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Simultaneous Ultrasonic Measurements of Temperature and Heat Flux in a Heated Medium

超音波による加熱媒体における温度と熱流束の同時計測

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1. Introduction

In heat-related treatments and/or processes of engineering and industries, both temperature and heat flux are often fundamental and important thermal parameters. This is because these parameters are indispensable to understand physical phenomena related to the thermal conduction and thermal resistance of the heated materials. Quantitative information on such parameters are also important to make accurate theoretical or computational analyses of the heated materials. It is, therefore, strogly required to conduct precise measurements of both parameters for heated materials during their processing at high temperatures.

Ultrasound, because of its high sensitivity to temperature, has the potential to be an effective means for measuring temperautres. Because of the advantages of ultrasonic measurements such as non-invasiveness and faster response, some works on the ultrasonic temperature estimations have been made extensively[1-8].

In this work, simultaneous ultrasonic measurements of temperature and heat flux in a heated material is proposed. Temperature distributions of a heated material can be determined by the ultrasonic thermometry we developed previously[5-8], and heat flux is estimated from the determined temperature distribution. It should be noted that both the temperature distribution and heat flux can simultaneously be measured using a single ultrasonic transducer and there is no need to insert the transducer into the heated material. To demonstrate the feasibility of the proposed technique, an experiments with a single-side heated steel plate is carried out.

2. Temperature and heat flux determinations by ultrasound

Assuming a one-dimensional temperature distribution in a single-side heated material, the transit time of ultrasound in the direction of the temperature distribution can be given by

$$t_L = \int_0^L \frac{1}{v(T(x))} dx \tag{1}$$

where L is the propagation distance of ultrasound, $v(T(x))$ is the ultrasonic wave velocity which is a function of the temperature T at the location x. Based on equation (1), the temperature distribution $T(x)$ can quantitatively be determined by the ultrasonic thermometry we developed[5-8]. This method consists of ultrasonic pulse echo measurements and a finite difference analysis. **Figure 1** shows the schematic of a single-side heated material with a one-dimensional temperature distribution (upper) and a finite difference model for temperature distribution analysis of the plate (lower). When initial temperatures at n=0 are known and temperature at non-heated surface (i=N) is given at any time step, the temperature distribution of the plate can be determined at any time step by the developed ultrasonic thermometry[5-8] as long as the ultrasonic pulse echo measurement is being conducted continuously.

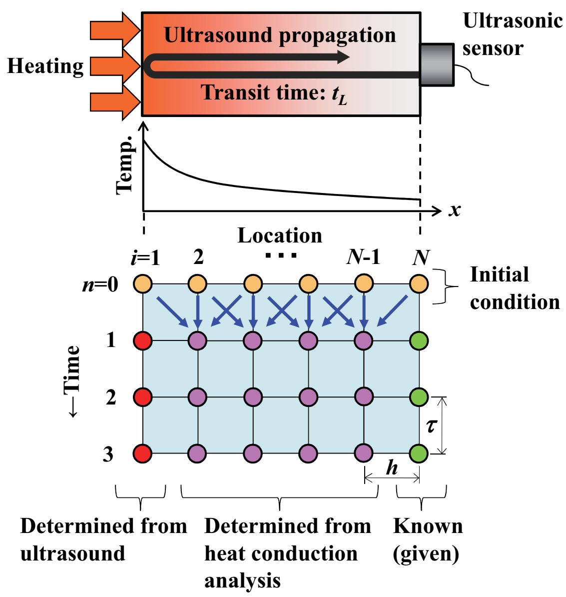

Fig. 1 Schematic of a single-side heated material with a one-dimensional temperature distribution (upper) and a finite difference model for temperature distribution analysis of the plate (lower).

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Heat flux q in the x direction is generally expressed by

$$q = -k\frac{dT}{dx} \qquad (2)$$

where k is thermal conductivity and dT/dx is temperature gradient. If the thermal conductivity is known, heat flux can be determined from the temperature gradient. By determining the temperature gradient using temperatures at two points, i=1 and i=2, in the vicinity of the heating surface, we can easily obtain the heat flux at the heating surface.

3. Experiment

Figure 2 shows a schematic of the experimental setup used. A steel plate of 30 mm in thickness is used as the specimen and its bottom surface is heated by a heater (400 °C). A longitudinal wave transducer of 5 MHz is installed on the top surface and ultrasonic pulse-echo measurements are made. The transit time of the ultrasonic pulse echo from the bottom is determined by a cross correlation method and used for estimating the temperature distribution in the steel. An infrared radiation camera is employed to measure the top surface temperature as a known value for the temperature estimation. Thermocouples are inserted into the steel at locations of 5, 10, 15, 20 and 25 mm from the bottom, for obtaining reference values of internal temperatures. Once the temperature distribution estimations are determined by the ultrasonic method, heat fluxes are then determined from equation (2).

4. Results

Figure 3 shows estimated temperature distributions at 0, 1, 5, 10 and 20 s after heating starts. The spatial resolution and time resolution of the present ultrasonic estimation are 2.5 mm and 0.02 s, respectively. Temperature distributions estimated by the ultrasonic method almost agree with those measured by thermocouples.

Figure 4 shows variations of estimated heat flux of the heating surface. We can see that a rapid rise in heat flux just after heating starts. It is noted that the random fluctuation in the estimated value is basically caused by the fluctuation in the estimated temperature. It is expected that those fluctuations can be reduced by improving the signal-to-noise ratio of the ultrasonic signals[8].

Acknowledgment

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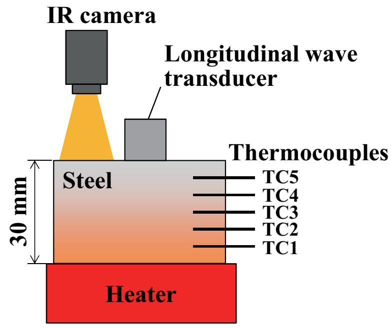

Fig. 2 Schematic of the experimental setup.

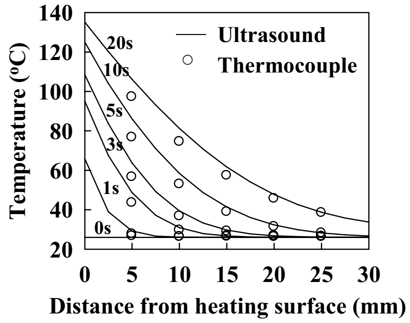

Fig. 3 Variations of the estimated temperature distributions of the single-side heated steel plate.

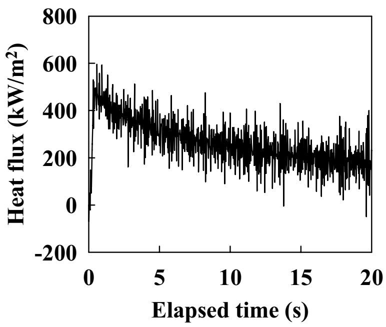

Fig. 4 Variation of the estimated heat flux of the heating surface with the elapsed time.

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