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Characterisation of the ultrasonic acoustic spectrum and pressure field in aluminium melt with an advanced cavitometer



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ABSTRACT

Currently, fundamental experimental studies in liquid metals are limited as there are very few available experimental tools for directly measuring acoustic cavitation in such extreme environments. In this work, a calibrated high temperature cavitometer was used for measuring acoustic emissions and acoustic pressure in sonicated liquid aluminium and in water. The extent of the cavitation zone was quantified in liquid aluminium and water. The differences between cavitation behaviour of water and liquid aluminium were explained in terms of acoustic shielding, attenuation, and bubble dynamics.

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1. Introduction

Ultrasonic treatment of liquid metals is closely related to cavitation and bubble dynamics and it has been proven as effective and promising in degassing and refining the grain structure of metallic melts as shown by Eskin and Eskin (2014). Cavitation involves the formation, growth, oscillation, collapse, and implosion of bubbles in liquids (Leighton, 1994). In the vicinity of collapsing bubbles, extreme temperatures (>10000 K) (Flannigan and Suslick, 2005), pressures (>400 MPa) (Flannigan and Suslick, 2005; Tzanakis et al., 2014) and cooling rates ($>10^{11}$ K/s) (Gedanken, 2004) occur. However, temperature requirements, opacity of metals, and the lack of advanced equipment for measuring cavitation activity have imposed strict limitations on the study of cavitation bubble dynamics within liquid metals. Only post-mortem analysis is generally used to correlate the final structure with ultrasonic parameters, as shown by Atamanenko et al. (2010) and Eskin and Eskin (2014). This impedes the industrial application of ultrasonic processing to liquid metals.

Recently, X-ray imaging technology in the form of third generation synchrotron radiation sources was applied for in situ studies of bubble dynamics (Xu et al., 2015) and nucleation (Huang et al., 2015) in liquid aluminium (Al) alloys. However, the small spatial and large temporal scales involved in the process hinder clear visualization of the physical processes and consequently a deeper insight into the behaviour of cavitation bubbles. Compared with the X-ray imaging, acoustic emissions, i.e. cavitation noise, could be a more powerful approach to record and analyse the dynamic process of cavitation. The cavitation noise spectra carry a multitude of information in their respective ultra-harmonic and broadband components that help to distinguish different regimes of acoustic cavitation and consequently measure acoustic pressures at particular frequencies.

Very few studies have been conducted on characterizing cavitation activity in liquid metals using various means, including cavitometers as reviewed by Eskin and Eskin (2014) and exemplified by Komarov et al. (2013). In the latter paper, a cavitometer was used for characterising the cavitation intensity in a molten Al alloy. However, the results were given in relative terms of electrical output of the cavitometer (mV), and not in the physical units of pressure. No analysis of the acoustic spectra was attempted. As a result, the reported data cannot be applied to, for example, validation of numerical models. This work is intended to fill this gap and to demonstrate the possibility of using a calibrated

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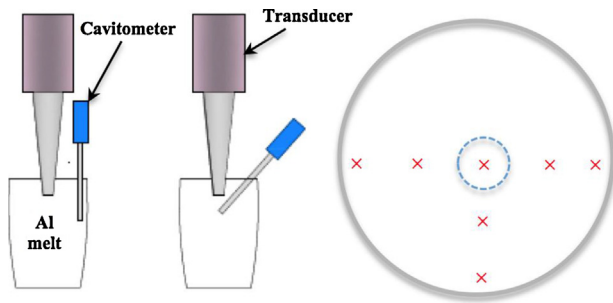


Fig. 1. Schematic of the experimental test rig. The cavitometer measures the activity at 3 different positions across the section of the vessel as indicated by the red marks (under the sonotrode, in the middle ($1/2 R$) and near the wall (R)). The blue dashed circle indicates the position of the sonotrode (top view of the crucible).

cavitometer for directly measuring acoustic spectra and pressure in low-temperature transparent (water) and high-temperature opaque (molten Al) liquids, with the benefit of getting physically-relevant data as well as characterising the extent of cavitation in treated liquids.

