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# Experimental Study of Acoustic Velocity Effects on Simulated Solid Fuel Pyrolysis

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**An experimental study of the effect of acoustic velocity oscillations on solid fuel pyrolysis, modeled using dry ice sublimation, was performed. Use of dry ice as a solid fuel simulant allows the fluid mechanics of the problem to be separated from the combustion process. The experimental facility was designed to model solid waste pyrolysis in an acoustically excited incinerator. Dry ice was placed in a rectangular chamber in which resonant acoustic oscillations could be driven. A mean flow of air entered from one end of the chamber, and exhaust was removed from the opposite end. Flow visualization indicated that the mass transport near the dry ice surface was greatly increased when velocity oscillations were present. When the dry ice was positioned at an acoustic velocity antinode of a 160-dB standing oscillation, the sublimation rate was nearly 60% greater than without oscillation. For the conditions studied, the effects of velocity oscillations at a constant amplitude became greater as the mean velocity was increased. Comparison of the sublimation rates measured with dry ice located at acoustic velocity and pressure antinodes shows that, at constant amplitude, acoustic velocity oscillations have a much greater effect on the sublimation rate than pressure oscillations.**

## Introduction

THE identification and implementation of mechanisms that enhance the rates of various transport processes are crucial to the development of combustors that are smaller, more efficient, and less polluting than currently utilized combustors. It has been demonstrated that acoustic oscillations and flow pulsations can be used to increase the rates of transport processes. Results of studies by Patera and Mikic[1] and Ghaddar et al.[2] have shown that mixing and heat transfer rates in laminar flow in a channel can be considerably increased by oscillating the flow rate into the channel at a frequency at which the flow's shear layer is unstable. Although there is considerable evidence that mass[3] and heat[4–7] transfer rates are increased by acoustic oscillations, the mechanisms responsible for these increases are not well understood. Evidence suggests that the increased transport rates are due to the excitation of turbulence and vortical structures by the acoustic oscillations.[4,8]

Results of several investigations of pulse combustors suggest that, when combustion occurs in an oscillatory flowfield, the combustion time is reduced and combustion efficiencies are increased with respect to combustion in a steady flowfield. For example, Lyman and Sabnis[9] showed that pulsations increased the burning rates of individual coal particles, and Zinn et al.[10] found that unpulverized coal nuggets can be burned in a Rijke-type pulse combustor with high combustion efficiency while utilizing little excess air. Bai[11] showed that heavy fuel oils, which are generally difficult to burn, can be burned with high combustion efficiencies in a pulse combustor specifically designed for this purpose.

It is also important to understand the effects of oscillations on combustion in order to reduce the occurrence of combustion instability in situations where such behavior is undesirable. In solid rocket motors, for example, it is generally accepted that the energy required to initiate and maintain acoustic mode instabilities is supplied by oscillatory burning of the fuel caused by the interaction of the solid propellant combustion process with acoustic oscillations present in the motor. It is well known that the solid propellant combustion process is sensitive to pressure, and this pressure coupling mechanism is fairly well understood. It has been proposed by some investigators that solid propellant combustion is affected by the periodic shearing due to acoustic velocity oscillations across the burning surface.[12,13] This velocity coupling mechanism remains somewhat controversial.

Studies by Beddini and Roberts[14,15] suggest that a principle factor of the velocity coupling mechanism is the transition to turbulence of the acoustic boundary layer. In a study of the velocity coupling phenomena by Ma et al.[16] in which dry ice (solid phase carbon dioxide) was used to simulate the fluid dynamic aspects of flow above a burning solid propellant, it was clearly shown that acoustic velocity oscillations affect sublimation process. Results suggested that turbulent forced convection was responsible for the increase in sublimation rate.

In previous studies that used dry ice to simulate solid fuel combustion by Ma et al.,[16,17] the mean flow through the cavity consisted solely of the sublimated gas from the surface of the dry ice. This technique, although similar to a solid rocket motor, in which all the flow is released from the burning propellant, does not allow for independent evaluation of the effects of mean velocity. The goal of the study reported in this paper is to investigate the effect of acoustic mode velocity oscillations on the pyrolysis rate of solid fuel, simulated by the sublimation of dry ice, under a variety of acoustic and flow conditions. This study was stimulated by the need to evaluate the potential benefits of acoustic oscillations in solid waste incinerators.

In this study, dry ice sublimation was used to simulate the pyrolysis of solid fuel in an acoustically excited incinerator so that the fluid mechanics of the problem, i.e., the heat and mass transfer processes, could be separated from the combustion process. The utilized experimental setup simulates a piece of solid waste in an acoustically excited incinerator or a chunk of wood or coal in a pulsed combustor or furnace. The results may be extrapolated, with some caution, to provide insight into the combustion of propellant in a rocket motor or fuel in a hybrid rocket or solid fuel ramjet. The use of blocks of dry ice, rather than the flush mounted samples used in some previous investigations,[16,17] adds a considerable amount of complexity to the fluid mechanics of the problem. However, it is believed that the presence of the sides and corners of the blocks will strongly affect the results and, therefore, to study the influence of flow oscillations on the pyrolysis of a body immersed in an acoustic field, the additional geometric complexities cannot be avoided.

