# Experimental Measurements of Pressure Waves Generated by Impulsive Heating of a Surface

**Matthew A. Brown and Stuart W. Churchill**
Dept. of Chemical Engineering, University of Pennsylvania, Philadelphia, PA 19104

*The first quantitative, reproducible experimental results are presented for the compressive wave generated in a gas by a rapid rise in the temperature of a bounding solid surface. When a resistive-capacitive electrical circuit rapidly heats a thin foil constituting one end of a closed polyacetal cylindrical tube to a high temperature, the amplitude of the initial traveling peak in pressure is proportional to the maximum rise in temperature of the heated surface and depends critically on the heating rate. This amplitude is twice as high for argon as for helium, and is intermediate and essentially the same for nitrogen and air. For all conditions, the wave celerity is slightly greater than the adiabatic acoustic velocity. The waves have a very sharp front and a long region of decay, which is contradictory to the sinusoidal waves postulated by Rayleigh and the nearly symmetrical ones predicted by all prior numerical solutions as well as by the asymptotic solution of Trilling. Such compressive waves and their reflections increase the transient heating rate of a confined gas, may produce unsuspected and unwanted disturbances in otherwise static systems, and offer a possible means of remote detection of excursions in the temperature of a surface.*

## Introduction

Consider a gas confined between two parallel surfaces of infinite extent as shown in Figure 1a. If the temperature of one of the solid surfaces bounding the gas is increased rapidly, the gas adjacent to the surface is heated by thermal conduction. The equation of state for an ideal gas then requires a decrease in density and/or an increase in pressure in this region. Calculations indicate that the density of the gas immediately adjacent to the heated surface decreases in close proportion to the increase in temperature of that surface, thereby requiring equivalent motion of the gas or an increase in density in the more distant gas. Owing to the inertia of the unperturbed distant gas, the gas slightly displaced from the heated surface is actually compressed adiabatically, producing a small increase in pressure, density, and temperature. The resulting incremental pressure propagates as a wave through the yet unheated gas as illustrated in Figures 1b and 1c. Because of the increase in density associated with the adiabatic compression, a small mass velocity away from the wall accompanies the wave. The amplitude of the pulses in pressure, temperature, density, and mass velocity decreases with distance owing to molecular dispersion of energy and momentum. When the wave impacts on the surface parallel to the first it is reflected. The reflected wave is then rereflected off the heated surface, and so on. Imperfect reflections are an additional possible source of decay in amplitude.

The overall heating process of a confined gas by the repeated reflection of a compressive wave is called *thermoacoustic convection*, since the velocity of the wave is observed to be approximately sonic and the process enhances the heat-transfer rate from the wall to the gas relative to pure conduction. Even without reflection, such waves differ, because of their relatively rapid decay rate by molecular dispersion, from the solitary, nearly invariant waves (hydrostatic, optical, or electronic) known as *solitons* (see, for example, Herman, 1992).

The theoretical work on thermoacoustic convection will not be reviewed here in detail because it has been discussed by Churchill and Brown (1987) and because the focus of this article is wholly experimental. It may be noted, however, that Rayleigh (1899) derived an approximate analytical solution for very idealized conditions, that Trilling (1955) derived an asymptotic solution for a single unreflected wave, and that Larkin (1967),

Correspondence concerning this article should be addressed to S. W. Churchill.
Current address of M. A. Brown: Cytec Industries, P.O. Box 60, Stamford, CT 06904.

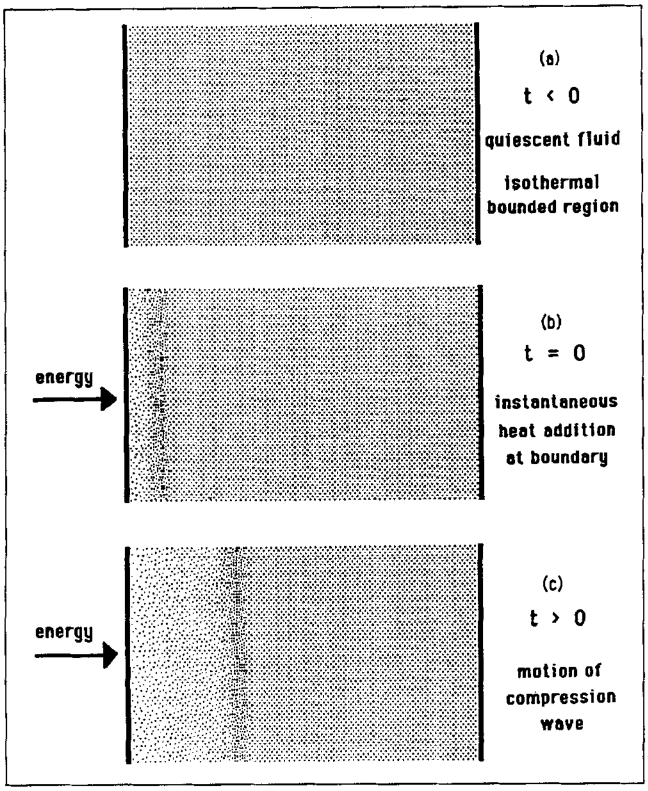


**Figure 1. Wave generation.**

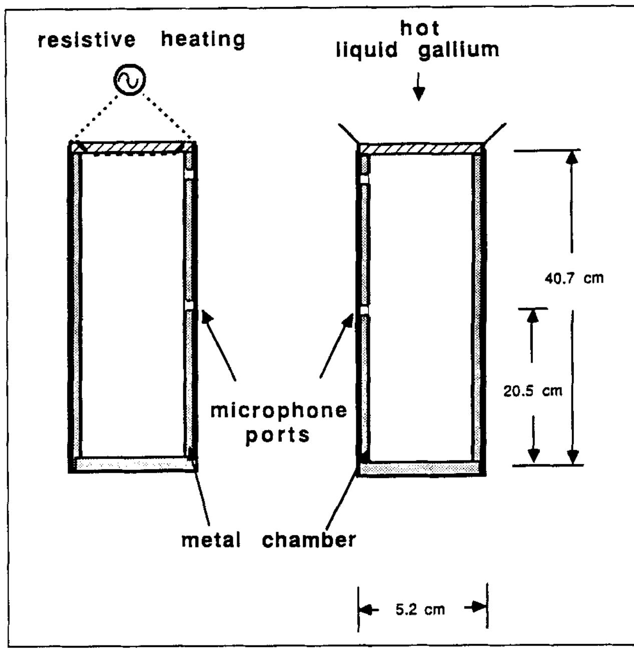


**Figure 2. Preliminary experimental methods of heating.**

Ozoe et al. (1980), and others developed finite-difference solutions for more general conditions.

