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Oscillatory Fuel Droplet Vaporization: Driving Mechanism for Combustion Instability

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Liquid fuels are commonly used in the propulsion of ramjets and rockets. They offer great flexibility in terms of controlling the rate of energy release. However, combustion instability has historically been a major problem in the development of liquid fueled ramjets and rockets. Previous investigations that employed a simplified droplet vaporization model indicated that droplet vaporization is indeed capable of driving an instability. In this study, an established droplet vaporization model has been used to make an exact evaluation of the effects of pressure and velocity oscillations on the vaporization process of a droplet moving through a longitudinal mode standing wave in a combustion chamber. It is then determined whether droplet vaporization as the burning rate controlling factor is capable of driving combustion instability. In addition, a parametric study has been conducted by using various frequencies of oscillation and amplitudes of fluctuation for the longitudinal mode. Depending on the local relative velocity between the gas and the droplet, it is possible that the wake may be ahead or behind the droplet, with reference to the chamber. This orientation has also been examined in the parametric study. It has been found that droplet vaporization is indeed capable of driving instability in some frequency domains and configurations. Preliminary results show that the amplitude of the oscillation does not have very significant effects on the response factor of the system. Orientation of the relative velocity, frequency of oscillation, and fuel volatility have strong influences on the instability.

Nomenclature

a = a'/a'_0, instantaneous radius
a'_0 = initial droplet radius
c' = speed of sound
G = response factor
m = $m'/(\rho'_{g,\infty}U'_{\infty,0}a_0'^2)$, vaporization rate fluctuation
P = $P'/(\rho'_{g,\infty}U'^2_{\infty,0})$, pressure fluctuation
p = $(p' - p'_\infty)/(\rho'_{g,\infty}U'^2_{\infty,0})$, pressure
T = T'/T'_∞, temperature
t' = time
U = $U'/U'_{\infty,0}$, horizontal component of velocity
V = $V'/U'_{\infty,0}$, vertical component of velocity
Y_i = mass fraction
z' = axial location
α' = liquid thermal diffusivity
γ = specific heat ratio
ε' = amplitude of oscillation
λ' = wavelength
μ'_g = viscosity of gas phase
τ_{Hg} = $t'\mu'_{g,\infty}/(a_0'^2\rho'_{g,\infty})$, gas–hydrodynamic–diffusion time
τ_h = $a_0'^2/\alpha'$, droplet heating time
ϕ = starting phase

Subscripts
f = fuel
h = droplet heating
p = pressure
po = position
r = radial direction
t = time
u = velocity
z = axial direction
∞ = conditions at the freestream

Superscripts
$'$ = dimensional quantity
$\bar{}$ = steady value

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Introduction

COMBUSTION instability has plagued liquid rocket development programs since the early fifties. Instabilities have been observed in almost all devices that involve combustion in a chamber and subsequent energy release, because any enclosed chamber has an infinite number of resonant modes of oscillation. Depending on the frequency and mode, varying levels of damage may be sustained. The spontaneous onset of instability in the combustion chamber usually augments heat transfer rates in the combustion chamber and can sometimes cause vibration levels in excess of 1000 g.[1]

In recent times, there has been a renewed interest in the study of combustion instability mechanisms in an effort to find a reliable method to predict the occurrence of this phenomenon in a particular liquid rocket combustor. There is reason to believe that instability can be understood by studying the vaporization process.[2–5] Droplet vaporization research has also made notable headway in the last decade and is now a highly developed science.[6–9] A large amount of time and resources has been invested in the accurate modeling of droplet vaporization. Experimental results have been used to validate the new theories, and as a result, substantial insight has been gained in droplet vaporization theory. It is now possible to use more accurate vaporization models to study the effect of an oscillating environment on a vaporizing droplet.

Experimental evidence shows that the combustion in a liquid propellant rocket combustion chamber is never perfectly smooth. The liquid rocket engine is susceptible to instabilities because it only takes a small fraction of the total energy released to sustain an unstable mode of operation and the nearly closed nature of the system prevents it from resisting the oscillations. For this reason, the supply of energy from the transient combustion process, which is in phase with the wave motion, sustains the oscillations in this closed loop.[10-13]

The design of a combustion chamber that would minimize the coupling between the combustion and the fluid mechanics would require a thorough understanding of the mechanism of combustion instability. Such an understanding would permit the lowering of rocket engine development costs and would allow the design of intrinsically stable, high-performance liquid rocket engines.[3,11]

The driving force behind combustion instability is the energy input from the combustion process. The Rayleigh criterion is the most commonly used criterion to determine if a particular mechanism is capable of driving the combustor into an unstable mode or not. The Rayleigh criterion may be stated as, a mechanism can drive the instability if the associated burning rate oscillates with the proper combination of a large enough amplitude and a small enough phase lag with the pressure oscillation.

Efforts to understand liquid rocket instability have typically been based on an acoustic analysis and the time-lag theory or an analysis of the vaporization process. Crocco and his researchers[12-14] developed the time-lag theory that is based on the time delay between the introduction of the fuel into the combustion chamber and the actual combustion process resulting in energy release. Therefore, if a small pressure pulse is applied to a steadily burning propellant, the regression rate will take a certain amount of time to reach its new steady value.[15] Although time-lag approaches are useful for a first look at instability, more detailed analyses of the flow can be better.[15]

The $n-\tau$ model accommodates both transverse and longitudinal mode waves and uses both linear (small perturbation) and nonlinear analysis for finite amplitudes.[1] This theory has its limitations in that it treats mainly one-dimensional mean flow cases. The time-lag theory was first applied to the nonlinear behavior by Sirignano.[14] There has been extensive work on the time-lag theory and it has been modified to include other physical phenomena such as shock waves.

