Ultrasonics Sonochemistry 21 (2014) 2151–2164

Contents lists available at ScienceDirect

Ultrasonics Sonochemistry

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

Separation of suspensions and emulsions via ultrasonic standing waves – A review

Francisco J. Trujillo [a,*], Pablo Juliano [b], Gustavo Barbosa-Cánovas [c], Kai Knoerzer [b]

[a] School of Chemical Engineering, University of New South Wales, Sydney, NSW 2052, Australia
[b] CSIRO Animal, Food and Health Sciences, Werribee, VIC 3030, Australia
[c] Center for Nonthermal Processing of Food, Washington State University, Pullman, WA 99164-6120, USA

ARTICLE INFO

Article history:
Received 22 December 2013
Received in revised form 3 February 2014
Accepted 17 February 2014
Available online 27 February 2014

Keywords:
Ultrasonic standing wave
Separation
High frequency
Emulsion splitting
Micro-fluidics
Review

ABSTRACT

Ultrasonic standing waves (USW) separation is an established technology for micro scale applications due to the excellent control to manipulate particles acoustically achieved when combining high frequency ultrasound with laminar flow in microchannels, allowing the development of numerous applications. Larger scale systems (pilot to industrial) are emerging; however, scaling up such processes are technologically very challenging. This paper reviews the physical principles that govern acoustic particle/droplet separation and the mathematical modeling techniques developed to understand, predict, and design acoustic separation processes. A further focus in this review is on acoustic streaming, which represents one of the major challenges in scaling up USW separation processes. The manuscript concludes by providing a brief overview of the *state of the art* of the technology applied in large scale systems with potential applications in the dairy and oil industries.

1. Introduction

The effect of acoustic vibrations to form nodal resonant patterns, and their effect on particles, was first reported over 200 years ago by Ernst Chladni [1]. His technique of exciting brass plates, lightly covered with sand, with a violin bow to vibrate and create resonance on the plates was published in 1787 in his book "Discoveries in the Theories of Sound" [2]. The edge of the plate was bowed at different positions to form geometrical patterns. Because brass is a highly resonant material he found that resonance is created within the plate, with regions vibrating in opposite direction separated by lines of zero vibration called nodal lines, where the superposition of the incident and reflected waves cancel each other. The sand particles are displaced by the vibration of the plate to the nodal lines where there is no net vibration. These patterns of sand revealing the nodal lines [3,4] are called Chladni figures.

A similar phenomenon is observed by creating ultrasonic standing waves (USW) in suspensions and emulsions. USWs are created by the superposition of an incident wave, travelling from the acoustic transducer, and the reflected wave moving from the reflector. Suspended particles and droplets experience the so called primary acoustic force that moves them towards the pressure nodes or antinodes of the standing wave, depending on the material properties. When particles and/or droplets are moved together they form bands and may aggregate or coalesce. Then, due to the increase in hydrodynamic radius, buoyancy forces can separate the phases at a faster rate of sedimentation and/or creaming. Phase separation of suspended particles and recovery of micro to millimeter liquid droplets within emulsions is of great importance in many food, biological, pharmaceutical, chemical and petrochemical applications [5]. A wide variety of food products such as milk and creams are oil-in-water emulsions in which an oil phase is dispersed into a continuous aqueous phase [6]. In those cases the stability of the emulsion is designed to extend the shelf life of the product. However, in several other extraction and refining processes, efficient separation and recovery of the oil phase is highly desirable such as in the case of extraction of virgin olive [7], peanut [8], sesame [9], rice bran [10] and canola oils [11].

The petrochemical industry is also in need to develop more efficient and economic technologies for separation of water-in-oil emulsion [12]. This is because as a current preliminary step of refinery treatment, water is deliberately mixed into the crude oil to remove hydrophilic species such as chloride which deactivate the refinery catalyst and cause corrosion in distillation columns. The emulsion must subsequently be broken to recover the "clean" crude oil [13]. Furthermore, the petrochemical industry as well as the mining, metallurgical and chemical industries generate huge amount of wastewater. For instance, during crude oil production,

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[*] Corresponding author. Tel.: +61 (2)93855648.
E-mail address: francisco.trujillo@unsw.edu.au (F.J. Trujillo).

