Thermal Profile and Calorimetric Power Analysis of 20-60 KiloHertz Ultrasonic Bath Reactor

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ABSTRACT

Bath-type ultrasonic system still lacks fundamental assessment including thermal profile and power behavior, despite being regarded as more promising than probe-type ultrasonic for large-scale application. Therefore, this report aims to explore the power pattern in ultrasonic bath reactor using calorimetry method derived from cavitation-generated heat. Ultrasonic power and frequency were varied from 30-120 W and 25-60 kHz, respectively, within a cylindrical bath reactor containing one litre of deionized water. Temperature sensors were placed accordingly, and the temperature difference was recorded in interval for 30 minutes. Result shows that the temperature change was larger near the ultrasonic emitter and dissipated as distance increased, implying higher calorimetric power or active cavitation action close to the source. Calorimetric power was generally enhanced as higher ultrasonic power was supplied, while ultrasonic frequency provided slightly intricate effect. From hypothesis testing, only ultrasonic power was statistically significant from its p-value < 0.05 based on 95% confidence interval.

1. INTRODUCTION

The basic configuration of ultrasonic setup can be divided into two categories, namely probe (also known as horn) and bath types. The trend shows more studies from probe-type ultrasonic system emerging in recent years due to its high energy and high intensity effects. However, its small surface area usually only generates violent action near the tip because the ultrasonic energy is attenuated severely [1]. If probe-type reactor is to be applied on industrial scale, it needs to have additional elevated-intensity mechanical mixing to bring around the substrate near the probe tip [2, 3]. Due to this, some researchers are of the opinion that ultrasonic bath is more effective on larger scale as compared to ultrasonic horn [4]. Bath system usually has wider area of irradiation that produces superior active volume for cavitation [5].

Ultrasonic mapping is a helpful technique when analyzing active cavitation region and attaining efficient design [6]. Mapping can be done by measuring primary or secondary impacts in ultrasound zones. The former assesses pressure or temperature fluctuations, while the latter describes about physical or chemical modifications. Pressure and temperature variations are normally detected using hydrophones and temperature sensors, which then are transformed into parameters such as acoustic pressure and calorimetric power [7, 8].

Calorimetry method is one of the common and efficient ways to gauge ultrasonic power [9]. This method measures the heat generated in an acoustic field by recording temperature changes and compute it alongside the acoustic medium's mass and heat capacity to represent the cavitation activity [7]. One research paper reiterated the importance of heat dissipation and proved the feasibility of using thermal parameters for estimating ultrasonic power [10]. It reported a thermal profile within a tank whose volume was multiple times bigger than its ultrasonic transducer (100-300 W 39 kHz), which was typical for a bath-type ultrasonic system. From the observation, the area ratio of transducer to reactor and the shape of reactor could be crucial factors toward the heat profile generated and subsequently the calorimetric power.

Other parameters influencing calorimetric power are the vapor pressure and viscosity of acoustic medium [11]. However, calorimetric power was discovered to be independent on the volume where various runs in 150 cm^3 reactor sonicated by horn up to eight minutes had similar heat dissipation at 14°C maximum [12]. The same study also found larger probe diameter among 3, 7, and 14 mm caused higher heat being released. In another work, the power was reportedly independent on the position of measurement while the heat in sonoreactor was established to accumulate over irradiation time [13]. Another team of researchers reported an ultrasound experiment with varied electrical

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power from mid to high ultrasonic frequency (209-1960 kHz) for 25-200 ml reactor at 120 s [14]. They found ultrasonic calorimetric power was almost directly proportional to the supplied electrical power up to 125 W.

Heterogeneous ultrasound system with filler particles was also investigated. A recent investigation found that a ultrasonic probe emitting 22 W at 202-1135 kHz produced calorimetric power up to 50 W, with no significant changes when addition of glass beads from 0.1-5 g/L concentration [15]. This defies the notion that filler addition could impact the calorimetric power of a reactor, although the heterogeneous media like glass beads are probably not sensitive enough for the ultrasound system.

To date, efforts to explore ultrasonic bath reactor for calorimetric properties are scarce as majority of reports focused on probe-type system [16]. Not only that, but most of the reports on bath system studied specific applications' performances rather than fundamental mapping and characterization. This creates gaps in the understanding and restricts quick growth of the technology. The literature noticeably do not cover some ranges of ultrasonic power-frequency combinations, the analyses sometimes lack temperature mapping, and the treatment time could be prolonged to suit the actual processing cases rather than just mere seconds. Heat generation and dissipation across spatial and temporal coordinates of ultrasonic system are required when investigating calorimetric power, making thermal mapping essential. In the effort to bridge these gaps of study, the objective of this article is to analyze the thermal and power behavior in ultrasonic bath reactor at various settings.

