Ultrasonic heating[1]

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Among the effective and precise energy generation technologies, an ultrasonic wave is one of the most interesting and applicable proximate sources. In order to understand the nature of ultrasound, it is necessary have a basic understanding of sound waves, how they are generated and how they travel through a conducting medium. Ultrasonic waves affect substances both in quantity and quality, and can be used in different applications. One of the most interesting scientific aspects is how the fluid thermodynamic properties are changed by ultrasonic cavitation. Water, as the most ubiquitous and accessible fluid on Earth, is the material which has the greatest potential for practical utilization as the delivery medium.

1. Introduction

Nowadays, "wave" is one of the most common words in human discourse, with sound waves being not only a means for human communication but also the most important longitudinal waves. They can pass through any material, with different speeds depending on the medium's properties. There are three different categories of sound waves, covering different frequency ranges, and known as audible, infrasonic and ultrasonic.[2]

Investigations into ultrasound and applications thereof started in 1912 after the ship Titanic sank following collision with an iceberg. Nature provides a solution for iceberg detection in the form of the way sea creatures, like dolphins, communicate, which is based on high-frequency acoustic waves. Early investigations were by Langevin, who generally is credited as the father of ultrasonics.[3]

When sound waves travel through a material, its particles are made to vibrate more than their natural vibration and some physical properties like density, temperature and pressure will change. There are many different applications of ultrasonic waves but in the present briefing, the thermodynamic effect in liquids is investigated.

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1 This paper is based on a thesis delivered at the 4th International Conference on Nanotechnologies, Georgian Technical University, Tbilisi (2016).

2 D. Halliday, R. Resnick and J. Walker, *Fundamental of Physics*, 8th edn, pp. 520–521. Wiley (2008).

3 J.D.N. Cheeke, *Fundamentals and Applications of Ultrasonic Waves*, pp. 15–21. Boca Raton: CRC Press (2002).

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With an increasing human population, increasing *per capita* energy consumption and environmental pollution increases, finding reliable and environmentally friendly sources of energy is increasingly sought after. Therefore, ultrasonic waves as a proximate energy source, which has the advantage of no environmental pollution, can be significant.

2. Ultrasonic waves in fluids

Sound, like other longitudinal waves, travels through a fluid, causing particle vibration and changing density and pressure. Pressure changes result in low-pressure and high-pressure regions (Figure 1); wave frequency in the fluid depends on the longitudinal wave frequency.[3]

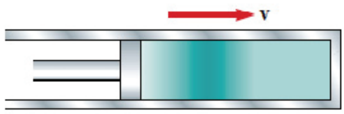

Figure 1. A longitudinal wave makes a low-pressure (rarefied) and a high-pressure (compressed) region.[2]

Whenever an ultrasonic wave, which is a high frequency longitudinal wave, passes through a liquid it generates acoustic cavitation, which is the basis of many applications. It forms fine bubbles in the low-pressure region of the fluid, because the decreased pressure results in a thermodynamic phase change from liquid to gas. The bubbles grow and, after attaining a critical size, they collapse in a microscopic implosion generating high local (Figure 2) turbulence, intense shear forces and heat energy.[4, 5]

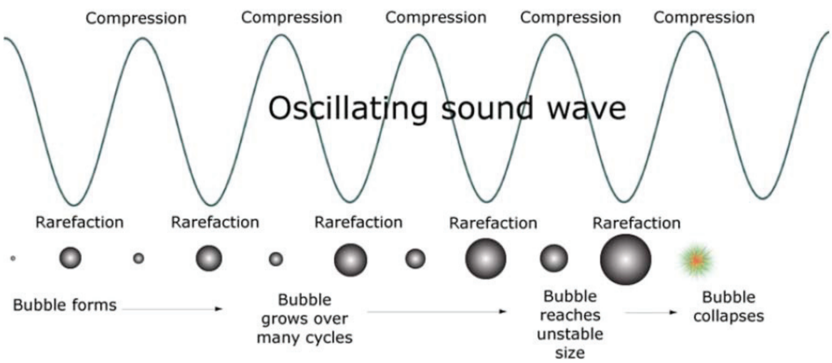

Figure 2. Pictorial summary of bubble formation, growth and collapse over several periods.[4]

Cavitation speed (bubble generation and collapse) is controlled by the oscillation frequency, which, as mentioned, depends on the longitudinal wave frequency interacting with the fluid. Therefore, higher frequency makes for faster cavitation, while stable cavitation is

[4] T. Leong, M. Ashokkumar and S. Kentish, The fundamentals of power ultrasound—A review. *Acoustics Australia* **39** (2011) 54–63.