Thunder is a manifestation of compressive waves in air as generated by localized self-heating by an electrical discharge rather than by a heated surface. (See, for example, Few, 1975, for a discussion of that behavior.) Laser beams generate similar waves but of much lower total energy. Waves can also be generated by local heating of a liquid or solid owing to their finite compressibility, but the thermal effects are less important in most instances because of the greater relative rate of thermal conduction as compared to a gas. (One obvious exception is the ignition of condensed explosive material by a compressive wave.) These several phenomena are related closely to the process considered here but are beyond its scope because of complications of geometry, boundary conditions or the equation of state.

Extensive measurements have been carried out for the compressive waves generated in a gas by shocks, detonations, and explosions, but not for those generated in an initially static gas by a heated surface. The only directly relevant measurements appear to be those of Parang and Salah-Eddine (1987) and Giarratano et al. (1990). Parang and Salah-Eddine measured with thermocouples the transient temperature of gas at the axis of a cylinder, initially at ambient conditions, following rapid heating (300 K/s) of one end. These experiments were carried out under microgravity in a drop tower (to minimize natural convection) and at normal gravity. The measured rate of temperature rise of the air was the same for both sets of experiments. It was greater than that predicted on the basis of pure conduction, but not nearly so great as that predicted for thermoacoustic convection by several prior numerical methods. Giarratano et al. heated, with a pulse of electric current, a narrow strip of titanium in a test cell containing Refrigerant 13. The temperature profile in the fluid adjacent to the heated strip was measured using diffuse-light holographic interferometry. The experiments were carried out in the low-gravity portion of an aircraft flight. Although the measurements demonstrate significant uncertainty, they appear to be in qualitative accord with numerical predictions for thermoacoustic convection.

We first attempted to measure thermoacoustic convection using a sudden pour of molten gallium at 623 K to heat the surface of one end of a cylinder (Figure 2a). This heating method did not prove to be rapid enough to generate waves that could be detected with the low-frequency sensors then being utilized, but the rise in mean pressure with time was observed (Figure 3) to be greater than that predicted for pure conduction. Measurements were then carried out for heating by an AC current passing through a coil of wire on a ceramic plate (Figure 2b). Detectable waves were generated using this technique, but their structure was very erratic and their amplitude was not reproducible. The experiments with gallium and the experiments and results with AC heating are described by Brown and Churchill (1993). The objective of this work is to improve on these preliminary experiments in order to obtain reproducible definitive measurements of broad scope.

Although applications of thermally generated compressive waves in a gas will not be detailed in the presentation of exploratory experimental results, four possible examples are mentioned. First, the repeated reflections of such waves may greatly accelerate the transient heating rate of a confined gas relative to thermal conduction. (See, for example, Larkin, 1967, Ozoe et al., 1980, and Figure 3.) Second, the pressure pulse(s) may be used to detect at a distance an unplanned thermal event such as a fire or an electrical short, or to time at a distance the onset of an anticipated process of heating

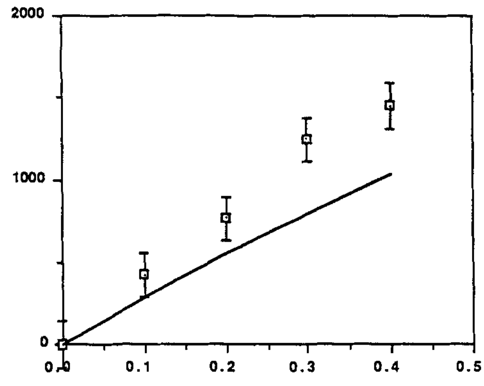


**Figure 3. Long-term measurements of pressure in air at midpoint of tube with AC-resistive heating.**
□, experimental; —, theoretical (conduction only).

such as by a chemical reaction. Third, a need may be identified for special care to avoid or account for the unwelcome disturbances caused by thermally generated waves in specialized applications such as microgravitational or cryogenic processing in which the gas would otherwise remain motionless. Fourth, transport of species may be enhanced or the selectivity of chemical reactions may be increased by the planned use of resonant waves.

## Experimental Apparatus and Method

With the knowledge gained from the preliminary work mentioned above, the experimental approach was modified to utilize direct-current heating of the metal-foil endpiece of a polymeric cylinder by means of an RC (resistive-capacitive) power-circuit. The RC circuit required careful design because of the presumed critical dependence of the amplitude of the thermoacoustic waves on the heating rate and on the maximum rise in temperature of the endplate. The overall scheme is shown in Figure 4 and the details of the apparatus and circuitry in Figures 5–11.

As shown in Figure 5, a polyacetal tube with an ID of 21.4 mm, a wall thickness of 5.95 mm, and a length of 616 or 911 mm was mounted vertically on a thin metal foil supported below by a section of fibrous ceramic insulation. The foil was anchored in thick slabs of copper serving as bus bars for the main heating circuit. An annular piece of ceramic fiber cloth served as a collar that separated the tube wall from direct contact with the foil. The square foil was larger than the end of the cylinder, leaving the top face of the foil exposed to gas in the interior of the tube, to the annular collar, and to the surroundings outside the tube at the four corners. This geometry was chosen, despite the indicated disadvantages, to attain a uniform electrical current across the foil. Condenser microphones (only one is shown) were mounted axially in 12.7-mm holes so that the location of their flat face was circumscribed within the interior wall of the cylinder. The microphones were thus exposed to the gas but disrupted the contour of the inside surface only minimally. Small holes were used for metering in and venting out gas samples. During the

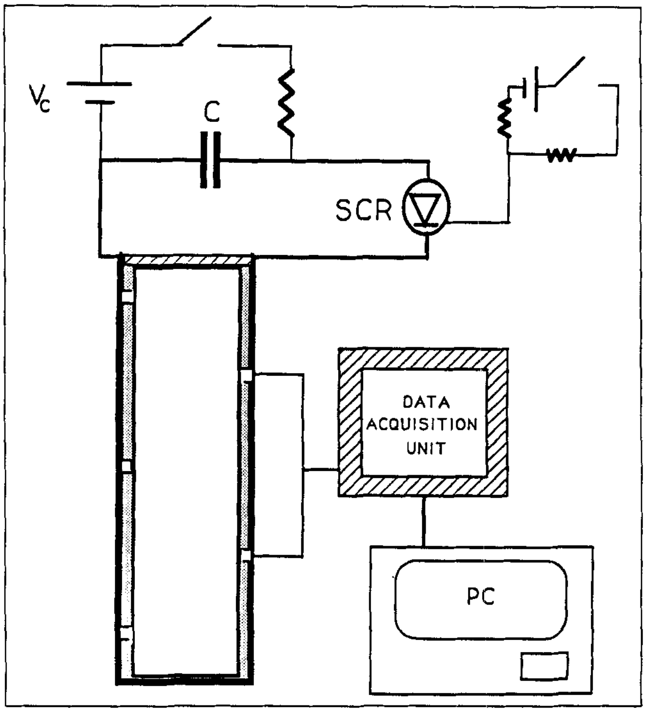


**Figure 4. Experimental apparatus with RC-discharge heating.**

thermoacoustic tests the vent hole was plugged and a thin polymeric plate with an overlying metal weight served as the top endpiece. Both the top end of the tube and the port holes for the microphone were fitted externally with polymeric putty as a sealant and support.

