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ACOUSTICAL EXCITATION OF BURNING FUEL DROPLETS

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Abstract

This experimental study focuses on quantifying and understanding the effects of external acoustical perturbations on condensed phase combustion processes. In the present configuration, a burning liquid methanol droplet is suspended within an essentially one-dimensional acoustic waveguide where standing waves of variable frequency and amplitude are generated by a loudspeaker placed at the end of the guide. The droplet is maintained at a constant diameter during combustion via continuous fuel delivery through a quartz capillary tube. Focus is placed in the present experiments on excitation conditions in which the droplet is situated at either: 1) a velocity antinode (pressure node), where the droplet experiences the greatest effects of velocity perturbations, or 2) at a velocity node (pressure antinode), where the droplet is exposed to minimal velocity fluctuations. The effects of the amplitude and frequency of excitation, the droplet position relative to pressure/velocity perturbation maxima, and conditions leading to increased burning rates are identified.

Introduction

Fuel droplet combustion is a heterogeneous reactive process which is a major contributor to the behavior of combusting sprays as well as being a fundamental geometry from which critical information concerning diffusion flame behavior may be obtained. Classical studies of the burning or evaporating droplet indicate that, assuming spherical symmetry and quasi-steady behavior, the temporal variation in droplet diameter follows the so-called $d^2$ law, that is, the square of the diameter decays linearly with time $t$:

$$d^2(t) = d^2(0) - Kt$$  \hspace{1cm} (1)

where $d$ is the time dependent diameter of the liquid droplet during combustion or vaporization and $K$ is known as the “burning rate constant”, which often is characterized in units of mm$^2$/sec. While under many circumstances in normal gravity the droplet is roughly spherical and the detectable droplet diameter does indeed follow a $d^2$ type of dependence on time, buoyant effects often render the diffusion flame shape non-spherical. An understanding of the applicability of the $d^2$ law to burning droplets has been one driver for fundamental microgravity droplet combustion research.

In a gravitational field, studies have shown that there can be a significant increase in fundamental heat and mass transfer rates from reactive surfaces with the imposition of an external acoustical field. In terms of fuel droplet combustion, the experiments of Blaszczuk examine the effect of acoustic waves imposed on a single burning droplet within an open-ended duct excited by a loudspeaker at the closed end. For diesel and petrol fuel droplets of initial diameters between 2.0 and 2.5 mm, Blaszczuk measures up to a 14% increase in the combustion rate constant $K$ during acoustic excitation (as compared with no acoustic excitation) in the excitation frequency range 150-300 Hz and sound pressure level range 100-115 dB. At frequencies above 300 Hz, Blaszczuk observes a dropoff in the droplet burning rate constant, asymptoting to values of $K$ that lie above the unforced value, while at forcing frequencies below about 150 Hz, the burning rate constants are observed to actually lie below the unforced value. These observations are likely influenced by the fact that standing waves are not always generated in this
waveguide.

The recent experiments of Sujith, et al. 7 examine the behavior of single evaporating methanol droplets which are injected within and move through an acoustic waveguide in which standing waves are generated. The 50-150 μm diameter droplets are imaged at integral multiples of the acoustic half wavelength in order to ensure that droplets are exposed to the same integrated velocity perturbation in each image; evaporation rate constants are then determined on the basis of these images. These researchers see a significant increase, over 100%, in the evaporation rate constant during acoustic excitation for amplitudes of excitation exceeding 160 dB, which correspond to velocity perturbations of the order 5 m/sec and above. For sound pressure levels of 150 dB and below, which correspond to velocity perturbations on the order 1.6 m/sec and below, there is very little change observed in the evaporation rates as compared with unforced evaporating droplets. These observations are primarily attributed to an “increase in convective heat and mass transfer to and from the droplet”, respectively, caused by acoustic oscillations”.