2. METHODOLOGY

2.1 Ultrasonic Reactor Setup

The constructed ultrasonic bath reactor in this study consisted of 80 mm diameter × 20 cm height cylindrical vessel made from Poly(methyl methacrylate), as shown in Figure 1. An ultrasonic transducer was mounted on aluminum steel plate at the bottom of the cylinder, which was securely fastened (liquid tight) to the cylindrical vessel. With this design, it was possible to observe the fundamental ultrasonic behavior with irradiation area of transducer to reactor's diameter approaching 1:1 and capacity of the reactor was one liter. All the transducers were acquired from OEM (accuracy ±1 kHz frequency) and tested accordingly prior to use. They were driven by ultrasonic generators, which connected to a metered power source.

2.2 Calorimetric Power Determination

There are several parameters used to represent power in a reactor or system, and perhaps the most widely used is calorimetric power, P_{cal} , given by the International Electrotechnical Commission Standard as

$$P_{cal} = \frac{dT}{dt} C_P M \quad (1)$$

where, $\frac{dT}{dt}$ is rate of temperature change, C_P is specific heat capacity of liquid medium (deionized water), and M is its mass.

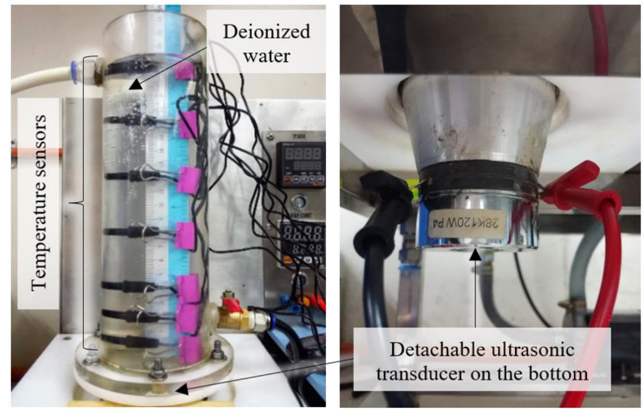

Fig. 1. Ultrasonic reactor setup; (left) the cylindrical tank with an array of temperature sensors & (right) ultrasonic transducer mounted to the cylinder's bottom.

Table 1 Settings of ultrasonic power & frequency for all the tests. Every setting requires different ultrasonic transducer

Test number	Ultrasonic setting	
	Power	Frequency
1	30	28
2	30	40
3	30	60
4	50	40
5	60	25
6	60	28
7	60	33
8	60	40
9	60	60
10	100	40
11	120	28
12	120	40
13	120	60

The determination of calorimetric power was carried out as per Table 1 by varying the power and frequency of the ultrasonic transducers and generators, ranging from 30-120 W and 25-60 kHz. An array of temperature sensors (accuracy ±1°C) was immersed in the reactor filled with deionized water ($C_P = 4.187 \frac{kJ}{kgK}, M = 0.997\ kg$) as in Figure 1 to measure the temperature change, dT . Temperature readings were taken every two minutes interval for up to 30 minutes sonication, dt, and each test was repeated three times. Only readings within acceptable standard deviation were recorded. The surrounding laboratory temperature was kept constant at 27°C with no thermal insulation to simulate the real heat characteristics during actual ultrasonic process. Finally, the average rate of temperature changes, $\frac{dT}{dt}$, were used to calculate the calorimetric power, P_{cal}.

3. RESULTS AND DISCUSSION

The temperature distribution in the ultrasonic reactor is depicted in Figure 2 and its subsequent P_{cal} attenuation is showcased in Figure 3. Direct thermocouple reading gave the average and maximum temperature increment to be 6.7°C and 13.4°C, respectively. The temperature mapping most likely indicates that the cavitation effect happened more vigorously near the ultrasonic source, as more heat was detected in the region. In certain physical and chemical processes, increase in temperature could act as a catalyst. Similar to previous reports of probe-type ultrasonic system [17], apart from the cavitational region mainly occurs at locations near the ultrasonic emitter, variation of cavitational activities in temporal and spatial aspects of an ultrasonic reactor was also seen in the bath reactor. Figure 4 indicates P_{cal} was directly proportional to time. As ultrasonic irradiation time increased, forming more cavitation bubbles and further power absorption, temperature rose steadily.

