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Calorimetric method for measuring high ultrasonic power using water as a heating material

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Abstract. The present study shows the calorimetric method for measuring high ultrasonic power using water as the heating material. In recent years, at the National Metrology Institute of Japan (NMIJ), an ultrasonic power primary standard of from 1 mW to 15 W has been established by the radiation force balance (RFB) method. Conventionally, the RFB method is widely used for ultrasonic power measurement, but this method is not suitable for very high power measurement due to thermal damages to the absorbing targets. High power ultrasonic standards, however, are being required by medical HITU measurements and in the sonochemistry industry. In order to meet these requirements, we have started to develop an ultrasonic power standard between 15 W and 200 W. Our final goal is an ultrasonic power standard of up to 500 W. The calorimetric method is an alternative ultrasonic power measurement method to the RFB method. We have adopted this method and use water as the heating material. Water has excellent features as a standard material, because the physical properties of water are well known. In the present study, we present an experimental system and the results for an ultrasonic power standard of up to 100 W. The measured ultrasonic power agreed well with the NMIJ primary standard up to 25 W.

1. Introduction

At the National Metrology Institute of Japan (NMIJ), an ultrasonic power standard from 1 mW to 15 W was established by the radiation force balance (RFB) method in 2006. Recently, a high-power ultrasonic standard has been required for High Intensity Therapeutic Ultrasound (HITU) measurement methods, such as those used for medical treatment and in the sonochemistry industry. To meet these requirements, we have started to develop an ultrasonic high power standard [1][2]. Our final goal of ultrasonic power measurement will be up to 500 W, because this appears to be of common interest worldwide [3]. Generally, it is difficult to apply the RFB method to ultrasonic high power measurement because of, for example, thermal damage to the absorbing targets and acoustic streaming. Experimentally, for absorbing targets, 20 W may be considered the upper limit of the RFB method. As such, an alternative ultrasonic power measurement method must be developed. The calorimetric method is well known as one of the ultrasonic power measurements. This method requires a thermal object, namely, a heating material. There are a number of general requirements for the heating material.

- 1) The acoustical and thermal properties of the material should be given or easily measurable.
- 2) The material properties of the material should be stable during measurement.
- 3) Steady supply should be guaranteed as the standard materials.

Based on these conditions, water is an excellent material for use in ultrasonic power standards. At the NMIJ, we have attempted to use water as the heating material for the calorimetric method.

2. Experimental methods

2.1. Measurement conditions for the calorimetric method

There are some important requirements when applying the calorimetric method to ultrasonic power measurement in water.

- 1) In order to avoid varying the radiation characteristics of the transducers, ultrasound should not return to the transducer. In other words, the “free field” condition must be achieved.
- 2) Ultrasound must be absorbed perfectly in water, i.e., the total ultrasonic power must be used for the water temperature rise. This requires ultrasound to be perfectly reflected at the walls and bottom of the water bath.
- 3) Thermal loss must be minimized, In other words, water must be thermally isolated.

2.2. Experimental system

The ultrasonic power measurement system using the calorimetric method has been set up so as to satisfy the conditions described in Section 2.1. Figure 1 shows a block diagram of the measurement setup and it is composed of three parts:

