Sensors and Actuators A 240 (2016) 57–69

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Calibration and performance assessment of an innovative high-temperature cavitometer

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ARTICLE INFO

Article history:
Received 27 August 2015
Received in revised form
21 December 2015
Accepted 13 January 2016
Available online 15 January 2016

Keywords:
Cavitation
Cavitometer
Liquid metal
Sensor
Acoustic emissions
Frequency spectrum
Sonochemistry

ABSTRACT

This paper describes a series of systematic experimental studies to evaluate the performance of a high-temperature cavitometer under well-controlled conditions. The cavitometer was specifically designed for measurements in liquid metals: it operates through a long tungsten waveguide (probe), providing thermal protection to the piezo sensing elements placed outside the hot area, and with sufficient bandwidth to enable the monitoring of broadband acoustic emissions associated with cavitation activity. It was calibrated electrically, and acoustically, at kHz and MHz frequencies, and so can be used to estimate acoustic pressures (in Pa), providing physical, and consequently practical, meaning to cavitation measurements within liquid metals. Results obtained from ultrasonic sources in a cylindrical vessel using water showed that the cavitometer is a reliable and robust device for characterizing direct field acoustic pressures and broadband emissions from the resulting cavitation. Additionally, preliminary characterization of the real-time acoustic pressures during ultrasonic processing of liquid aluminium (Al) in a standard clay-graphite crucible were performed for the first time. The use of the calibrated cavitometer will establish a more generalized approach for measuring the actual acoustic pressures over a broad range of liquid temperatures within a sonicated medium, demonstrating its potential use as a tool for optimizing, controlling, and scaling-up processes.

1. Introduction

Acoustic cavitation is the formation of highly energetic gas or vapour bubbles, primarily from pre-existing nuclei, within a sonicated liquid volume due to local pressure fluctuations of the acoustic field. Bubbles grow during the rarefaction phase and then collapse during the compression phase. Cavitation is usually distinguished into two classes of behaviour: non-inertial (or stable) cavitation, and inertial (or transient) cavitation. Two categories of stable bubbles may be distinguished: (a) pulsating linearly (low energy bubbles) contributing to an increase in the fundamental frequency component peak f_0 and its harmonics i.e. nf_0; (where n is an integer) and (b) pulsating and collapsing nonlinearly (higher energy bubbles) in the so-called "repetitive transient cavitation" regime, generating sub- and ultra-harmonic peaks i.e. nf_0, $nf_0/2$, $nf_0/4$ as well as distinctive broadband signals [1]. Transient cavitation is associated with the dynamics of the collapse and is characterised by material erosion [2], sonocapillary effect [3], biomedicine [4] etc. and the generation of sub- and ultra-harmonic peaks as well as an increase in the broadband signal, the so-called cavitation noise, in the acoustic spectrum. Cavitation noise has long been considered as a phenomenon that contains information about the cavitation zone [5–9] and for this reason, it is a versatile candidate for cavitation activity monitoring.

Many commercially available acoustic cavitation devices operate in the range 20–50 kHz; yet acoustic emissions from collapsing bubble clouds extend readily to MHz frequencies, such is the non-linear nature of energy redistribution. This enables detailed information to be captured and extracted when suitable detectors are applied. Since the pioneering work of Esche [10] in the 1950s, the detection of acoustic emissions from cavitating bubbles or a bubbly cloud has been extensively studied, with the majority of these studies performed in aqueous media. The frequency spectra of acoustic cavitation noise have been studied by many groups

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http://dx.doi.org/10.1016/j.sna.2016.01.024

[7–9,11]. The broadband cavitation noise spectrum has the form of line components overlaid on a wide band (continuous) noise spectrum. The presence of line spectra and their harmonics is usually related to the nonlinear pulsation of cavitation bubbles [6] or the nonlinear propagation of ultrasound in bubbly liquid [12]. The presence of the wide band component in a cavitation noise spectrum is generally attributed to the generation of shock waves. A shock wave can be represented mathematically by a Dirac delta-function, and the frequency spectrum of the delta-function is white noise [13]. It has been shown [11] that the appearance of sonoluminescence emissions from the cavitating regions of a fluid correlates with the appearance of broadband acoustic emissions, showing that both phenomena relate to bubble collapse [14,15]. Thus, the higher the number of collapsing bubbles in the cavitating fluid, and the greater the energy or 'violence' with which they collapse, the higher the integrated value of the broadband acoustic emission. However, obtaining a real-time indication of cavitation activity based on acoustic detection of emissions is complex because shielding and scattering effects can potentially reduce the emitted acoustic pressure levels travelling through the liquid media, even over length scales of millimetres [16], and defining the spatial resolution of any sensor can also be difficult.

