Development of high ultrasonic power measurement technique by calorimetric method using water as heating elements for high ultrasonic power standard

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1. Introduction

Total ultrasonic power produced from ultrasound transducers used in medical ultrasound diagnostic and therapy devices is a key quantity related to thermal hazards on patients in the medical field \[1\]. In order to use ultrasound safely on patients, ultrasonic power must be accurately measured. Therefore, an accurate ultrasonic power measurement technique is required. An ultrasonic power standard is also required to estimate the validity of the measurement values.

Recently, medical devices using high power ultrasound have been developed. Therefore, the ultrasonic power standard in the high power region is required to ensure the safety and security of the patients. Traditionally, the radiation force balance (RFB) method is the most accurate method of measuring ultrasonic power \[2,3\]. Therefore, the ultrasonic power standard for the range of less than about 15 W has been established by the RFB method at each country’s national metrology institute. National Metrology Institute of Japan (NMIJ) provides an ultrasonic power standard with the uncertainty of about 5%. The uncertainty of about 5% meets the requirement of medical device manufacturers.

However, the RFB method is not well suited to high ultrasonic power measurements because of problems including thermal damage to the absorbing targets. Experimentally, approximately 15 W is the upper limit of the power that the RFB method can measure \[4\]. Hence, a new ultrasonic power measurement technique should be developed as an alternative to the RFB method in order to further extend the measurement range \[5\].

We have started to develop an accurate measurement technique by a calorimetric method with the aim of setting the national measurement standards for high ultrasonic power. In a previous study, we developed an ultrasound transducer with low heat generation for the calorimetric method \[6\]. In this paper, an accurate ultrasonic power measurement technique by the calorimetric method using the less calorific transducer, the water vessel for calorimetry, and the new calculation procedure developed by NMIJ is proposed. Ultrasonic power of up to 100 W by the calorimetric method can be measured. The measurement values obtained by the calorimetric method are compared with the results obtained by the RFB method, which is the primary standard of NMIJ, between 10 W and 15 W, which is the ultrasonic power range that can be measured by the two methods.

2. Experimental method

2.1. Cylindrical water vessel for calorimetric method

In the concept of the calorimetric method, if the specific heat capacity and mass of the material of the ultrasound irradiation target are known, ultrasonic power can be calculated using the temperature rise that results from the absorption of the ultrasound waves. Therefore, accurate measurement by the calorimetric method requires the following conditions: a) The total ultrasonic energy should be converted to the temperature rise. b) To avoid any change in the acoustic characteristics of the ultrasound transducer, irradiated ultrasound should not return to the transducer transmission surface. Namely, the measurement should be conducted under free-field conditions. c) Heat loss should be minimized.

Figure 1 shows the block diagram of our calorimetric measurement system. A cylindrical water vessel with a diameter of 150 mm and a depth of 90 mm is made of stainless steel to meet the above conditions. The wall of the vessel is designed to obtain a 10 mm thick air layer in order to exploit the characteristic that ultrasound is almost reflected by air. The transducer is mounted to the vessel through the hole at the cylindrical wall of the vessel. The transducer transmission surface is perpendicular to the bottom of the vessel. The transmission surface of the transducer is retracted from the inside wall of the vessel so that the transducer does not disturb the ultrasound propagation path.

The ultrasound is irradiated directly to the water in the vessel. The irradiated ultrasound is reflected on the very thin inside wall almost perfectly. The ultrasound circulates along the circumference of the inside wall of the vessel. The ultrasound energy is almost entirely absorbed and attenuated in water. Because the transducer is retracted from the circumference of the inside wall of the vessel, the ultrasound does not reenter the transducer transmission surface. This was confirmed by the experiment using pulse-echo signals of the transducer \[7\]. Also, the entire body of the vessel is covered...
by a heat-shielding material of polyethylene foam to prevent heat loss.

2.2. Experimental conditions

An ultrasonic power standard is recommended for medical ultrasound. Consequently, water is adopted in order to obtain acoustic characteristics similar to those of the human body in the experiment. The water temperature is measured by two thermistors placed at the center and near the wall of the vessel, as shown in Fig. 1. In this measurement, the water temperature is defined as the average value of the two temperature measurements. Water is agitated by acoustic streaming induced by high power ultrasound irradiation. Therefore, the temperature gradient in the vessel is very low. The resolution of the temperature measurement is 0.01°C. Room temperature during measurement is always 23°C ± 0.5°C. Water is degassed to avoid acoustic cavitation. The dissolved oxygen level in the degassed water is below 2 mg/l. The water mass is 1,200 g.

The air-backing ultrasonic transducer is used for the experiments. The transducer has low heat generation owing to low elastic and dielectric losses. The resonance frequency is 1 MHz, and the diameter of the piezoelectric material in the transducer is 20 mm.