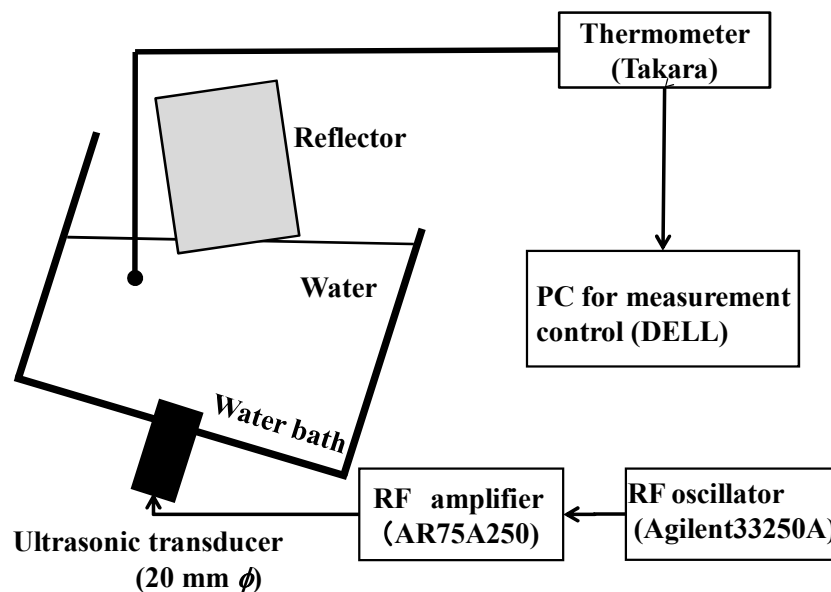
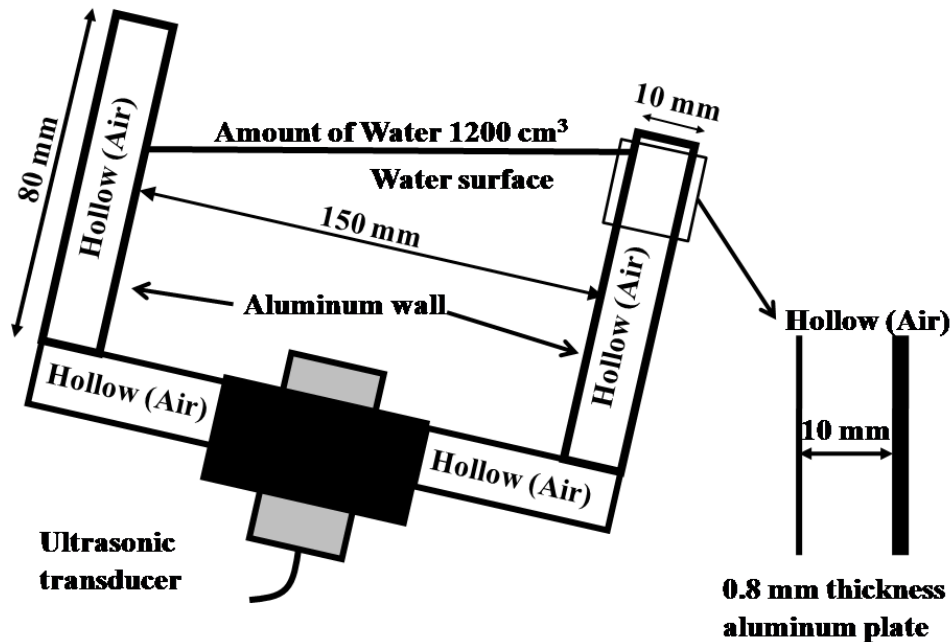


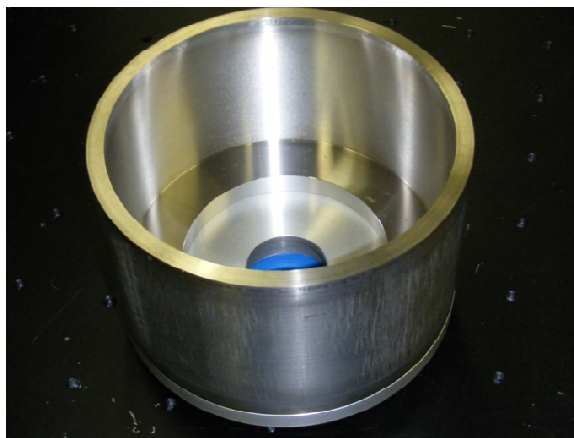
Figure 1. Block diagram of the measurement system.

- 1) The water bath and reflector
- 2) The temperature measurement system
- 3) The ultrasonic transducer, oscillator, and power amplifier

Figure 2(a) shows a section view of the water bath, which has an inner diameter of 15 cm and a depth of 8 cm. In order to achieve perfect reflection, the walls and bottom of the water bath are constructed of thin aluminum plates having a thickness of 0.8 mm, and the inside of walls and bottom of the water bath are hollow. The thermal loss from the water bath can also be minimized by this structure. Figure 2(b) shows a photograph of the water bath.



(a) Section view of the water bath and the structures of the wall and bottom plates.



(b) Photograph of the water bath



(c) Photograph of ultrasonic transducer

Figure 2. Measurement setup

Figure 2(c) shows the custom air-backing type ultrasonic transducer used in the experiments. The center frequency is 1 MHz, and the diameter is 20 mm.

Degassed water was used for the power measurements. The water temperatures were measured using a thermometer with a resolution of 0.01°C. The room temperature was maintained at $23^{\circ}\text{C} \pm 0.5^{\circ}\text{C}$ during the measurements. As shown in figure 2(a), the water bath was tilted approximately 30° , and a hollow aluminum reflector was placed on the water surface. Using this setup, the free field condition is almost satisfied, namely, returning ultrasound to the transducer is minimized.