2. Experimental setup

In the current study, characterisation of the cavitation intensity and the corresponding acoustic pressure fields in liquid Al and in water was conducted using the experimental setup that is schematically shown in Fig. 1. Ultrasonic excitation was achieved with a 5-kW generator and a 5-kW water-cooled magnetostrictive transducer (Reltec/Russia). A conical Nb sonotrode with a 20 mm tip diameter was driven by the transducer, which oscillates at a nominal fundamental frequency of 17 kHz. The input power from the generator was varied in the range of 2.5–4 kW in both cases. To sonicate the liquid, the Nb sonotrode tip was vertically immersed to a depth of approximately 20 mm into the liquid volume. The sonicated water liquid was contained in a cylindrical, glass-walled vessel with diameter of 150 mm. The liquid level in the vessel was at 110 mm (approximately 2000 cm³). To prevent water heating by acoustic energy, each experiment lasted for a few seconds. Water temperature was maintained at $22 \pm 2^\circ\text{C}$. In the case of liquid Al, a charge of 5.2 kg (approximately 2000 cm³) of commercially pure 99.7% Al was melted in a clay-graphite crucible coated inside with boron nitride (BN), with the size and geometry being similar to that of the glass vessel. The melt temperature was stabilised to $710 \pm 10^\circ\text{C}$ and was continuously monitored by a K-type thermocouple. There was no controlled atmosphere.

Features of the observed spectra were captured with an advanced calibrated cavitometer ICA-3HT (BSUIR/Belorussia) equipped with a 4-mm diameter tungsten probe, with a spatial resolution of 50 ± 10 mm and a bandwidth of up to 10 MHz. The cavitometer was specifically designed to measure cavitation activity in high temperature melts and in high power ultrasonic fields, i.e. in molten metals. This cavitometer can equally well measure cavitation activity in low temperature liquids. A full account of the cavitometer design and performance can be found in Tzanakis et al. (2015a). To investigate the effect of distance relative to the sonotrode on cavitation intensity, the measurements of acoustic emissions were taken at several points as shown in Fig. 1 (indicated by crosses), i.e. (i) below the sonotrode, (ii) at half radius distance ($1/2 R$) (about 38 mm off the sonotrode axis) and (iii) at full radius distance (R) (about 75 mm off the sonotrode axis) with the cavitometer probe submerged at 70 ± 5 mm below the liquid free surface, which was monitored through the known length of the cavitometer probe outside the melt.

The frequency spectrum was acquired by an external digital oscilloscope device “Picoscope” attached to the cavitometer. This

Picoscope device allowed real-time signal monitoring of the cavitometer sensor’s data and ultrasonic parameters. The raw voltage signal is transformed to the frequency domain via a Fast Fourier Transform. A number of 30 signal averages of the acquired signal were taken using a resolution bandwidth of 500 Hz. The time for this signal acquisition was approximately 30×2 ms (time gate) = 60 ms. A total of 1000 wave patterns were analysed in each of the measurement points as shown in Fig. 1.

3. Results and discussion

The local cavitation phenomena in the vessel were explained based on the spectral characteristics of acoustic emissions. Acoustic pressures at the driving frequency of 17 kHz and at an acoustic frequency of 1 MHz (associated with acoustic pressures exerted from the activity of the cavitation bubbles) were calculated using the methodology described in Tzanakis et al. (2015a). Results were then interpreted based on averaging the values taken in equivalent measurement points in Fig. 1, except for the position under the sonotrode. By bridging these two liquid environments, a more comprehensive picture of the phenomena governing the cavitation process within liquid Al can be constructed, thus advancing the existing knowledge in liquid metal processing.