Stable cavitation may be relevant in some applications of high power ultrasound such as degassing [17–19], while transient cavitation is associated with technologically important phenomena such as grain refinement in solidification of metals and deagglomeration of reinforcing particles in composite materials [20,21], as well as cleaning and sonochemistry [22]. In liquid metals, the effective action of high pressure acoustic waves is attributed to the occurrence of mechanically violent cavitation bubbles, a mechanism that is still under scrutiny due to the experimental challenges involved [21–25]. In recent years, there has been an increased interest in fundamental and applied investigations of metal solidification promoted by ultrasound since ultrasonic treatment improves the material properties and structure of the solidified metal [21]. However, temperature requirements, medium opacity, and lack of advanced equipment for measuring cavitation activity have restricted investigations of cavitation bubble dynamics within liquid metals. These difficulties have impeded the industrial take-up of ultrasonic vibrations in liquid-metal processing. Thus, despite the well-known and growing technological importance of high power ultrasound, no standardised measurement methods applicable to measuring the cavitation activity and map acoustic pressures in the melt exist to date and very few studies have been conducted to characterize cavitation activity in liquid metals [21,26,27].

In a recent study, a cavitometer similar to the one used in this study was used by Komarov et al. [26] to characterize cavitation intensities in a molten aluminium (Al) alloy. The filter settings of the cavitometer that they used for measuring cavitation noise include six different frequency bands. In their results, the cavitation activity within the liquid Al alloy is presented in terms of the electrical output of the cavitometer sensor (mV). However, these results cannot be practically applied, for example, in the validation of numerical acoustic models, as the output provided by the cavitometer is not in useful physical units, i.e. Pa. Thus, in the current study, calibration of the high-temperature cavitometer was performed at the National Physical Laboratory (NPL), UK. Although carried out under well-controlled conditions in the absence of cavitation, the derived calibration sensitivity factors can be used to estimate acoustic pressures (in Pa) in the presence of cavitation, providing physical and, consequently practical, meaning to cavitation measurements within liquid metals. After the calibration process, a comparison with a cavitation sensor (Cavisensor) developed at NPL [28,29] was performed under aqueous conditions. Preliminary measurements with the high-temperature cavitometer were then conducted in liquid Al.

2. Description of cavitometer

The cavitometer (Fig. 1) was developed and manufactured by the Belarusian State University of Informatics and Radioelectronics, Belarus, and is specifically designed to measure cavitation activity in high-temperature and high-power ultrasonic fields, i.e. in molten metals. The cavitometer consists of an electronic block device (ICA-3HT) and a hydrophone designed to be protected against heat and cavitation erosion. The hydrophone has a probe (receiver) that is attached to a piezoceramic plate. The receiver acts as a waveguide, coupling the acoustic signal from the cavitation zone to the piezoceramic plate. The waveguide is long so that the distance between the hot metal and the sensitive piezoelectric element as well as the casing of the latter ensures the protection from heat both by conduction and radiation. The hydrophone is electrically connected to the electronic block that displays and processes the electrical signal produced by the piezoelectric probe in response to acoustical stimulation. Various settings and outputs are available for optimising the detection regime and for enabling offline signal monitoring and analysis using external oscilloscopes and voltmeters.

It is impossible to use conventional hydrophones (mechanical or piezoelectric) for direct measurements at temperatures higher than 150 °C due to thermal stability of a piezoceramic membrane or a plate. The cavitometer hydrophone receiver is hence made of a tungsten alloy (97.3–97.8% W), such as that used in welding electrodes. Tungsten has a much higher melting temperature than aluminium (3420 °C vs 660 °C), very low solubility in liquid aluminium, and high thermal stability of properties [30]. The manufacturer of the cavitometer has estimated theoretically the temperature variation of the piezoceramic plate with time for different immersed lengths of the tungsten probe in a molten alloy at temperatures near to 800 °C. On the basis of these estimates, the dimensions of the tungsten waveguide were chosen to be 500 mm in length and 4 mm in diameter, which allows for 10–15 min of continuous measurements in liquid Al, after which the cavitometer might overheat. The disadvantage of a tungsten alloy is its high ultrasound absorption coefficient. This leads to signal losses in the waveguide, especially for frequency components approaching MHz ranges.

The working principle of the cavitometer is based on the detection of acoustic signals generated in a fluid, from both the direct field and acoustic emissions produced by cavitation. A raw broadband signal is received from the cavitometer and can be analysed and displayed on the accompanying electronics, or accessed via BNC connection and processed offline by appropriate instrumentation and software. Processing offline allows measured voltages to be converted to acoustic pressure using the calibration described in the following sections. Measurement of the cavitation noise carried out using the cavitometer positioned within or close to the cavitation zone in a fluid is used to provide a measurement of the acoustic emissions generated by the cavitation bubbles. Specifically, the integrated cavitation noise over the frequency spectrum up to 10 MHz is considered as an indicator of total cavitation activity. It has been shown in experiments similar to [11] that, for ultrasonic fields having driving frequencies in the range 20–25 kHz, transient cavitation is accompanied by the appearance of frequencies higher than $10f_0$. Based on this, we assume that the integral intensity of the cavitometer hydrophone output in the range of frequencies $10f_0$ −10 MHz represents transient cavitation activity, with the onset of inertial cavitation indicated by the first peak of the generated sub-harmonic [31]. Total cavitation activity, includ-