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International Journal of Heat and Mass Transfer 49 (2006) 575–581

International Journal of HEAT and MASS TRANSFER

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Measurement of thermo-acoustic waves induced by rapid heating of nickel sheet in open and confined spaces

In-Ju Hwang [a], Youn-Jea Kim [b,*]

[a] Fire and Building Services Research Department, Korea Institute of Construction Technology, Goyang 411-712, Republic of Korea
[b] School of Mechanical Engineering, Sungkyunkwan University, Suwon 440-746, Republic of Korea

Received 7 September 2004; received in revised form 27 August 2005
Available online 14 October 2005

Abstract

Experimental investigation on the generation and propagation of thermo-acoustic waves induced by rapid heating of the metal sheet was carried out. This study focuses on the temperature profiles, measurement of pressure wave induced by rapid heating of nickel sheet in open and confined spaces. The *R*–*C* (resistance–capacitance) heating devices and high-speed measurement systems are designed, and methodologies on measurement are established. Results show that the waves have sharp and weak pin profile in an open space, but these waves have sharp front shape and decay with tail in the case of confined space. Results also show that the propagation velocity of thermo-acoustic wave, that is estimated as Mach number (M), generated by rapid heating of nickel sheet, is located in the range of $M = 0.99$–1.04.

1. Introduction

Thermo-acoustic waves can be thermally generated in a compressible flow field by rapid heating, cooling and chemical reactions near the boundary walls. These thermally induced phenomena within the boundary of compressible fluids are referred to as thermo-acoustic convection for description of heat transfer relation [1]. This mode of heat transport has been deemed by a number of researchers to be of particular importance in space environments, where other modes of transport such as free convection may be absent or weak. This may also be significant factor for heat transfer when the fluids approximate their thermodynamic critical points [2].

Recently, these thermo-acoustic theories have been studied for application in refrigerators, compressors, acoustic sensors and improvements to heat transfer, stability of thermal systems and tomography of medical devices, etc. in the developed countries [1–6].

Early interest in thermo-acoustic waves was motivated by the desire to understand their contribution to sound generation and energy conversion. Trilling [7] examined the sound fields induced in a real gas by employing boundary temperature variations. He linearized one-dimensional compressible flow equations and obtained a closed form asymptotic solution, using a Laplace transform technique.

Numerical studies of one- and two-dimensional thermo-acoustic waves in a confined region have been carried out by Ozoe et al. [8]. Their computational studies used a finite difference method of the compressible Navier–Stokes equations for a gas with temperature-independent thermo-physical properties.

Farouk et al. [5] studied the behavior of thermo-acoustic waves in a nitrogen-filled two-dimensional cavity to investigate how the waves might be used as an effective heat removal mechanism. Their result on the pressure distribution is showed comparatively more feasible shape of wave and peak than the previous research. It was also clearly demonstrated that thermo-acoustic convection is much more effective than purely transient conduction.

* Corresponding author. Tel.: +82 31 290 7448; fax: +82 31 290 5889.
E-mail address: yjkim@skku.edu (Y.-J. Kim).

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doi:10.1016/j.ijheatmasstransfer.2005.08.025

But, there are only a few experimental studies that focus on thermo-acoustic waves. Parang and Salah-Eddine [9] measured the temperature of enclosed air that was rapidly heated by the top surface of the cylinder as a function of time in a point inside a cylinder, which consisted of a thin stainless steel foil connected to a power source. They also showed that thermo-acoustic waves increase thermal mixing. Brown and Churchill [1] measured pressure as a function of time, showing that rapid heating of a solid surface bounding a region of gas generates a slight supersonic wave with positive amplitude in pressure, temperature, density and mass velocity.

Systematic studies on the thermally induced thermo-acoustic phenomena were numerically carried out during the end of the twentieth century. Many problems exist, such as accurate numerical schemes, experimental methods, and visualizations requiring more parameters.

In this study, we have experimentally investigated the generation and propagation of thermo-acoustic waves induced by rapid heating of the metal sheet. Specifically, we have focused on the profiles of temperature and pressure waves induced by rapid heating of nickel sheet in open and confined spaces. Furthermore, the *R*–*C* (resistance–capacitance) heating devices and high-speed measurement systems are designed, and methodologies on measurement are established.