Typical acoustic spectra for water and liquid aluminium, as received from the inside of the cavitation zone by the cavitometer, are shown in Fig. 2. The fundamental frequency component at 17 kHz (f_0) is apparent producing broadband signals well into the high frequency domain associated with the activity from cavitation bubbles with further contributions from harmonics, sub- and ultra-harmonic frequencies (numerous irregularly spaced peaks superimposed on cavitation noise background). A full discretization of the spectrum at lower frequencies is described in the previous work by Eskin et al. (2015) and Tzanakis et al. (2015b). Additionally, discretization of frequency peaks in the region of 1 MHz is shown by the insets in Fig. 2. A background noise is shown for reference. The background “noise” measurement was performed with the transducer switched off and the cavitometer submerged into the tested liquid. These data show that the level of noise (note that dBu axis is logarithmic) is very small and does not affect the acoustic measurements.

The general shape of the spectrum in liquid aluminium is comparable to that of the water, further reinforcing the accepted views that water and aluminium share similar fluid and dynamic behaviour as previously demonstrated by Eskin et al. (2015) for ultrasonic processing and by Xu et al. (1998) for casting processing. In the case of ultrasonic cavitation, the main difference is that the broadband spectrum generated by the collapsing bubbles of a wide range of sizes with their shock emissions and liquid jets is significantly higher in the case of liquid aluminium (about 10 dBu on average) as compared with water. In some particular high frequencies, it can be as high as 20 dBu (see dashed arrow in Fig. 2b). This implies that transient cavitation associated with the level of the broadband cavitation noise is more prominent in liquid aluminium and thus higher activity from the cavitation bubbles is expected. Additionally, single (dashed arrow) or populated (solid arrows) discrete peaks (see Fig. 2) at higher frequencies, i.e. in the range of 200–250 kHz and 300–600 kHz, suggest non-linear stable or transient cavitation activity from numerous cavitation bubbles. This leads us to the conclusion that, in the studied melt, the activity of bubbles with resonance sizes of 5–15 μm according to Minnaert (1933) can prevail in the cavitation regime, increasing the intensity of the corresponding peaks in these frequency ranges. This is in agreement with an in situ study of cavitation in Al melts, showing that the majority of cavitation bubbles are indeed fall in that particular size range (Xu et al., 2015).

