Ultrasonics Sonochemistry 18 (2011) 1263–1273

Contents lists available at ScienceDirect

Ultrasonics Sonochemistry

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

A computational modeling approach of the jet-like acoustic streaming and heat generation induced by low frequency high power ultrasonic horn reactors

Francisco Javier Trujillo [a,*], Kai Knoerzer [b]

[a] CSIRO Food and Nutritional Sciences, North Ryde, NSW, Australia
[b] CSIRO Food and Nutritional Sciences, Werribee, VIC, Australia

ARTICLE INFO

Article history:
Received 19 January 2011
Received in revised form 4 April 2011
Accepted 12 April 2011
Available online 30 April 2011

Keywords:
Acoustic streaming modeling
Ultrasonic reactors
High power ultrasound
Acoustic heat generation

ABSTRACT

High power ultrasound reactors have gained a lot of interest in the food industry given the effects that can arise from ultrasonic-induced cavitation in liquid foods. However, most of the new food processing developments have been based on empirical approaches. Thus, there is a need for mathematical models which help to understand, optimize, and scale up ultrasonic reactors. In this work, a computational fluid dynamics (CFD) model was developed to predict the acoustic streaming and induced heat generated by an ultrasonic horn reactor. In the model it is assumed that the horn tip is a fluid inlet, where a turbulent jet flow is injected into the vessel. The hydrodynamic momentum rate of the incoming jet is assumed to be equal to the total acoustic momentum rate emitted by the acoustic power source. CFD velocity predictions show excellent agreement with the experimental data for power densities higher than $W_0/V \geqslant 25\ \text{kW m}^{-3}$. This model successfully describes hydrodynamic fields (streaming) generated by low-frequency-high-power ultrasound.

1. Introduction

Over the last two decades, the use of ultrasound has become a very active research area in food technology, food processing and food engineering [1]. Power ultrasound can be used for cleaning and surface decontamination [1], for ultrasonically assisted pasteurization of milk [2], aging of wines and spirits [3] and enhancing the extraction of bioactives [4,5]. Furthermore, it can be applied for emulsification applications, where the formation of cavitation bubbles and micro-jets enables the production of fine oil-in-water emulsions [6] and protein suspensions of improved textures [7,8]. Power ultrasound can also be used to modulate, activate, inactivate and/or denaturize enzymes, such as the inactivation of pectin methylesterase in orange juice to improve the juice cloud stability [9].

These sonication technologies are based on the effects of cavitation, which is the formation of bubbles generated by pressure changes during the propagation of high intensity ultrasonic waves in liquids. The bubbles gradually grow with each passing wave and then violently collapse during a compression stage resulting in local temperatures of up to 5000 K and pressures of up to 50 MPa [10]. These extreme conditions can generate sonoluminescense, hydroxyl radicals, streaming and enormous shear forces, which are responsible for the effects on food materials caused by sonication. Most of the new food processing developments, however, have been based on time- and labor-intensive trial-and-error approaches. Furthermore, scaling up of ultrasound processes have shown to be difficult due to the complexity of the interactions between the sound field, cavitation and the induced flow and temperature distributions. Most of the sonochemical activity concentrates close to the horn were the highest acoustic intensity is observed [11]. Thus, the treatment of food materials can be inhomogeneous depending on horn location, operating conditions, residence time and size of the vessel. Achieving a homogeneous treatment is strongly influenced by the hydrodynamic behavior and temperature profile inside the reactor. Hence, developing and validating mathematical models, describing hydrodynamic fields (streaming) and the heat generated by the acoustic field are needed to improve, optimize and standardize the operation and design of ultrasound processes.

The steady flow induced by the absorption of acoustic energy during the passage of acoustic waves is usually referred as acoustic streaming [12,13]. In this work, a computational fluid dynamics (CFD) model was developed to predict the acoustic streaming and heat generation induced by an ultrasonic horn reactor, which behaves like a liquid jet emitted from the horn tip [14]. Section 2.1 explains the mathematical basis of acoustic streaming developed by Rayleigh [15], Nyborg [12] and Westervelt [16] (RNW).

Abbreviations: 2D, two-dimensional; 3D, three-dimensional; CFD, computational fluid dynamics; FEM, finite element method; LDA, laser doppler anemometry; RMSE, root mean square error.

* Corresponding author.
E-mail address: Francisco.Trujillo@csiro.au (F.J. Trujillo).