Because of the inadequate understanding of droplet vaporization theory, engineers and scientists could only suspect that unsteady droplet vaporization may be a driving force behind instability. In addition to the lack of adequate understanding of droplet vaporization phenomenon, the computational facilities required to conduct such a numerically intensive study did not exist at the time.

Classical droplet vaporization theory is founded in the well-known d^2 law. However, this analysis assumes that the droplet is traveling at the velocity of the gas and that there is spherical symmetry. This theory, though well formulated, has rather limited applications. The relative motion between the droplet and the ambient gas (which is nonzero in most cases), leads to an increase in the heat and mass transfer rates. For droplets with an initial radius of 25 μm and greater, the time for velocity relaxation because of drag is comparable or greater than the droplet lifetime.[7] These and other effects like internal circulation, neglected by the classical droplet vaporization theory, lead to considerably smaller characteristic lengths and times for liquid-phase heat and mass transfer. The strong coupling between the drag, heat transfer, mass transfer, relative droplet velocity, and internal circulation necessitates a numerical solution.

Strahle[16] studied unsteady droplet combustion in 1960 using a linear theory. He used an infinite thermal inertia model and neglected the thermal wave within the droplet. The assumption prevented the droplet from responding to the ambient oscillations.[16] This yielded results that did not suggest that vaporization was a candidate-driving mechanism for instability. The assumption of infinite thermal inertia was not made by Priem and Heidman,[17] who used instead a uniform temperature assumption. This still resulted in an overestimation of the liquid thermal inertia. However, they successfully demonstrated that vaporization did affect stability and that it could be controlled by varying the vaporization process parameters.[18,19] However, the amplitude of the response was not sufficient to drive the instability.

There is adequate reason to believe that the liquid-phase heating affects the driving mechanism for instability. For this reason, the transient heating and vaporization of the fuel droplets under oscillating conditions must be examined. This is based on the knowledge that transient droplet heating and liquid thermal inertia are very important even under steady operating conditions, and therefore, it is expected that they should also be important under unsteady conditions. Tong and Sirignano[4] used a more exact one-dimensional droplet model and examined the response of a vaporizing droplet to oscillating ambient pressure and velocity conditions. They examined the effect of both standing and traveling waves. The component of the vaporization rate in phase with the pressure was found to be larger for a traveling wave than for the stationary wave. The model assumed that vaporization was rate controlling and that mixing and chemical reactions were very rapid. In addition, a quasisteady gas-phase behavior was assumed. Internal circulation in the liquid was considered by a vortex model. The Tong and Sirignano model addresses only heating and vaporization, and therefore, vital information such as the drag coefficient cannot be obtained from their study.

Bhatia and Sirignano[5] employed a one-dimensional vaporization model developed by Abramzon and Sirignano[6] to study ramjet instability. Their results indicated that vaporization was rate controlling, and they were also successful in identifying a ratio of oscillation period to droplet heating time.

Chiang et al.[9] and Chiang[8] developed an advanced exact droplet vaporization model with fewer assumptions so that it might serve as a reference model against which simpler models could be measured. This axisymmetric, single-droplet model included effects of surface blowing, transient heating, and internal circulation. Variable properties of the gas phase were taken into account and viscosity variations in the liquid phase were also calculated.

Note that not all of the droplets injected into the chamber of a liquid rocket combustor, which is under an oscillatory mode of operation, experience the same ambient conditions. As combustion is a continuous process and fuel droplets are injected constantly, droplets injected at different times generally do not experience the same cycle. Acoustics plays a crucial role in the instability phenomenon as indicated by the resemblance between the frequency of the oscillations and the acoustic mode frequencies of the combustor. There was an interest in the problem of acoustic resonance in tubes.[20,21]

This study examines the role of droplet vaporization under oscillating atmospheric conditions and is an extension of the previous works by Chiang et al.[9] and Tong and Sirignano.[4] Details of this work may be found in Ref. 22. In this article, an advanced model with fewer assumptions is used and the emphasis is on the effects of an oscillating gas phase on the heat and mass transfer processes in the liquid phase. This analysis differs from previous works in several significant aspects: an unsteady, axisymmetric, variable property model is employed; drag coefficients, Nusselt numbers, and Sherwood numbers are determined and not prescribed for the droplet; the accelerated droplet motion through the longitudinal standing mode in the chamber is determined and considered; and the importance of the orientation of the relative droplet-gas velocity is demonstrated. The oscillations of temperature, pressure, and velocity in the gas phase will cause significant changes in the heat and mass transfer rates and also in the drag coefficients. The response factor of the system is calculated to determine the conditions under which the vaporization process is capable of driving a longitudinal mode instability.