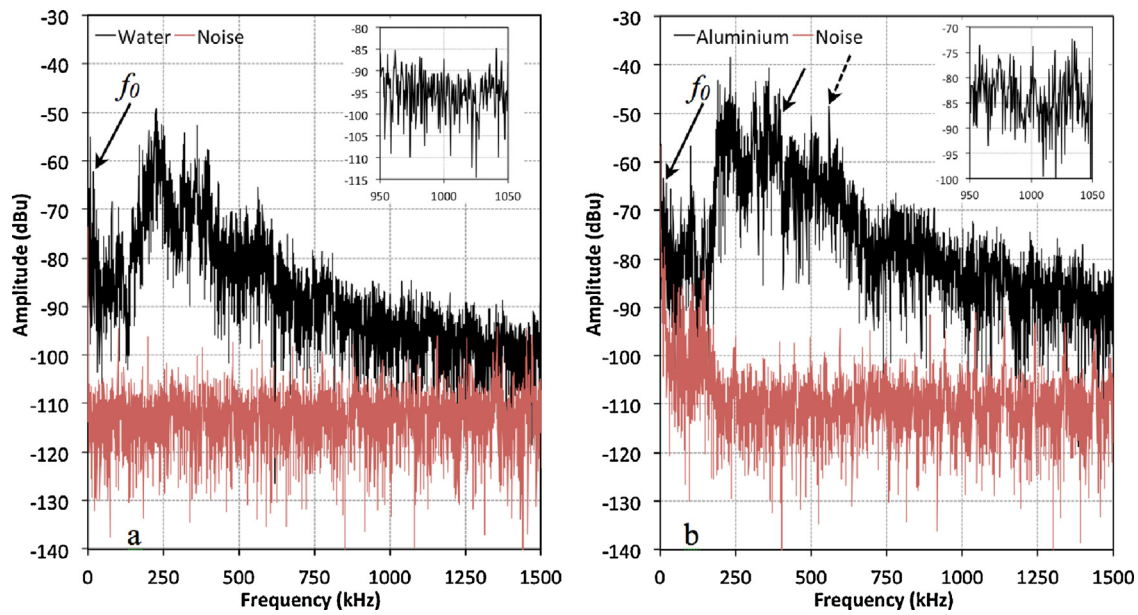


Fig. 2. Typical examples of acoustic spectra generated by magnetostrictive ultrasonic transducer at 17 kHz driving frequency (f_0) and measured with the cavimeter tip positioned about 3–4 cm below the sonotrode's tip in (a) water and (b) liquid Al. Inset shows the spectrum in the range of 1 MHz.