[5] M. Ashokkumar, S. Kentish, R. Bhaskaracharya, J. Lee, M. Palmer and B. Zisu. The ultrasonic processing of dairy products—An overview. *Dairy Sci. Technol.* **90** (2010) 147–168.

commonly observed at frequencies greater than 200 kHz.[5] This cavitation process can be used in different ways in the food industry, humidifiers, painting etc., but one of the most interesting capabilities of acoustic cavitation is heat and pressure generation. During cavity collapse, the local temperature may theoretically reach 10 000 K[6] (experiments have suggested that the temperatures generated within cavitation bubbles are in the range of 2000–5000 K[5]) and local pressure is theoretically estimated to reach up to 100 Mpa, (estimated from experiment as 0.01–0.5 Mpa[6]). Hence, ultrasound-induced cavitation could be significant as a new method of steam generation. There is a relation between bubble resonant frequency and equilibrium radius as shown in Figure 3, which indicates the most effective frequency range for producing a substantial concentration of large cavitation bubbles.[7]

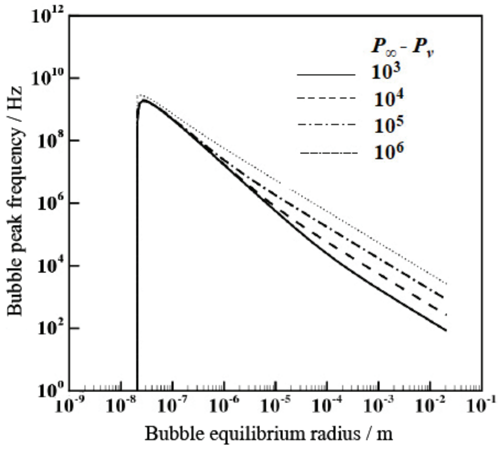

Figure 3. The bubble resonant frequency in water at 300 K.[7]

One of the applications is liquid atomizing (making fine particles of liquid). Small liquid size, direct and indirect capabilities can be exploited in different fields like mass transfer and heat transfer, where the thermodynamic character of the fine particles is an indirect capability. Ultrasonic atomizing in practice is poorly represented by mathematical models because of different complexifying effects; under practical conditions atomizing with a 250 mL/h flow rate with 12 W power and 2–5 μm particle size is possible.[8]

3. Analysis and discussion

For conventional heating, water has to change its liquid state to vapour, which consumes 2260 kJ/kg at 100 °C and 1 atm. Latent heat is the main source of energy consumption, and any decrease of latent heat immediately yields a lower energy consumption.

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6 P.J. Torley and B.R. Bhandari, *Handbook of Food Preservation*, 2nd edn, pp. 713–717. Boca Raton: CRC Press (2007).

7 N.K. Akafuah, Visualization and characterization of ultrasonic cavitating atomizer and other automotive paint sprayers using infrared thermography (thesis), p. 60. University of Kentucky (2009).

8 T. Häkkinen, *Ultrasonic atomizer*. United States Patent № 5,063,922 (1991).

Evaporation means loss of force between molecules. As Figure 2 showed, bubbles bursting not only releases heat but generates turbulence, which makes fine water particles; these atomized water particles splash from the surface (Figure 4) and the surface/volume ratio is increased, leading to less energy being required for evaporation than in conventional boiling.

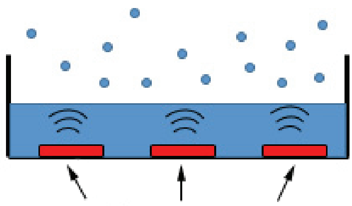

Figure 4. Ultrasound makes atomized particles with a greater surface/volume ratio.