The experiments of Saito, et al. 8,9 also examine the effects of acoustic waves on single evaporating and burning fuel droplets (kerosene, in the size range 1.3-1.8 mm in diameter). Here there is an emphasis on the position of the droplet, which is fixed at either a pressure node or antinode of standing waves formed within a closed acoustic waveguide. These researchers find that when the fuel droplet is situated at a pressure node (corresponding to a velocity antinode), there can be a two to three-fold increase in evaporative or combustion rate constants, but when the droplet is located at a pressure antinode (or velocity node), there is little appreciable change in the evaporation or combustion rates. The frequency range for which substantial increases in combustion rates are observed here is about 70-100 Hz, for excitation amplitudes between 95 and 115 dB. For excitation above 100 Hz, even when the droplet is situated at a pressure node, there is no appreciable increase in the combustion rate constant $K$, which asymptotes to its unforced value at high frequencies. Similarly, for excitation levels below 95 dB, there is no appreciable change in droplet evaporation or burning rate constants as compared with unforced values. These researchers also quantify changes in flame temperature, for the acoustically excited kerosene droplets situated at a pressure node, which are 673-1073K higher than for unforced, burning droplets9. These significant increases in flame temperature, and associated significant increases in burning rate constants, are thought to result from promotion of “mixing between fuel vapor and oxygen in the air...by applying acoustic excitation” when the droplet is situated at a pressure node.

The present study similarly examines single fuel droplet combustion within an acoustic waveguide, in the absence of any mean (imposed) air flow. Focus is placed in the present experiments on excitation conditions in which the droplet is situated at either: 1) a velocity antinode (pressure node), where the droplet experiences the greatest effects of velocity perturbations and fluid mechanical straining of flame structures, or 2) at a velocity node (pressure antinode), where the droplet is exposed to minimal velocity fluctuations. The effects of the amplitude and frequency of excitation, the droplet position relative to pressure/velocity perturbation maxima, and conditions leading to increased burning rates are explored, and possible physical phenomena underlying these observations are identified. In the future it is expected that these experiments will be conducted in NASA Microgravity Combustion facilities.

Experimental Facility and Methods

In the present configuration, the fuel droplet (here, liquid methanol) and surrounding diffusion flame are situated within an essentially one-dimensional, closed, cylindrical acoustic waveguide operating at background atmospheric pressures. Standing waves are generated within the waveguide by a loudspeaker placed at one end. The speaker generates acoustic perturbations with varying frequency and amplitude via a function generator and amplifier. The basic configuration for the waveguide and droplet is shown conceptually in Figure 1. The length of the acoustic waveguide is adjustable so as to maintain standing waves in the guide.

A detailed schematic diagram of the experimental apparatus is shown in Figure 2. The waveguide is constructed of aluminum, with an inner diameter of 11.4 cm and a maximum length of 150 cm. Quartz
windows (2.5 cm diameter) are situated at either side of the center of the waveguide for optical access. An 8-ohm audio speaker with a maximum power output of 40 W is placed at one end of the waveguide, and a wave reflector is placed at the opposite end. The distance \( L \) between the speaker and the reflector is adjustable by moving both the speaker and reflector so that \( L \) can be made to be an integral multiple of half the acoustic wavelength, \( \frac{1}{2} \lambda = \frac{1}{2} \frac{a}{f} \), where \( a \) is the speed of sound in the waveguide and \( f \) is the applied frequency of acoustic excitation. This allows standing waves to be generated so that if the droplet is situated at the center of the waveguide, it may be exposed to conditions corresponding to either a pressure node or a pressure antinode, depending on the applied frequency \( f \) and the length \( L \).

Since the diameter of the waveguide is much larger than that of the droplet (which is between 1.0 and 1.6 mm), the droplet is essentially exposed to plane acoustic waves. The presence of standing waves is verified in measurements by two pressure transducers labeled PT1 and PT2 in Figure 2, situated at the center and reflector end of the waveguide, respectively. For a fixed waveguide length, a sweep in frequencies of the applied acoustic excitation will indicate the presence of a pressure node (or velocity antinode) at the center of the waveguide when the sound intensity measured by PT2 is a local maximum and the intensity measured by PT1 is a local minimum. Similarly, a pressure antinode (velocity node) at the center of the waveguide will be detected when both PT1 and PT2 measure local maxima in sound intensity. Figure 3, for example, shows the variation in sound intensity measured at transducers PT1 and PT2 as a function of the frequency applied to the loudspeaker, for a fixed waveguide length of approximately \( L = 1346 \text{ mm} \). The gain to the amplifier is fixed here so that the local increases in sound pressure level are only the result of changing the applied frequency to the speaker. Conditions at the center of the waveguide corresponding to a pressure node are clearly identified at approximately 135, 370, 393, 860, and 1170 Hz, while pressure antinodes appear at the waveguide center at applied frequencies of 250, 480, 730, 990, and 1230 Hz. Hence it is a relatively straightforward task to create conditions where the burning fuel droplet is exposed to standing waves at either a pressure node or antinode.

