Ultrasonics 57 (2015) 18–30

Contents lists available at ScienceDirect

Ultrasonics

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

Energy characterisation of ultrasonic systems for industrial processes

Raed A. Al-Juboori [a,*], Talal Yusaf [b], Leslie Bowtell [b], Vasantha Aravinthan [a]

[a] School of Civil Engineering and Surveying, Faculty of Health, Engineering and Sciences, University of Southern Queensland, Toowoomba, 4350 QLD, Australia
[b] School of Mechanical and Electrical Engineering, Faculty of Health, Engineering and Sciences, University of Southern Queensland, Toowoomba, 4350 QLD, Australia

ARTICLE INFO

Article history:
Received 12 May 2014
Received in revised form 4 September 2014
Accepted 3 October 2014
Available online 12 October 2014

Keywords:
High power ultrasound
Convective heat loss
Sonochemistry
Calorimetric techniques
Heat transfer

ABSTRACT

Obtaining accurate power characteristics of ultrasonic treatment systems is an important step towards their industrial scalability. Calorimetric measurements are most commonly used for quantifying the dissipated ultrasonic power. However, accuracy of these measurements is affected by various heat losses, especially when working at high power densities. In this work, electrical power measurements were conducted at all locations in the piezoelectric ultrasonic system equipped with ½″ and ¾″ probes. A set of heat transfer calculations were developed to estimate the convection heat losses from the reaction solution. Chemical dosimeters represented by the oxidation of potassium iodide, Fricke solution and 4-nitrophenol were used to chemically correlate the effect of various electrical amplitudes and treatment regimes. This allowed estimation of sonochemical-efficiency (SE) and energy conversion (X_{US}) of the ultrasonic system. Results of this study showed overall conversion efficiencies of 60–70%. This correlated well with the chemical dosimeter yield curves of both organic and inorganic aqueous solutions. All dosimeters showed bubble shielding and coalescence effects at higher ultrasonic power levels, less pronounced for the ½″ probe case. SE and X_{US} values in the range of 10^{-10} mol/J and 10^{-3} J/J respectively confirmed that conversion of ultrasonic power to chemical yield declined with amplitude.

1. Introduction

Despite the many and varied potential applications of high power ultrasound technologies for different treatment purposes, industrial scalability of ultrasonic treatment processes is still difficult to achieve. One of the crucial elements of ultrasound scalability is the quantification of energy losses involved in the conversion of the electrical energy into several forms of mechanical energy [1]. The ultrasonic energy distribution of acoustic cavitation effects within an ultrasonic reactor is also important for scalability as this aspect allows engineers to determine the optimum operating conditions for a particular application. Furthermore, scrutinizing energy conversion in ultrasonic reactors enables researchers to rigorously compare results of different experiments and report reproducible reaction conditions [2].

For typical ultrasonic treatment systems the mains frequency electrical power is transformed electronically from low frequency (50–60 Hz) into high frequency (20–40 kHz). The input and output power to the generator and transducer is normally measured by means of wattmeters and oscilloscopes. However, measuring these forms of power is rarely conducted due to the general difficulty of access and electrical shock hazards involved.

The correlation between the electrical power supplied to the vibrating probe and the acoustic events can be established through localized and/or bulk average techniques [3–5], which include:

(1) Physical properties measurement methods.

The propagation of ultrasound waves causes pressure variation in the irradiated medium that results in changing some properties such as the optical index of refraction [4]. This change can be detected via measuring the diffraction in an optical beam [6], schlieren visualization [7] and interferometric technique [4]. These measurements are unsuitable for high power quantification and they require sophisticated setups.

(2) Acoustic cavitation based methods.

The acoustic cavitation effects that occur inside or in the vicinity of the collapsing bubbles can be evaluated through Sonoluminescence methods, sonochemical methods or erosive and dispersive effects measurements [3]. Sonoluminescence methods are used for acquiring spatial and temporal resolution of cavitation sites. These methods have some shortcomings such

* Corresponding author.
E-mail addresses: RaedAhmed.mahmood@usq.edu.au, Raedahmed.mahmood@gmail.com (R.A. Al-Juboori).

http://dx.doi.org/10.1016/j.ultras.2014.10.003
0041-624X/© 2014 Elsevier B.V. All rights reserved.

as the requirement for specific experimental conditions (i.e. transparent media under blackout), unclear mechanisms of light emission and their restriction to the events occur at the gas phase of the collapsing bubbles [3,8].

Sonochemical techniques are normally applied to measure the chemical efficiency of ultrasonic reactors using chemical probes such as oxidation of potassium iodide (KI) and Fricke solution or decomposition of macromolecules [9]. Using sonochemical techniques alone may give an under-estimation of the overall ultrasonic energy dissipated as they are only concerned with the power involved in chemical reactions [10]. The recombination of the free radicals is another limitation of these techniques [11]. Hence, performing sonochemical measurements jointly with calorimetric measurements is encouraged in the literature [12,13].

Power measurements based on dispersive and erosive effects are only correlated to the strong mechanical effects of ultrasound propagation and their measurement accuracy is negatively affected by corrosive actions of free radicals. These downsides make their application unsuitable for ultrasonic power measurements [3].

(3) Energy or flow velocity method.