Heat flux q is dependent on the convectional heat coefficient h and the temperature difference ΔT:[9]

$$q = h\,(\Delta T). \tag{1}$$

Typical units of q are W m^{-2} and of h, W m^{-2} K^{-1}, with ΔT in K. Small water particles with relatively more contact surface area allow greater convectional heat transfer Q:

$$Q = h\,A\,(\Delta T) \tag{2}$$

where A is surface area (m^2); typical units of Q are W. Therefore, evaporation will be faster and more efficient than bulk heating.

Boiling water may be divided into different régimes, see Figure 5. Water boils only if it is in contact with its vapour, so in the first step, natural convection leads to a rise in temperature until bubbles begin to form. After that, in the second régime, bubbles arise from isolated nucleation sites (Figure 5) until they become very numerous and the bubbles start to merge with one another. This régime is like ultrasonic cavitation, where bubbles start to form and then grow larger.

In the region of isolated bubbles at the base of the container and at the effective start of the boiling process, cavitation bubbles act in some ways as micropumps and transfer heat. Molecular vibration and cavitation carry energy to the other, cold, parts of the liquid and according to the Yamagata experiments on heat transfer, the flux is related to the difference of temperatures and bubble quantity:[9]

$$q \propto \Delta T^{a}\, n^{b} \tag{3}$$

where n is the number of bubbles, and a and b are constants. Consequently, more isolated bubbles means more heat is transferred to different parts throughout the bulk, resulting in stable boiling (cf. Figure 6).

9 J.H. Lienhard IV and J.H. Lienhard V, *A Heat Transfer Textbook*, 3rd edn, pp. 19–21 and pp. 457–470. Phlogiston Press (2008).

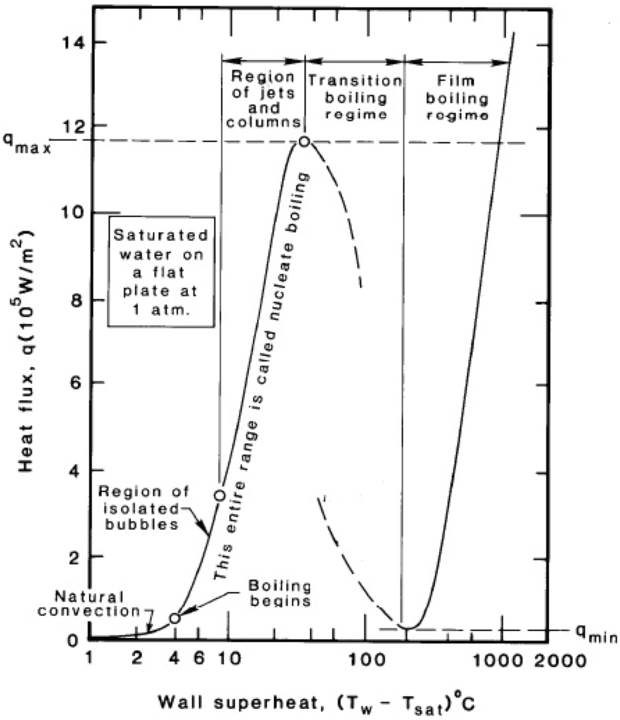

Figure 5. Typical boiling curve and régimes of boiling for an unspecified heater surface.[9]

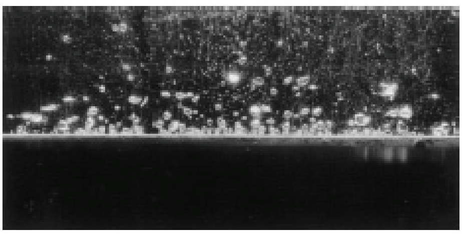

Figure 6. Isolated bubbles in the pool boiling method.[9]

When the pressure exceeds the tensile strength (cohesion) of water molecules in the low-pressure region of the wave, small vapour-filled voids called cavitation bubbles are formed. Therefore, bubble generation depends on the low- and high-pressure frequency, namely the ultrasound frequency (the rhythm of the longitudinal wave). At the same time, the spacial extent of the low-pressure regions should be sufficient to enable separation of the bubbles, which therefore depends not only on frequency but also on ultrasound amplitude (intensity). However, high frequency at a certain amplitude will reduce cavitation because the low (negative) pressure cycle will be insufficient to initiate cavitation and the high-pressure (compression) cycle will occur faster than the time needed for the microbubbles to collapse (cf. Figure 2).[10] In other words, frequency must be optimized.