Description of the Problem and Model

Fuel injection in liquid propellant rockets is performed with an atomization device. Upon injection, the droplet experiences an acceleration and the gas quickly adjusts to the presence of the droplet and a boundary layer is formed. Internal circulation within the droplet and a recirculation zone in the wake are soon established. The continuous transfer of momentum results in a reduction of the relative velocity between the gas and the droplet, causing a drop in the relative droplet Reynolds number. The surrounding gas heats the droplet interior and also supplies energy for the vaporization of the fuel at the surface. The vaporization process is initially slow, but accelerates later. This heat transfer process results in nonuniform and transient droplet temperatures for the entire droplet lifetime. The primary heat transfer mechanism is initially diffusion, but switches to convection with the establishment of internal circulation and then reverts back to diffusion as the droplet decelerates relative to the gas. The vaporizing fuel vapor has significant effects on the properties of the surrounding gas. In the case of an unstable combustor, the ambient conditions fluctuate in time and space, as these complex processes are taking place. The value of the phase in the cycle at the instance of injection identifies the time history of the ambient condition variations seen by the droplet. For a given droplet (or phase value), the droplet heating and acceleration cause an unsteady behavior in a Lagrangian frame, even when the combustor is in steady-state operation.

Numerical computation of a detailed spray model is not feasible with the facilities available today. The problem considered in this study is that of a single *n*-octane droplet, injected into the hot gases of a combustor. The model employed in this study is shown in Fig. 1. This axisymmetric model with variable properties has been employed to be able to make a detailed calculation of the heat and mass transfer process. In the computations, the effects of decreasing relative velocity, varying thermophysical properties, transient heating, internal circulation of liquid, boundary-layer blowing, and moving interface have been considered.

The steady part of the relative velocity is taken to be 25 m/s, upon introduction of the droplet into the combustor. A mean pressure of 10 atm is used. The operating pressure again varies with time and the actual value depends not only on the magnitude of the velocity oscillation, but also the initial phase of injection. Gas-phase perturbations are introduced on the velocity, pressure, and temperature. The velocity and pressure oscillations are dictated by the classical standing wave pattern and the corresponding temperature oscillation is calculated by assuming an isentropic flow. This study examines the effects of variations of critical parameters such as the initial phase of injection, frequency, and amplitude of oscillation on the vaporization history of the droplet.

The exact solution of this problem requires the simultaneous solution of the hydrodynamic, energy, and transport equations in the gas phase. This would necessitate the inversion of large matrices and imposes great demands on the computing resources available. To solve the equations in a more efficient manner, an iterative technique is utilized. The gas-phase temperature, momentum, and species equations are solved using the alternate direction predictor corrector method.[8] The pressure equation is indirectly satisfied by using a pressure correction to update the pressure and velocity fields in a manner that ensures the satisfaction of the continuity equation. An underrelaxation is used to ensure that the pressure correction does not diverge.

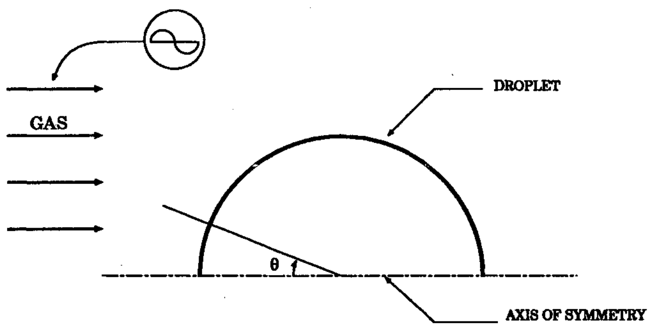


Fig. 1 Droplet model employed in the present study.

A stream function–vorticity formulation is used in the liquid phase to simplify the calculations. This allows for all of the important flow characteristics to be captured while preserving a good degree of accuracy. The elliptic stream function equation is solved by using the successive-overrelaxation technique. The vorticity and liquid temperature equations are parabolic and are solved by the alternate direction predictor corrector method.[8]

Governing Equations

For the governing equations in the liquid and gas phase, refer to the work by Chiang[8] and Chiang et al.[9] The initial conditions corresponding to the injection of a droplet into an unstable combustor would depend on the particular time and location of injection. Therefore, T, p, and V_z are dependent on ϕ_t and ϕ_{po}. Both V_r and Y_f are set to zero on the inflow side and the gradients set to zero on the downstream side. The flow may reverse at lower Reynolds numbers, but the boundary conditions remain the same. In such a situation, the downstream boundary conditions are, in effect, specified with the gradient set to zero on the upstream side.

Velocity condition:

$$U'_\infty(z', t') = \bar{U}'_\infty + \varepsilon'_u \sin(2\pi z'/\lambda')\sin(2\pi c' t'/\lambda')$$

Pressure condition:

$$p'_\infty(z', t') = \bar{p}'_\infty + \varepsilon'_p \cos(2\pi z'/\lambda')\cos(2\pi c' t'/\lambda')$$

where

$$\varepsilon'_u = (a'/\gamma)(\varepsilon'_p/\bar{p}'_\infty)$$

Temperature condition:

$$\frac{T'_\infty}{\bar{T}'_\infty} = \left(\frac{p'_\infty}{\bar{p}'_\infty}\right)^{(\gamma-1)/\gamma} \approx 1 + \frac{\gamma-1}{\gamma}\frac{\varepsilon'_p}{\bar{p}'_\infty}\cos\frac{2\pi z'}{\lambda'}\cos\frac{2\pi c' t'}{\lambda'}$$

On the outlet side, the pressure is specified in a similar manner, but the gradients of the temperature and velocity are set to zero.

