INTERFACE FOCUS

rsfs.royalsocietypublishing.org

Introduction

Cite this article: Li S, Brennen CE, Matsumoto Y. 2015 Introduction for amazing (cavitation) bubbles. *Interface Focus* **5**: 20150059.
http://dx.doi.org/10.1098/rsfs.2015.0059

One contribution of 13 to a theme issue 'Amazing (cavitation) bubbles: great potentials and challenges'.

Subject Areas:
biophysics

Keywords:
cavitation, bubbles, biomedicine

Author for correspondence:
Shengcai Li
e-mail: s.li@warwick.ac.uk

Introduction for amazing (cavitation) bubbles

Shengcai Li[1], Christopher E. Brennen[2] and Yoichiro Matsumoto[3]

[1]School of Engineering, Warwick University, Coventry, UK
[2]Engineering & Applied Science, California Institute of Technology, Pasadena, USA
[3]School of Engineering, University of Tokyo, Tokyo, Japan

Although the word 'cavitation' was originally coined by R. E. Froude and first cited by Barnaby and Thornycroft in 1895, the phenomenon was conjectured much earlier by L. Euler in his theory of water turbines in 1754. However, actual cavitation was first discovered and investigated by Barnaby and Parsons in 1893 when they found that the formation of vapour bubbles on the propeller blades was responsible for the sea-trial failure in 1885 of a British high-speed warship HMS Daring. In 1895, Parsons established the first water tunnel for cavitation study and discovered the relationship between cavitation and the damage to the propeller. It was Rayleigh who, in 1917, laid the theoretical foundation for cavitation study by solving the problem of the collapse of an empty cavity in a large mass of liquid.

Following these pioneering works, it was discovered that these tiny bubbles have a remarkable ability to focus intense energy and forces and the capacity to erode almost any material in any fluid machine. Cavitation thus became the focal point of research in turbo-machinery.

In more recent times, it has become clear that this amazing ability of tiny bubbles could be beneficially deployed in many technologies, but most especially in biomedical situations, such as non-invasive lithotripsy of kidney and gall stones, targeted drug delivery and gene therapy, and much more.

The articles published in this issue of *Interface Focus* are from presentations at the Royal Society Theo Murphy International Scientific Meeting entitled 'Amazing (cavitation) bubbles: great potentials and challenges', 4–5 November 2014. This grew out of an International Cavitation Forum Series for promoting cross-disciplinary knowledge exchange that was established at Warwick University in 2006. This Royal Society Meeting is the fourth event of the forum series.

This theme issue on amazing bubbles illustrates the amazing ability of these tiny (cavitation) bubbles; the breadth of these beneficial functions explored in the past two decades in the biomedical sciences and technologies; and the challenges faced in both the traditional fields (e.g. water turbines and propellers) and the life sciences. Primary topics on bubble physics are also reviewed.

The collection starts with a paper by Brennen [1] that introduces this amazing ability of cavitation bubbles and their applications in medicine. The physics behind their beneficial functions are revealed using concise and understandable language to readers from varied disciplines.

Two papers then provide an overview of the conjecture and discovery of cavitation in traditional fields of water turbines and propellers, demonstrating that cavitation is still a major challenge in these fields. The paper by Li [2] reveals a very strange erosion occurring on the giant turbines installed at the Three Gorges project that puzzles professionals. A hypothesis is proposed to illustrate this unknown cavitation–inception process. The presentation by Arndt *et al*. [3] introduces a singing phenomenon from the tip vortex cavitation of propellers. It can be viewed as a canonical problem that captures many of the essential physics and is still far from fully understood. This paper focuses on its energy and frequency content of the radiated pressures.

A selection of six papers on the physics of (cavitation) bubbles follows. The significantly reduced speed of sound in a bubbly mixture, in which bubbles contain both the permanent gas and the vapour, will affect the overall flow field as well as the dynamics of cavitation itself. The paper by Prosperetti [4]

THE ROYAL SOCIETY PUBLISHING

provides, for the first time, a simplified linear model for the propagation of monochromatic pressure waves in a bubbly liquid of such characteristics.

The bubble dynamics near various boundaries is another focal topic of research that provides physical insight into the traditional problems such as erosion and coating protection, as well as the recent applications in biomedicine, etc. The presentation by Blake *et al.* [5] developed the Kelvin impulse principle capable of providing analytical predictions on bubble behaviour near a number of types of boundaries such as rigid, free surface, two-fluid interface and flexible. Considering the compressibility of the liquid, bubble behaviour predictions near the rigid boundary is provided by Wang *et al.* [6] using the weakly compressible theory coupled with the boundary integral method.

Cavitation inception from bubble nuclei is an essential phenomenon involved in cavitation process. The tensile strength of these nuclei depends not only on the water quality, but also on the pressure-time history of the water. The paper by Mørch [7] introduces such a model showing the effects of transient pressures on the tensile strength of water, which may be notably reduced or increased by such pressure changes.