2.3. Ultrasonic power measurement procedure

We suggest a new procedure for calculating the ultrasonic power from the water temperature before and after the irradiation of ultrasound. In the conventional calorimetric method, ultrasonic power is calculated from the temporal differentiation in the temperature rise during ultrasound irradiation as [8]

\[ P = \frac{dT}{dt} \cdot C_P \cdot M, \]  

where \( dT/dt \) is the temporal differentiation of temperature rise, \( C_P \) is the specific heat capacity of water, and \( M \) is the measured mass of water. However, it is difficult to measure the water temperature precisely during high power ultrasound exposure owing to viscous heating [9]. Viscous heating is a phenomenon that results in an apparent steep temperature rise at the ON time of ultrasound. The effect is caused by direct ultrasound heating of the temperature sensor. The temperature rise caused by viscous heating is not a result of the actual water temperature rise due to the absorption of the ultrasound waves. Also, the reproducibility of the method using Eq. (1) was very poor for abrupt temperature rises due to viscous heating. Therefore, it is difficult to apply the method using Eq. (1) to accurate ultrasonic power measurement.

A new calorimetric calculation method is suggested for the elimination of the effect of viscous heating. The method obtains ultrasonic power from water temperature before and after ultrasound irradiation. The method eliminates the effect of viscous heating by not taking into account the temperature change during ultrasound irradiation. The equation used to obtain the ultrasonic power is

\[ P = \frac{\Delta T}{t_x} C_P \cdot M, \]  

where \( \Delta T \) is the difference in water temperature before and after ultrasound irradiation, and \( t_x \) is the ultrasound exposure time.

An example of water temperature measurement in the experiment is shown in Fig. 2. Water temperature measurement is divided into three time domains. The first time domain \( t_b \) is prior to ultrasound exposure, the second time \( t_s \) is during ultrasound irradiation, and the third time \( t_a \) is post-irradiation. The water temperature measurement times \( t_b, t_s \), and \( t_a \) are 180 s, 180 s, and 480 s, respectively. Water temperatures at the first and last time domains are extrapolated to the midpoint of ultrasound irradiation time in the second time domain. The difference between the two extrapolated temperatures is defined as \( \Delta T \), which is equivalent to the water temperature rise that results from the absorption of the ultrasound waves. The apparent steep temperature change at the ultrasound ON and OFF times by the effect of viscous heating is observed as shown in Fig. 2. Therefore, at the first time domain, the temperature data between 1 s and 175 s is used to determine \( T_{on} \) by extrapolation, in order to eliminate the effect of viscous heating. Similarly, the extrapolated range at the last time domain is between 380 s and 840 s. If the time domain having a steep temperature change is excluded from the determination of \( \Delta T \), the temperature fluctuations at the first and third time domains, namely, before and after ultrasound irradiation,
are very small. Therefore, it is possible to define $\Delta T$ calculated by linear extrapolations of before and after ultrasound irradiation as the temperature rise due to ultrasound irradiation. Also, temperature measurement is started after the water temperature in the vessel becomes stable, because the stability of water temperature affects the extrapolated values. Water temperature measurement is started 15 minutes after the water is poured into the vessel.

3. Results and discussion

Figure 3 shows the results of measurements by the calorimetric method. The calorimetric system constructed by NMIJ could measure ultrasonic power of up to around 100 W.

Figure 4 shows the values obtained by the calorimetric method and those measured by the RFB method between 10 W and 15 W. The error bars of the values in Fig. 4 show the standard deviation. The values obtained by the calorimetric method are within 5% of those obtained by the RFB method. Therefore, the difference between the values obtained by the calorimetric and RFB methods was within 5% and we could obtain stable measurement results.

It is thought that the systematic difference is mainly caused by the balance of heat loss and heat generation in the calorimetric method, because the RFB method is the most accurate method of measuring ultrasonic power up to about 15 W. The heat loss from the vessel was estimated to be about 5% by using the downward curve of the water temperature in the vessel. This is almost the same as the difference observed between the values obtained by the calorimetric and RFB methods, as shown in Fig. 4. Thus, it can be inferred that the effect of the inflow of heat from the transducer is very small when using the transducer with low heat generation. The heat loss from the vessel can explain the experimental results that the values measured by the calorimetric method were lower than those measured by the RFB method. Stainless steel, which is the material of the vessel, has high thermal conductivity.

4. Conclusions

We constructed a calorimetric cylindrical water vessel and suggested a new calculation method. As a result, ultrasonic power of up to 100 W could be measured using the calorimetric measurement system constructed by NMIJ. The values obtained by the new calorimetric method were within 5% of those obtained by the RFB method. We created a stable and accurate method for the establishment of a high ultrasonic power standard.

For the establishment of more accurate ultrasonic power measurement by the calorimetric method in the future, we plan to produce a new water vessel using materials with large heat capacity. Also, the vessel will be divided by a very thin sheet of, for example, silicon because it will prevent the inflow of the heat from the transducer to the measurement region.

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