[10] T.Y. Wu, N. Guo, C.Y. Teh and J.X.W. Hay, *Advances in Ultrasound Technology for Environmental Remediation*, ch. 2, pp. 6–8. Springer (2013).

With direct heating, energy is conducted from the source to the water across the contact face, like the "fire tubes" in boilers. Heating in a boiler using conduction incurs energy waste because of conduction inefficiency. But in the ultrasonic method, the acoustic source is effectively in direct contact with the water, which eliminates conduction heat loss.

Control of ultrasound frequency and amplitude (intensity) to achieve optimum cavitation is the key to generate efficient (compared with conventional vaporization) boiling. Referring to Figure 3, the practical stable radius of a bubble generated at 10^7 Hz is about 10^{-6} m. The average thermal vibration of water molecules is about 10^{11} Hz, or 10^4 times greater than the optimal ultrasonic frequency.[11] Uncontrollable thermal boiling via heating (conduction) makes the case more complicated. It is advantageous to control vaporization via controllable ultrasonic frequency and amplitude.

Consider a water droplet heated by ultrasound but not directly. At 1 bar and 100 °C, water has the density 1.04×10^3 m^3/kg, which is about 615 times greater than the 1.69 m^3/kg density of vapour. To find the surface/volume ratio of water in a container (Figure 4) and to compare heating methods, consider the energy–depth function for ultrasonic penetration:[12]

$$f(x) = dx^{-c} \tag{4}$$

where x is penetration depth (see Figure 7). There is no maximum (according to the power function), hence an arbitrary depth (1 cm) of the water container has been assumed.

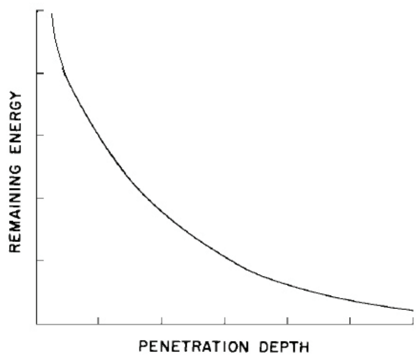

Figure 7. Ultrasound energy–depth ratio function.[12]

Atomizing with a 12 W power source to produce a 250 mL/h flow rate, giving a 2–5 μm particle size is practicable.[8] Thus a volume of 250 mL with 1 cm container depth means an area of 250 cm^2. Therefore, the surface/volume ratio will be 1 cm^{-1}. But the spherical water particles of average radius r = 1.5 μm resulting from ultrasonic vibration splashing have a surface/volume ratio $3/r$; hence the particle will have a surface/volume ratio 2×10^6 times greater. Then from equation (2), the heat flux in the particle is much greater than with direct water heating, resulting in much faster heat transmission and faster evaporation.

Therefore, with an optimized cavitation frequency, ultrasound is an efficient boiling method.

[11] N. Koshkin and M. Shirkevich, *Handbook of Elementary Physics*, p. 92. Moscow: Mir (1968).
[12] W.R. Hendee and E.R. Ritenour, *Medical Imaging Physics*, 4th edn, ch. 19, p. 303. Wiley–Liss (2002).

4. Conclusions

According to the preceding analysis, acoustic cavitation by ultrasonic waves can be used as an essentially new proximate source of energy in diverse applications.

There are two stages in the process, (i) ultrasonic cavitation and then (ii) boiling; and two important considerations: first, the surface/volume ratio effect on vaporization speed as consequence of atomization; second, bubble generation via cavitation dependent on ultrasound frequency and amplitude (intensity).

In summary, only rough estimations may be made of the energy saving using ultrasonic heating, due to the complexities of steam generation modelling.