The configuration of the resistances in the RC circuit is shown in Figure 6. The thin metal foil undergoes ohmic heating. The resistance of the several elements was chosen to result

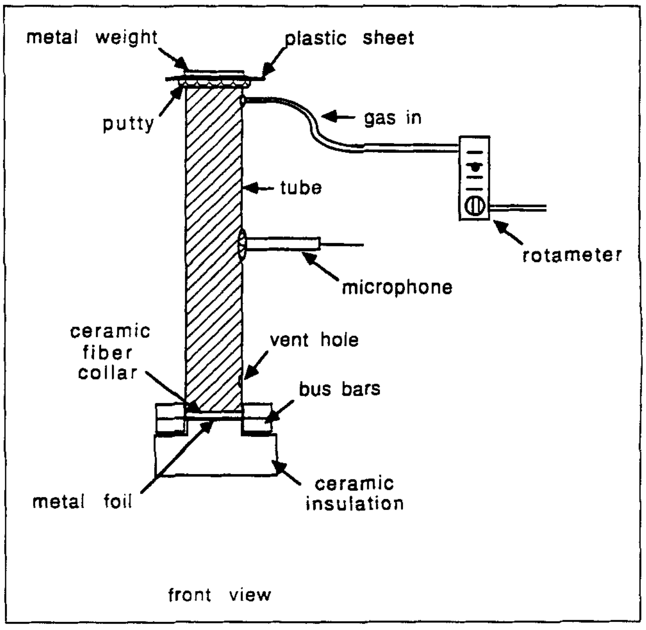


**Figure 5. Experimental chamber and accessories.**

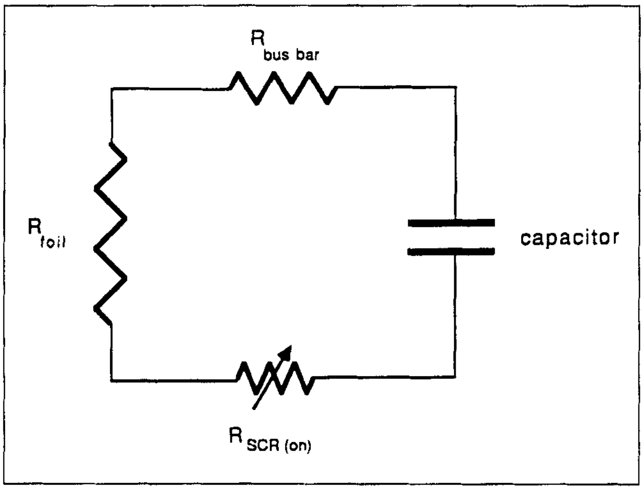


**Figure 6. RC circuit.**

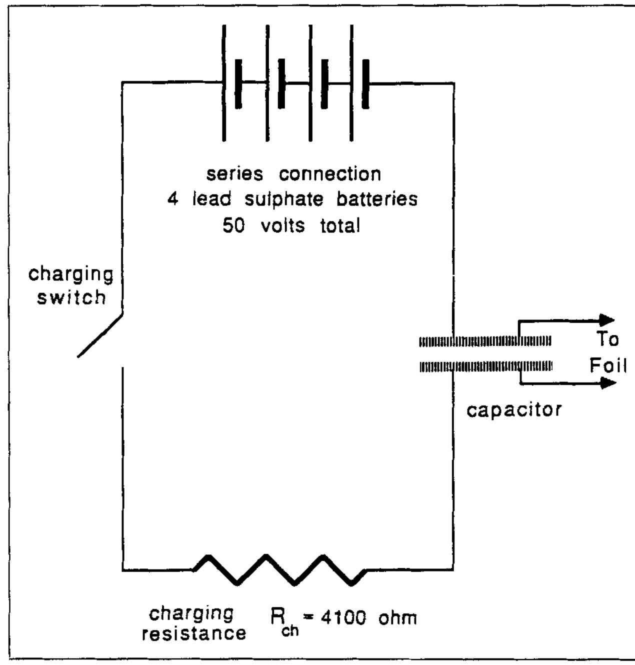


**Figure 8. Charging circuit.**

in a small time constant for the discharge of the capacitor together with a high resistance for the foil relative to the other elements of the circuit. The discharge of the capacitor is triggered by an SCR (silicon-controlled rectifier) gate-switching circuit (Figure 7). The SCR (also known as a thyristor) blocks the current until a small voltage is applied to the gate terminal; at which point the internal semiconductor switches to the "on" state. This behavior is characterized by a rapid transition from a large to a small resistance. Figure 8 shows the circuit used to charge the capacitor before each run. Four lead-sulfate automobile batteries served as the source of voltage in all but two series of runs. In the latter, ten 9-V batteries in series were used to deliver a greater charge to the capacitor. The charging resistance was chosen to produce an acceptable time constant for the process of charging-up.

An analytical expression was derived to estimate the foil temperature as a function of time on the basis of the above circuitry (see Brown, 1992, for details). Values computed from this expression are plotted in Figure 9 for a nickel foil with a capacitance of 0.021 F, 45 V and a circuit efficiency (the ratio of the resistance of the foil to the total resistance) of 0.3. The points labeled "with losses" represent the effect of the estimated rates of conduction, convection and radiation from the foil. The maximum temperature is seen to be nearly independent of the estimated heat losses for these conditions. Also, the times (> 10 ms) required for significant losses are much greater than the entire period of the experiments for which data are reported here. The effect of heat losses on the temperature profile across the foil (Figure 10) is confined to the region very near the wall.