There are a number of reasons why dry ice makes an attractive model for solid fuel combustion. First, the sublimation of dry ice provides a reasonable model of the pyrolysis process; the rate of sublimation depends on the heat transfer rate to the dry ice and the sublimated mass is transferred away in gas phase. Second, due to ambient water vapor convected to the surface of the dry ice and the presence of a small amount of water trapped in the dry ice during

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the manufacturing process, dry ice produces a visible fog as it sublimates, which provides an excellent visualization opportunity. Third, it has been shown that dry ice sublimation provides a reasonable degree of dynamic similarity to a burning solid propellant.[15]

## Experimental Facilities

Figure 1 is a schematic diagram of the utilized experimental setup. The facility consists of a rectangular wood and acrylic box with a 3.8-cm (1.5-in.)-diam air inlet on one end and a 5.1-cm (2.0-in.)-diam exhaust port on the opposite end. The inside of the cavity is 69.9 cm (27.5 in.) long, 20.3 cm (8.0 in.) wide, and 12.7 cm (5.0 in.) high.

Two Atlas 100W, compression type, siren drivers are mounted in the centers of the opposing 12.7-cm (5.0-in.) walls near the downstream end of the chamber. Although it has been the authors' experience that positioning the drivers near the downstream end of the duct reduces the maximum amplitude obtained when driving the fundamental transverse resonant mode, i.e., with velocity oscillations perpendicular to the flow axis, with constant input power, it was necessary to place them as far as possible downstream of the inlet to minimize the effects of secondary mean flows generated by the acoustic drivers.[18] This positioning of the drivers was reasonably effective for driving the longitudinal, transverse, and combined two-dimensional resonant modes of the cavity. The acoustic amplitude was determined using Kistler piezoelectric pressure transducers mounted on the walls and a Brëul and Kaër $\frac{1}{4}$-in. microphone on a movable probe.

Dry ice for this experiment was produced using an Insta-Ice, 454-g (1-lb) capacity, dry ice mold and standard 23-kg (50-lb) cylinders of commercial grade $CO_2$. This produces rectangular blocks of dry ice, $17.2(6\frac{3}{4}) \times 7.3(2\frac{7}{8}) \times 4.8$ cm ($1\frac{7}{8}$ in.). The center of a block of dry ice was placed at $0.25L$ (where $L$ is the chamber length) downstream of the air inlet and centered between the sides. The blocks were placed on a 1-cm ($\frac{3}{8}$-in.)-thick layer of quartz felt insulation to minimize heat losses to the bottom wall. Tests were performed in two different configurations: with the long axis (17.2 cm) of the blocks aligned with the long axis (69.9 cm) of the cavity, referred to as longitudinal orientation, and with the long axis of the dry ice block perpendicular to the long axis of the cavity, referred to as transverse orientation. The smallest dimension of the dry ice block, 4.8 cm, was always in the vertical direction.

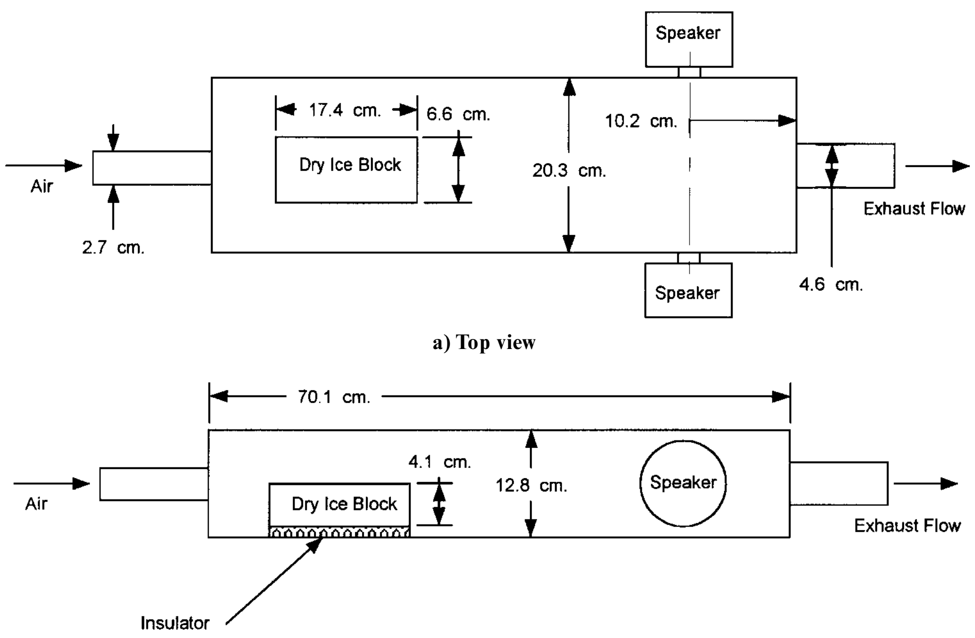
The exhaust flow from the chamber was sampled with a Beckman model 864 infrared $CO_2$ analyzer to measure the percentage of carbon dioxide present. The $CO_2$ concentration was recorded using a Pentium computer running a LabVIEW data acquisition program and an IOTech 488/8SA A/D converter. The analyzer was calibrated over the operating range to ensure proper conversion of voltage output to concentration. The calibration was checked for a midrange value using a commercially obtained calibration reference gas at the beginning and end of each run to ensure accuracy and determine drift. The accuracy of the analyzer measurements is estimated to be 2% of full scale, or $\pm 0.1\%$. From the measured exhaust $CO_2$ concentration data and the known flow rate of incoming air, the amount of excess $CO_2$ sublimated from the block of dry ice was calculated using the following formula:

