Technical Notes

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Convective Evaporation of an Extremely Volatile Fuel Droplet

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Nomenclature

B_H = heat transfer number, $c^*_{P,g}(T^*_\infty - T^*_s)/h^*_{fg}$
B_M = mass transfer number, $(Y_{F,s} - Y_{F,\infty})/(1 - Y_{F,s})$
Nu = Nusselt number, $2R^*h^*_H/k^*$
Pr = Prandtl number, $\mu^* c^*_P/k^*$
Q = heat transfer rate
R = instantaneous droplet radius, R^*/R^*_0
Re = Reynolds number, $2R^*\rho^* v^*_\infty/\mu^*$
Re_m = Reynolds number, $2R^*\rho^*_\infty v^*_\infty/\mu^*_f$
Sh = Sherwood number, $2R^*h^*_M/(\rho^*\mathcal{D}^*)$
Sc = Schmidt number, $\mu^*/(\rho^*\mathcal{D}^*)$
t = time, $t^* v^*_{\infty,0}/R^*_0$
T = temperature, T^*/T^*_∞
V = instantaneous freestream velocity, $v^*_\infty/v^*_{\infty,0}$
Y = mass fraction
ρ = density, ρ^*/ρ^*_∞

Subscripts

f = film conditions
F = fuel component
g = gas phase
ℓ = liquid phase
0 = initial conditions
∞ = freestream conditions

Superscripts

* = dimensional quantity
— = spatial average

Introduction

ADVANCES in fuel technology have led to the development of fuels characterized by extremely high vaporization rates. For example, a recent paper by Lee et al.[1] details an experimental study of the vaporization and combustion of organic azides at $Re < 1$. Their data on diazido-heptane droplets show an order of magnitude increase in the value of the transfer number B_H as compared to n-heptane droplets. Clearly, such fuels are very attractive for propulsion systems.

In spray combustion, most droplets evaporate in a highly convective environment with associated $Re \gg 1$. Therefore, the present work is concerned with convective evaporation of an extremely volatile droplet at relatively high Reynolds numbers. Due to lack of thermophysical property data on organic azides, the droplet is modeled as n-heptane in all respects except one: the latent heat of vaporization is arbitrarily defined as one-tenth that of n-heptane. Henceforth the modified fuel shall be referred to as *pseudo-heptane*. A conservative numerical method has been used to study the behavior of this droplet in air at 800 K, 1 atm. Initially the Reynolds number is 100, and the droplet is at 298 K. The corresponding $B_{H,f}$ is 29. All transient and variable property effects as well as liquid-phase motion and heating are included in the analysis. It has been assumed that the shrinking droplet remains spherical, the flowfield is laminar and axisymmetric, effects due to gravity and thermal radiation are negligible, and the air is insoluble in the liquid phase. The relevant literature and the complete mathematical formulation of the problem can be found in Haywood et al.[2]

Results and Discussion

Calculations were performed to a nondimensional time of $t = 5000$, when $Re_\infty = 24$, and the fraction of initial mass remaining, m/m_o, was 0.14. Comparisons are drawn between the results obtained in this study and the results obtained by Haywood et al.[2] from a study of an n-heptane droplet with identical initial and ambient conditions.

Histories of R, V, $Re_\infty/Re_{\infty,0}$, and m/m_0 for the pseudo-heptane and n-heptane droplets are given in Fig. 1. The R and m/m_0 for the pseudo-heptane droplet decrease quickly with time as expected. The variation of V with time, however, is very similar to that of the n-heptane droplet despite a significant reduction in total drag due to surface blowing. In fact, at $t = 5000$, $V = 0.46$ for both droplets. This behavior may be explained by examining the global momentum equation:

$$\frac{dV}{dt} = -\frac{3}{8}\frac{C_D V^2}{\bar{\rho}_\ell R} \tag{1}$$

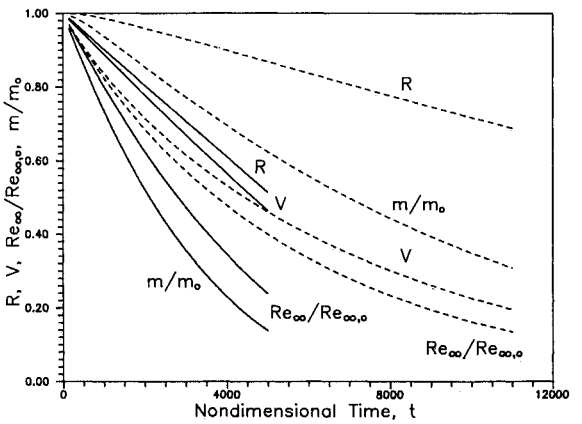

Fig. 1 Radius, velocity, Reynolds number, and mass fraction histories: —— pseudo-heptane, - - - n-heptane.