The pressure measurements were made with 12.7-mm Bruel and Kjaer 4134 condenser-microphones. The detection train included Bruel and Kjaer 2639T preamplifiers and an isolated

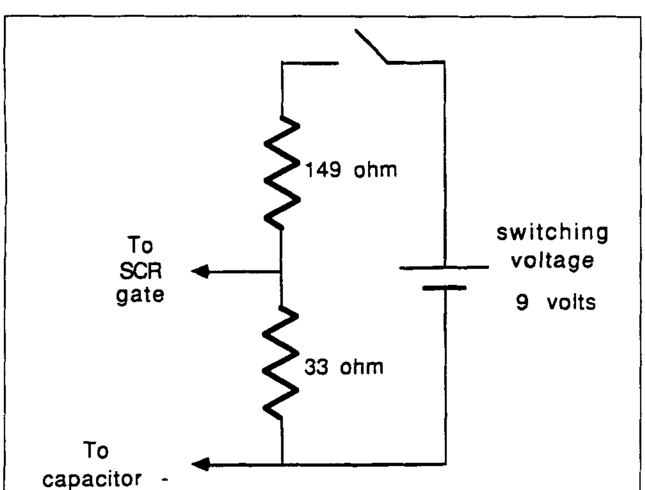


**Figure 7. SCR gate-switching circuit.**

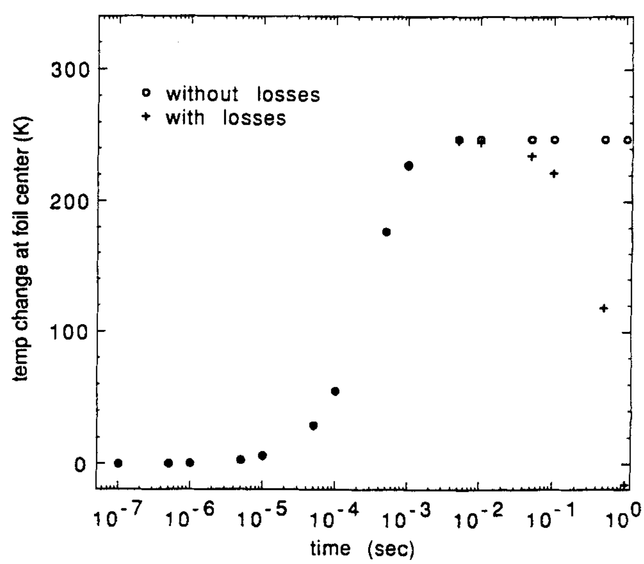


**Figure 9. Predicted transient temperature of foil.**

60-$\mu$m nickel foil, 21-mF capacitor, 45-V discharge, circuit efficiency of 0.3.

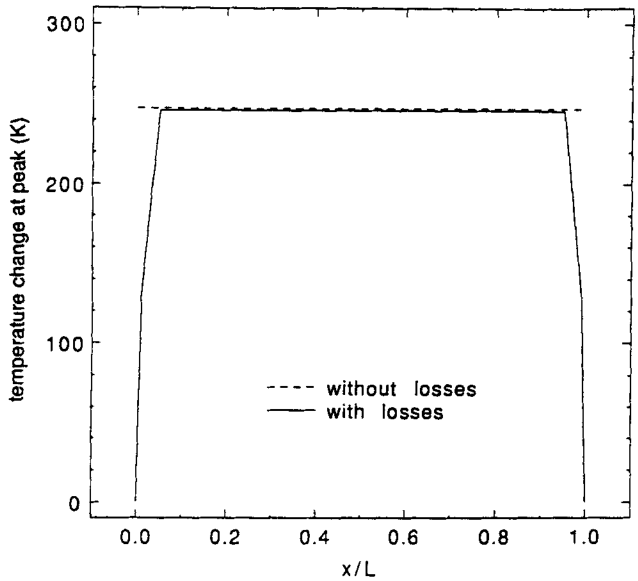


**Figure 10. Predicted effect of heat losses on temperature profile across foil.**
Same conditions as for Figure 9.

Bruel and Kjaer 2804 microphone-power-supply. With the shorter tube, one microphone was located at the midlength (305 mm from the heated end) and the second one at 566 mm from the heated end (50 mm from the adiabatic end) at the same circumferential orientation. With the longer tube the first microphone was located 76 mm from the heated end, and the second at 74 mm from the adiabatic end and at an angle of $\pi/2$ rad from the first. The temperature was measured with 152.4-mm-long Chromel-Constantan type-E thermocouples with wire diameters of 12.7 $\mu$m. The analog measurements were recorded, digitized, and saved through a Kiethley 570 data-acquisition unit with a host IBM PC-XT. A sampling rate of 36.04 kHz was determined from the response of the acquisition system to an external time base provided by a Textronix Type 549 storage-type oscilloscope. The voltage offset (Figure 11a) was used with a single microphone to provide acceptable levels to the analog convertor. The configuration of Figure 11b was required when using the two microphones to retain the maximum rate of sampling for the simultaneous measurements. Resistance was measured with a Kiethley Model 503 milliohmmeter.

### *Scope of measurements*

Approximately 300 experimental runs were carried out with the above apparatus using helium, argon, nitrogen, and air at ambient conditions, foils of nickel, zirconium, titanium, and copper with a collective range of thicknesses from 6 to 127 $\mu$m, and capacitors rated at 1.2, 5.7, and 21 mF in the RC circuit. For a given configuration of the circuit, a number of different voltages were discharged across the foil. Two different silicon-controlled rectifiers were used as switching controllers. Destruction of the foil due to overheating occurred in only five runs and breakdown of the SCR in only four runs. Some of these terminating runs actually produced satisfactory data. Runs repeated over a period of several months exhibited a remarkable degree of reproducibility.