Cavitation erosion is a long-lasting and not well-resolved problem. Recently, there was a programme aiming to build a potential basis for implementing numerical predictions. The presentation by Franc and co-workers [8] overviews the outputs from this programme, showing encouraging evidence of predicting the erosion in foreseen future. Among the programme is a core topic that predicts the boundary-material deformation under the load from the collapse of a single bubble nearby. For this topic, Chahine & Hsiao [9] provide a hybrid approach for estimating the collapsing loads in their fluid–material interaction-simulation to predict the material deformation and pitting.

Bubbles in biomedicine are reflected by three papers. The interaction of bubbles with shockwaves and ultrasound is a major scenario in biomedical applications and is often referred as 'acoustic cavitation'. A comprehensive review on applications and underlying physics has been presented by Khoo and co-workers [10]. The bubble-cloud is often the case in these applications. In this paper, particular attention is paid to the cloud bubbles in the context of high-intensity focused ultrasound.

Retaining the functioning microbubbles in the targeted region is essential to the success of therapeutic applications such as targeted drug delivery and gene therapy. The presentation paper by Stride and co-workers [11] found the magnetic approach is superior over other localization approaches for *in vivo* microbubble retention, which was further demonstrated using a perfused porcine liver model.

Increasing utilizations of microbubbles in biomedicine give impetus to studies on bubble dynamics in the context of cell mechanics. The presentation by Liu and co-workers [12] reviews mechanical models of cell membranes and liposomes together with state of art techniques for quantitative measurement of viscoelasticity for a single cell or coated microbubbles with a view to their future development. A numerical work simulating the dynamic behaviour of ultrasound contrast agents is presented as well.

The presentations of above papers at the meeting raised exciting discussion and idea exchanges among the participants during the formal sessions, as well as coffee breaks and the last dinner at Chicheley Hall. This event was a great success and the support from the Royal Society, the Manager for Scientific Programmes, Ms Rachel Cohen, and the Event Officer, Ms Catriona Ross, was marvellous. The publishing of these presentations in this journal was made possible owing to the dedicated effort from the Managing Editor, Dr Tim Holt.

The fifth event of this forum series, in 2017, will be announced soon. The proceedings of previous forums (2006, 2008 and 2011) are available free at https://files.warwick.ac.uk/shengcaili/browse/.

References

1. Brennen CE. 2015 Cavitation in medicine. *Interface Focus* **5**, 20150022. (doi:10.1098/rsfs.2015.0022)
2. Li S. 2015 Tiny bubbles challenge giant turbines: Three Gorges puzzle. *Interface Focus* **5**, 20150020. (doi:10.1098/rsfs.2015.0020)
3. Arndt R, Pennings P, Bosschers J, van Terwisga T. 2015 The singing vortex. *Interface Focus* **5**, 20150025. (doi:10.1098/rsfs.2015.0025)
4. Prosperetti A. 2015 The speed of sound in a gas–vapour bubbly liquid. *Interface Focus* **5**, 20150024. (doi:10.1098/rsfs.2015.0024)
5. Blake JR, Leppinen DM, Wang Q. 2015 Cavitation and bubble dynamics: the Kelvin impulse and its applications. *Interface Focus* **5**, 20150017. (doi:10.1098/rsfs.2015.0017)
6. Wang Q, Liu WK, Zhang AM, Sui Y. 2015 Bubble dynamics in a compressible liquid in contact with a rigid boundary. *Interface Focus* **5**, 20150048. (doi:10.1098/rsfs.2015.0048)
7. Mørch KA. 2015 Cavitation inception from bubble nuclei. *Interface Focus* **5**, 20150006. (doi:10.1098/rsfs.2015.0006)
8. Fivel M, Franc J-P, Chandra Roy S. 2015 Towards numerical prediction of cavitation erosion. *Interface Focus* **5**, 20150013. (doi:10.1098/rsfs.2015.0013)
9. Chahine GL, Hsiao C-T. 2015 Modelling cavitation erosion using fluid–material interaction simulations. *Interface Focus* **5**, 20150016. (doi:10.1098/rsfs.2015.0016)
10. Ohl S-W, Klaseboer E, Khoo BC. 2015 Bubbles with shock waves and ultrasound: a review. *Interface Focus* **5**, 20150019. (doi:10.1098/rsfs.2015.0019)
11. Owen J, Rademeyer P, Chung D, Cheng Q, Holroyd D, Coussios C, Friend P, Pankhurst QA, Stride E. 2015 Magnetic targeting of microbubbles against physiologically relevant flow conditions. *Interface Focus* **5**, 20150001. (doi:10.1098/rsfs.2015.0001)
12. Wang Q, Manmi K, Liu K-K. 2015 Cell mechanics in biomedical cavitation. *Interface Focus* **5**, 20150018. (doi:10.1098/rsfs.2015.0018)