar. Comparison of radiation absorption models.

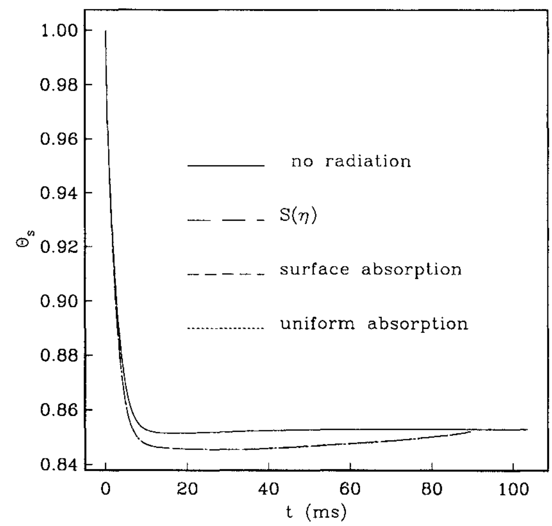

Fig. 12 Dimensionless surface temperature variation for a water droplet, initially at 300 K and 50 μm in radius, irradiated by a blackbody at 1450 K, in a medium at 1000 K and 10 bar. Comparison of radiation absorption models.

We now return to the discussion of the possible dependence of the effective-conductivity factor χ on F. Such dependence implies that internal circulation can enhance the transfer of the absorbed heat, spreading it more uniformly along the flow streamlines. However, the global effects of radiation absorption have been shown to be almost independent on the absorption distribution itself. Thus, it can be concluded that the effective-conductivity factor does not depend appreciably on the dimensionless radiation absorption.

Some conclusions can also be drawn for the general case with nonblack, nonsymmetric incident radiation, even though our results have been obtained only for spherically symmetric blackbody irradiation (or blackbody radiation in a finite wavelength interval, for decane). Nonsymmetric radiation incidence and an arbitrary spectral radiation distribution will modify the amount of radiation that the droplet absorbs (given by α or F) and the absorption distribution [given by $S(\eta, \theta, \phi)$]. Since it has been verified that the shape of the absorption distribution plays a small role in the overall vaporization process (which is substantiated by other vaporization studies for nonblack or nonspherical-symmetric irradiation[7,9]), the influence of the internal radiation absorption in the single-droplet vaporization for a general irradiation case must be given only by the total amount of energy which is really absorbed by the droplet. The nonuniformities of a radiation absorption distribution would only be important if the incident radiative energy could be large enough to lead to the fast heating regime. Based on the above discussion, it is believed that the use of Fig. 10, as an a priori criterion for radiation absorption effect in droplet vaporization, can be extended to general irradiation cases.

Final considerations must be given regarding the importance of radiation in spray combustion. The results shown are obtained using the largest possible irradiation for a given temperature (except for wavelength interval limitations). In a spray combustion environment, the incident radiation upon a droplet will be asymmetric, and further, it will be difficult to characterize it by a unique temperature. Moreover, gas absorption can take place, acting like a radiation shield. On the other hand, the flame temperatures are usually very high (over 1500 K), and soot emission tends to give a blackbody-like character to flame irradiation, sometimes surpassing gas emission. Since radiation emission varies roughly with the fourth power of temperature, the higher flame temperature must increase the importance of internal radiation absorption. Furthermore, fuels other than hydrocrabons (e.g., methanol) have appreciably larger absorption, closer to that of water than to the decane absorption. Thus, from the present results and the above considerations, it is believed that internal radiation absorption can play a non-negligible role in droplet vaporization in spray combustion and should be considered in any analysis.

Conclusions

Single-droplet vaporization calculations have been presented for three liquid phase heating models, namely, the infinite-conductivity model, the conduction-limit model, and the effective-conductivity model, which have been extended to include internal radiation absorption, under spherically symmetric conditions. A large number of simulations have been performed with water and decane, covering ambient temperatures from 500 to 1800 K, ambient pressures of 1 and 10 bar, initial droplet radius from 25 to 100 μm, initial Reynolds number from 0 to 322, and blackbody irradiation temperatures in the 1000–2000 K interval. Two important dimensionless quantities have been identified: 1) the radiation absorption to liquid heat transfer (conduction plus internal circulation) parameter F/χ; and 2) the gas-liquid heat transfer to liquid heat transfer Λ/χ. Vaporization results with radiation absorption considered spatially uniform and as a surface phenomenon, have also been presented. From all these results, the following conclusions can be drawn:

1) In usual combustion spray conditions, there is not enough radiative energy to induce explosive vaporization of monocomponent hydrocarbon droplets, while it may be possible for other highly absorbing fuels if heterogeneous nucleation is possible.

2) In spray combustion environment, droplet heating occurs in the slow heating regime.

3) The radiation absorption distribution pattern is not important in the overall results of the single-droplet vaporization process, under the conditions analyzed; only the total absorptance values are needed for vaporization studies, under spherically symmetric irradiation conditions.

4) Due to the above fact, the effective-conductivity factor is basically independent on the radiation absorption.

5) The parameter space $F(0)/\chi(0) - \Lambda(0)/\chi(0)$ is a good way of representing the vaporization conditions.

6) The ratio Λ/F, which represents the gas-liquid heat transfer to the radiation internal absorption, decreases very rapidly during the droplet vaporization, which makes its initial value a good measure of the importance of radiation absorption.

7) There is a correlation between the effect of radiation, measured as the percent error in droplet lifetime caused by radiation absorption neglect, and the ratio $F(0)/\Lambda(0)$, which can be represented as a straight line in a log-log plot; this plot allows the determination a priori of the radiation absorption effect on the vaporization process.

Furthermore, droplet vaporization under a nonblack asymmetric irradiation will modify the total fraction of the incident radiation which is absorbed, which is taken into account by the total absorptance, and the radiation absorption distribution. Since the radiation absorption distribution pattern has little effect on the vaporization process, a spatially uniform radiative heat absorption model is believed to be applicable even for the general irradiation case. In this case, the $F(0)/\Lambda(0)$ criterion (Fig. 10) should still be applicable for general irradiation conditions.

For spray combustion using alkane fuels (low absorptive index), radiation absorption has only a small effect in the vaporization process (around 5%), unless the radiation source effective temperature is considerably larger than the gas temperature. In any specific case, a simple calculation using the gas-phase model[5] and the use of Fig. 10 determines whether or not radiation absorption may be neglected in the analysis.

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