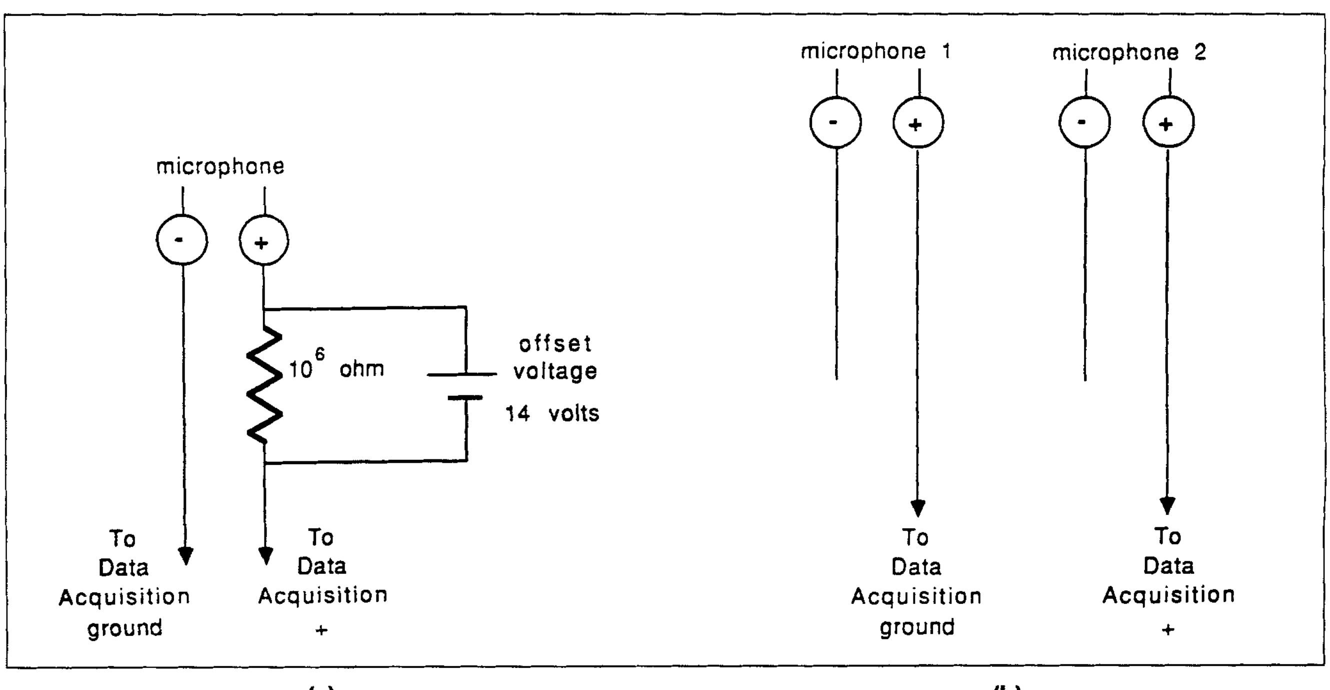


**Figure 11. Connections for microphones.**
a) Single microphone; b) coupled microphones.

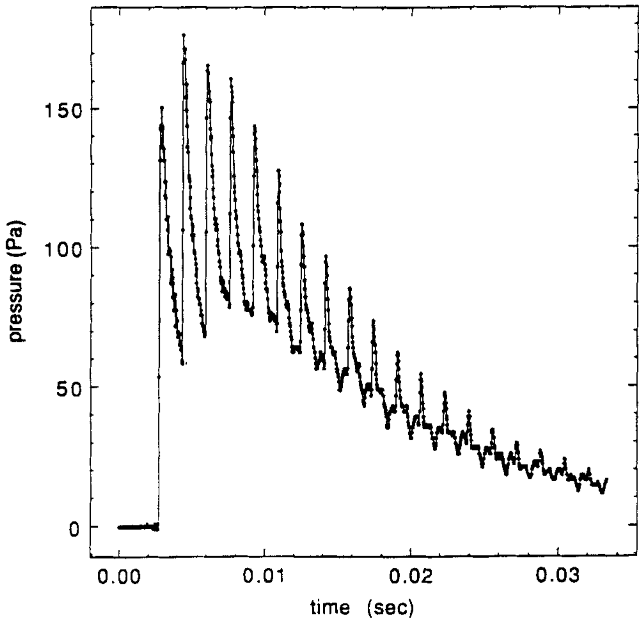


**Figure 12. Experimental trace of pressure with one microphone at 305 mm from the heated end of 616-mm tube with nitrogen.**

At 301.15 K and 756 mm Hg, $(T_{max}-T_o)/T_o=0.695$, and $\tau_h=341$ $\mu$s.

## Experimental Results

### *Transient pressure*

Figure 12 exhibits a representative measurement of the transient pressure at a distance of 305 mm from the heated end (311 mm from the adiabatic end) of the shorter tube with the

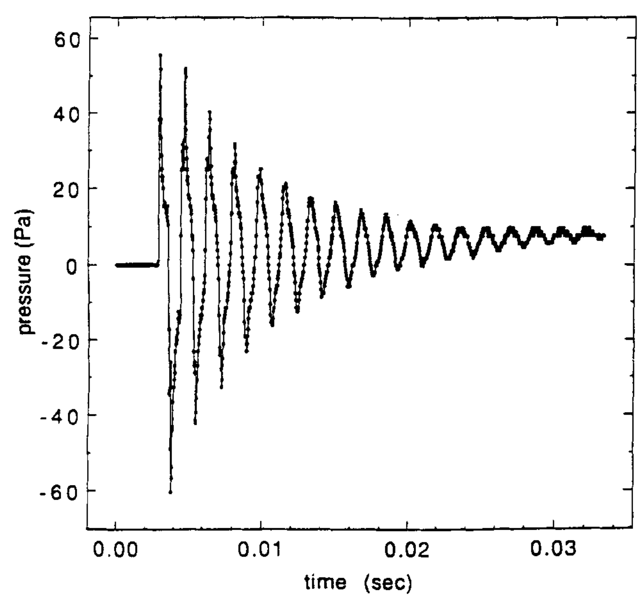


**Figure 13. Experimental trace of pressure with coupled microphones at 76 and 838 mm from the heated end of 911-mm cylinder with helium.**

At 303.15 K and 763 mm Hg, $(T_{max}-T_o)/T_o=0.0577$, and $\tau_h=864$ $\mu$s.

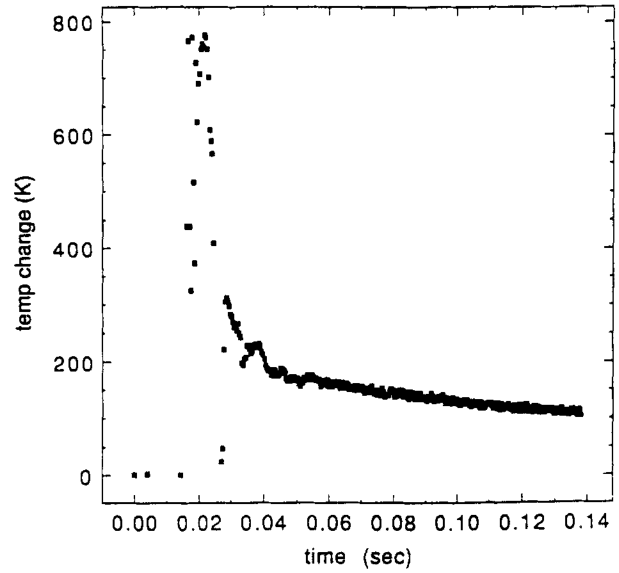


**Figure 14. Transient temperature of foil as measured by a thermocouple.**

A 60-$\mu$m nickel foil, a 21-mF capacitor, a 45-V discharge, and a circuit efficiency of 0.3.