$$\dot{m}_{CO_2} = (f_m - f_{air})\left(\frac{\dot{m}_{air}}{1 - f_m}\right)\left(\frac{W_{CO_2}}{W_{air}}\right) \tag{1}$$

where $\dot{m}_{CO_2}$ is the sublimation rate of the dry ice, $f_m$ is the measured volume fraction of $CO_2$, $f_{air}$ is the volume fraction of $CO_2$ present in the incoming air, $\dot{m}_{air}$ is the measured mass flow rate of air into the chamber, and $W_{CO_2}$ and $W_{air}$ are the molecular weights of $CO_2$ and air. These mass flow rates can be integrated over time to determine the total amount of mass sublimated during a test. The errors involved in this calculation depend on the amount of drift during the measurement time and will be further addressed subsequently. A digital balance was used to directly measure the mass of the dry ice block at the start and conclusion of each test. The difference of these masses equals the mass of $CO_2$ lost by the dry ice block. Therefore, comparison of this value and the sublimated mass calculated from the exhaust gas analysis technique just described was used to check the results of the experiments.

Because the velocities in the facility and the exhaust were relatively low, there is a danger of flow stratification in the exhaust gas sampling region causing erroneous $CO_2$ measurements. In an effort to enhance the mixing of the $CO_2$ and air in the exhaust flow, a 5.0-cm (2.0-in.)-i.d., 3-m (10-ft)-long, corrugated PVC hose was attached to the exhaust port. A 6.4-mm (0.25-in.) o.d. Teflon® tube inserted in the downstream end of the corrugated hose was used to draw the sample gas for the $CO_2$ analyzer. It was determined that, when the sampling tube was inserted 61 cm (2 ft) into the corrugated hose, i.e., samples were taken 2.4 m (8 ft) down the corrugated tube from the facility, the cross-sectional position of the sampling tube in the corrugated hose did not affect the measurement, indicating that the exhaust flow was well mixed.

The presence of a cold dry ice block in the cavity results in temperature and density gradients in the facility. These gradients affect the speed of sound and, therefore, the wavelength of the standing acoustic oscillation in the cavity. To confirm that the acoustic velocity maximum was indeed located above the block of dry ice, pressure measurements were taken at a number of positions along the axis of the cavity with an inlet flow velocity of $1.0 \pm 0.025$ m/s and a $145 \pm 1$-dB acoustic oscillation amplitude. Figure 2 shows the measured acoustic pressure along the axis of the cavity for the