Evaluation of Rayleigh Criterion

To determine whether vaporization is capable of driving instability, it is necessary to consider the contributions of every droplet present in the combustor at a particular instant of time. For the vaporization to be able to drive instability, it is necessary to evaluate the component of the vaporization rate that is in phase with the pressure. This is done by evaluating G as suggested by the Rayleigh criterion[4]:

$$G = \frac{\oint\int mP \, d\tau_{Hg} \, d\phi}{\oint\int P^2 \, d\tau_{Hg} \, d\phi}$$

where ϕ is a constant for each droplet during its lifetime. The ϕ value represents the phase at the time of injection.

The definition of G given previously involves integration in an Eulerian frame of reference. To apply this to the present model it is adapted to a Lagrangian frame of reference. Figure 2 shows the droplets born at various phases. In an Eulerian time frame, droplets injected at different phases are present at different axial locations at a given time. By the previous definition, G is calculated by integrating in horizontal sweeps, over axial location, and then over the Eulerian time. Lagrangian time varies along the dotted lines of constant initial phase value (constant ϕ) in the figure. Therefore, G can be evaluated by integrating in diagonal sweeps, over Lagrangian time, and then by integrating over the phase value at the time of injection.

Figure 3 shows the vaporization rate histories (schematic) of all the droplets present in a combustor at a particular instant

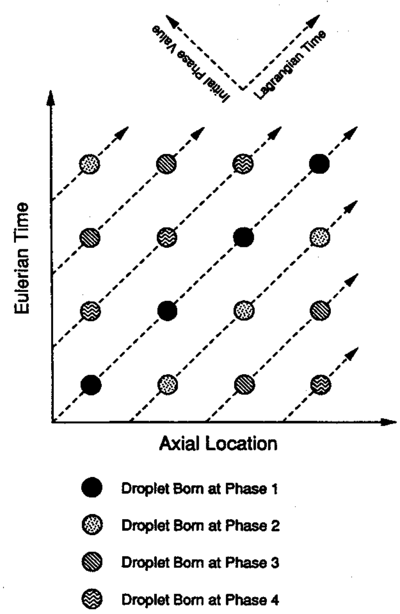


Fig. 2 Evaluation of G in a Lagrangian frame of reference.

of time. The area of interest is that between a phase of 0 and 2π. It is seen that droplets injected at phases of -2π, $-3\pi/2$, $-\pi$, and $-\pi/2$ have contributions to the area of interest (marked as A, B, C, and D, respectively). However, it may be seen that this area corresponds to the area marked A, B, C, and D on the vaporization curves of droplets injected at 0, $\pi/2$, π, and $3\pi/2$, respectively. Thus, integrating over the vaporization curves of all droplets born between 0 and 2π would in effect give the contributions of all droplets present in the combustor. The integral is evaluated over time, at intervals of $\pi/2$ to obtain the elementary response factor G_e, which is defined as

$$G_e = \frac{\int mP \, d\tau_{Hg}}{\int P^2 \, d\tau_{Hg}}$$

The elementary response factor is fitted with a cubic spline. The spline was fit from both directions and the difference was evaluated to be less than 0.5%. The elementary response factor is then integrated over the phase to evaluate the total response factor. Note that the denominator is independent of phase, but the integral was left to maintain consistency. The sophisticated droplet vaporization model used in this study is highly computationally intensive. The solution of each phase point requires over 200 min of Cray time. To remain within the Cray time available, only four phase values were computed and then a spline was fit to the results to integrate over the period to obtain the total response factors. Therefore, while the results of the elementary response factor calculations are quite accurate, the total response factor results should be regarded as qualitative.