An unusual feature of the present experiments is that the fuel droplet here is suspended within the waveguide from a quartz capillary of approximately 0.3 mm OD, through which methanol fuel is continuously delivered during droplet combustion. The methanol is stored inside a Helium-pressurized 300 ml tank, after which it is filtered to eliminate particulate contaminants and then metered to the capillary by a solenoid valve (manufactured by the Lee Co.). The volume flow rate \( Q_v \) of the fuel into the capillary is altered by changing either the duty cycle or the frequency of operation of the solenoid valve. \( Q_v \) may be determined in either of two ways in the present setup: 1) through measurement of the volume of methanol exiting the capillary over fixed periods of time, or 2) through measurements of the instantaneous droplet diameter \( d_i(t) \) during valve operation, as described below. Either method gives approximately the same value of \( Q_v \) under specific valve operation conditions, with a relative error of about 5% between the two methods. An example of the relationship between the measured volume flow rate \( Q_v \) and the valve duty cycle DC, for a fixed frequency of operation of the valve, 250 Hz, is shown in Figure 4. Similar data are obtained at other valve frequencies but the current experiments are conducted at a constant valve frequency of 250 Hz, so that a reading of duty cycle indicates directly the volume flow rate of fuel used to feed the droplet.

In the present experiments the instantaneous fuel droplet diameter \( d_i \) is determined by back-lighting the droplet and imaging the magnified droplet shadow onto a linear photodiode array (EG&G Reticon Model RC0730). The photodiode is set to operate at 50 Hz (i.e., 50 images/sec) by an external trigger. A 12 bit acquisition card (Tattletale Model 8) is used to acquire the droplet’s shadow image from the photodiode. The image is then digitized at 100 KHz to obtain the droplet diameter \( d_i \) as a function of time. In the present experiments, a steady volume flow rate of methanol, \( Q_v \), is sufficient to maintain an essentially constant (burning) droplet diameter \( d_i \) in time (within 1.2% of the mean value). This behavior is indicated in Figure 5. Larger values of \( Q_v \) naturally produce larger droplets burning in a quasi-steady manner.

It should be noted that, in order to prevent vapor-
izalization of the fuel within the quartz capillary just above the droplet, which can occur if the flame surrounding the droplet is directly exposed to the capillary for any significant period of time, an insulating shroud is placed above the end of the quartz capillary. A schematic of this arrangement is shown in Figure 6. The variable distance $X$ between the shroud and the end of the capillary (and hence the approximate center of the droplet) can influence the droplet burning characteristics, although this influence is applied systematically to both unforced and acoustically forced droplets. The influence of the parameter $X$ is explored in the Results section below.

Knowledge of the applied fuel volume flow rate $Q_v$ and the instantaneous droplet diameter $d_i$ may be used to determine the effective droplet burning rate constant $K$. Assuming the fuel droplet suspended from the quartz capillary to be roughly spherical, the rate of change in the droplet volume must be balanced by the difference between the volume flow rate of fuel delivered to the droplet ($Q_v$) and the rate of loss of fuel at the droplet surface due to the evaporation/combustion process ($\dot{m}$.K). Hence the “burning rate constant” $K$ may be estimated from measurements of the temporally evolving diameter $d_i(t)$, the time derivative in $d_i$, and the volume flow rate $Q_v$, according to the relation:

$$K = \frac{4Q_v(t)}{\pi d_i(t)} - 2d_i \dot{d}_i$$  (2)

While the transient term in equation (2), $2d_i \dot{d}_i$, is generally rather small, its size can depend on the noise associated with measurements of droplet diameter and hence on the means by which the derivative is evaluated. Since the main focus of the present experiments is on the evaluation of mean burning rate constants (that is, averaged over 2-3 seconds of data) and their sensitivity to the presence of acoustic excitation, the results described below are essentially the same whether or not the transient term in equation (2) is included.