1350-4177/$ - see front matter
doi:10.1016/j.ultsonch.2011.04.004

Nomenclature

Latin letters

A	transversal area (m^2)
b	characteristic width of the jet approach 1 (m)
c	speed of sound (1480 m s^{-1})
c_p	specific heat capacity at constant pressure (J kg^{-1} K^{-1})
$\vec{F}$	force vector per unit of volume (N m^{-3})
F_a	acoustic momentum flow rate of force (N)
F_j	j component of $\vec{F}$ (N m^{-3})
F_h	hydrodynamic force or momentum rate (N)
F_L	force per unit length (N m^{-1})
H	total distance between the horn tip and the bottom of the vessel (m)
$\vec{I}$	sound intensity vector (W m^{-2})
$\vec{I}_g$	Gaussian sound intensity distribution vector (W m^{-2})
k	thermal conductivity (W m^{-1} K^{-1})
k_{eff}	effective thermal conductivity (W m^{-1} K^{-1})
K	kinematic momentum (kg^2 m^{-2} s^{-2})
m	total mass of liquid (kg)
p	pressure (Pa)
P	pressure amplitude (Pa)
Pr	Prandtl number (0.85)
r	radial distance (m)
r_H	horn radius (0.0065 m)
R	reactor radius (0.135 m)
Re	Reynolds number
S	measure of the width of the jet approach 2 (m)
t	time (s)
T	temperature (K)
$\vec{v}$	velocity vector (can be streaming or particle velocity) (m s^{-1})
v	velocity (can be streaming or particle velocity) (m s^{-1})
V	total volume (m^3)
x	distance from the fictitious "orifice" (m)
x_i	spatial coordinate in the i direction (i = 1, 2 or 3) (m)
X	distance from acoustic source (m)
z	acoustic impedance (kg m^{-2} s^{-1}), or Distance on the centre line (r = 0) below the horn tip (m)
W	acoustic power (W)
W_0	acoustic power emitted by the source (W)

Greek letters

α	absorption coefficient -damping of the acoustic pressure (m^{-1})
β	absorption coefficient -damping of the acoustic energy or power (m^{-1})
C_μ	constant (0.09)
ε	turbulent energy dissipation rate (m^2 s^{-3})
η	value defined by Eq. (26)
ρ	density (kg m^{-3})
ι	length scale (m)
κ	turbulent kinetic energy (m^2 s^{-2})
μ	dynamic viscosity (Pa s)
μ_t	turbulent viscosity (Pa s)
ρ	density (1000 kg m^{-3})

Subscripts

0	equilibrium value (v_0 is equilibrium value of v); or Initial value (I_0 is initial value of I at the acoustic source)
1	first order approximation value ($\vec{v}_1$is the first order approximation of $\vec{v}^1$)
2	second order approximation value ($\vec{v}_2$is the second order approximation of $\vec{v}^1$)

Superscripts

1	perturbation ($a^1$is perturbation of a; $a^1 = (a - a_0)$)

Other symbols

$\bar{a}$	time average of a general variable a
$\vec{a}$	vector a general variable a

Operators

d	differential
∂	partial differential
∇	nabla operator (vector differential operator)

The RNW theory is the mathematical approach most widely encountered in the scientific literature and it applies correctly for very low Reynolds numbers. However, as seen in Section 2.1, assumptions on the RNW approach (neglecting the convective acceleration term from the Navier–Stokes equation) do not apply for modeling the fast jet streaming induced by high power horn reactors. The fast jet behavior is due to the high absorption of sound produced by cavitation bubbles. The formation of those bubbles depends on the acoustic power emitted by the horn. Section 2.2 explains the high increase on the effective sound absorption on horn reactors and its correlation with acoustic power. Section 2.3 explains the Stuart streaming theory proposed by Lighthill [17], who established that at powers above 4×10^{-4} W the acoustic streaming takes the form of an inertially dominated turbulent jet. Lighthill proposed that the inertial terms on the Navier–Stokes equation must be included in order to model streaming at higher Reynolds numbers. Lighthill is credited as the founder of aeroacoustics [18,19], and proposed the analogy that not only a turbulent jet can generate sound, but also sound can generate turbulent jets. The model assumes that the horn releases the acoustic radiation as beams or rays of sound following a Gaussian distribution. Then, the law of conservation of momentum was applied to account for the transfer of momentum from the acoustic rays to the induced hydrodynamic jet. This approach was further simplified for cases of high acoustic power where the acoustic momentum transfers into hydrodynamic momentum in the close vicinity of the horn tip due to the strong scattering produced by cavitation bubbles. This allows assuming that the horn tip is an inlet where all the acoustic energy absorbed by the liquid is immediately converted into turbulent motion, the jet. Using this assumption, the Navier–Stokes and $k - \varepsilon$ turbulent equations were solved with the Finite Element Method in COMSOL Multiphysics™ (COMSOL AB, Stockholm, Sweden) to determine the hydrodynamic field in the reactor. Section 2.4 explains a similar approach to model the heat generated also valid for cases of high sound absorption. Section 2.5 describes the CFD model and the experimentation conducted by Kumar et al. [14] and Kumaresan et al. [20], whose data was used to validate the model. Sections 3 and 4 contained the results and conclusion, respectively.

2. Model description

2.1. Rayleigh, Nyborg and Westervelt (RNW) streaming theory

Rayleigh [15], Nyborg [12] and Westervelt [16] established that streaming can be calculated from the continuity equation