2. Experiments

2.1. Experimental apparatus

Temperature of metal sheet with a resistance can be increased abruptly using the characteristics of a capacitor which is able to rapidly discharge an electric power. This *R*–*C* heating system consists of charging and discharging circuits, electric switch and triggering unit, etc. around the capacitor as shown in Fig. 1.

First, the charging circuit consists of capacitor for charging electric power, power supplier of direct current, resistor for protection of exceed current and on/off switch. Discharging circuit consists of capacitor, metal sheet heated by discharging power, electronic switch for instant opening of the electric circuit. Tables 1 and 2 described the specifications of the capacitor, SCR (Silicon Controlled Rectifier, T32-20, Lamina S. I. Co.) and the properties of nickel sheet, which are applied to these circuits, respectively.

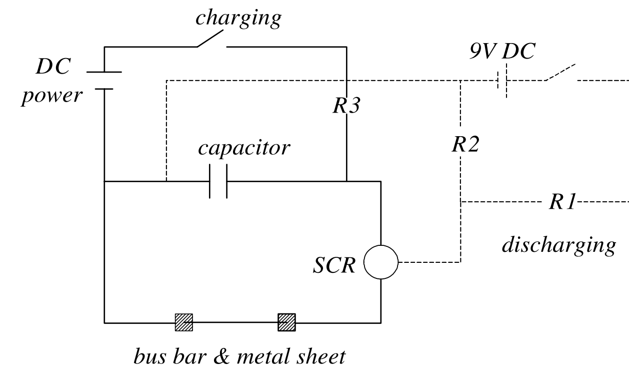

Fig. 1. Circuit diagram of the resistance–capacitance heating.

Fig. 2 presents the front and section views of experimental apparatus for the measurement of pressure wave and temperature in open and confined spaces. In both apparatus, all components are the same except the thermo-acoustic generation space. And detailed explain of the apparatus is as follows. As shown in Fig. 2(a), the experimental apparatus in an open space consists of bus bars, connecting bolts and nickel sheet. In order to minimize the thermal loss, insulating material is attached under the metal sheet. Nickel sheet is anchored in bus bars for the connection of heating circuit.

The experimental apparatus for a confined space shown in Fig. 2(b) is designed as a hexahedron shape. The size of it is 20 mm width, 30 mm height and 90 mm length. The top, bottom and right-hand side walls of the experimental apparatus are made of insulating material. The left-hand side vertical wall of the confined space can be opened in order to install a metal sheet. An optical glass, which has low index of refraction, is installed in the front and rear walls for future visualization experiments.

The experimental apparatus has connection holes for easy initialization of the experimental space and environmental state after one experiment. Microphones for the pressure fields are installed in the prepared holes and specified location for the measurement of velocity of the pressure wave.

In addition, the experimental space can be sealed up. The square shape experimental apparatus is compressed

Table 1
Specifications of the applied capacitor and SCR

Capacitor ($C = 68{,}000$ μF)		SCR (Lamina S.I., T32-20)	
Diameter (mm)	76.0	$I_{T(AV)}$(A)/T_c (°C)	20/85
Length (mm)	105.0		
Surging voltage (V)	50	V_{DRM}, V_{RRM} (V)	100–1400
Operating temperature (°C)	−40 to 85	I_{TSM} (A)	350
Max. equivalent series resistance (Ω)	0.012	$I_{T(AV)}$: on-state current	
Max. ripple (RMS Amps)	16.0	I_{TSM}: surge (non-repetitive) on-state current	
Max. DC leakage current (A)	$I = 0.006\sqrt{C \cdot V}$	V_{DRM}: repetitive peak off-state voltage	
Working voltage (V)	50	V_{RRM}: repetitive peak reverse voltage of an SCR	

Table 2
Physical and mechanical properties of the tested metal sheets

Property		Nickel
Physical	Specific weight (kg_f/m^3)	8900
	Electrical resistance (μΩ cm)	6.84
	Specific heat (J/kg K)	445.9
	Thermal conductivity (W/m K)	83
	Thickness (mm), δ	0.012, 0.01, 0.0075
Mechanical	Yield strength (kg/mm^2)	15
	Tensile strength (kg/mm^2)	47
	Elongation length (%)	50