single-microphonic arrangement. This particular experiment was one of several for nitrogen at 301.1 K and 756 mm Hg with a maximum dimensionless temperature on the surface, $(T_{max}-T_o)/T_o$, of $\sim 0.695$, and an exponential time constant for heating of the foil of 341 $\mu$s. The latter value, which corresponds to the time required for the metal foil to attain 63% of its maximum rise in temperature, characterizes the ohmic heating rate as determined by the specific circuitry. The origin of time in this tracing could not be synchronized with the onset of heating and is therefore arbitrary. The initial amplitude in pressure of about 153 Pa is seen to be far above the background noise. The succeeding peaks represent the passage of the wave following the first reflection off the far end, the first reflection off the heated end, the second reflection off the far end, and so on. The wave front is very steep with a long tail which is cut off by the signal from the succeeding reflection. This shape differs radically from the sinusoidal waves postulated by Rayleigh (1899) and the nearly symmetrical ones computed numerically (Larkin, 1967; Ozoe et al., 1980), but agrees qualitatively with and is predicted analytically by the asymptotic solution of Trilling (1955).

Figure 13 exhibits a representative measured trace of the pressure for the dual-microphonic arrangement. This experiment was for helium at 303.15 K and 763 mm Hg in the longer tube with a maximum dimensionless temperature on the surface of $\sim 0.0577$ and an exponential time constant for heating of the foil of 86.4 $\mu$s. With this arrangement the pressure from the first microphone registers as positive and that from the second as negative. The recorded pressure represents the sum of those measured by the two microphones. The successive extreme positive peaks (maxima) correspond to waves with a positive velocity (the initial wave and its reflections off the heated wall) as they pass the first microphone. The extreme negative peaks (minima) correspond to waves with a negative velocity (reflections off the adiabatic end) as they pass the second microphone. The transitions, observed in Figure 13 intermediate between a maximum and a minimum, correspond to waves with a positive velocity passing the second microphone while those between a minimum and a maximum correspond to waves with a negative velocity passing the first microphone.

If the tube were truly adiabatic, absolutely rigid, and perfectly sealed, the space-averaged pressure would have increased monotonically. The decrease in the peaks in pressure in both Figures 12 and 13 is due to the leakage of gas and heat. The accumulative heating rate of the gas could therefore not be determined quantitatively from the experiments described here. The primary source of the loss of pressure is presumed to be leakage since some success was achieved in the preliminary experiments (see Figure 3), which utilized a metal tube and therefore allowed better sealing, but also some extraneous heating by conduction along the tube wall.

### *Maximum temperature on the surface of the foil*

The maximum temperature attained by the electrically heated foil was determined by two independent procedures. Figure 14 illustrates the temperature history indicated by a thermocouple on the foil. The origin of the time scale is arbitrary; triggering occurred at ~17 ms in this experiment. The large initial excursion in the indicated temperature is an artifact of the severe electromagnetic environment existing in the vicinity of the thermocouple during the discharge of the RC circuit. The real temperature is indicated by the long-term decay after ~40 ms. The maximum temperature attained by the foil was estimated by extrapolation of this latter portion of the data to 17 ms. In the most common experimental configuration such values agreed within 10% with those calculated from the idealized theoretical model for the electrical circuit.

### *Variation of the maximum pressure with the maximum temperature on the surface*

As indicated in Figure 15, the amplitude of the initial peak in pressure was found to vary linearly with the maximum temperature attained by the foil. The upper set of points are for 302.15 K, 768 mm Hg, and an exponential time constant of 86.4 μs, while the lower set are for 300.15 K, 756 mm Hg, and an exponential time constant of 341 μs. Both sets of measurements are for argon in the shorter tube with a single microphone. The slower heating rate, which corresponds to the larger time constant, resulted in a lower peak in pressure for a given maximum temperature on the surface.

### *Decay of the wave*

The decay of the wave with distance is indicated in Figure 16 by the peak pressure of the initial wave at two locations 690 mm apart in the longer tube for air at 305.15 K and 763 mm Hg, and for an exponential time constant for the foil heating of 86.4 μs. A wave experiencing no decay would yield points along the line for $x=y$. The observed decay in the measured amplitude is thus about 7%.

### *Variation of the maximum pressure from gas to gas*

The representative data for the variation of the peak pressure

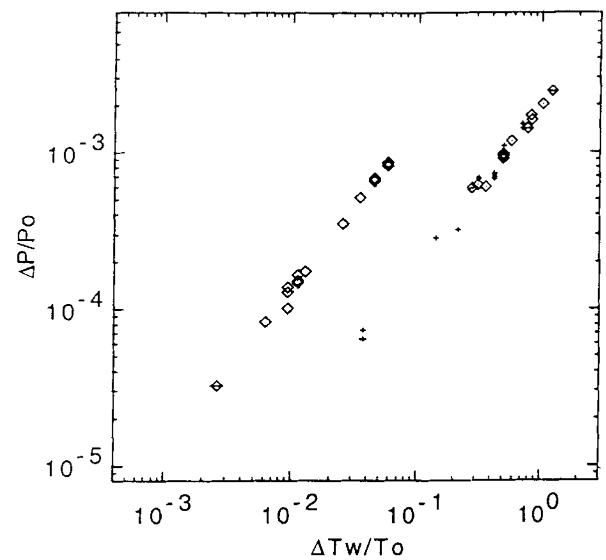


**Figure 15. Effect of heating rate and maximum rise in temperature of the wall on maximum amplitude of pressure in the 616-mm tube with air.**

At ~300 K and ~760 mm Hg, the time constant for heating was 86.4 μs for the upper set of measurements and 341 μs for the lower set.

from gas to gas in Figure 17 were obtained with a single microphone in the shorter tube for an exponential time constant of 341 μs and essentially constant ambient conditions. The amplitudes in pressure for argon are about twice those for helium. The amplitudes for air and nitrogen are essentially the same and fall in between those for argon and helium.