**a) Top view**

**b) Side view**

**Fig. 1 Schematic of the dry ice sublimation facility.**

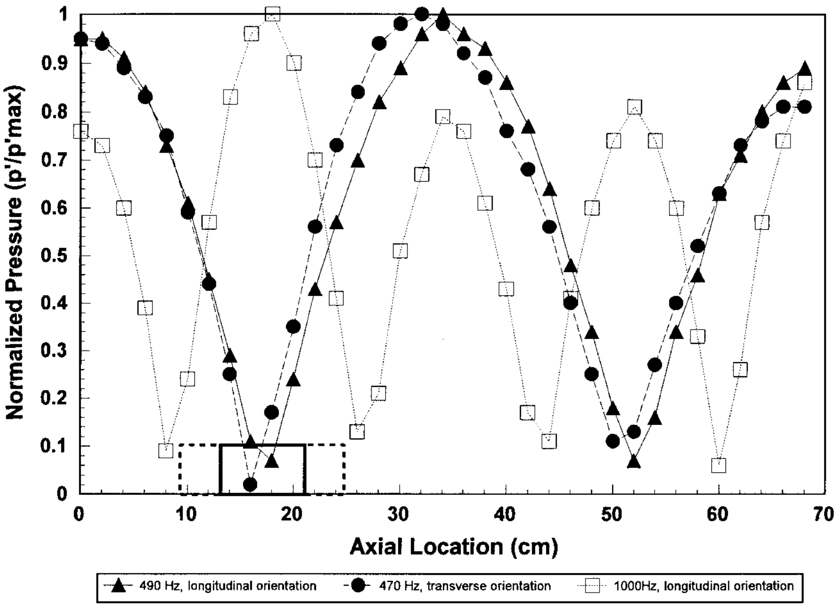



**Fig. 2 Measured axial dependence of the pressure amplitude of several resonant modes excited in the chamber.**

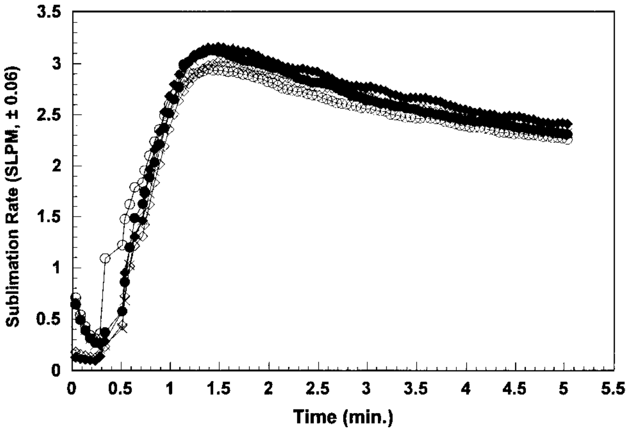



**Fig. 3 Series of tests demonstrating the repeatability of the startup procedure.**

second longitudinal mode with the dry ice block in both the longitudinal and transverse orientations. The frequencies that corresponded to these modes were 490 and 470 Hz, respectively. To provide uniform scaling, the measured pressure amplitudes were normalized by the maximum pressure amplitude measured at those conditions. It is clear that, whereas the temperature effects and the geometrical disturbance imposed by the dry ice affect the standing wave shape, the location of the acoustic pressure minimum (and the acoustic velocity maximum) occurred near the center of the ice block. Also shown in Fig. 2 is the pressure distribution when the cavity was excited in its fourth longitudinal mode with the block oriented longitudinally, which corresponds to a driving frequency of approximately 1000 Hz. In this mode, an acoustic pressure maximum occurred at the center of the dry ice block.

A time sequence of events was established to maintain as much repeatability of conditions between runs as possible. This sequence included making a dry ice block, weighing the block, placing the block in the facility, triggering the data acquisition system, and initiating the acoustic driving. Because the temperature of the gas in the cavity was dependent on the heat transfer to the ice block, the frequencies corresponding to the various resonant modes varied slowly with time. To compensate for this, the driving frequency and power input to the speakers were periodically adjusted to maintain a constant amplitude of the driven acoustic mode. The amplitude of the oscillation was never allowed to vary more than 5% during a run. At the end of a 45-min period, the block was weighed again. The total run time of 45 min was chosen as a compromise between a long period of sublimation to maximize the change in mass of the dry ice block and a short test time that would minimize the change in area of the block due to sublimation. The area change presents some difficulty to the interpretation of the results, because the sublimation rate depends on the surface area, and the change in surface area with time is not easily determined. Over the chosen 45-min test period, the change in mass is typically 30%, with a corresponding change in surface area of about 20%.

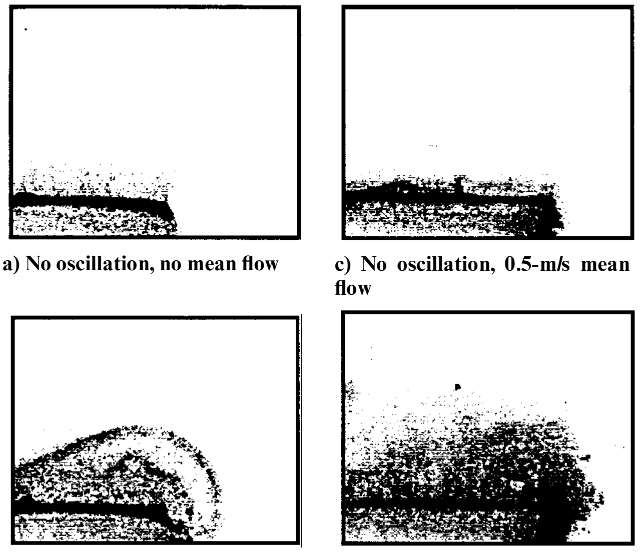
To establish the repeatability of the procedure, a series of tests was performed in which the startup procedure was followed but no acoustic driving was used. The results of this series of tests is shown in Fig. 3. The data show that about 1 min was required for the cavity to reach operating conditions and for the exhaust gas to pass through the sampling system. After this period had passed, the range of measured $CO_2$ flow rates observed was about 0.3 l/min (0.01 $ft^3$/min), which corresponds to about 10% variability. Drift of the analyzer output was negligible over the 5-min duration of these tests.

## Flow Visualization

A Metalaser Technologies 20-W copper vapor laser and a combination of spherical and cylindrical lenses was used to generate a light sheet that was approximately 1.9 mm (0.075 in.) thick at the observed region. The light sheet was introduced into the chamber through the exhaust end of the box. The sheet was oriented in the vertical direction and bisected the chamber and the dry ice block. To avoid focusing problems due to chromatic aberration, the two components of the laser light were separated using an optic that reflects the yellow light and transmits the green component. Only the green light (510.6 nm) was used for visualization. The pulse rate of the laser can be varied from 100 Hz (for short periods of operation) to 10 kHz, and the pulse width is nominally 30 ns. The short pulse width and relatively high pulse energy of the copper vapor laser make it especially well suited to stop-motion photography in high-speed flows.