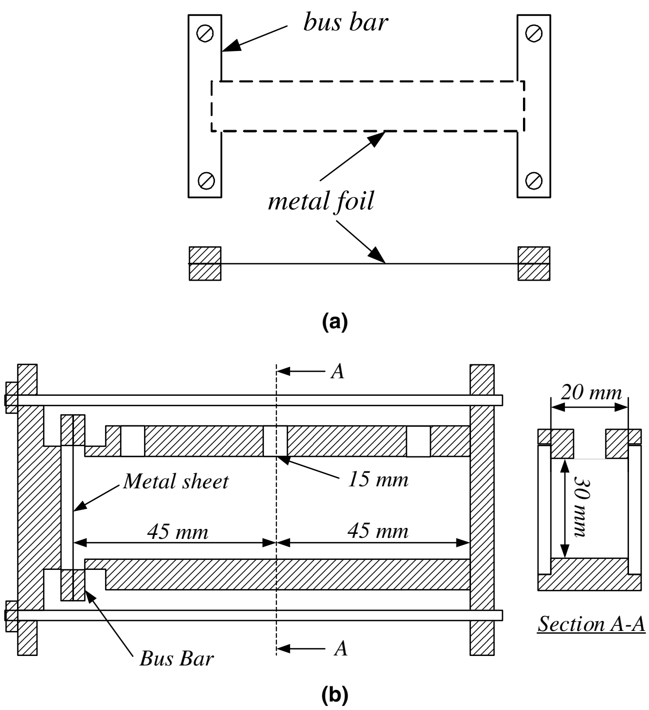

Fig. 2. Detail drawings of the experimental chamber: (a) open space and (b) confined chamber.

with the left wall and the metal sheet is located between them. Thermocouple amplifier module, voltage and current input module, converter the sound pressure signal of microphone into current input, are installed in a signal conditioner. And personal computer is connected with LAN in order to transmit experimental data. Table 3 described the details of measurement devices for the present study.

A measuring circuit, based on the LabVIEW program (National Instrument Co.), is composed in order to acquire physical data using these systems. The measuring circuit for this experiment is composed, and Fig. 3 is an example of application.

2.2. Experimental methods

The experimental apparatus used in this study is very complex with many modules. Therefore, tuning of the apparatus is very important for the operation and reliability of system. The measurement of thermo-acoustic wave is conducted as follows; preceding experiment, main experiment, estimation of the data reproduction and data processing.

Before the experiment, charging and discharging modules, triggering module and a measuring instrument device are checked for the reliability of experiment. Then, the nickel sheet is made according to sizing plan. And thermocouple is attached to the surface of the metal sheet using an electric arc welding. The left- and right-hand sides of metal sheet are compressed by bus bars, which are connected with a rapid heating circuit.

The capacitor is charged up to a setting voltage and the average, minimum and maximum values of charging voltage are checked out with an accurate multi-meter. The reliability of capacitor with charging and discharging repeated is evaluated by the sample test in the temperature range of 300–500 °C.

And, the LabVIEW system is ready for measurement of temperature profile and pressure wave. Pulse generator has a triggering function that makes each module work at the same time. The temperature and pressure distribution data are saved as a digital file. After one experiment was carried out in an open or closed space with nickel sheet, the experimental conditions are initialized and the experiment is repeated several times in order to confirm the reproduction of experiment. The sample rates for data collection of temperature and pressure were set up 10 kHz and 70 kHz by thermocouple and microphone, respectively.

Table 3
Specification of the measurement systems

System	Specification	Model/Maker
PC	PIII - 1GHz	
DAQ board	1.25 MHz	PCI-MIO-16E-1, NI Co.
Temp. module	isolation, 333 kHz	SCXI-1120, NI Co.
Input module	isolation, 333 kHz	SCXI-1125, NI Co.
Thermocouple	0.127 mm K-type	OMEGA
Microphone	pressure field, 12.5 mV/Pa, 70 kHz max. range: 160dB	40BP, SV Co.
Pulse generator	4 output, 1 input	BNC Model 555

3. Results and discussion

Experimental results are obtained to investigate the generation and propagation of the thermo-acoustic waves by the R–C rapid heating of nickel sheet. Temperature profile and pressure distribution are measured, also the raw data measured are reviewed by curve fitting of temperature profile and analysis of pressure waves.