Results

The combustion processes associated with a suspended methanol droplet within the present waveguide in the absence of acoustic excitation may be first explored and compared with published data. The primary differences in the method of determining $K$ between the present studies and more conventional droplet combustion studies are as follows. First, in the present experiments the droplet is continuously supplied fuel through the capillary during combustion, as opposed to the conventional method of igniting and burning a single, “unfed” droplet and measuring $K$ from the observed variation in droplet diameter according to equation (1). Second, the presence of the shroud (Figure 6) is not common to most droplet combustion experiments, and the value of the length of the capillary, $X$, can affect combustion characteristics. The effect of continuous fuel feeding here may be explored by comparing $K$ values obtained here with and without such feeding. The latter is accomplished by simply allowing the valve to deliver only a fixed amount of fuel to form a droplet of initial diameter $d_i$, then closing the valve. Ignition and burning of this “unfed” droplet allows measurements of the variation in $d_i(t)$ to be compared with the classic “$d^3$ law” (equation (1)) and hence allows a conventionally determined $K$ to be extracted. The effect of the length of the quartz capillary extending from the shroud, $X$, may be explored systematically as well.

Figure 7 shows the dependence of the mean (time-averaged) burning rate constant, $<K>$, on the initial diameter $d_i$ for the “unfed” droplet and on the quasi-steady value of $d_i$ for the continuously fed droplet. Two different values of the capillary length $X$ are considered here; for $X$ values smaller than 2 mm there is severe distortion of the droplet shape, with liquid “riding up” the capillary, and for $X$ values larger than 3 mm, vaporization of the fuel within the quartz fiber occurs when the droplet is ignited, so that coherent droplets are not sustained. In the conventional (“unfed”) evaluation of the mean burning rate constant, $<K>$ is relatively invariant with the initial droplet diameter, consistent with published data, for the regime of droplet sizes considered here (ranging from 1.0 to 1.6 mm). In contrast, the continuously fed, burning fuel droplet experiences a reduction in the burning rate constant with increasing droplet diameter, asymptoting to a constant value of $<K>$ at droplet diameters above about 1.3 mm.

As might be expected, as the quartz capillary is extended further from the shroud (increasing $X$), the mean burning rate constant increases for both methods of evaluation because the surrounding dif-
fusion flame is somewhat better able to envelope the droplet at a larger \( X \) and hence more fuel is vaporized in a given amount of time. The average burning rate constant for the “unfed” droplet at \( X = 3 \) mm, \( < K > \approx 0.87 \text{ mm}^2/\text{s} \), is closest to most published values of \( < K > \) for methanol droplet combustion in normal gravity: 0.86 mm\(^2\)/s measured by Smith and Graves\(^{12}\) and 0.9 mm\(^2\)/s seen by Vielle, et al.\(^{11}\), for example.

What is most striking in Figure 7, however, is that the asymptotic values of the mean burning rate constants for the continuously fed droplets situated at \( X = 2 \) mm and \( X = 3 \) mm are each about 40\% greater than their corresponding “unfed” droplet \( < K > \) values. We believe that these higher burning rates are due at least in part to the velocity field set up within the droplet and at its surface during the continuous fuel delivery. Some researchers have studied the effect of the liquid internal and surface flows for vaporizing and burning droplets, but which are produced by an external gas flow\(^{13,14}\). The internal and surface flows in the present context, in the absence of an external gas flow, could be even more significant an influence on transport properties at the droplet surface. Non-zero surface velocities of the liquid, estimated here to be of the order of 3 cm/sec, set up additional contributions to viscous stresses, which in turn contribute to the heat and mass transport in this vicinity, likely increasing vaporization and burning rates. The effect of surface velocities here may in fact be somewhat analogous to the effects of gravity-driven natural convection in the vicinity of a burning (unfed) fuel droplet. The latter phenomenon, with effective convective speeds of the order 5 cm/sec\(^{16}\), also contributes additional viscous stresses at the droplet surface (when compared to the burning droplet in microgravity), resulting in burning rate constants which can be 30-40\% higher than those in microgravity\(^{2,11}\).

