Ultrasonics Sonochemistry 22 (2015) 272–277

Contents lists available at ScienceDirect

Ultrasonics Sonochemistry

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

Modeling the shear rate and pressure drop in a hydrodynamic cavitation reactor with experimental validation based on KI decomposition studies

Mandar P. Badve [a], Tibor Alpar [b], Aniruddha B. Pandit [a], Parag R. Gogate [a,*], Levente Csoka [b,*]

[a] Department of Chemical Engineering, Institute of Chemical Technology, Mumbai 400 019, India
[b] University of West Hungary, Institute of Wood Based Products and Technologies, 9400 Sopron, Hungary

ARTICLE INFO

Article history:
Received 2 May 2014
Received in revised form 22 May 2014
Accepted 22 May 2014
Available online 2 June 2014

Keywords:
Hydrodynamic cavitation
Simulation
Computational fluid dynamics
Weissler reaction
Shear rate

ABSTRACT

A mathematical model describing the shear rate and pressure variation in a complex flow field created in a hydrodynamic cavitation reactor (stator and rotor assembly) has been depicted in the present study. The design of the reactor is such that the rotor is provided with surface indentations and cavitational events are expected to occur on the surface of the rotor as well as within the indentations. The flow characteristics of the fluid have been investigated on the basis of high accuracy compact difference schemes and Navier–Stokes method. The evolution of streamlining structures during rotation, pressure field and shear rate of a Newtonian fluid flow have been numerically established. The simulation results suggest that the characteristics of shear rate and pressure area are quite different based on the magnitude of the rotation velocity of the rotor. It was observed that area of the high shear zone at the indentation leading edge shrinks with an increase in the rotational speed of the rotor, although the magnitude of the shear rate increases linearly. It is therefore concluded that higher rotational speeds of the rotor, tends to stabilize the flow, which in turn results into less cavitational activity compared to that observed around 2200–2500 RPM. Experiments were carried out with initial concentration of KI as 2000 ppm. Maximum of 50 ppm of iodine liberation was observed at 2200 RPM. Experimental as well as simulation results indicate that the maximum cavitational activity can be seen when rotation speed is around 2200–2500 RPM.

1. Introduction

Cavitation is the formation, growth and collapse of vaporous cavities in the liquid and typically high energy shock waves are generated due to the implosion of cavities. Pressures up to 1000 atm and temperatures up to 10,000 K can be reached locally over a microsecond interval due to the cavity collapse under conditions of water being used as medium [1]. Millions of such cavities form and collapse in the region where cavitation takes place which creates a number of small shock wave reactors locally under overall ambient conditions. The high energy release by implosion can be harnessed for useful effects such as chemical/physical transformations. There are mainly two types of cavitation viz. acoustic cavitation in which cavitation takes place in a liquid due to compression and rarefaction cycles of the propagating sound waves and hydrodynamic cavitation, in which flow geometry is altered in such a way that pressure in the fluid at certain point falls below its vapor pressure resulting in the formation of cavities. When cavitation takes place, highly reactive hydroxyl radicals are formed due to the dissociation of vapor trapped in cavitating bubbles, which are capable of chemical transformations [2]. Also shock waves generated due to cavitation are capable of breakage of chemical bonds and cell lysis. There have been various recent studies related to hydrodynamic cavitation being used for different applications such as wastewater treatment, cell disruption, chemical synthesis and biodiesel production [3–7].

In hydrodynamic cavitation, orifice or venturi are commonly used for the generation of cavitation, with possible variations in the geometric designs of orifice plates and venturi [8,9]. In addition, the high pressure and high speed homogenizers also generate cavitating conditions [10]. From the application point of view as well as for obtaining efficient design of cavitational reactors, it is very important to understand the physics behind the actual phenomenon of cavitation occurring inside the cavitational reactor. Various models have been proposed for the quantification of the chemical transformations and to establish a link between bubble behavior and chemical kinetics. Moholkar et al. [11] have

* Corresponding authors. Tel.: +91 22 33612024; fax: +91 22 33611020 (P.R. Gogate). Tel.: +36 99 518 305; fax: +36 99 518 302 (L. Csoka).

E-mail addresses: pr.gogate@ictmumbai.edu.in (P.R. Gogate), levente.csoka@skk.nyme.hu (L. Csoka).

http://dx.doi.org/10.1016/j.ultsonch.2014.05.017
1350-4177/

Nomenclature

C_v	cavitation number
D	outer diameter of the rotor (m)
F	volume force vector (N/m^3)
N	rotation speed of the rotor per second (RPS)
p	pressure (Pa)
P	power input (W)
Re	Reynolds number
u	velocity (m/s)
V	volume of the fluid (m^3)