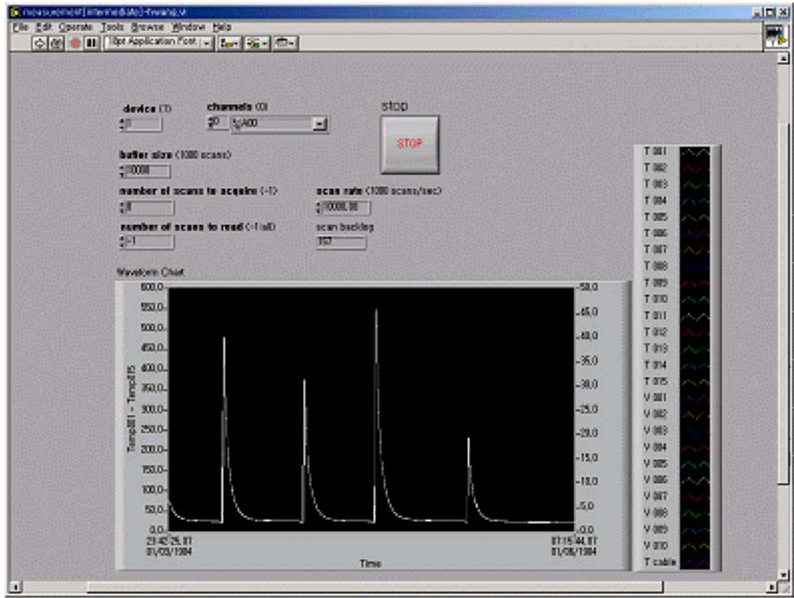

Fig. 3. Screen view of the data acquisition process.

Fig. 4 depicts the thickness effect of nickel sheet on the temperature variation in the case of a constantly discharging energy by capacitor of $C = 68{,}000$ μF and 21 V. In the case of the thickness (δ) of 0.0125 mm, the peak temperature of nickel sheet is measured as 142 °C, and it takes 0.35 s until the temperature increase to peak. For the case of the nickel sheet of 0.01 mm, the peak temperature of nickel sheet is measured as 185 °C, and the time to peak takes 0.065 s. In the case of nickel sheet with $\delta = 0.01$ mm, the peak temperature increase about 43 °C and need time to peak temperature decrease about 6 times as compared with the nickel sheet of 0.0125 mm. And the decreasing tendency of temperature after peak showed trends with gentle slope.

Finally, in the case of $\delta = 0.0075$ mm, the peak temperature increased up to 475 °C and need time to peak temperature takes about 0.045 s. It is noted that the decreasing rate of temperature after peak showed very steep trend as compared with the nickel sheet of 0.0125 mm and 0.01 mm.

Fig. 5 presents the effect of discharging energy on the temperature variation in the case of nickel sheet with $\delta = 0.0075$ mm thickness and capacitor of $C = 68{,}000$ μF. The peak temperature was obtained as about 257 °C, 362 °C and 475 °C when the discharging voltage of capacitor is 16 V, 19 V and 21 V, respectively. And also, need time to peak temperature was evaluated that it takes about 0.045 s like the result of Fig. 4.

Fig. 6 shows the curve fitting result of the temperature profile induced by rapid heating when the capacitor discharges as 21 V for the nickel sheet of 0.0075 mm. The temperature profile can be expressed as following equation with four variables.

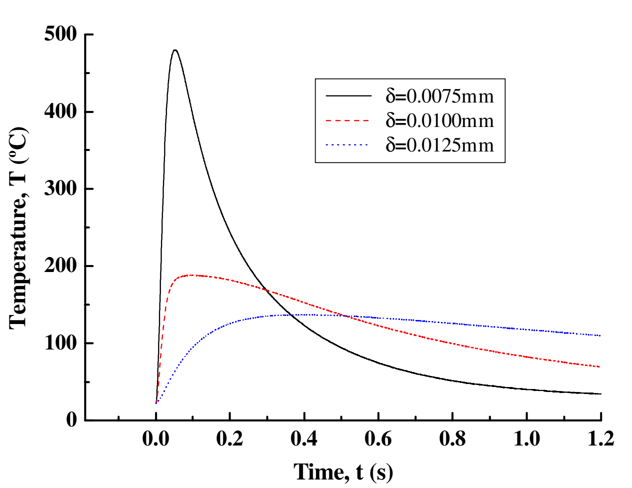

Fig. 4. Thickness effects of nickel sheets on the temperature variation with $C = 68{,}000$ μF and 21 V.