While the primary method for determining burning rate constants here produces values of \( < K > \) which are systematically higher, by 40\%, than conventional values, the relative change in \( < K > \) resulting from acoustic excitation actually is the same irrespective of the method of evaluation. Tests conducted as described above, comparing “unfed” and continuously fed burning fuel droplets but with the imposition of an acoustic field, show that fractional changes in burning rate constant observed due to acoustic excitation for the unfed droplet are virtually the same (i.e., lie within the experimental error) as those for the continuously fed, burning droplet. Hence it is appropriate to quantify the ratio of acoustically forced to unforced burning rate constants in all results shown here, as these should be valid irrespective of the method of forming the droplet and measuring the burning rate.

The present experiments confirm the observations of Saito, et al.\(^{8,9}\) which suggest that the effect of acoustic excitation on droplet burning rates can be substantial if the droplet is situated at a pressure node, where the velocity perturbations are large. In this instance, Figure 8 demonstrates that the effective burning rate constant \( < K > \) can increase with acoustic intensity, particularly at sound pressure levels above 125 dB. At an SPL of 137 dB, the burning rate constant can be more than 20\% above that for a non-forced, burning droplet. These results are qualitatively consistent with earlier experimental studies of the burning droplet in an acoustic field\(^{8,9}\), as well as with our own group’s corresponding computational studies\(^{9}\). But increases in burning rate of two-to-three fold, as seen in the studies of Saito, et al.\(^{9}\) for kerosene droplets, are not observed here. When the droplet is situated at a pressure antinode (velocity node), the negligibly small velocity perturbations cause the droplet burning rate constant to be essentially the same as that of the unforced burning droplet. These results are shown in Figure 9. The large pressure oscillations appear to have little effect on droplet combustion characteristics. These results are again consistent with those of Saito, et al.\(^{8,9}\).

Figure 10 further exhibits the increase in burning rate with high acoustic intensity when the droplet is situated at a pressure node, and in addition exhibits preferred frequencies of excitation that appear to enhance the combustion process. This figure shows that the burning rate begins to increase with forcing frequency, and that there is a preferred frequency range (200-400 Hz) within which the mean burning rate constant increases substantially at a given amplitude of excitation. Above excitation frequencies of 400 Hz the burning rate starts to decrease, asymptoting to values somewhat above the non-acoustically forced burning rate constants, as seen by Blaszczyk\(^{9}\).
As a means of understanding in a preliminary sense the phenomena which could lead to such changes in burning rate constants during acoustic excitation, photographs of the droplet and flame structure during combustion are shown in Figures 11. The integration time of the photographs is 5 msec, so that the photographs represent flame (and droplet) images integrated over a single acoustic cycle for 200 Hz excitation. Differences between unforced and acoustically forced droplet combustion may then be ascertained in an average sense. Interestingly, when the droplet is exposed to acoustic excitation levels that are relatively low (107 dB), whether or not it is situated at a pressure node or antinode, its flame structure is virtually identical to that for the unforced, burning droplet (see Figure 11(b)). Similarly, when the droplet is situated at a pressure antinode, irrespective of the applied sound pressure level, the flame structure appears unperturbed. It is only when the droplet is situated at a pressure node (velocity antinode), with high amplitudes of excitation, that the flame structure changes (see Figure 11(c)). The flame structure appears substantially broadened when compared with that associated with the unforced burning droplet, and the flame appears to envelope the droplet somewhat more completely. The broadening of the flame appears to be indicative of periodic motion of the flame, toward and away from the droplet surface, likely in response to the applied acoustic periodicity. As the flame periodically moves closer to the droplet surface over a given acoustic cycle, as also seen in numerical simulations, the cycle-averaged vaporization rate at the droplet surface can increase. This phenomenon likely is the major contributor to the larger mean burning rate constants observed in Figure 8. Moreover, also as seen by others, at high levels of acoustic excitation and at specific frequencies, the flame may tend to be displaced somewhere to one preferred side of the droplet, as suggested in Figure 11(c). It is not known why during droplet combustion the flame prefers to be stabilized closer to one side of the droplet than the other, since present observations suggest that either side of the droplet is equally likely to be the “preferred” one for a given test. This and related issues will be explored in future studies.