Flow visualization images were recorded using a Kodak EktaPro EM1012 intensified motion analyzer. This charge-coupled device (CCD)-based system allows a maximum full-frame collection rate of 1000 frames/s. The camera provides 8-bit gray scale response and has a full-frame resolution of $239 \times 192$ pixels. The imaging system is equipped with enough memory to store 3600 full size frames, which can then be downloaded to a personal computer for analysis and storage using an IEEE 488 interface or recorded on videotape.

The images in Fig. 4 show closeup views of the fog layer at the downstream corner of the dry ice block. The dry ice block was positioned in the transverse orientation, as described earlier. The images have been printed in negative for clarity. Figure 4a shows the thin, uniform layer present in the absence of mean flow and acoustic oscillations. Figure 4b shows the same block positioned with its center at a velocity maximum of a $145 \pm 1$-dB acoustic oscillation that is directed left and right across the page. This amplitude corresponds to a velocity fluctuation amplitude of approximately $1.3 \pm 0.1$ m/s



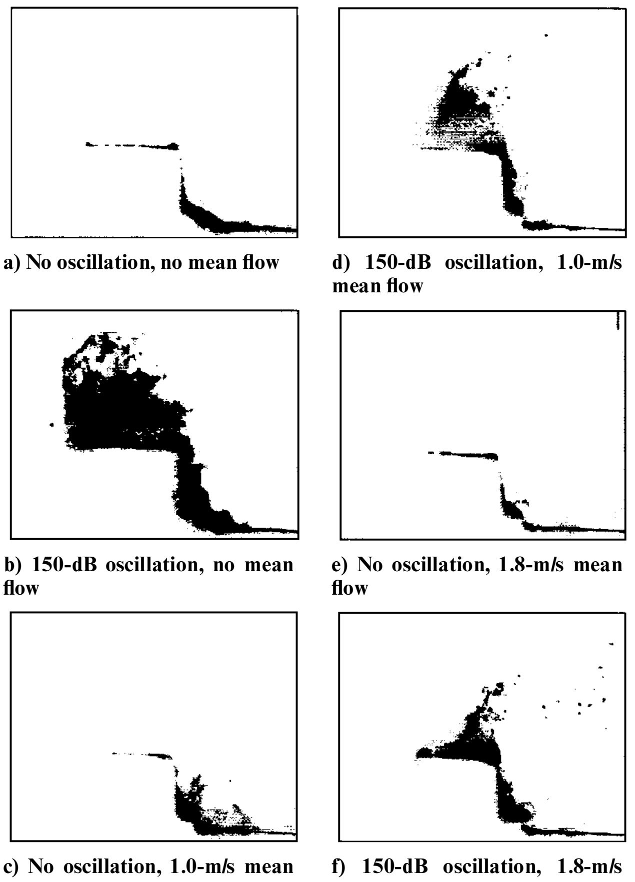
a) No oscillation, no mean flow

b) 150-dB oscillation, no mean flow

c) No oscillation, 0.5-m/s mean flow

d) 150-dB oscillation, 0.5-m/s mean flow

**Fig. 4 Images of the fog layer at the downstream corner of the dry ice block under various conditions.**



a) No oscillation, no mean flow

b) 150-dB oscillation, no mean flow

c) No oscillation, 1.0-m/s mean flow

d) 150-dB oscillation, 1.0-m/s mean flow

e) No oscillation, 1.8-m/s mean flow

f) 150-dB oscillation, 1.8-m/s mean flow

**Fig. 5 Images of the fog layer at the downstream corner of the dry ice block under various conditions.**

(4.3 ft/s) above the ice block. The frequency of the acoustic driving was 490 Hz. A vortical structure is visible around the corner of the block. When a mean flow of air is injected into the chamber (from left to right) at 0.5 $\pm$ 0.025 m/s (1.6 ft/s) without acoustics (as shown in Fig. 4c), small, irregular structures are present in the boundary layer and are convected downstream by the flow. Figure 4d is an image in which the same mean flow is present and a 145 $\pm$ 1-dB oscillation is excited. In this case, the combined effects of the mean convective flow and the acoustically forced velocity oscillations increase the size of the cloud and the chaotic behavior of the flow above the dry ice.

Figure 5 presents images of the illuminated fog layer with higher amplitude acoustic oscillations present in the chamber. The dry ice block was again positioned in the transverse orientation. The perspective has been slightly altered, providing a more complete view of the flow around the block. Because the light sheet enters from the downstream end of the facility, the upstream face of the block is in shadow. In Fig. 5a, where no oscillations and no mean flow are present, the condensation layer above the dry ice block is very thin (as in Fig. 4a), and the cold, sublimated gas simply spills over the edges of the block. Figure 5b illustrates the mixing effect of the acoustic oscillations. The fog layer, under these conditions, extends above the dry ice to a height greater than the thickness of the block. At this amplitude, laminar coherent structures like those visible in Fig. 4b no longer occur, and the boundary layer appears turbulent. In Figs. 5c and 5e, the fog layer above the block is again thin, but in these images some fog can be seen to collect in the wake of the dry ice block. The images in Figs. 5d and 5f show that the thick cloud generated above the block by the acoustic excitation is sheared downstream by the mean flow.