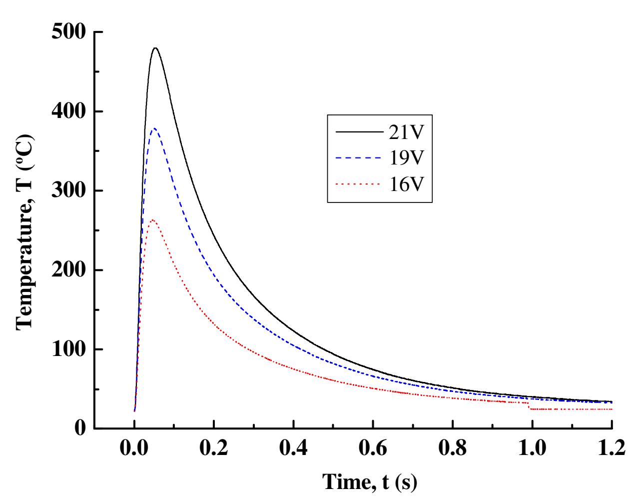

Fig. 5. Effects of voltage variation on the surface temperature of nickel sheet with $C = 68{,}000$ μF and $\delta = 0.0075$ mm.

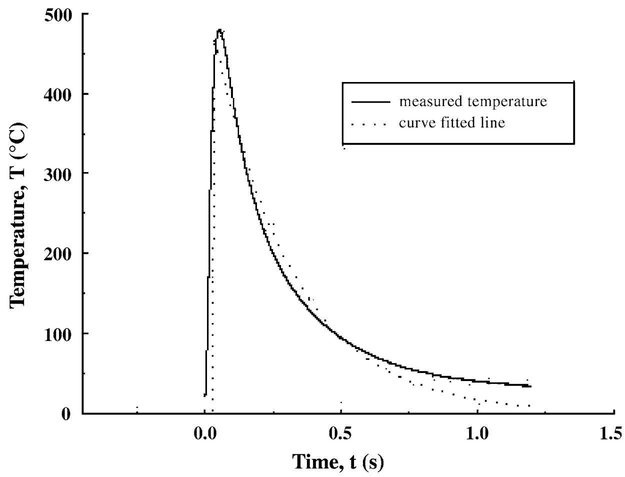

Fig. 6. Temperature profile on the nickel sheet with $C = 68{,}000\ \mu F$, 21 V and $\delta = 0.0075$ mm.

$$T = aA^{c-1}B^{\frac{1-c}{c}}\exp(-A^c) + B, \tag{1}$$

where

$$A = \left[\frac{t - t_0}{b} + \left(\frac{c-1}{c}\right)^{\frac{1}{c}}\right], \quad B = \left(\frac{c-1}{c}\right). \tag{2}$$

Here the constants a, b and c are 4.71×10^2, 2.925×10^{-1} and 1.1, respectively. And time t_0 is 3.18×10^{-2}.

Fig. 7 depicts a triggering signal of pulse generator for synchronous operation of the experimental apparatus and measurement system, and also the profile of pressure wave is showed simultaneously. And this generating voltage comes into action both the heating circuit and measuring equipment. The high values in the temperature profile shown in Figs. 4 and 5 might be resulted from the electromagnetic environment by the discharging of capacitor [1]. In this study, this result is analyzed by comparing the triggering pulse of Fig. 7 with the approach time of peak pressure. The pressure wave is generated at the mid-point of a confined space after about 10^{-4} s. It takes about 0.003 s for the measured pressure wave at microphone, which is located away about 0.05 m from heating surface, to pass the measuring point. Maximum heating temperature is about 230 °C at that time. This is similar with a predicted result with the function depends on time which is developed by Brown and Churchill [1]. Furthermore, the real temperature of metal plate is about 50% of the converted maximum temperature by obtained data from thermocouples. In order to ensure the accuracy of experimental results and to distinguish the measured pressure by the actual heating, the background noise level of experimental circumstance is maintained below the maximum value of 0.03 Pa during experiment.

Fig. 8 presents the sound pressure of wave, which is generated by heating of a metal sheet located in open space

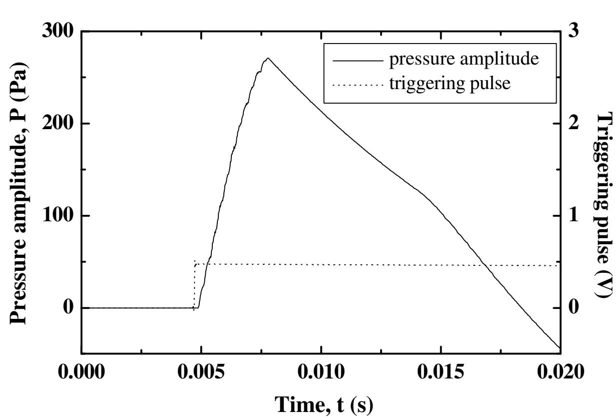

Fig. 7. Pressure initiation by triggering output of pulse generator.