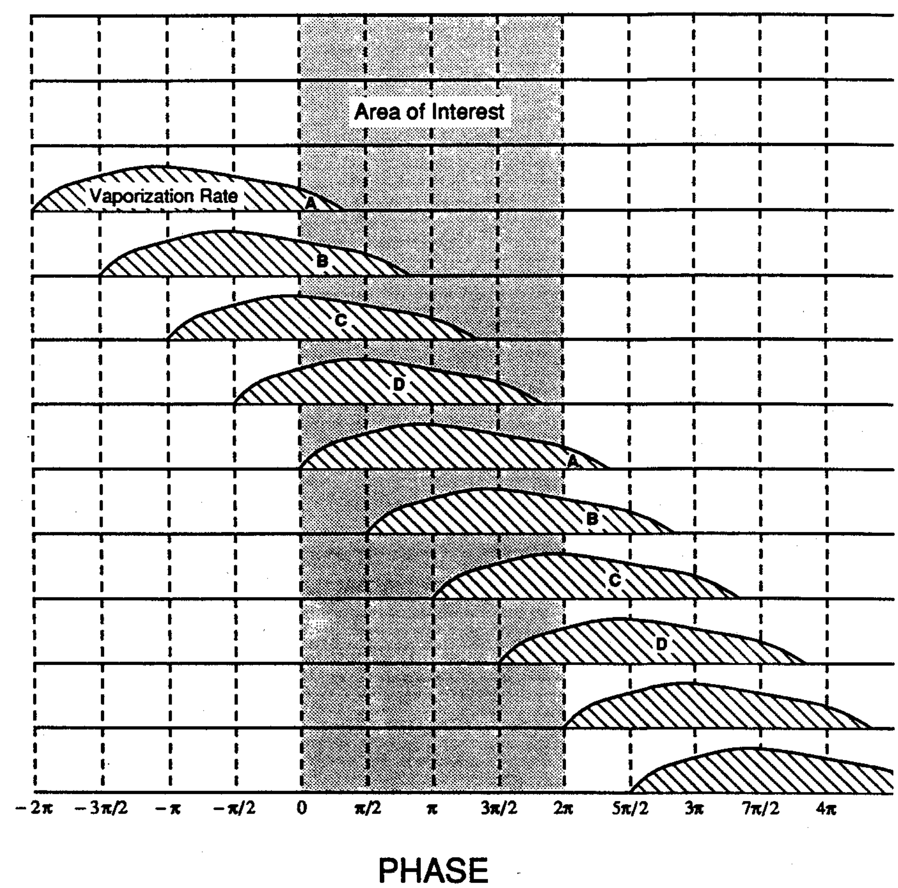


Fig. 3 Vaporization rate (schematic) distribution for various droplets present in the combustor.

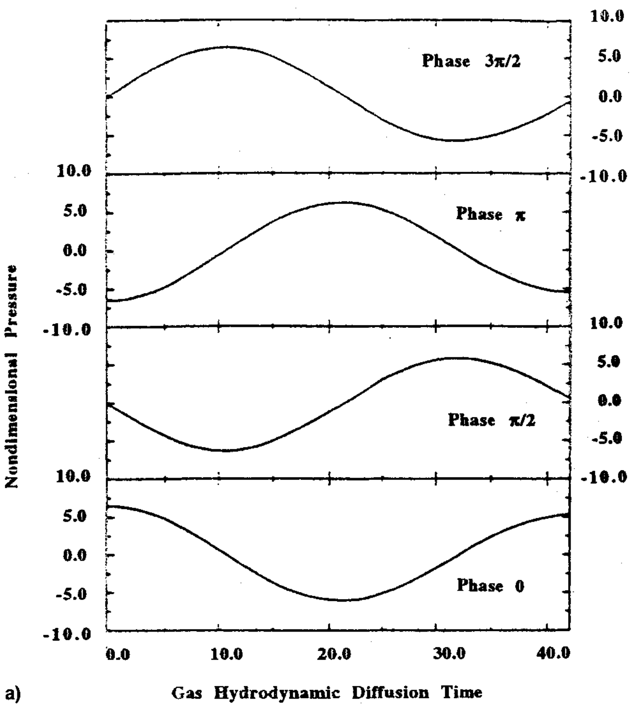
To overcome the losses and drive combustion instability, G should have a minimum positive value. For the case of distributed combustion, this value corresponds to 3.72 for longitudinal mode instability.[12]

Results and Discussion

Numerical codes exhibit varying degrees of grid and time-step dependence. To evaluate the accuracy of the results, it is important to estimate the degree of dependence on the grid chosen and the time step used. All results are relatively insensitive to the time-step size. A time step of 0.001 has been used throughout this investigation. Four different parametric studies have been conducted. These involved 1) frequency comparison, 2) amplitude comparison, 3) droplet configuration comparison, and 4) variation in the liquid fuel.

The variations of pressure and velocity for each of the four phases are shown in Fig. 4. Each droplet undergoes a unique cycle of ambient conditions. A variety of frequencies has been known to occur in liquid propellant rockets and in ramjets. For this reason, the frequency of the instability is a key parameter in the study of combustion instability and it is necessary to identify the frequencies that may be sustained by droplet vaporization. For the purposes of this study, the frequency may be better described by the time period of the oscillation in terms of the droplet heating time. Three different time periods, corresponding to 0.3, 0.6, and 0.9 droplet heating time have been examined. This nondimensional range implies that a 100-μm initial radius droplet would experience an oscillation in the approximate range of 100–1000 cycles/s. In all the cases, the spatial phase of injection corresponds to an eighth of a wavelength and the amplitude of the pressure oscillation is 2% of the steady value (10 atm). The response factor G was calculated for each case in the manner described earlier. Figure 5 shows the pressure history of droplets moving through the standing wave and exposed to the three frequencies. The imposed 2% pressure oscillation has a significant effect on the variation of the vaporization rate. The distribution of the elementary response factor for the three cases is shown in Fig. 6.

a)



b)

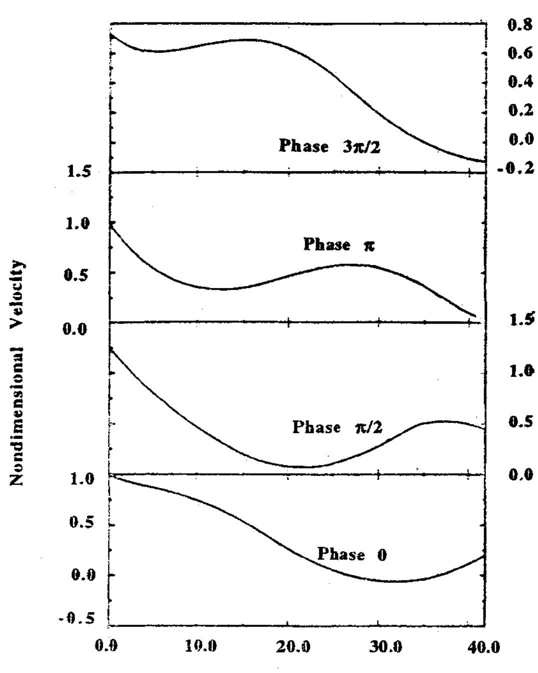


Fig. 4 Ambient a) pressure and b) velocity history with varying injection times.

