Ultrasonics 57 (2015) 11–17

Contents lists available at ScienceDirect

Ultrasonics

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

The comparison of ultrasonic effects in different metal melts

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ARTICLE INFO

Article history:
Received 8 April 2014
Received in revised form 27 August 2014
Accepted 3 October 2014
Available online 1 November 2014

Keywords:
Ultrasonic treatment
Metal melt
Streaming
Cavitation
Velocity

ABSTRACT

The effect of ultrasonic treatment of the melts is mainly ultrasonic streaming and cavitation. In this paper, the ultrasonic streaming in water, aluminum and steel melts was numerically simulated and compared. And the simulated results of streaming in water were validated by experimental results. In the experiment, the ultrasonic booster was immersed vertically into water, the ultrasonic streaming phenomenon was observed by high-speed CCD (Charge-coupled Device) system, then the streaming velocity and streamlines were obtained. The cavitation area and threshold in aluminum and steel melts were compared. The results show that the effective streaming and cavitation area in steel melt is smaller than that in aluminum melt, and far smaller than that in water. A symmetrical vortex forms both in water and aluminum melt by the drive of downward ultrasonic streaming caused by the booster tip. However, in steel melt, a double-vortex structure, including a vortex in the upper part and a vortex with reverse cycling in the lower part appears in the flow field. As a result, inclusions and air bubbles may be trapped in steel melt. The density and viscosity of the fluids are the main factors influencing ultrasonic streaming and cavitation. The results provide references for the application of ultrasonic treatment in metal melts.

0. Introduction

Ultrasonic treatment of metal melt is coming into more and more common use in the field of casting for its effect in refining grains and the avoidance of casting defects so as to improve the performance of metal materials [1–5]. Ultrasonic treatment is a kind of external-field processing, which contributes to the refinement of solidification structure mainly through cavitation and ultrasonic streaming [6–14].

Substantive researches about the ultrasonic streaming have been carried out with the aid of PIV (Particle Image Velocimetry) technology. Nowicki et al. [15] measured the ultrasonic streaming velocity in water using Doppler velocimeter and tracer grains, the streamline generated by boosters of different shapes was revealed through PIV technology, the ultrasonic power ranged from 1 μW to 6 mW. Dai et al. [16] studied the velocity field, the distribution of flux and vorticity of ultrasonic jet. Cosgrove et al. [17] observed the streaming phenomenon in water generated by a medical ultrasonic transducer operating at the frequency of 3.3 MHz. Yao et al. [18] studied the vortex structures and flow patterns of ultrasonic jet and found that the flow field structure of ultrasonic jet was helical. These experimental researches on ultrasonic streaming were mainly for water, and the ultrasonic parameters in some of the experiments were obviously different from that in industrial application (power 100–2000 W, frequency 10–60 kHz [19]). Although the simulation of ultrasonic streaming involved in metal melts, the relationship between streaming features and ultrasonic treatment effect has not been analyzed yet.

In order to figure out the cavitation effect, many researchers investigated the motion of cavitation bubbles and the high pressure released by bubbles' collapsing. Xu et al. [20] studied the impact of ultrasonic frequency, power and the bubble's initial radius on the motion of cavitation bubbles in water. Zhengcai et al. [21] analyzed the relationship between the collapsing time of cavitation bubbles and the maximum value of temperature and pressure inside the cavitation bubbles in water. Kong et al. [22,23] investigated the impact of factors such as sonic pressure, frequency and the bubble's initial radius on the motion of cavitation bubbles in steel melt through numerical simulation. Liu et al. [24] studied the impact of ultrasonic frequency, sonic pressure and initial radius of the cavitation bubble on ultrasonic treatment in aluminum alloy melt. Liu et al. [25] researched the influence of air content in water on cavitation, and found that the degassing process could improve the cavitation intensity significantly. These researches about cavitation were mainly based on numerical simulation through solving Rayleigh–Plesset equations [26], however, studies about cavitation areas and cavitation threshold were rarely found, and there was no apparent relationship between the research results and ultrasonic treatment effect.

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http://dx.doi.org/10.1016/j.ultras.2014.10.004
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In this paper, a high-speed CCD was applied to track the movement of bubbles in water and then, the velocity vectors of the ultrasonic streaming in water were determined. The ultrasonic streaming phenomenon in water, aluminum melt and steel melt was numerically simulated through the CFD (Computational Fluid Dynamics) software Fluent and the results for water were validated experimentally. The ultrasonic streaming and cavitation results in these fluids were compared and analyzed.

1. Numerical simulation

1.1. Numerical simulation model and parameters

The numerical simulation in water was carried out by Fluent. The coordinates and meshes used in the CFD calculation are shown in Fig. 1. The model is two dimensional and symmetrical, and one half was selected for simulation. The booster of Φ 30 mm is immersed vertically into the fluid 10 mm deep in a container of Φ 100 mm × 200 mm, the water level is 180 mm. The ultrasound with power 200 W and frequency 20 kHz is introduced into the fluid along the gravity direction (x direction).