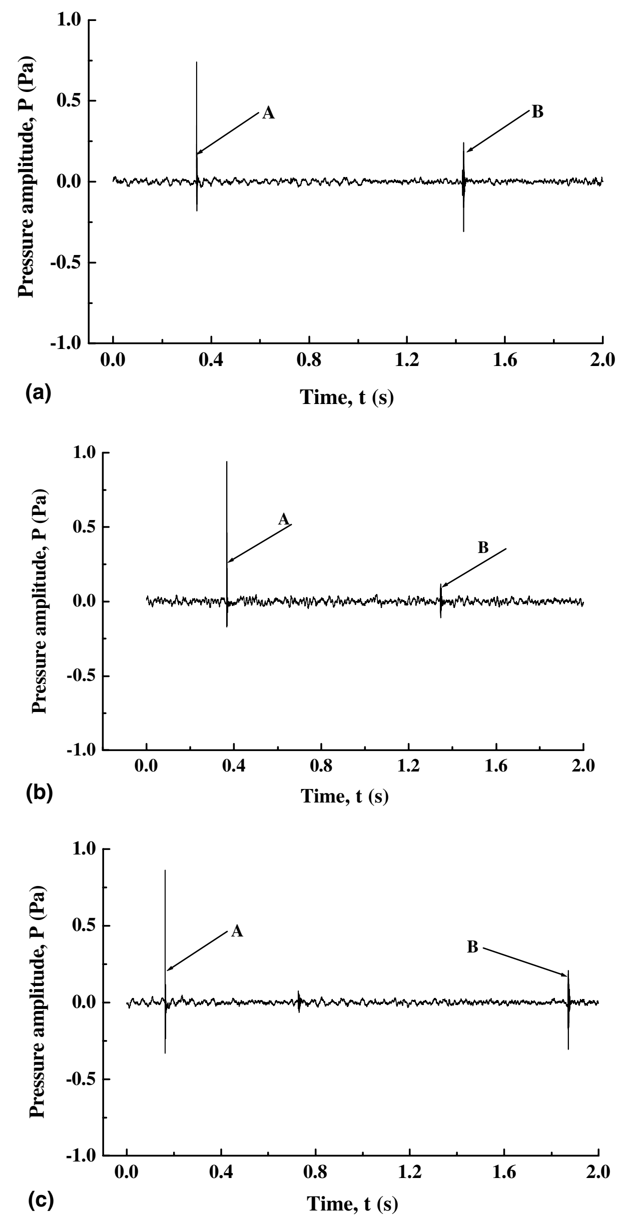

Fig. 8. History of pressure amplitude at 0.2 m in air at 293 K and 1 atm from the microphone in the open space. Charging voltages: (a) 17 V, (b) 19 V and (c) 21 V.

horizontally. The marker '*A*' represents the measured pressure at the beginning of heating. Specifically, it is a pressure wave that comes from rapid expansion of heated air by generated electric power. The second pressure peak (marker '*B*') might be resulted from the friction or deformation of the heating foil. The first pressure peak (marker '*A*') tends to increase as the charging voltage of capacitor, but the second one (marker '*B*') shows no specific tendency. The second measured pressure peak assumed as the wave reflecting from the bottom surface after the wave was generated at the rear side of metal sheet. That is, the pressure wave is expanded in a moment when the metal sheet is heated and it shrank when the metal sheet is cooled. In the case of an open space, the peak value of pressure wave is observed below 1 Pa because the waves disperse into the semi-infinite space.