Conclusions

The present experiments quantify increases that can occur in mean burning rate constants associated with a single burning fuel droplet during acoustical excitation. Such increases, which may be as high as 20%, can occur only when the droplet is situated at a pressure node (or velocity antinode), and appear to be associated with periodic perturbations in the velocity field which result in periodic flame stretch and cyclical flame motion and broadening. No such changes in burning rate, nor in flame structure, are observed when the droplet is exposed to acoustic excitation when situated at a pressure antinode (or velocity node). These results are further consistent with prior observations of increases in convective heat and mass transfer rates during acoustical excitation, although the magnitude of increase in burning rate is not nearly as high in the present studies as in these prior studies. Future studies will continue to explore such amplification of droplet combustion response during acoustic excitation, in addition to the effects of a microgravity environment.

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References


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Fig. 1: Schematic diagram of a fuel droplet situated at a pressure node (velocity antinode) within an acoustic waveguide.
Fig. 2: Schematic diagram of the acoustic waveguide with a fuel droplet situated in the center.
Fig. 3: Sound intensity, given in mV, measured by the two pressure transducers P1 (located at the center of the waveguide) and P2 (located at the reflector end of the waveguide) as a function of applied frequency $f$. The length of the waveguide is fixed at $L = 1346$ mm, and the gain applied by the amplifier to the speaker is constant.

Fig. 4: Variation in fuel volume flow rate $Q_v$ through the quartz capillary as a function of the duty cycle DC of the solenoid valve, for valve operation at 250 Hz.

Fig. 5: Measured droplet diameter as a function of time for different (constant) volume flow rates $Q_v$ delivered by the solenoid valve.

Fig. 6: Schematic of the suspension of the fuel droplet, which is fed by the quartz capillary. The shroud helps to insulate the capillary and flowing fuel from the diffusion flame associated with the burning droplet.
Fig. 7: Dependence of the mean burning rate constant $<K>$ for the non acoustically forced droplet on droplet diameter $d_l$. The “unfed” droplet refers to evaluation of $<K>$ via the conventional method, whereas the “continuously fed” droplet refers to evaluation of $<K>$ via the method outlined in the present study. Two different values of $X$, the distance between the end of the insulating shroud and the end of the quartz capillary, are also explored.

Fig. 8: Effect of acoustic intensity (sound pressure level, in dB) on the droplet mean burning rate constant $<K>$, normalized by the value of $<K>$ in the absence of acoustic excitation. Here the droplet is situated at a pressure node, for various frequencies of acoustic excitation, with $X = 2$ mm.

Fig. 9: Effect of acoustic intensity (sound pressure level, in dB) on the droplet mean burning rate constant $<K>$, normalized by the value of $<K>$ in the absence of acoustic excitation. Here the droplet is situated at a pressure antinode, for various frequencies of acoustic excitation, with $X = 2$ mm.

Fig. 10: Effect of frequency on the droplet mean burning rate constant $<K>$, normalized by the value of $<K>$ in the absence of acoustic excitation. Data points for different values of acoustic intensity (sound pressure level, in dB) and droplet position are shown. Pressure node points are designated by PN, open symbols, and pressure antinode points are designated by PAN, filled symbols. Here $X = 2$ mm.
Fig. 11: Photographs of suspended droplet and flame under conditions of: (a) no acoustic excitation, (b) acoustic excitation at 107 dB and 200 Hz, at a pressure node (velocity antinode), and (c) acoustic excitation at 137 dB and 200 Hz, at a pressure node. Here $X = 2\ mm$, and the quasi-steady droplet diameter is 1.2 mm.