The ultrasonic treatment in aluminum and steel melts was simulated based on the same geometry. The aluminum and steel melts were chosen due to their wide industrial application [27–30]. The parameters [22,26,27] of water (20 °C), aluminum melt (670 °C), and steel melt (1520 °C) are listed in Table 1.

1.2. Basic hypothesis

(1) Ignoring the ultrasonic heating effect to the fluid and the heat transfer between container wall and the external environment.
(2) Treating the fluid as incompressible fluid.
(3) Ignoring the natural convection caused by density variation.
(4) No oxidation reaction occurs during the processing of metal melts.

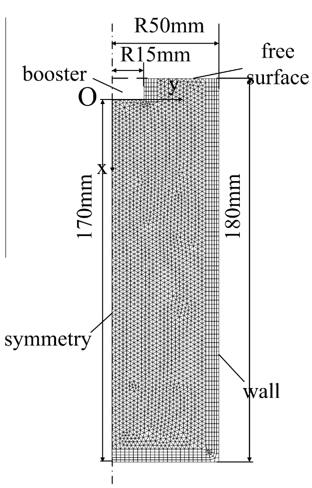

Fig. 1. Coordinate and meshes used in CFD calculation.

Table 1
Parameters of the fluids in CFD calculation.

Properties	Water	Aluminum melt	Steel melt
Density/kg m^{-3}	1000	2350	6900
Viscosity/Pa s	0.001	0.0026	0.006
Surface tension/N m^{-1}	0.0728	0.86	1.665

1.3. Governing equations

The governing equations contain continuous and momentum (N–S) equations, turbulence and turbulence dissipation equations are also considered because turbulence flow may form during ultrasonic treatment.

(1) Continuous equation

$$\frac{\partial u_j}{\partial x_j} = 0 \tag{1}$$

(2) Momentum equation (the N–S equation)

$$\rho\frac{\partial(u_i u_j)}{\partial x_j} = -\frac{\partial P}{\partial x_j} + \frac{\partial}{\partial x_j}\left(\mu_{eff}\frac{\partial u_i}{\partial x_j}\right) + \frac{\partial}{\partial x_j}\left(\mu_{eff}\frac{\partial u_j}{\partial x_i}\right) + \rho g_i \tag{2}$$

$$\mu_{eff} = \mu + \mu_t = \mu + \rho_{cu}\frac{k^2}{\varepsilon} \tag{3}$$

(3) Turbulence equation

$$\rho\frac{\partial(u_i k)}{\partial x_i} = \frac{\partial}{\partial x_i}\left[\left(\mu + \frac{\mu}{\sigma_k}\right)\cdot\frac{\partial k}{\partial x_i}\right] + G - \rho\varepsilon \tag{4}$$

$$G = u_t\frac{\partial u_i}{\partial x_j}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) \tag{5}$$

(4) Turbulence dissipation equation

$$\rho\frac{\partial(u_i\varepsilon)}{\partial x_i} = \frac{\partial}{\partial x}\left[\left(\mu + \frac{\mu}{\sigma_\varepsilon}\right)\cdot\frac{\partial\varepsilon}{\partial x_i}\right] + c_1\frac{\varepsilon}{k}G - c_2\frac{\varepsilon^2}{k}\rho \tag{6}$$

In the equations above, ρ (kg m^{-3}) is the density of fluid, u (m s^{-1}) stands for the velocity, μ (Pa s) is the viscous coefficient of laminar flow while μ_t (Pa s) is the viscous coefficient of turbulent flow, k (m^2 s^{-2}) stands for the turbulence energy, g (m^2 s^{-1}) is the gravitational acceleration, ε (m^2 s^{-3}) is the turbulence energy dissipation rate, c_1, c_2, c_μ, σ_k and σ_ε are empirical constants with values 1.44, 1.92, 0.09, 1.0 and 1.3 respectively [14].

1.4. Boundary conditions

The simulation condition is considered to be transient as the acoustic streaming is an unsteady phenomenon, the boundary conditions in the CFD calculation are defined as follows:

(1) Pressure inlet

The boundary of the booster tip from which ultrasound is introduced into the fluid is set to be the pressure-inlet boundary. The pressure is assumed to be a normal distribution along the radial direction (y direction) of the booster tip, meanwhile, it varies with time according to the sine law at the frequency of the booster [13]. The pressure inlet condition was defined by UDF (User Defined Functions, ANSYS, Inc., US) files. The expression of pressure variation is as follows:

$$P = \frac{P_0}{\sqrt{2\pi}\sigma_0}e^{-\frac{y^2}{2\sigma_0^2}}\sin 2\pi f t \tag{7}$$

where P_0 is a constant, σ_0 is the standard deviation of normal distribution, taken as greater than one third of the booster radius, which means the pressure at the tip edge is almost zero, f stands for the ultrasonic frequency, 20 kHz. The highest pressure is 825 kPa, determined through calculation with dynamic mesh model [28]. Here, σ_0 is set as 5.0×10^{-3} m. Therefore, the constant P_0 is deduced to be 8 kPa m.

(2) Pressure outlet

The outlet boundary is set to be free-pressure outlet, the pressure of the outlet is considered as one atmosphere (0.1013 MPa).