### *Celerity of the wave*

The celerity of the wave can, in principle, be determined

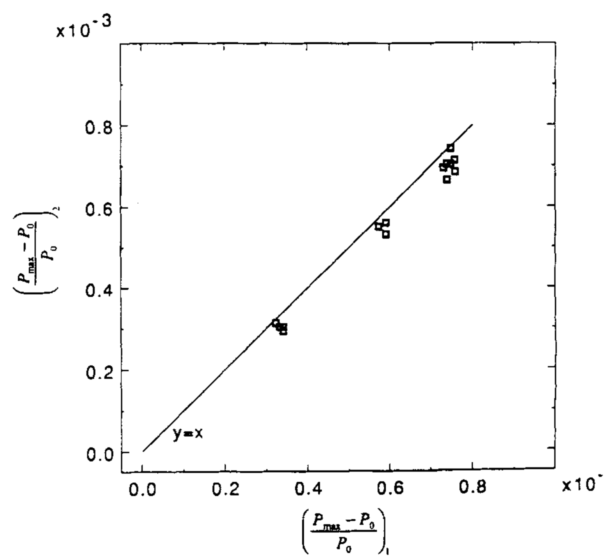


**Figure 16. Rate of decay of amplitude over 762 mm for air.**

At 303.15 K and 763 mm Hg, and $\tau_h = 86.4$ μs.

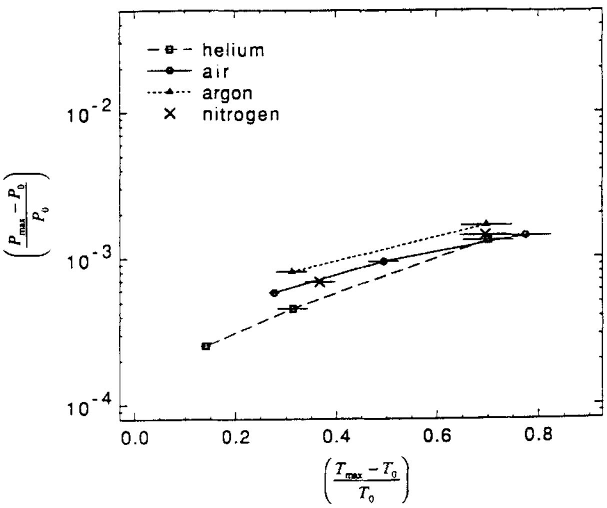


**Figure 17. Maximum amplitudes for different gases at 305 mm from the heated end of the 616-mm tube.**

At ~300 K and 760 mm Hg, and $\tau_h = 341$ μs.

from the locations and times of the successive peaks in Figures 12 and 13, but significant uncertainty arises owing to the finite width of the microphones, the processing of their signals, and the decay of the wave with distance. Values determined with two microphones for argon at 303.15 K and 774 mm Hg in the longer tube with an exponential time constant for the foil heating of 86.4 μs are plotted in Figure 18 in terms of the Mach number based on the initial conditions. These celerities are consistently above the adiabatic acoustic velocity but reveal considerable scatter and no definite trend with the maximum dimensionless temperature of the heated wall. The bounds of uncertainty associated with the finite width of the microphonic

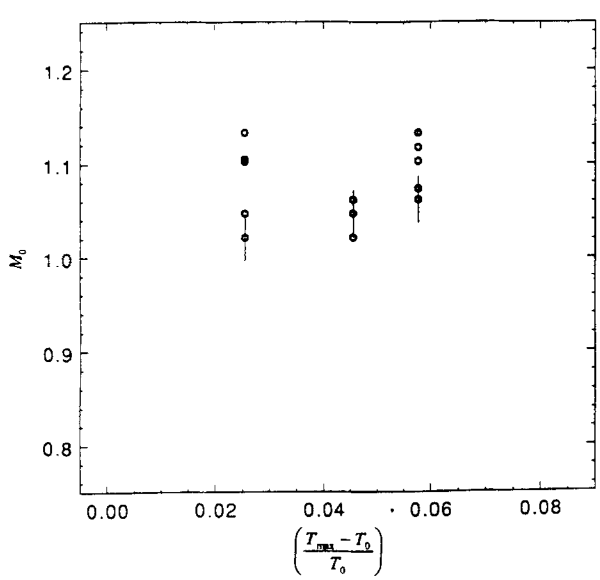


**Figure 18. Celerities determined from passage of peak pressure past two microphones in the 911-mm tube for argon.**

At 303.15 K and 760 mm Hg, and $\tau_h = 86.4$ μs.

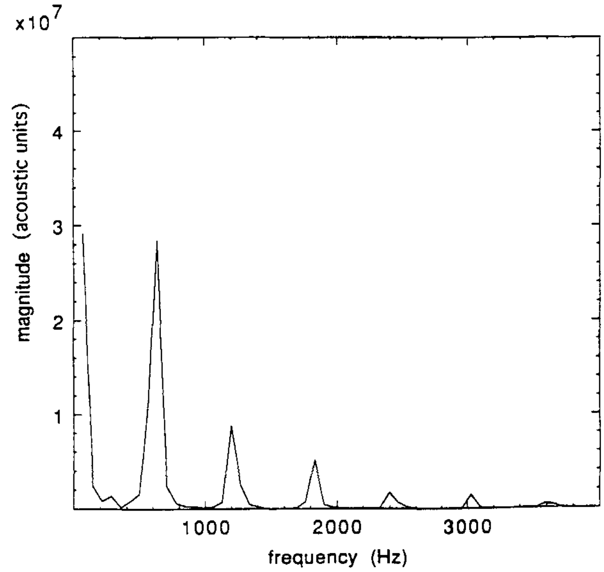


**Figure 19. Power spectrum for air in the 616-mm tube with a microphone 305 mm from the heated end.**

At 297.65 K and 771 mm Hg, $(T_{max} - T_o)/T_o = 0.703$, and $\tau_h = 341$ μs.

detectors are indicated for several of the measurements. The celerity can also be determined from the frequency components of the measurements; the power spectrum of the signal from a single microphone is calculated from the square of the magnitude of the fast Fourier transform at discrete frequencies. The resulting spectrum for measurements in air is illustrated in Figure 19. The dominant frequency of 640 Hz indicates a Mach number of 1.136 for the associated conditions.

## Summary and Conclusions

These measurements are apparently the first for the structure of the compressive wave generated in a confined gas by a rapid rise in the temperature of a bounding surface. They reveal behavior (in particular the shape of the wave) which is not in accord with either the analytical solutions of Rayleigh and Trilling or the various numerical predictions, and thereby raise questions regarding the reliability of both the former and the latter.