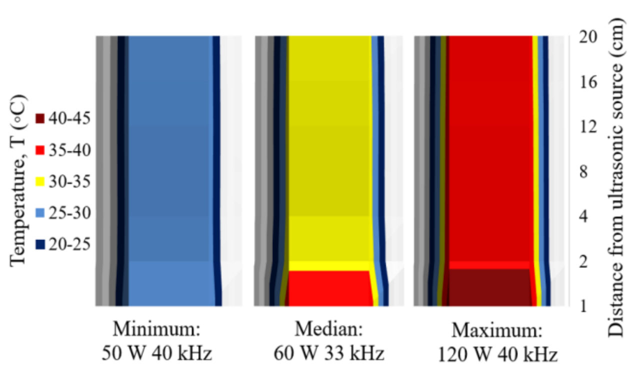

Fig. 2 Temperature distribution in ultrasonic reactor at selected ultrasonic settings.

Figure 5 display the individual relationship of calorimetric power, P_{cal} with ultrasonic power and frequency, respectively. A good linear regression could be seen between P_{cal} and ultrasonic power (frequency fixed at 40 kHz) with R^2 around 0.95, while no clear pattern was observed with ultrasonic frequency (power fixed at 60 W). P_{cal} proportionality with ultrasonic power was parallel to a previous study by Kojima et al. [18], but there is no report found on ultrasonic frequency yet. Similarly, report by Son et al. [19] found that cavitation energy was directly proportional to input energy. They also discovered the cavitation energy distribution to be the highest and most constant at higher frequency of 72 kHz, although the amount of cavitation energy per cycle was greater at lower frequency of 35 kHz. Thus, it is possible that higher frequency would bring cavitation effects further distance away from ultrasonic source, although the interaction between power, frequency, and even reactor geometry could play a major role [20].

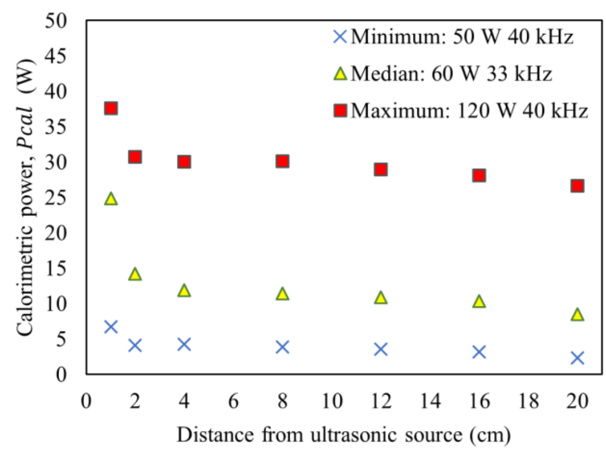

Fig. 3. Calorimetric power attenuation with increasing distance from ultrasonic source.

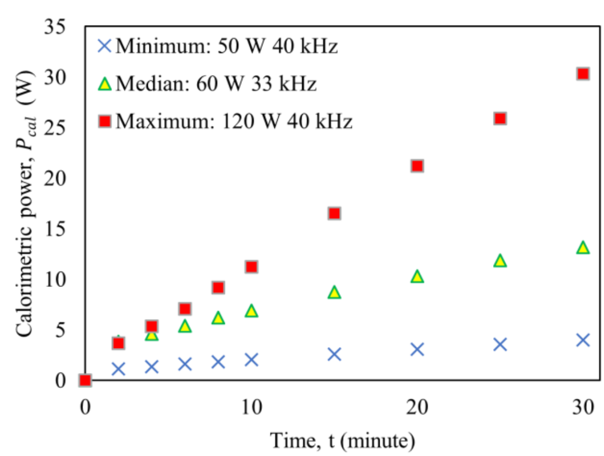

Fig. 4. Calorimetric power at various ultrasonic settings versus time.

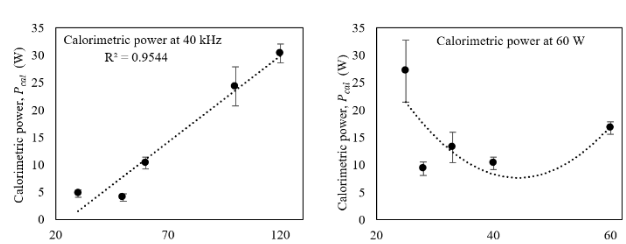

Fig. 5 Calorimetric power at various ultrasonic powers (left) & frequencies (right).

To further understand the association between ultrasonic power and frequency towards P_{cal}, contour, main effects, and interaction plots were contrived in Figure 6, 7 and 8, respectively. Increasing ultrasonic power generally would obtain larger P_{cal} as can be seen in Figure 6. This however, depended on the frequency setting as well. Although the main effect plot (Figure 7) implies increasing ultrasonic frequency would also improve the P_{cal} , it was not straightforward. For instance, the interaction plots (Figure 8) suggest ultrasonic frequency below 40 kHz seems to favor power at 30 W towards achieving higher P_{cal}, while system at 40 kHz was more sensitive to power than at other frequencies. Hypothesis testing via statistical analysis software (Minitab) was performed to compare the effect of ultrasonic power and frequency. The former had more influence towards P_{cal}, verified by p-value of less than 0.05 based on 95% confidence interval, whereas frequency was statistically insignificant. They definitely interacted with each other as proven by the interaction plot, but more research needs to be done in this area.