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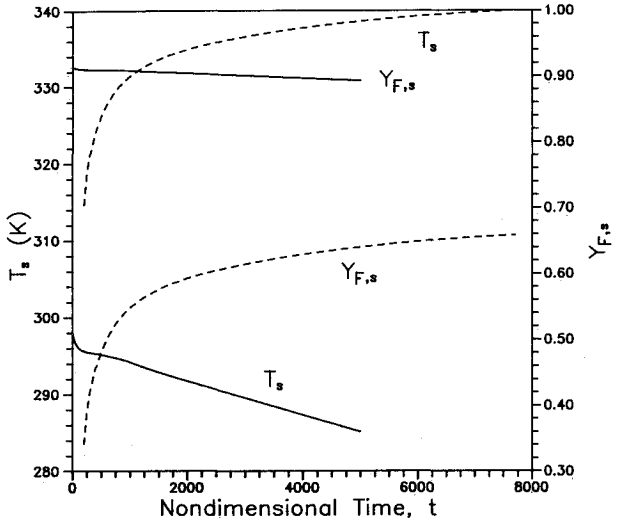

Fig. 2 Surface temperature and fuel mass fraction: —— pseudo-heptane, - - - *n*-heptane.

Pseudo-heptane values of C_D and R are both less than corresponding values associated with the n-heptane droplet, and thus C_D/R is approximately equal for the two cases. As variations in $\bar{\rho}_\ell$ are small over the liquid temperatures encountered in the studies, histories of V and dV/dt for the two cases are very similar.

The droplet surface temperature $\bar{T}_s$ and fuel concentration $\bar{Y}_{F,s}$ histories are shown in Fig. 2. Although the energy required for pseudo-heptane vaporization is less than one-third of that required by the n-heptane droplet (mass transfer increased two- to three-fold, but the latent heat of vaporization decreased ten-fold), heat transfer from the gas phase is unable to meet the demand, and consequently the droplet is forced to cool in contrast to the n-heptane case. It is also to be noted that $\bar{Y}_{F,s} \sim 0.9$ throughout the droplet lifetime due to the extreme volatility of the fuel.

Figure 3 shows the Nusselt and Sherwood number histories. The correlations of Haywood et al.[2] and Renksizbulut and Yuen[4,5] for Nusselt number and Sherwood number incorporate $B'_{H,f}$ and B_M into solid-sphere correlations to account for the effects of surface blowing

$$Nu_f = (1+B'_{H,f})^{-0.7}\left\{2+0.57Re_m^{1/2}Pr_f^{1/3}\right\};\quad 10 \le Re_m \le 2000 \quad (2)$$

$$Sh_f = (1+B_M)^{-0.7}\left\{2+0.87Re_m^{1/2}Sc_f^{1/3}\right\};\quad 10 \le Re_m \le 2000 \quad (3)$$

where

$$B'_{H,f} = B_{H,f}\left(1-\frac{Q_\ell}{Q_g}+\frac{Q_r}{Q_g}\right) \quad (4)$$

$$B_M = \frac{\bar{Y}_{F,s}-\bar{Y}_{F,\infty}}{1-\bar{Y}_{F,s}} \quad (5)$$

As thermal radiation effects were assumed negligible in this study, $Q_r = 0$. The correlations proved quite accurate in modeling the results of n-heptane droplet vaporization characterized by values of both $B'_{H,f}$ and B_M of order 1. The vaporization of pseudo-heptane is characterized by much larger values: $B'_{H,f}$ decreases from 61 to 39 and B_M from 10 to 8 over the droplet lifetime. The correlated values of Nu_f are within 13% and values of Sh_f are within 5% of the detailed numerical calculation.

Figure 4 shows the total drag C_D and component coefficients C_P, C_F, and C_T for the pseudo-heptane droplet, C_D for a solid sphere, and C_D for the n-heptane droplet at corresponding Reynolds numbers. Pressure drag C_P dominates representing a minimum of 85% of total drag at $t = 5000$. Pressure drag increases as a result of greater surface blowing and a corresponding larger wake, in agreement with the findings of Cliffe and Lever.[6] Friction drag C_F decreases by an order of magnitude from values associated with the n-heptane droplet as increased surface blowing dramatically reduces velocity gradients at the surface. The "thrust" coefficient C_T results from a nonsymmetrical surface mass flux; it increases from 1% of total drag to 4.3% over the droplet lifetime.