These methods involve radiation force, sound pressure measurements and calorimetric techniques. The mechanism of radiation force measurement is that when an object is exposed to ultrasonic energy, the object experiences a steady force (radiation pressure force) [14]. This force is directly proportional to the applied ultrasonic power. This technique can only be used for measuring ultrasonic power in medical imaging devices below the cavitation threshold [15,16].

Measuring sound pressure using hydrophones is conducted for identifying the spatial distribution of ultrasonic pressure intensity. The fragile nature of hydrophones and their sensitivity to the interfering pressure signals of the oscillating bubbles can limit their application high power measurements [17,18].

The calorimetric measurement of ultrasonic power is based on the notion that almost all the ultrasonic power is converted into heat [19,20]. The calorimetric techniques represent the most suitable methodology for measuring high ultrasonic power due to its simplicity and cost-effectiveness. However, calorimetric measurements for high power densities can be inaccurate due to convective heat losses [18]. Because of this limitation, heat transfer models have been proposed in this work to account for such losses during calorimetric measurements. Electrical power measurements were conducted at various locations within the system and the energy conversion efficiency of all system components was evaluated. The chemical efficiency at various amplitudes for 5, 10 and 15 min was investigated using the oxidation of potassium iodide, Fricke solution and 4-nitrophenol. The ultrasonic energy fractions consumed by the chemical reactions were determined using two approaches SE and X_{US}.

2. Materials and methods

2.1. Experimental setup

The experimental setup of this study is illustrated in Fig. 1. The setup consists of electrical power measurements gears, an ultrasound horn system, cavitation chamber, temperature sensors and data acquisition system. An ultrasonic reactor with maximum power of 400 W and frequency of 20 kHz was used in this study. Two different stainless steel tapped probes; one with a diameter of ½″ and the other with diameter of ¾″ were tested. In a typical run, the horn was immersed in a steel cavitation chamber that contains deionised water at a depth of 1.5 cm.

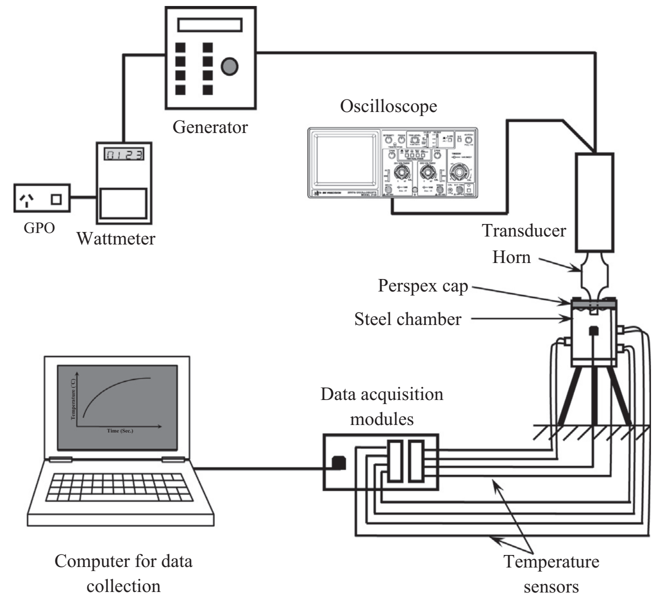

Fig. 1. Schematic of the experimental setup.

The cavitation chamber was fabricated at the workshop of the University of Southern Queensland with a capacity of 400 mL. The chamber is made of 316 stainless steel cylinder with 1 cm wall thickness. The cylinder is sealed from the bottom by a 1 cm thick 316 stainless steel disk with the use of screws and fitting O-ring. The top of the cylinder is sealed with a 2 cm thick Perspex disk. The probe is fitted through the Perspex disk with the aid of Viton O-rings. The cavitation chamber was fabricated from a thick wall steel body in order to examine the suitability of the intended calorimetric measurements in this study for the calibration of the industrial scale ultrasonic reactors where such reactors are anticipated to be made of thick metals.

Eight temperature sensors were set at various sites in and outside the chamber. Platinum thin film detectors (supplied by RS Australia) were used for measuring the temperature. These detectors are positive temperature coefficient sensors in which the resistance of the construction materials (platinum) increases linearly with temperature. These detectors have been chosen for this study due to their high stability (±0.05% as indicated by the manufacturer), ease of calibration and ability to outperform thermocouples in cavitation measurements. Thermocouples are susceptible to the corrosive action of cavitation due to their bi-metallic nature. This corrosive action causes a variable voltage to be produced which interferes with the temperature induced voltage generated by the thermocouples. Platinum films are inert to such an action, this removes one source of error when trying to estimate the actual ultrasonic energy produced. The temperature sensors were calibrated within the range of 5–100 °C using TH8000 precision immersion circulator (Ratek, Australia).

The distribution of the temperature sensors was as follows;

- Three temperature sensors were set axially underneath the irradiated surface of the vibrating probe at a distance of $\lambda/2$, $3\lambda/4$ and λ to capture the effect of the standing waves on temperature rise in the irradiated water.
- One temperature sensor was fixed close to the irradiating face of the horn where the effect of energy absorption by the bubbles is the least [21] and hence the highest temperature is expected.
- Four sensors where installed on the inner and outer surfaces of the steel cylinder and the Perspex disk.