Because of the absence of prior experimental work it was necessary to devise completely new techniques for the controlled generation and characterization of these waves. In our prior work, heating a metal disk with a pour of molten gallium was first utilized for generation of such waves, but that procedure resulted in too slow a rate of rise in the temperature of the surface owing to the resistance of the gallium and the metal disk to thermal conduction. Heating of a coil of wire on the inner surface of a ceramic disk with an alternating current, which was tried next, generated a detectable compressive wave, but had poor reproducibility owing to the nonuniformity of the temperature of the ceramic disk, the termination of the heating by failure of the wire, and the long period of the electrical cycle relative to that of the process of heating.

In this work, DC heating of a thin metal foil by a RC-discharge circuit proved to be much more satisfactory (Figure 9). A wide range of readily controlled heating rates and maximum temperatures was readily attained. Furthermore, the foil temperature remained close to its maximum value over the effective duration of the experiments (Figure 9). The maximum foil temperature as determined with a thermocouple agreed well with the value predicted from the calibration circuitry. (The severe electromagnetic environment imposed by the discharge of the RC circuit actually caused a spurious short-term excursion in the reading of the thermocouple, and extrapolation of the long-term measurements to the time of discharge was necessary to determine the real value.)

Condenser microphones proved to be satisfactory for measurement of the amplitude of the transient pressure (Figure 12), but a somewhat restrictive circuitry was necessary when two were used simultaneously owing to the finite sampling rate of the data-acquisition system (Figure 11b).

The amplitude in pressure of the initial wave was found to be directly proportional to the maximum rise in temperature attained by the foil (Figure 15). Slower heating rates (as characterized by a greater exponential time constant) resulted in lower amplitudes in pressure for a given temperature rise of the foil (Figure 15). These measurements of both the rise in temperature and the maximum amplitude in pressure proved to be very reproducible.

The maximum amplitude of the pressure depended on the nature of the gas, presumably on its molar mass and heat capacity ratio. An increase by a factor of about two resulted from using helium in place of argon (Figure 17).

The wave was found to decay quite rapidly in amplitude with distance (or time) owing presumably to molecular dispersion of energy and momentum (Figure 16). Some decay also appears to ensue from reflection.

The wave had a very sharp front and a long tail (Figures 12 and 13). This observation is contradictory to the sinusoidal form postulated by Rayleigh and the nearly symmetrical ones predicted by the several numerical solutions, and the asymptotic solution of Trilling.

The celerity of the wave was determined from the time of passage of the peak in pressure from one microphone to another as well as from the power spectrum of the signal from the microphones. These determinations were all incrementally above the adiabatic acoustic velocity (Figure 18), but the uncertainty of about 10% in these determinations was of the same order of magnitude as the incremental differences.

The accumulative rate of heat transfer to the confined gas could not be determined accurately and confidently from the long-term rise of pressure in these experiments of limited duration owing to heat losses of unknown magnitude and the probable leakage of gas.

These first quantitative, reproducible, experimental determinations of the amplitude and celerity of thermally induced compressive waves in a confined gas have possible importance in several respects. First, such waves increase the transient heating rate of the gas relative to pure thermal conduction. Second, they may produce unsuspected dynamic disturbances in otherwise static processes. Third, they may provide a means of quantitative detection of excursions in temperature by a surface. Fourth, the deviation of the observed form of the wave front from that of prior finite-difference calculations raises doubt as to the accuracy of the associated predictions such as the accumulative rate of heating.


## Acknowledgments

This material is based in part on work supported by the National Science Foundation under Grant No. GBT 8721365. Support for MAB in the form of a fellowship was also provided by the AMOCO Foundation. Professor F. D. Ketterer and Mr. Bernard Cohen of the Department of Electrical Engineering of the University of Pennsylvania offered useful suggestions for the design of the electrical circuitry. We acknowledge gratefully all of the support and assistance.


## Notation

$L$ = length of cylinder, m
$M_o$ = $U_w(\rho_o/\gamma_o P_o)^{1/2}$ = Mach number of wave based on adiabatic acoustic velocity at $P_o$ and $T_o$
$P$ = absolute pressure, Pa
$P_{max}$ = maximum absolute pressure, Pa
$P_o$ = absolute pressure at initial state, Pa
$t$ = time, s
$T$ = absolute temperature of heated wall, K
$T_{max}$ = maximum absolute temperature of heated wall, K
$T_o$ = absolute temperature of heated wall at initial state, K
$U_w$ = celerity (velocity of propagation) of wave, m/s
$x$ = distance from heated wall, m

### *Greek letters*

$\gamma$ = heat capacity ratio
$\rho_o$ = specific density of gas at initial state, kg/m$^3$
$\tau_h$ = exponential time constant for heating of foil, s

## Literature Cited


Brown, M. A., "Thermally Induced Pressure Waves in a Gas: Experimental Observation and Theoretical Prediction of Thermoacoustic Convection," PhD Thesis, Univ. of Pennsylvania, Philadelphia (1992).

Brown, M. A., and S. W. Churchill, "Transient Behavior of an Impulsively Heated Fluid," *Chem. Eng. Technol.*, **16**(2), 82 (1993).

Churchill, S. W., and M. A. Brown, "Thermoacoustic Convection and the Hyperbolic Equation of Conduction," *Int. Commun. Heat Mass Transf.*, **14**(6), 647 (1987).

Few, A. F., "Thunder," *Sci. Amer.*, **233**(1), 80 (July, 1975).

Giarratano, P. J., A. Kumakawa, V. D. Arp, and R. B. Owen, "Transient Heat Transfer Studies in Low-Gravity Using Optical Measurement Techniques," *J. Thermophys. Heat Transf.*, **4**(1), 53 (1990).

Herman, R., "Solitary Waves," *Amer. Scientist*, **80**(4), 350 (1992).

Larkin, B. K., "Heat Flow to a Confined Fluid in Zero Gravity," *Prog. Astro. Aeronaut.*, **20**, 819 (1967).

Ozoe, H., N. Sato, and S. W. Churchill, "The Effect of Various Parameters on Thermoacoustic Convection," *Chem. Eng. Commun.*, **5**, 203 (1980).

Parang, M., and A. Salah-Eddine, "Experiments on Thermoacoustic Convection Heat Transfer in Gravity and Low Gravity Environment," Paper AIAA-87-1651, AIAA Thermophysics Conf., Honolulu, HI (1987).

Rayleigh, Lord (J. W. Strutt), "On the Conduction of Heat in a Spherical Mass of Air Confined by Walls at Constant Temperature," *Phil. Mag.*, **47**, 314 (1899).

Trilling, L., "On Thermally Induced Sound Fields," *J. Opt. Soc. Amer.*, **27**(3), 425 (1955).



*Manuscript received Dec. 17, 1993, and revision received Mar. 7, 1994.*