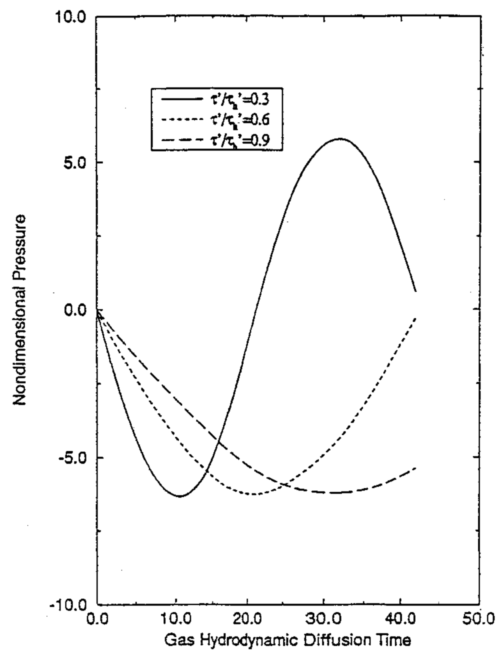


Fig. 5 Ambient pressure history with varying frequencies.

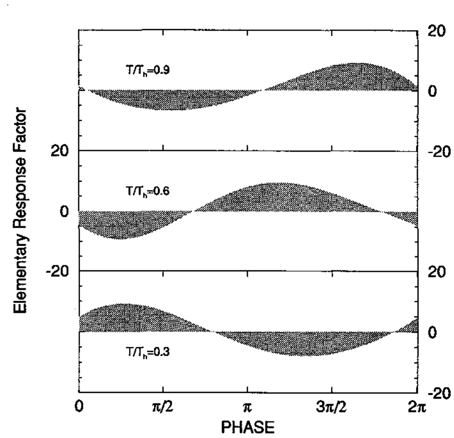


Fig. 6 Distribution of elementary response factor for varying time periods.

The elementary response factor distribution is periodic but varies substantially for the three time periods studied. The total response factor for each of the frequencies is shown in Table 1.

A response factor greater than 3.72 is required for the vaporization process to be able to drive instability in the case of uniformly distributed combustion.[12] The oscillation with a time period of 0.3 droplet heating time is not capable of driving instability. A negative value of G implies that the system damps any oscillations. The oscillation with a time period of 0.6 droplet heating time has a high response factor and is therefore capable of driving longitudinal mode instability. This means that the component of the vaporization rate in phase with the pressure is large enough to supply enough energy to the system to drive it into an unstable mode of operation. With a time period of 0.9 droplet heating time, the system is not capable of driving instability. The response factor is positive, but it is not strong enough to overcome the losses in the combustor. As noted previously, the response factor results of Tables 1–4 should be regarded as qualitative. For example, a more accurate computation using more phase values indicates that the largest value in Table 1 should appear at a higher τ/τ_h value (lower frequency).

Figure 7 shows the two different droplet configurations studied. In the first case, the droplet is moving faster than the ambient gas and the wake of the droplet is therefore behind the droplet. In the second configuration, the droplet is moving slower than the gas and, in this configuration, the wake is ahead of the droplet. The velocity fluctuation is in phase with the steady component of the velocity. Thus, a positive velocity fluctuation means an increase in the Lagrangian velocity. This augments the vaporization rate and other surface properties. In the first case, however, a velocity increase in the gas phase means a decrease in the relative velocity of the droplet. Note that, in actual rockets, both of these situations exist since the droplet is initially faster than the gas, but as the combustion process proceeds, the gases accelerate and eventually move faster than the droplet. Thus, in practical rockets, the wake is initially behind the droplet, but moves ahead of the droplet with the passage of time. In the case of ramjet combustors, the gases are initially at high velocity and the fuel is injected at nearly zero velocity. In this situation, the wake remains ahead of the droplet for the entire lifetime. The two droplet geometries described earlier have been studied with a 2% pressure

Table 1 Comparison of response factor for varying frequencies

τ/τ_h	G
0.3	−0.52
0.6	5.81
0.9	2.98

Table 2 Comparison of response factor with droplet faster and gas faster geometries

Configuration	G
Gas faster	5.81
Droplet faster	−76.47

Table 3 Comparison of response factor with varying amplitudes

Pressure oscillation, %	G
1	5.02
2	5.81

Table 4 Comparison of fuels with varying volatility

Configuration	G
Octane	5.81
Pseudodecane	4.97

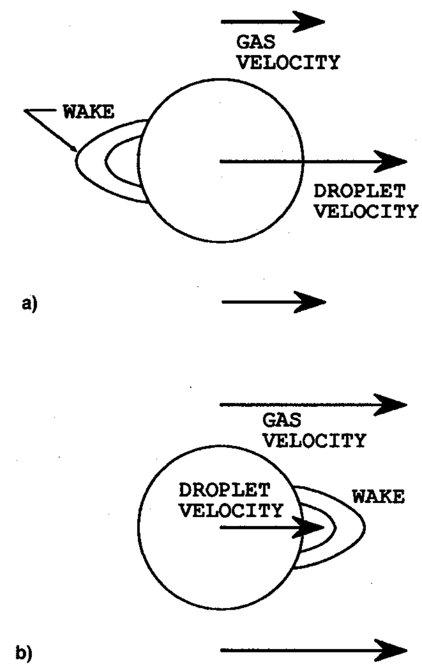


Fig. 7 Schematic of a) droplet faster and b) gas faster configurations.