Greek symbols

γ	shear rate (s^{-1})
η	dynamic viscosity (Pa s)
ν	kinematic viscosity (Pa s)
ρ	density of the liquid (kg/m^3)
τ	shear stress (Pa)

illustrated with the numerical simulations the role played by the turbulence in altering the single cavity behavior downstream of a cavitating orifice in a liquid flow. It has been established that bubble behavior changes drastically under turbulent conditions compared to non turbulent conditions and bubble behavior under turbulent condition is transient and resembles the behavior of a cavity under acoustic conditions. Gogate and Pandit [12] numerically studied the effect of various operating parameters such as the inlet pressure, initial cavity size, orifice diameter on dynamic cavity behavior. An empirical correlation was developed to anticipate the collapse pressure generated as a function of above mentioned parameters. Kanthale et al. [13] have used the cavity cluster (group of cavities) approach instead of a single cavity approach to understand the mechanism of cavitational effects. The effect of intensity, frequency of ultrasound and initial size of the cluster on pressure pulse generated by cavity cluster as well as the active cavitation zone has been investigated based on the bubble dynamics equations.

In the present study, a different type of hydrodynamic cavitating device comprising of a stator and rotor assembly has been modeled to predict the fluid flow pattern. A rotor rotates at very high speed in a confined annular space and liquid is passed through the gap between the stator and the rotor. Due to high speed of rotation, very high surface velocities are generated. Some indentations are also provided on the surface of the rotor. Liquid at high velocities enters the indentation due to the rotary action of the rotor and when liquid comes out of the indentation due to centrifugal flow, a low pressure region/vacuum is created near the upper surface of the indentations resulting into cavitation. At such high velocities of the liquid on the surface of the rotor, pressure drop across the surface of the rotor and indentation is sufficient enough for cavitation to occur and the magnitude of the pressure drop decides the cavitational intensity. In our previous work, the effectiveness of this type of setup for wastewater treatment [3] and for digestion (delignification) of wheat straw pulp [14] has been reported. Almost 90% reduction in COD of the wastewater was observed in the wastewater treatment study [3] and the mechanical properties of the paper hand sheets made from cavitationally treated pulp were found to be superior by almost 50–55% [14]. Although applicability of this type of setup for transformations has been tested, overall physics and the mechanism behind the generation of cavitation have not been fully realized. To address this issue and to analyze the phenomenon of cavitation inside such reactors, finite element simulation of the fluid flow inside the reactor has been investigated in the present study. The conception and scale-up of these reactors generally depend on the hydrodynamic characteristics (mainly water media) i.e., transport properties and enhanced mixing of the colloidal phases, heat and mass transfer characteristics and chemical kinetics of the reacting system. In this work, the application of finite element method to simulate fluid flow in a hydrodynamic cavitation reactor has been presented and the results of the simulation have been compared with the model reaction carried out to study the cavitational effects. The work presents useful design related information which would be very significant in getting optimum designs of large scale hydrodynamic cavitation reactors.

2. Experimental methodology and modeling details

2.1. Stator–rotor assembly

Fig. 1 shows schematic details of the stator–rotor assembly being used as the cavitating device. The rotor is attached to a gear assembly, which is connected to a variable frequency drive (VFD: YASKAWA J1000, type: CIMR-JC 4A0011BAA). With the help of VFD, the rotor can be rotated at different speeds of rotation. The rotor is a solid cylinder which has indentations/surface irregularities on its surface. There are a total of 204 indentations equidistant from each other. Each indentation is 12 mm in diameter and 20 mm deep. Gap between stator and rotor is fixed at 10 mm.

2.2. Experimental work

In order to analyze the behavior of cavitation inside this type of reactor, some experiments were carried out to quantify the cavitational effects. Weissler reaction, which has been used extensively as a model reaction for cavitation based transformations was also used in the present work [15]. Weissler reaction can be used to quantitatively analyze the degree of cavitational activity in the reactors. Weissler reaction is the decomposition of KI which liberates free iodine. Weissler reaction can be induced under cavitating and thermal oxidation conditions due to the fact that $OH^{\cdot}$ radicals are formed in the solution. In order to avoid the thermal oxidation of iodine, all the experiments were carried out at 25 °C and the volume of KI (2000 ppm initial concentration) solution taken was

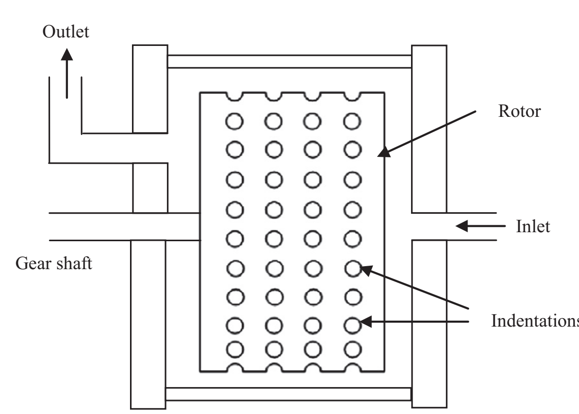

Fig. 1. Schematic of the cavitating device (stator and rotor assembly).