A correlation for total drag proposed by Renksizbulut and Yuen[5] and modified by Renksizbulut and Haywood[3] to account for liquid-phase heating:

$$C_D(1+B'_{H,f})^{0.2} = \frac{24}{Re_m}(1+0.2Re_m^{0.63});\quad 10 \le Re_m \le 300 \quad (6)$$

proved less accurate than the correlations for Nu_f and Sh_f. The C_D is underpredicted by 30%, leading one to conclude that the term $(1+B'_{H,f})^{0.2}$ overcompensates for the effect of blowing on drag. Rather than invalidate the correlation, these results limit its applicability to moderate values of $B'_{H,f}$. This correlation proved much more accurate in previous studies.[2,3] It appears that Eq. (6) remains accurate as long as friction drag contributes to the total drag, which is true for the evaporation

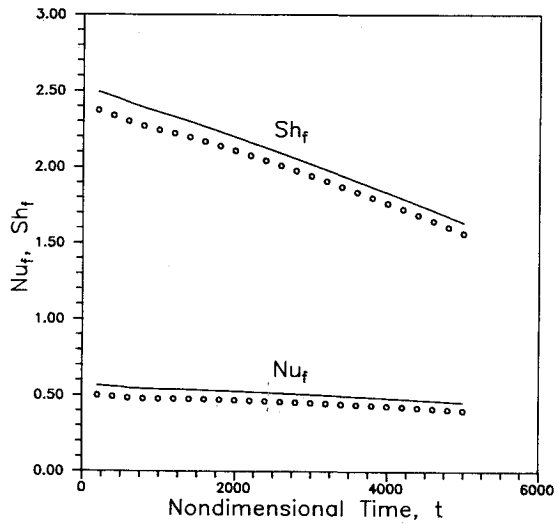

Fig. 3 Nusselt and Sherwood number histories: o —full numerical solution, —— Eqs. (2) and (3).

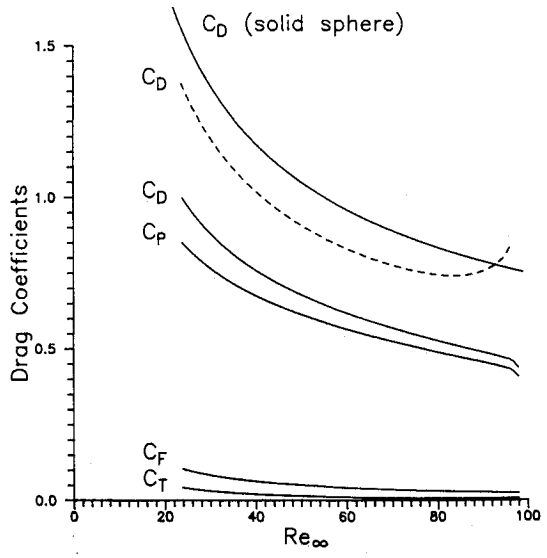

Fig. 4 Drag coefficient: —— pseudo-heptane, - - - *n*-heptane.

and combustion of conventional hydrocarbons. In such cases the increase in pressure drag due to blowing is largely offset by the reduction in friction drag and hence the weak dependence of C_D on mass transfer. However, in the presence of excessive volatility, friction drag essentially vanishes, resulting in the deterioration of the Renksizbulut-Yuen correlation.

References

[1]Lee, A., Law, C. K., and Randolph, A. L., "Aerothermochemical Studies of Energetic Liquid Materials. 2. Combustion and Microexplosion of Droplets of Organic Azides," *Combustion and Flame,* Vol. 71, No. 2, 1988, pp. 123–136.

[2]Haywood, R. J., Nafziger, R., and Renksizbulut, M., "A Detailed Examination of Gas and Liquid Phase Transient Processes in Convective Droplet Evaporation," *Journal of Heat Transfer,* Vol. 111, No. 2, 1989, pp. 495–502.

[3]Renksizbulut, M., and Haywood, R. J., "Transient Droplet Evaporation with Variable Properties and Internal Circulation at Intermediate Reynolds Numbers," *International Journal of Multiphase Flow,* Vol. 14, No. 2, 1988, pp. 189–202.

[4]Renksizbulut, M., and Yuen, M. C., "Experimental Study of Droplet Evaporation in a High-Temperature Air Stream," *Journal of Heat Transfer,* Vol. 105, No. 2, 1983, pp. 384–388.

[5]Renksizbulut, M., and Yuen, M. C., "Numerical Study of Droplet Evaporation in a High-Temperature Air Stream," *Journal of Heat Transfer,* Vol. 105, No. 2, 1983, pp. 389–397.

[6]Cliffe, K. A., and Lever, D. A., "Isothermal Flow Past a Blowing Sphere," Theoretical Physics Division, Atomic Energy Research Establishment, Harwell, Oxfordshire, England, UK, TP.1042, May 1984.