http://dx.doi.org/10.1016/j.ultsonch.2014.02.016

Latin symbols

a_0	Acceleration at the wall boundary ($m\ s^{-2}$)
c	Speed of sound ($m\ s^{-1}$)
c_l	Speed of sound of the liquid ($m\ s^{-1}$)
c_p	Speed of sound of the solid particles ($m\ s^{-1}$)
c_{pa}	Concentration of particles ($mole\ m^{-3}$)
c_{sat}	Concentration of particles at saturation ($mole\ m^{-3}$)
c_D	Drag coefficient ($kg\ s^{-1}$)
D	Diffusion coefficient ($m^2\ s^{-1}$)
D_0	Diffusion coefficient at low concentration ($m^2\ s^{-1}$)
f	Frequency (s^{-1})
F_{ac}	Primary acoustic radiation force (N)
F_B	Force due to buoyancy (N)
F_D	Drag force (N)
F_μ	Force due to the gradient of chemical potential ($N\ mole^{-1}$)
g	Gravitational acceleration ($m\ s^{-2}$)
h	Height (m)
i	Imaginary unit number
k	Wave number ($Radian\ m^{-1}$)
k_b	Boltzmann constant = 1.3806×10^{-23} ($J\ K^{-1}$)
l	length (m)
$\vec{n}$	Unit normal vector
N_A	Avogadro constant = 6.022×10^{23} ($particles\ mole^{-1}$)
$\dot{N}_p$	Molar flux of particles ($mole\ m^{-2}\ s^{-1}$)
p	Local time dependent pressure (Pa)
p_1	Pressure amplitude of the acoustic wave (Pa)
p_a	3D pressure amplitude of the acoustic wave (Pa)
$\langle p_1^2 \rangle$	Mean square pressure fluctuation of the sound field (Pa^2)
r	Radius of particles (m)
R	universal gas constant = 8.314 ($J\ mole^{-1}\ K^{-1}$)
t	Time (s)
T	Temperature (K)
U_{ac}	Acoustic force potential ($kg\ m^2\ s^{-2}$)
v_1	Particle velocity = local velocity of the oscillating fluid ($m\ s^{-1}$)
v_l	Liquid velocity in the equation of buoyancy ($m\ s^{-1}$)
v_p	velocity of particles or droplets ($m\ s^{-1}$)
$\langle v_1^2 \rangle$	Mean square velocity fluctuation of the sound field ($m^2\ s^{-2}$)
w	width (m)
x	x coordinate, distance from the acoustic source (m)
x_p	Mass fraction of particles
y	y coordinate (m)
z	z coordinate (m)

Greek symbols

α	Attenuation coefficient (m^{-1})
δ	Thickness of the Stokes layers (m)
η	Viscosity (Pa s)
κ	Compressibility $\kappa = 1/\rho c^2$ (Pa^{-1})
λ	Wavelength (m)
μ_p	Chemical potential of particles ($J\ mole^{-1}$)
ν	Kinematic viscosity ($m^2\ s^{-1}$)
ρ	Density ($kg\ m^{-3}$)
ρ_l	Liquid density ($kg\ m^{-3}$)
ρ_p	Solid particle density ($kg\ m^{-3}$)
ρ_T	Total density ($kg\ m^{-3}$)
σ	Stress tensor(Pa)
ϕ	Acoustic contrast factor
$\omega = 2\pi f$	Angular frequency ($rad\ s^{-1}$)

Operators

<>	Time average
∇	Nabla operator
∂	Partial differential

Subscripts

l	liquid
p	particle

large volumes of residual waste water are produced bearing hydrocarbon species and containing salinity and suspended solids [14]. Consequently, treatment of these effluents containing oil droplets in water is required before discharging to the environment. Conventional separation techniques of liquid emulsions include traditional gravity settlers, applications of external centrifugal or electric fields, and the use of membranes. However, each of these methods have difficulties such as the need of large residence times, environmental footprint and low efficiencies on large scale [15], which exacerbates when continuous and dispersed phase have similar densities.

During the last two decades, the control and manipulation of solid particles in liquid suspensions by means of USW has gained increased attention [16]. The primary acoustic force decreases with the decrease of particle size but increases with the increase of frequency. Hence, in order to separate particles with sizes of few micrometers, frequencies higher than 1 MHz have been suggested to achieve efficient separation. This principle has been successfully implemented in microchannel devices, where the acoustic resonator can be tuned to match a half wavelength (less than a millimeter for frequencies higher than 1 MHz). Because of recent advances on microfabrication technologies, where laminar flow regime is ensured, new lab-on-a-chip applications have been rapidly developed, allowing efficient acoustic trapping in continuous fluid currents. These technologies have shown great potential to develop application for microbiological cell [17] and droplet sorting [18], acoustic levitators [19] and cytometers [20].

Ultrasound has been actively researched for food processing applications [21,22] aiming at enhanced productivity, better quality and higher yield while preserving and enhancing food organoleptic properties. Leong et al. [23] have identified three ultrasound frequency regions: the first region, where frequencies are between 20 and 100 kHz is called power ultrasound [24] because of the high energy density delivered into the medium. Food processing research ranges from enzyme inactivation [25], pasteurization [26], extraction of bioactives [27,28], enhanced oxidation processes [22], improved food textures [29,30] and emulsification [31]. Power ultrasound is based on acoustic cavitation, where bubbles of dissolved gases oscillate, expand and collapse during the propagation of high intensity ultrasonic waves. The violently collapsing cavitation bubbles can result in local temperatures and pressures in the order of several thousand Kelvin and several hundred bars [32]. These extreme conditions generate pressure shock waves, intense acoustic streaming, hydroxyl radical formation and sonoluminescence.

The intermediate region ranges from frequencies between 100 kHz and 1 MHz [23]. Cavitation effects are less pronounced in this frequency range because the resonance size of the expanding bubbles is inversely proportional to frequency [33]. The intensity of bubble collapse during cavitation is proportional to the expansion volume of the bubbles. Hence, the smaller the resonance bubble size the weaker the effects of cavitation. Even though the mechanical effects in this region are lower compared to the power ultrasound region, studies have shown that the intermediate region generates more sonochemical effects [23]. The third is the high frequency range for frequencies over 1 MHz. As mentioned, this is the preferable range for acoustic separation of micron size particles and droplets because the acoustic forces increase and