## Experimental Results

In the first series of tests performed, the cavity was forced to resonate in the fundamental transverse acoustic mode. The frequency corresponding to this mode is approximately 835 Hz when the box is filled with air at room temperature and is roughly 10% lower when dry ice is positioned in the cavity. For these tests, the block of dry ice was placed in the transverse orientation (described earlier), where it was subjected to the maximum amplitude of acoustic velocity oscillations. The mean air velocity at the inlet for this sequence of tests was 1.25 $\pm$ 0.025 m/s. Runs were performed at six amplitudes of acoustic oscillation, ranging from no excitation to 150 $\pm$ 1 dB. Each curve in Fig. 6 shows the averaged results from three tests. The sublimation rates are observed to reach a peak when newly formed blocks are placed in the box and then slowly decrease, due to the reduction in surface area of the dry ice blocks as mass sublimates over time. The acoustic driving is initiated at 2 min into the run, which accounts for the discontinuity apparent in some of the curves at that time. It is clear from the data that the sublimation rate increases in the presence of acoustic excitation. The magnitude of the increase depends on the amplitude of the oscillations. Figure 6 indicates that for the investigated test conditions, an amplitude of 145 $\pm$ 1 dB is needed before the effects of the oscillations become evident, and an amplitude at or above 150 $\pm$ 1 dB is necessary before these effects become significant. Note that 145 dB corresponds to a velocity amplitude of roughly 1.25 m/s, which is the air inlet velocity.

Comparison between the measured mass of $CO_2$ lost by the dry ice block and the integral of the flow rate of $CO_2$ in the exhaust determined by gas sampling is shown in Fig. 7. The measured weight losses are shown to be in good agreement with the values calculated from the exhaust sampling procedure, which provides validation of the gas sampling results. The errors involved in the low-technological method of comparing the initial and final masses is estimated to be $\pm$2 g, which is much less than the error of $\pm$8 g estimated for the concentration approach when the drift over a 45-min

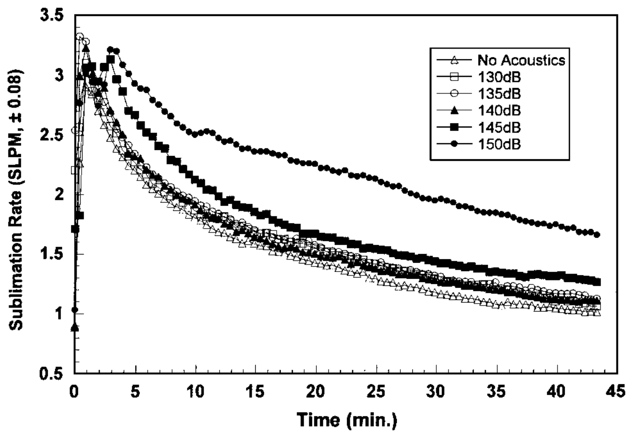



**Fig. 6 Measured sublimation rate at different acoustic amplitudes in the presence of a 1.25-m/s mean flow velocity.**

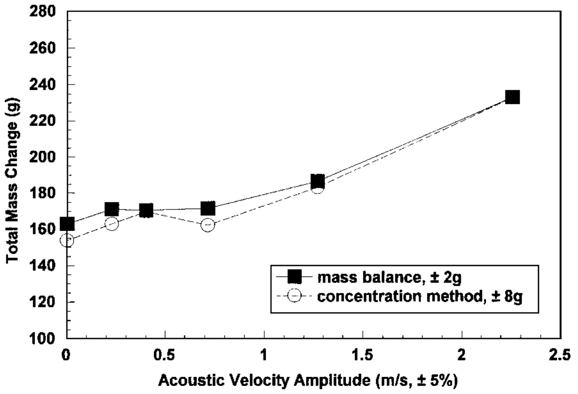



**Fig. 7 Comparison of the measured dry ice mass loss with that calculated from exhaust gas carbon dioxide sampling.**

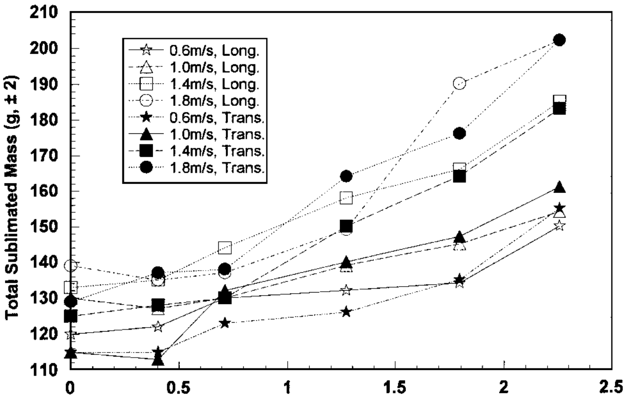



**Fig. 8 Dependence of the total dry ice mass loss on the excitation amplitude and mean flow velocity.**

run is considered. Therefore, the difference of measured masses is used throughout the remainder of this paper.