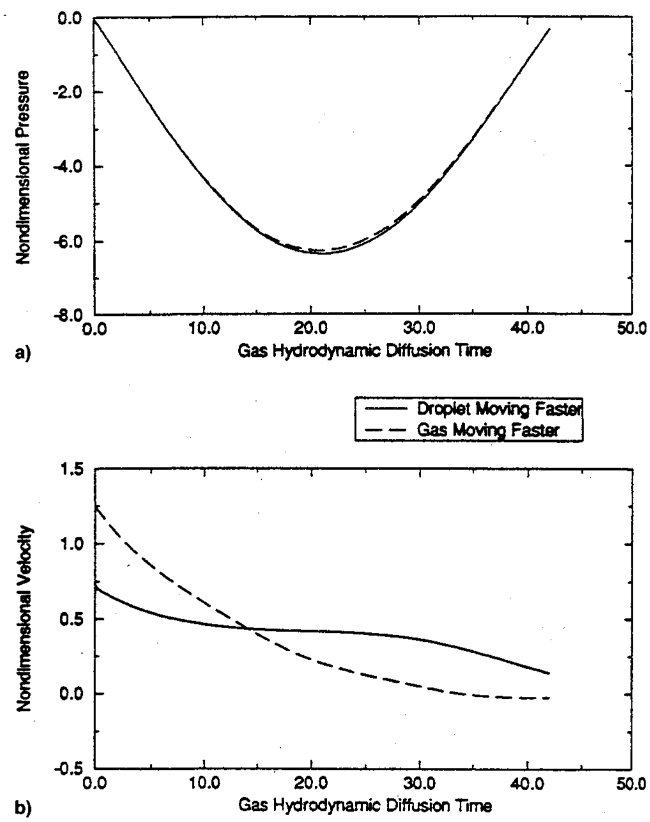


Fig. 8 a) Pressure and b) absolute magnitude of the relative velocity variations for droplet faster and gas faster configurations.

oscillation. The spatial phase of injection corresponds with an eighth of a wavelength and the time phase of injection corresponds to a quarter time period. The time period of the oscillation for the two configurations is 0.6 droplet heating time. A comparison of the ambient pressures and velocities for the two cases is shown in Fig. 8. The pressure variation remains the same for both cases, but there is a substantial difference in the absolute magnitude of the relative velocity history of the two droplets because of the difference in the effect of the velocity fluctuation. The distribution of the elementary response factor for the two cases over the entire time period is shown in Fig. 9. The elementary response factor for the droplet faster case is negative over the entire time domain, indicating a heavy damping. The case with the gas moving faster than the droplet has both negative and positive elementary response factor values. The integrated response factor values for these two situations have been evaluated and the results are given in Table 2.

For the case with the gas traveling faster than the droplet, the response factor is high and capable of driving instability; but, in the case of the droplet traveling faster than the gas, the response factor is negative and actually damps the oscillations.

Depending on the nature of a particular combustor and the operating conditions, the magnitude of the amplitude of the oscillation may vary. To get a better understanding of the effects of varying amplitudes, two cases with pressure oscillations of 1 and 2% have been studied. The cases shown here correspond to a time period of 0.6 droplet heating time and the time-phase injection corresponds to a quarter time period. The spatial phase of injection corresponds to an eighth of a wavelength. The responses for the two cases with different amplitudes of oscillation have been computed to understand the effects of amplitude variation on the response factor of the combustor. Figure 10 shows the velocity and pressure variation for the two cases. The pressure is seen to vary in the same manner in both cases, though the amplitude is different. The velocity cycle for the droplets is, however, entirely different. The initial velocity of the 2% oscillation case is higher than that of the 1% oscillation case. However, a more rapid decrease in the relative velocity causes it to intersect the velocity curve of the 1% pressure oscillation case. The distribution of the response factor is shown in Fig. 11. It may be seen that the distribution of the response factor is different for the two cases. The total response factor for the two cases examined is shown in Table 3.

There is a decrease in the response factor with a decrease in the amplitude of the oscillation. However, a 50% decrease in the amplitude of the pressure oscillation only causes a 13% decrease in the response factor, which is still capable of driving the instability. Though the distribution of the response factor is very different for the two cases, its effect on the response factor is not so marked.

The effects of varying the volatility of the fuel were studied. The base fuel that has been employed in the calculations is normal octane. A second fuel has the latent heat of decane, but otherwise has the properties of octane. We refer to this less

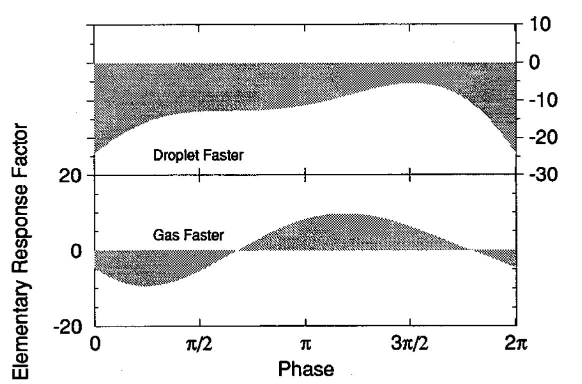


Fig. 9 Distribution of elementary response factor for varying configurations.