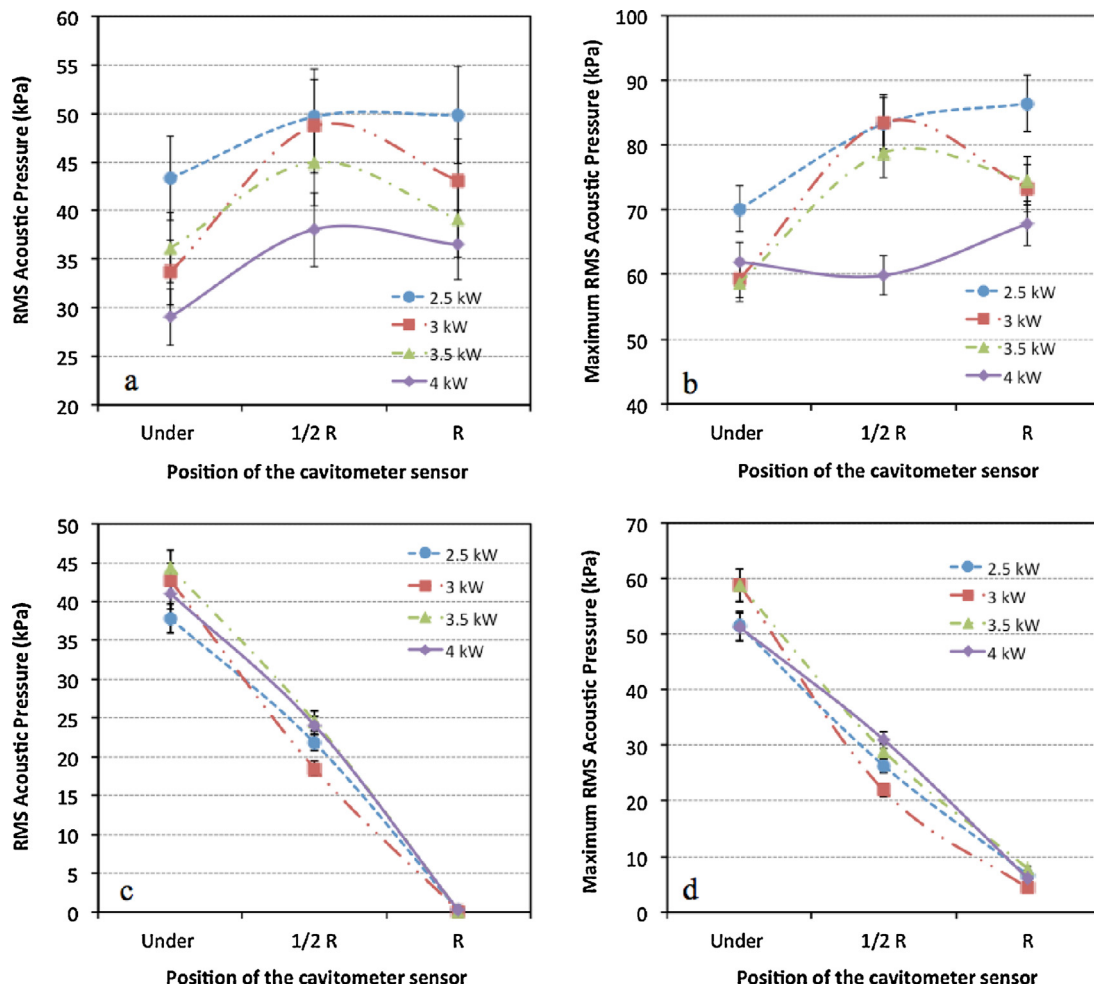


Fig. 3. Variation in RMS acoustic pressures and maximum RMS acoustic pressures (representing the average of the maximum RMS acoustic pressure measured for each position) of the driving frequency (17 kHz) in (a–b) water and (c–d) liquid Al. The average of three different positions as indicated in Fig. 1 was taken.

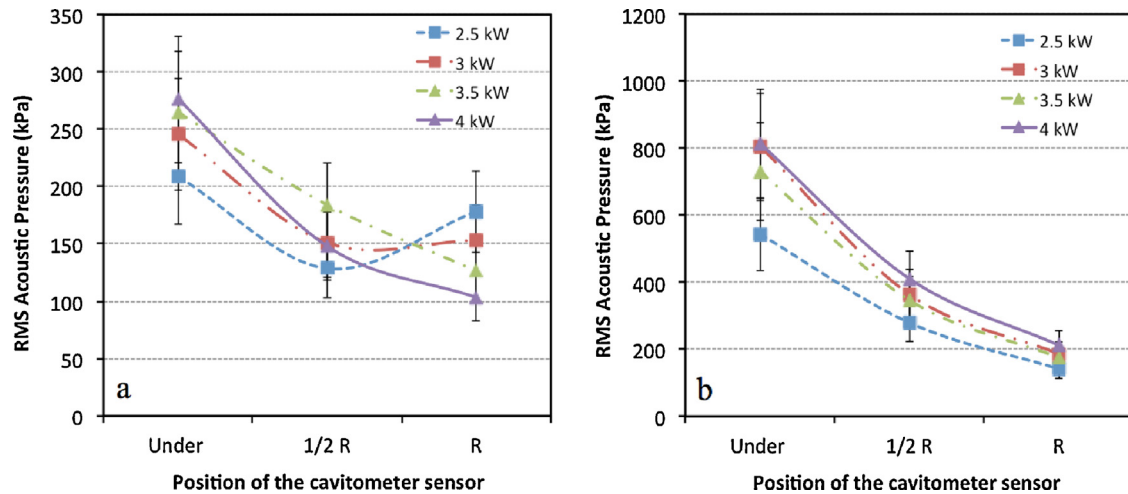


Fig. 4. Variation in RMS acoustic pressures at 1 MHz (associated with bubbles cavitation activity) for (a) water and (b) liquid aluminium.

In Fig. 3, acoustic pressures in the range of the driving frequency f_0 for both of the studied liquids are shown for the three different positions across the vessel. Fig. 3 demonstrates that an increase in power input does not result in an equivalent increase in cavitation activity. This is more obvious in the case of water where results clearly show that the highest acoustic pressure in water (Fig. 3a and b) was obtained near to the wall (R) when the lowest power setting (2.5 kW) was used. At higher input powers, the large bubbly cloud that is formed inside the cavitation shields and scatters the bubble energy released from the cavitation bubbles, as shown by Rozenberg (1968). As a result, the propagation of acoustic waves into the liquid bulk is obstructed. In contrast, at lower power settings, bubbles migrate more easily towards the side walls due to primary Bjerknes forces. With fewer bubbles and bubbly clouds, the propagation of waves into the liquid bulk is less disturbed. The bubbles formed or transported to the vessel wall collapse more easily. Consequently, the overall cavitation activity in the bulk liquid is increased further.