A sequence of tests was performed in which the effect of the acoustic amplitude on the average sublimation rate was investigated at various mean flow velocities. In these tests, the second longitudinal resonant mode of oscillation was excited. In this mode of excitation, the center of the dry ice blocks were subjected to an acoustic velocity maximum. Tests were performed with the dry ice blocks positioned in both the longitudinal and transverse orientations. The frequency corresponding to this mode is approximately 490 Hz with longitudinal orientation of the dry ice block and roughly 470 Hz with transverse orientation.

The results of this series of tests (plotted in Fig. 8) present the total mass change of a block of dry ice at the given acoustic amplitude for several mean flow rates. For both longitudinal and transverse orientations of the block, the sublimation rate increases with the amplitude of the acoustic oscillation. It is also clear that, as expected, increasing the mean flow rate of air into the cavity increases the sublimation rate. Note that, because the error on the acoustic velocity is given as a percentage, as the acoustic velocity amplitude increases its errors become more significant than the error in the sublimated mass measurements.

Figure 9 shows the relative importance of the acoustic velocity effects at different mean flow velocities. It is difficult to directly compare results measured with different mean flow rates, because the sublimation rate depends on both the mean flow rate and the acoustic velocity amplitude. To allow comparison of data acquired with different mean flow rates, the data were normalized by dividing the total mass change at any given air flow rate and amplitude by the total mass change at the same air flow rate but without acoustic excitation, then subtracting unity so that the results show only the increase in sublimation rate. This is expressed as

$$E = \frac{\Delta m_{v,p\prime} - \Delta m_{v,0}}{\Delta m_{v,0}} \qquad (2)$$

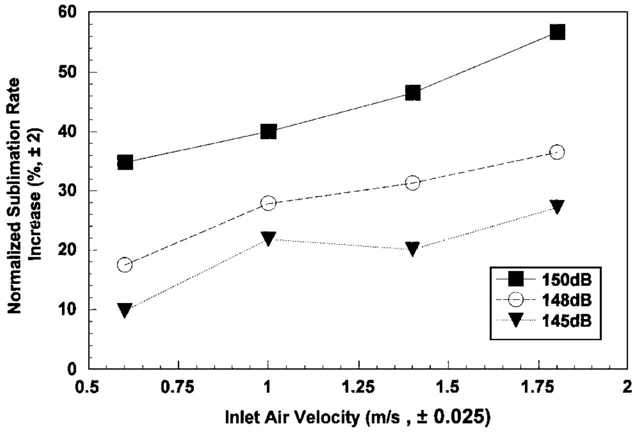



**Fig. 9 Effect of the air inlet velocity and oscillation amplitude on the acoustic enhancement of the dry ice sublimation rate.**

where $E$ is the normalized sublimation rate increase, $\Delta m_{v,p\prime}$ is the change in mass measured at mean velocity $v$ and acoustic pressure amplitude $p\prime$, and $\Delta m_{v,0}$ is the change in mass with the same mean velocity but without acoustic oscillations. The results show, quite interestingly, that, when the acoustic velocity amplitude was held constant and the mean air flow rate was increased, the relative effect of the acoustic velocity on the sublimation rate increased. An explanation for this behavior is suggested by the images shown in Fig. 4. When acoustic oscillations are present, the mass transport rate in the vicinity of the dry ice is apparently much greater than when no oscillations are present. At low mean velocities, the mass that is released from the dry ice is recirculated in the vicinity of the block. If there is little mean flow to convect away the cold $CO_2$, the region near the block will cool and become saturated with $CO_2$, reducing both the heat transfer rate and the diffusive driving potential. As the convective velocity increases, however, this sublimated mass is sheared away from the dry ice block and is replaced by the flow of warm incoming air. Therefore, in this configuration, the combined effect of the acoustic scouring action and the forced convection provides an effective means of transporting warm air to the surface of the dry ice block and cold sublimated gas away from the surface.

Tests were also performed to compare the sublimation rates measured with the dry ice block located at an acoustic velocity maximum to the rates measured with the block located at an acoustic pressure maximum. Considering the geometry of the experiment and of the acoustic wave structure (shown in Figs. 1 and 2), it is clearly impossible to keep the dry ice block in the same position with respect to the incoming mean jet of air and change its position with respect to the acoustic wave without changing the frequency of the excitation. Because previous evidence suggests that acoustic enhancement of the heat and mass transfer is not noticeably affected by the frequency,[5] maintaining the mean velocity distribution was considered more important to the results of the test than the frequency of the excitation. Therefore, the position of the dry ice block in these tests was the same in each run. An acoustic velocity maximum could be excited above the dry ice block by driving the system in its second longitudinal mode. Alternately, by forcing the cavity to resonate in its fourth longitudinal mode (approximately 1000 Hz), a pressure maximum was positioned above the center of the block instead of a velocity maximum (as shown in Fig. 2). For both acoustic modes, the acoustic amplitude was fixed at 150 dB. Transverse orientation was used in this phase of the investigation, because (as shown in Fig. 2) the wavelength of the higher frequency oscillation is only about twice the length of the dry ice block, and so in a longitudinal orientation, it would be impossible to consider the block compact with respect to the wavelength. It is also true, however, that even in the transverse orientation the block is approximately $\lambda/4$ long, which is also not particularly compact. Because of this problem and the possibility that the frequency has some effect on the sublimation rate, however, the results of this test should be considered qualitative only. The results of this test, normalized using Eq. (2), are shown in Fig. 10. The results indicate that the acoustic velocity oscillations have a much more pronounced effect on the sublimation rate than pressure oscillations for this experimental configuration and test conditions.