Dusty Supersonic Viscous Flow over a Two-Dimensional Blunt Body

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Nomenclature

c = sound speed, $\bar{c}/\bar{u}_\infty$
C_D = drag coefficient of particle
$\bar{C}_p$ = gas specific heat at constant pressure, J/kg-K
$\bar{C}_v$ = gas specific heat at constant volume, J/kg-K
$\bar{C}_m$ = specific heat of particle material, J/kg-K
$\bar{L}$ = reference length, m
M_∞ = freestream Mach number
p = pressure, $\bar{p}/\bar{\rho}_\infty\bar{u}_\infty^2$
Pr = Prandtl number
$\bar{R}$ = gas constant, J/kg-K, or leading-edge radius, m
Re_L = Reynolds number based on characteristic length, $\bar{\rho}_\infty\bar{u}_\infty\bar{L}/\bar{\mu}_\infty$
Re_p = Reynolds number based on particle diameter [see Eq. (5)]
Re_r = relative Reynolds number [see Eq. (4)]
T = gas temperature, $\bar{T}/\bar{T}_\infty$
T_p = particle temperature, $\bar{T}_p/\bar{T}_\infty$
$\bar{T}_\infty$ = freestream gas temperature, K
u = gas velocity component in x direction, $\bar{u}_p/\bar{u}_\infty$
u_p = particle velocity component in x direction, $\bar{u}_p/\bar{u}_\infty$
$\bar{u}_\infty$ = freestream gas velocity, m/s
v = gas velocity component in y direction, $\bar{v}/\bar{u}_\infty$
v_p = particle velocity component in y direction, $\bar{v}_p/\bar{u}_\infty$
x,y = Cartesian coordinates in physical space, $x=\bar{x}/\bar{L}$, $y=\bar{y}/\bar{L}$
Γ = particle material specific heat ratio, $\bar{C}_m/\bar{C}_p$
γ = gas specific heat ratio, $\bar{C}_p/\bar{C}_v$
δ = freestream loading ratio, $\bar{\rho}_{p\infty}/\bar{\rho}_\infty$
μ = gas viscosity, $\bar{\mu}/\bar{\mu}_\infty$
$\bar{\mu}_\infty$ = freestream gas viscosity, kg/s-m
ρ = gas phase density, $\bar{\rho}/\bar{\rho}_\infty$
$\bar{\rho}_m$ = density of particle material, kg/m^3
ρ_p = particle phase density, $\bar{\rho}_p/\bar{\rho}_\infty$
$\bar{\rho}_\infty$ = freestream gas density, kg/m^3
$\bar{\sigma}$ = particle radius, μm
τ_T = temperature relaxation time [see Eq. (3)]
τ_v = velocity relaxation time [see Eq. (2)]
$(\bar{})$ = dimensional quantities

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I. Introduction

DUSTY gas flows have been studied by a number of authors[1–8] in the past due to applications of the flows in rocket nozzle flow, supersonic flight through dust clouds, in the prediction of erosion damage caused by dust particles, and in flow-measuring instruments that use particles as tracers. In such two-phase flows, the gas phase and particle phase may have different velocities and temperatures, and as a consequence the two phases interact through viscous drag and heat transfer. As a result of the interaction, the gas phase flowfield differs from its corresponding pure gas flowfield. When a two-phase flow encounters a disturbance such as a shock wave, nonequilibrium is created between the two phases, and some relaxation distance is required before the gas and particle phases obtain a new equilibrium state.

Numerous inviscid analytical and numerical solutions of dusty supersonic flow over simple two-dimensional geometries, such as wedges and cones with attached shocks, can be found in the literature.[2,5–7] All of these solutions are based on the method originally proposed by Carrier.[9] The Carrier method anlysis requires the specification of gas and particle properties behind the gasdynamic shock as initial conditions for numerical integration. The determination of gas properties behind the gasdynamic shock requires knowledge of the shock location and shape. In a recent investigation,[10] which is also based on the Carrier method, inviscid dusty supersonic flow over a blunt axisymmetric body with a detached shock was treated. The solution technique used in the investigation is the so-called inverse method in which the shock shape is specified and the flowfield and body shape are numerically determined.

In problems of practical interest, neither the shock position nor the shape is known beforehand. When a detached bow shock wave is present, the gas properties behind the shock required for numerical solution cannot be determined accurately. The presence of multiple shocks complicates the problem further, since both the gas and the particle properties needed for numerical solution are not known due to the equilibration process taking place between the shocks. In this paper, a general direct numerical method for solving the full dusty gas viscous flow equations is presented. The numerical method is validated by comparing the normal shock structure solution obtained by solving the two-dimensional equations using the present method with that of the Carrier method solution. The present method is also used to compute the dusty gas flowfield over a two-dimensional blunt body.

II. Model Equations

The basic equations of motion governing dusty viscous flow[1] in two dimensions can be written in conservation form as

$$\frac{\partial U}{\partial t}+\frac{\partial F}{\partial x}+\frac{\partial G}{\partial y}=H \tag{1}$$