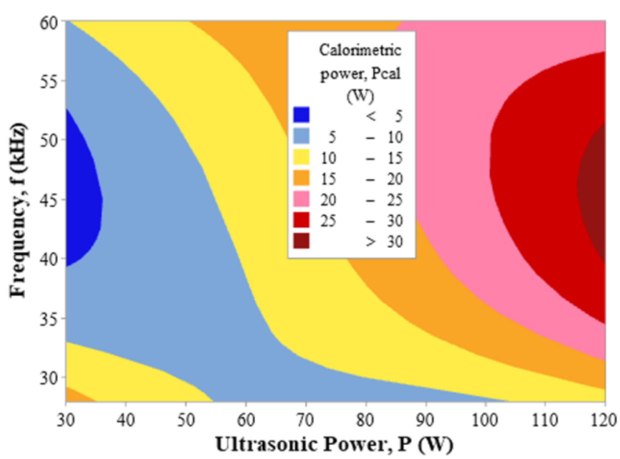

Fig. 6. Contour plot for calorimetric power.

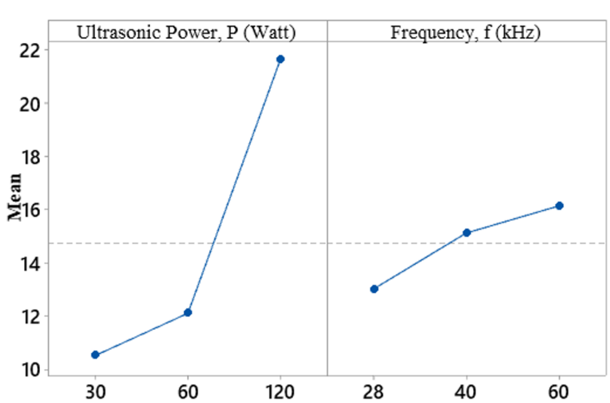

Fig. 7. Main effects plot for calorimetric power.

It is largely accepted that ultrasonic energy at laboratory scale is best measured using calorimetric method, provided capable measurement system is used [21]. Despite the benefits of the calorimetric method, ultrasonic emitter primarily is not a heat source. Hence, to quantify the change of temperature alone has its drawbacks and error consideration. This method assumes that heat is mainly generated and accumulated through sound attenuation or absorption, whereas in reality, there could be heat transfer and dissipation due to boundaries, solid-liquid-air interfaces, and mass transfer from acoustic streaming, liquid agitation, and shockwaves. Improvement towards the power quantification method and related equations can be found in literatures of recent years.

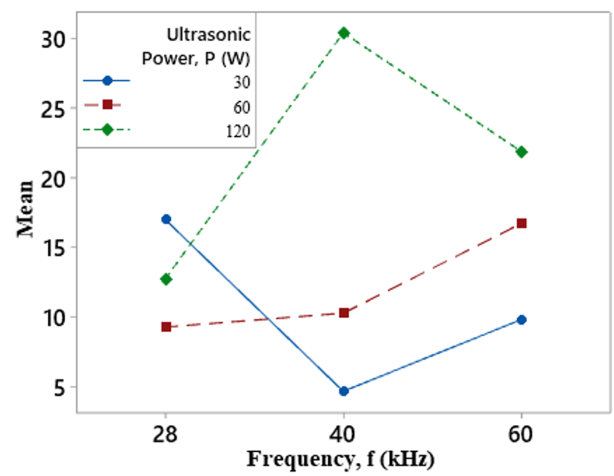

Fig. 8. Interaction plot for calorimetric power.

In the context of ultrasonic hardware, the power indicated in the specification of ultrasound generator normally states its capacity. It does not mean that the generator will provide that power level constantly [22]. Sometimes the power provided by generator depends on the load of the system. Similarly, the ultrasonic power in this study was the rated power of individual ultrasonic transducers and was assumed to be fulfilled when powered up by the ultrasonic generators.

4. CONCLUSION

It is imperative to analyze power behavior to comprehend ultrasonic bath performance. In this study, an ultrasonic reactor capable of varying ultrasonic power and frequency was mapped for heat profile and calorimetric power, P_{cal}. Result implies that as the ultrasonic power increased, so did the P_{cal}. Ultrasonic frequency also influenced the generated P_{cal} despite not being statistically significant. More studies are needed to uncover association between ultrasonic power and frequency towards power propagation and cavitation effect distribution in ultrasonic bath reactor.

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