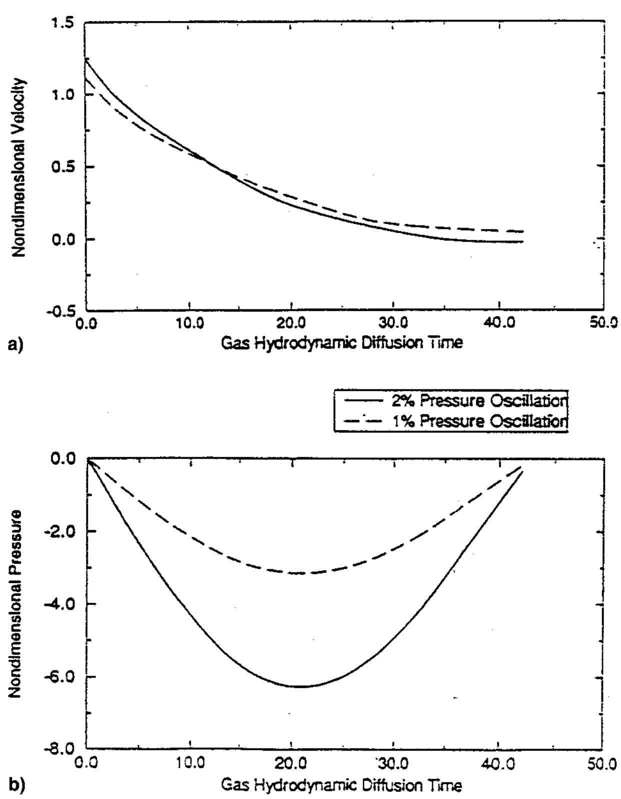


Fig. 10 a) Velocity and b) pressure variations for varying amplitudes.

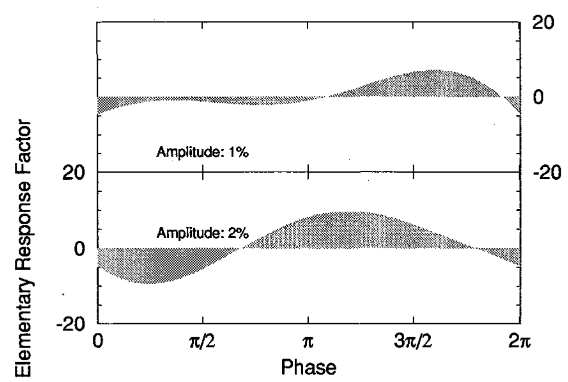


Fig. 11 Distribution of elementary response factor for varying amplitudes.

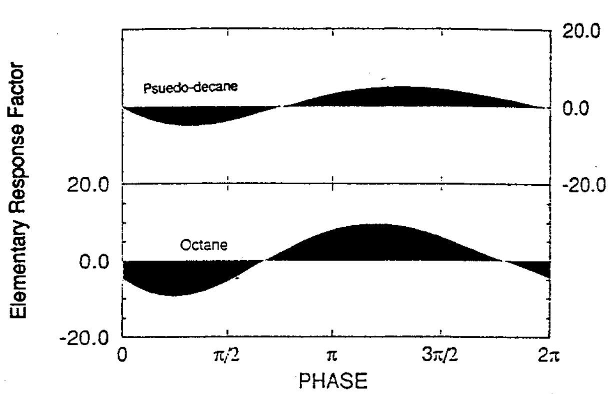


Fig. 12 Distribution of elementary response factor for varying fuel volatilities.

volatile fuel as pseudodecane. The distribution of the elementary response factor is shown in Fig. 12. The integrated response factor values for the two cases have been evaluated and the results are given in Table 4. Clearly, the more volatile fuel has a larger response factor, but the instability can be driven with either fuel.

A limited number of computations have shown a sensitivity to the downstream position where the droplets are introduced. Because of the importance of relative velocity to the vaporization rate, the relationship between the point of introduction and the velocity antinode is important.

Conclusions

An advanced, axisymmetric convective droplet vaporization code has been successfully employed in the study of combustion instability. The imposed oscillations have significant effects on the heat and mass transfer process and on the liquid properties. Droplet vaporization as a rate-controlling factor can allow the chemical energy conversion to be in phase with the pressure and to drive longitudinal mode combustion instability. An investigation of the frequency domain showed that droplet vaporization was only capable of driving combustion instability in certain frequency domains. This is in good agreement with previous work done by Tong and Sirignano[4] and Bhatia and Sirignano.[5] The frequency of the oscillation is a key parameter in determining the fraction of the total energy that is in phase with the pressure oscillation. An evaluation of the effect of the disturbance amplitude on the response factor indicates that the effects of amplitude variation are not very significant.

It is important to identify whether the wake is ahead of the droplet or behind it, as there is a significant change in the response factor for the two situations. Previous droplet vaporization studies related to combustion instability have neglected to emphasize whether the wake of the droplet is ahead of the droplet or behind it. It is necessary to identify the particular configuration because the response factor for the two is vastly different. When the droplet is faster than the gas, the system has a high damping, whereas when the gas is faster than the droplet, the response factor is high enough to drive the instability. This is primarily because of the effect that the velocity oscillation has on the relative velocity.

A variation of the volatility of the fuel has a fairly significant effect on the response factor, though it is not as significant as identifying the orientation of the wake. Our results are consistent with previous findings that the convective vaporization mechanism is much more strongly coupled to velocity oscillations than to pressure oscillations.

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