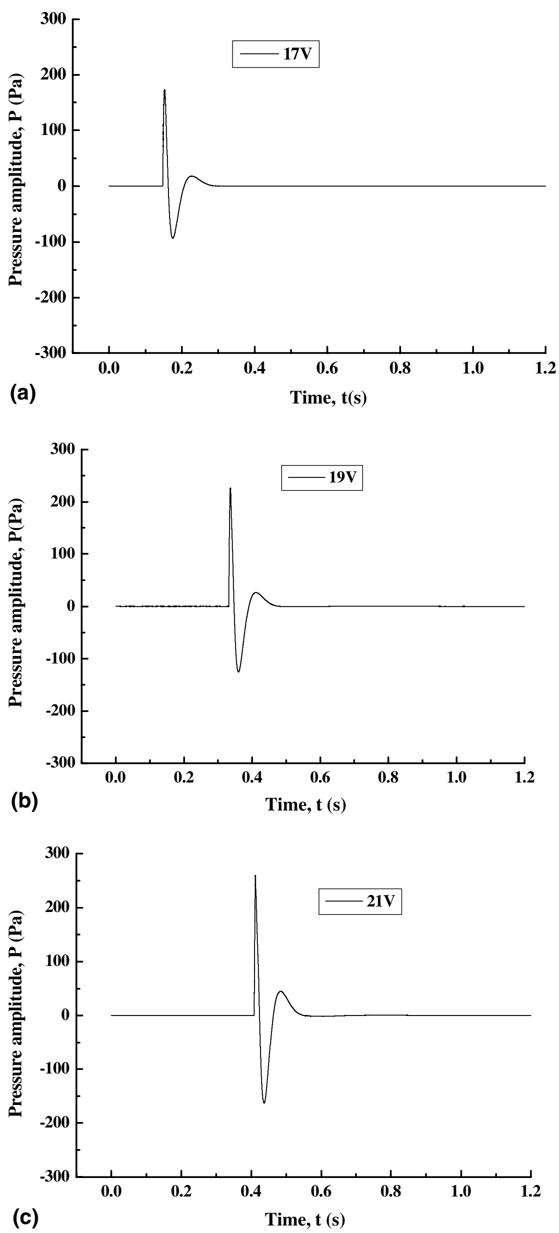

Fig. 9. History of pressure amplitude at 0.05 m in air at 293 K and 1 atm from the microphone in the confined chamber. Charging voltages: (a) 17 V, (b) 19 V and (c) 21 V.

Fig. 9 presents the variation of measured pressure wave with the increase of metal sheet's heating energy in the confined chamber. Measurements were performed at the midpoint of confined chamber away about 0.05 m from the heating surface. A microphone is set parallel to the propagation direction of pressure wave. Fig. 9(a) shows the propagation phenomenon of the pressure wave which is generated by heating of metal sheet, when the charging voltage of capacitor is 17 V. At the beginning, the pressure increases rapidly and makes sharp peak by the compression of fluid, under the influence of pressure wave. After that, the pressure decreases as the fluid expands again. The maximum pressure is about 180 Pa.

The negative values of the ordinate represent the pressure waves that pass through the mid-section of the confined chamber after being reflected from the right-hand side wall. Also, the second peak positive values show the amplitude of pressure waves that were reflected again from the left-hand side heating wall. Fig. 9(b) and (c) shows the results when the charging voltages are 19 V and 21 V, respectively. The peak values of pressure, compressed and expanded, tend to increase sharply. At the beginning of measurement, a foregoing part of pressure wave increases rapidly and makes a steep peak like Fig. 9(a). This result tends to be similar with predicted result in numerical analysis qualitatively [4]. The maximum peak value of pressure wave is 250 Pa and 280 Pa, respectively.

The propagation velocity of pressure wave, that is estimated as Mach number $M = 0.99$ in the case of 19 V charging voltage, and $M = 1.04$ in the case of 21 V. The propagation phenomenon of thermo-acoustic wave is measured at the first heating surface, but the influence of reflected pressure wave at the right surface is slight. The reason for this is that the value of pressure wave is small and the material characteristics of walls, which compose the confined space.

4. Conclusions

The characteristics of thermo-acoustic waves induced by the *R*–*C* rapid heating of nickel foil are experimentally investigated. The following results are obtained:

Temperature profiles of nickel sheet were analyzed with the conditions such as the thickness of nickel sheet and the discharging voltage of capacitor. Based on the experimental results, a curve fitted equation with four variables was suggested. Also, the pressure waves in open and confined spaces are experimentally measured. For the case of an open space, the waves have sharp and weak pin profile, but these waves have sharp front shape and decay with tail in the case of the confined chamber.

In this experimental study, the propagation velocity of thermo-acoustic waves, generated by rapid heating of nickel foil with $\delta = 0.0075$ mm, is located in the range of

$M = 0.99$–1.04 with discharging voltage of capacitor. In order to increase the velocity, very thin metal foil should be considered as a key factor for the case of constant discharge energy.

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