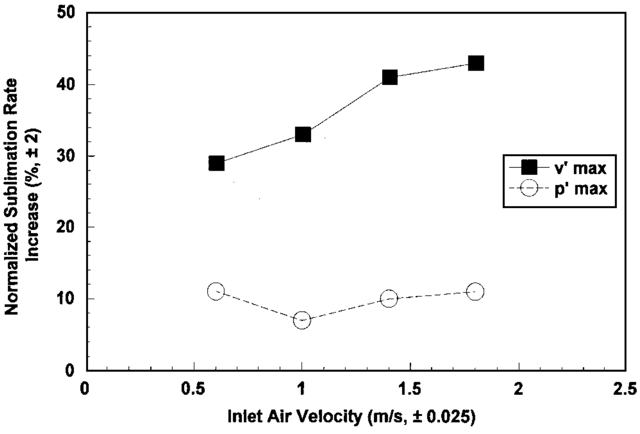



**Fig. 10 Effect of dry ice location relative to the standing acoustic oscillation on acoustic enhancement of the dry ice sublimation rate.**

## Summary and Conclusions

Dry ice sublimation was used to simulate the pyrolysis of a solid fuel in the presence of acoustic oscillations. The use of dry ice as a pyrolysis model allows investigation of the effects of the acoustic oscillations on the heat and mass transfer decoupled from the chemical combustion process.

Visualization reveals that oscillations greatly disturb the boundary layer above the dry ice. The mass transport rate in the vicinity of the dry ice appears much greater when acoustic oscillations are present. The thickness of the fog layer around the dry ice is greatly increased due to the presence of induced turbulence and vorticity. In the range of conditions tested, the combined effects of the mean convective flow and the acoustic oscillations generates a more chaotic flow behavior than either acoustic driving or mean flow alone.

The presence of resonant acoustic oscillations generally increased the sublimation rate of dry ice used to simulate the pyrolysis of a solid fuel. An oscillation amplitude of 150 dB was shown to increase the average sublimation rate nearly 60% above the unexcited sublimation rate at the same conditions. The surface area change of the dry ice block that occurred during the sublimation process presents some difficulty in quantitative analysis, however, because the sublimation rate depends on the surface area, and the change in surface area with time is not easily determined. Over the chosen 45-min test period, the change in mass is typically 30%, with a corresponding change in surface area of about 20%. The maximum change in mass that occurred during this period was 50%, corresponding to a change in area of approximately 37%. Because the sublimation rate decreases as the surface area decreases, the measured enhancement of the average sublimation rate due to the acoustic oscillations underestimates the actual instantaneous increase.

Results of tests at different mean flow velocities and acoustic amplitudes were normalized by the sublimation rates without oscillations so that the effect of the mean flow rates on the sublimation rate could be compared at different amplitudes of oscillation. This revealed that, for the range of conditions studied, the effects of acoustic velocity oscillations at a given amplitude became more important as the mean velocity increased. This is believed to be due to the combined effects of the velocity oscillations, which cause increased heat and mass transfer at the surface of the dry ice, and mean velocity, which convects sublimated mass away from the dry ice region.

A quasisteady fluid mechanical description sheds some insight into the behavior of the flow. As shown in Fig. 4, large vortices can be generated by the acoustic velocity oscillations at the corners of the dry ice. It is expected that, for example, when the acoustic velocity is directed downstream toward the block, the flow will separate at the leading-edge corner, leaving a recirculation region behind the corner and enhancing the mass transport away from the surface. If the flow reattaches along the top surface, it will separate again at the trailing-edge corner. If the acoustic amplitude is greater than the mean flow velocity, this pattern will be reversed during the opposite half of the acoustic cycle. The argument that this is the mechanism responsible for the observed increase in sublimation rate is suggested by the fact that the enhancement seems to be a velocity effect rather than a pressure effect. However, the fact that the sublimation rates did not change significantly with the orientation of the blocks suggests that separation at the corners is not the critical factor in the acoustic interaction with the sublimation rate. It is expected, though, that, in geometries where corners and edges are not prevalent, the results will differ from those measured here. Also, in the investigated configurations, the geometry influences the results in that the sublimated gas can be convected downstream where it no longer affects the sublimation process.

The facility used and the tests performed in this study investigated the pyrolysis of a simulated solid fuel under a variety of acoustic and flow conditions. The utilized dry ice was intended to represent a chunk of solid waste material in an incinerator or wood or coal in a pulsed combustor or acoustically excited furnace. The results of this study indicate that solid fuel will pyrolyze faster in an environment in which high-amplitude acoustic oscillations are present.

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