The maximum RMS acoustic pressures representing the average of maximum RMS acoustic pressure at the three equivalent measurement points are shown in Fig. 3b and d for water and aluminium respectively. In the case of liquid aluminium, the highest cavitation pressure was measured at 3.5 kW, closely followed by the rest of the power settings (Fig. 3c and d). Significantly (20–30%) higher pressure values in water compared with liquid aluminium were observed. At each measuring point, the maximum pressure is 40–50% higher than the average pressure value (Fig. 3a): this indicates the presence of a more fluctuating pressure field, resulting in a more chaotic cavitation activity within the water bulk. On the contrary, in liquid aluminium, the maximum RMS pressure is only a 20–25% higher implying that a more stable and controlled cavitating environment without significant pressure fluctuations is achieved. Controlling cavitation intensity is one of the key factors for the optimization of melt processing and solidification.

Fig. 3c and d show an almost linear drop of the acoustic pressure field with distance in liquid aluminium. As a rule of thumb, cavitation acoustic pressure in liquid aluminium drops about 50% at every half radius distance from the source. This acoustic field attenuation may be due to the absorption of acoustic energy by the viscous environment and accumulation of long-lived aluminium cavitation bubbles. Unlike in water, the borders of the cavitation zone in liquid aluminium can be well defined, indicating the region of active cavitation regime. Thus, most of the processes responsible for grain structure refinement, such as de-agglomeration and sono-fragmentation, should take place in that particular region, unlike in

water where cavitation treatment may be active everywhere in the vessel.

The acoustic pressure results in Fig. 3 demonstrate higher values for water than for liquid aluminium, while the overall acoustic spectrum in Fig. 2 suggests the opposite. This could be related to the release of bubble energy at high frequencies, as supported by the results in Fig. 4. In water, RMS acoustic pressures at 1 MHz are 2–3 times lower than in liquid aluminium, meaning that energy is indeed stored during relatively long life-time of Al cavitation bubbles and then released back into the bulk in a form of cavitating and collapsing bubbles. Results are in a good agreement with X-ray imaging results where numerous cavitation bubbles were seen sustained for long periods of time in the bulk before they disappear (Xu et al., 2015). Therefore, the significant shielding and scattering of acoustic waves at the lower frequencies in the range of 17 kHz does not exclude the possibility of powerful collapses of cavitation bubbles, as attested by strong pressure surges detected at the higher frequencies (1 MHz).

The results in Fig. 4 confirm that cavitation treatment in liquid aluminium should take place inside the cavitation zone unlike in water where pressure exerted from bubbles is less dependent on the distance from the ultrasound source. RMS acoustic pressures in liquid aluminium could be as high as 800 kPa certainly enough to break cluster of particles facilitating the de-agglomeration process and wetting through sono-capillary effect (Eskin and Eskin, 2014). Results are in a good agreement with a recent study where the filling process depending the geometry and size of cracks can be achieved at similar pressure scales tied up with the collapse of cavitation bubbles (Tzanakis et al., 2015c).

4. Conclusions

1. The cavitation acoustic pressure and the borders of the cavitation zone were quantified using a calibrated cavimeter in liquid aluminium and the results were compared with those obtained in water.
2. In the low frequency domain reflecting the overall acoustic field, shielding and acoustic damping is more pronounced in liquid aluminium, obstructing the wave propagation into the bulk. In contrast, a more consistent pressure regime is established across the treated volume in water. Consequently, the measured RMS acoustic pressures in liquid aluminium are lower than in water.
3. At higher frequencies, associated with cavitation bubble emissions, the acoustic pressures are much higher in liquid

aluminium than in water implying that bubbles accumulate large amounts of energy prior to release them upon collapse.

4. This work demonstrated the feasibility and practical value of direct acoustic measurements in liquid metals. These measurements can be used for validating the numerical models that are required for optimisation of ultrasonic melt processing.

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