2.3. Calculation of ultrasonic power

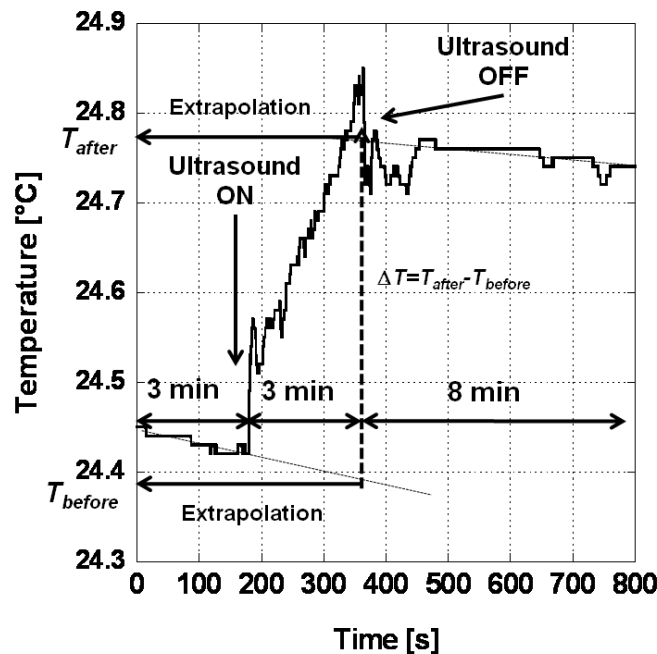


Figure 3. Example of the time dependence of water temperature during measurement.

Figure 3 shows an example of the time dependence of water temperature variation during actual ultrasonic power measurements. The water temperature measurement starts at 0 seconds, and ultrasound exposure begins three minutes after starting the measurement. The water temperature then gradually rises due to ultrasound exposure. Ultrasound exposure continues for three minutes, and then temperature measurement continues for eight minutes after exposure OFF, until the temperature stabilizes. Generally, it is difficult to perform stable measurements during ultrasound exposure, because there are several instability factors, including viscous heating, acoustic streaming, and inhomogeneous temperature distribution.

In order to avoid these instability factors, the water temperature is not measured during ultrasound exposure, but rather is measured both before and after ultrasound exposure. The temperature variations before and after the exposure are approximated by linear regression and are then extrapolated to the time that ultrasonic exposure finishes, as shown in figure 3. The true water temperature increase ΔT is then defined as the difference between the two extrapolated temperatures, namely, T_{before} and T_{after} . The ultrasonic power P can then be calculated as

$$P = \frac{\Delta T}{t_x} C \cdot M$$

where ΔT is the water temperature increase, t_x is the exposure time (three minutes in this experiment), C is thermal constant of the water ($4.18 \text{ J g}^{-1} \text{ K}^{-1}$) [4], and M is the mass of the water (1200 cm^3).

3. Results and discussion

Figure 4 shows the powers measured by the calorimetric method and by the primary standard of the NMIJ at 1 MHz as a function of oscillator output voltage. The expanded uncertainty of the RFB

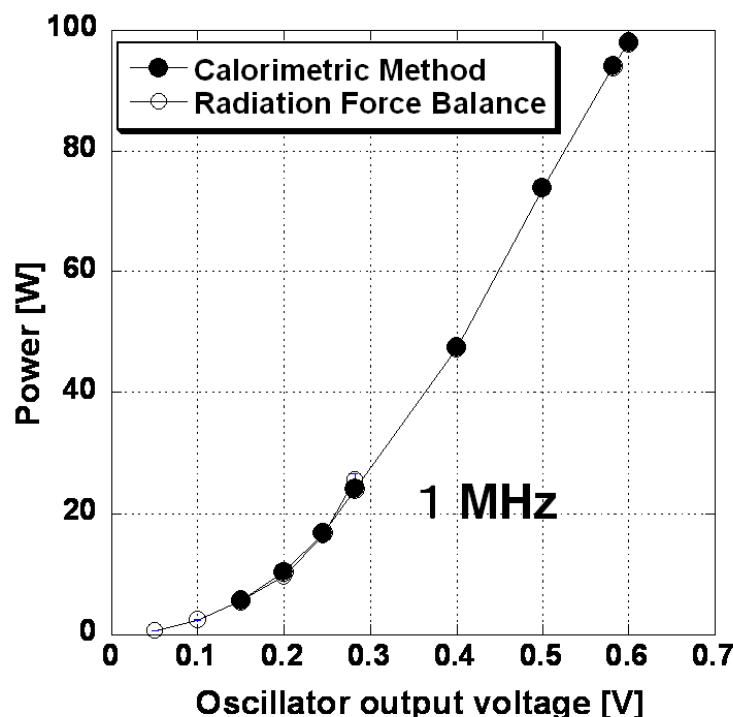


Figure 4. Ultrasonic power measured by the calorimetric method and the RFB method at 1 MHz.

method is estimated to be approximately 4%. The measurement uncertainty for the calorimetric method has not yet been estimated, but the reproducibility of the measurements (standard deviation) is estimated to be approximately 10%. The ultrasonic powers measured by the calorimetric method are validated up to 25 W through comparison with the primary standard. Under the present measurement conditions, ultrasonic power measurement up to 100 W is established, as shown in figure 4.

4. Conclusions

In the present paper, the calorimetric method using water as the heating material is proposed as an alternative ultrasonic power measurement method to the RFB method. Measured ultrasonic powers were validated by comparison with the primary standard of NMIJ (RFB) up to 25 W, and ultrasonic power measurements can be achieved up to 100 W.

Acknowledgments

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