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High-speed visualization of multiphase dispersions in a mixing tank

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ABSTRACT

A high-speed video system was used for studying multiphase dispersions by image analysis. A high-speed video camera, coupled to a stereomicroscope was used to record the dispersion occurring in a mixing tank. A high intensity direct light probe submerged in the liquid was used for illumination. Sequences of 200 images (512 × 384 pixels) at rates up to 5130 frames/s (fps) and magnification up to 11× were obtained and analyzed. A detailed observation of the mixing dynamics at a high video rate allowed visualizing how oil drops and air bubbles move and interact. Velocity of the objects could be calculated at different focal planes. Rotational movement and trajectories in different directions, depending on the physicochemical properties of the system could be observed and recorded. The implemented methods also allowed the recording of the deformation of complex drops and were useful to discern situations of inclusions of objects (i.e. bubbles inside oil drops) in multiphase dispersions under power inputs up to 0.50 kW/m^3.

Keywords: High-speed video; Multiphase dispersion; Drop and bubble trajectories

1. Introduction

Two or more phases (gas–liquid, immiscible liquid–liquid and solid–liquid dispersions) are involved extensively in the chemical, biochemical, petroleum, mining, pulp and paper industries (Leng and Calabrese, 2004), as well as in other industrial processes which carry out oxidations, hydrogenations and aerobic fermentations (Paul et al., 2004). The gas and the immiscible liquid are present in the form of small bubbles and drops to yield a large surface area, as well as to improve the mass transfer efficiency, which is a key parameter for the successful performance of the process. The composition of the dispersion and the operational parameters of the bioreactor control the coalescence-breakup events (Lagisetty et al., 1986) and hence they determine the size distribution of drops and bubbles (Leng and Calabrese, 2004).

Image analysis techniques are valuable tools that can provide insights of interesting hydrodynamic phenomena occurring in multiphase systems, since these techniques have allowed the observation of phase interactions resulting in complex structures (e.g. inclusion of air bubbles and aqueous droplets inside oil drops) (Larralde-Corona et al., 2002), phenomena not evidenced with studies focused only in the hydrodynamics or even with non-high-speed visualization techniques. This is why the use of high-speed camera systems to evaluate dispersion processes by image analysis has been recently reported (Lovick et al., 2005). However, the experiments performed have been limited to characterize two-phase systems.

Our research group has been working with image analysis systems for the characterization of complex multiphase dispersions, using as a model system a fungal fermentation process that produces natural aroma compounds (e.g. coconut and peach) (Serrano-Carreón et al., 1997). The image analysis system used in previous works (Galindo et al., 2005) consisted of a 30 fps-CCD (frames/s, charge-coupled device) camera adapted to a stereomicroscope and a high-energy stroboscope lamp which feeds a submergible light probe placed

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Nomenclature

c	distance from the tank bottom to the impeller
d	impeller diameter
K	flow consistency index
n	flow behavior index
Q	ratio between projected pattern size and embedded sphere diameter
r, θ, z	cylindrical coordinates
Re	Reynolds number
t_0	reference time
T	tank diameter

Greek letters

β	reference angle
γ	shear rate
η	non-Newtonian viscosity
μ	Newtonian viscosity
ρ	density
τ	shear stress

inside the tank. This system has allowed the acquisition of high quality images for measuring the sizes of the bubbles and drops generated in the model fermentation process stirred at 0.2 kW/m^3. Additional information has been obtained regarding the complex phase interactions, the oil-trapped bubbles and multiphase drops formed in the mixing tank (Galindo et al., 2005). However, when the power input was increased above 0.2 kW/m^3, the images obtained were poorly defined, blurred and with low contrast, as a result of the faster moving speed of the objects in the reactor, leading to a intensified foam production, turning the dispersion dark and turbid and making practically impossible the characterization of the dispersion.

In this work, a high-speed video system was used to acquire sequences of images of events occurring in multiphase dispersions at power inputs up to 0.5 kW/m^3. This approach allowed us recording and measuring several interesting phenomena occurring in multiphase systems, such as the speed and trajectories of the moving objects, spinning of the oil drops, as well as observing the deformation of oil drops and to discern inclusions. Visualization and characterization of these phenomena is a first step to a deeper and mechanistic understanding of the complex phenomena determining mass transfer.

2. Methods

2.1. Stirred tanks and impellers

Two flat-bottom glass tanks were used, one having a diameter T_1 = 0.21 m and a liquid volume of 6.7 L and the other one with a T_2 = 0.12 m and a liquid volume up to 1.5 L. In order to correct the optical distortion caused by the refraction of the cylindrical tank during the image acquisition, a square jacket (filled with water) was used. The vessels had four equally spaced stainless-steel baffles, T/10 wide. Air was supplied at 0.25 or 1.6 vvm, respectively, using a stainless steel sintered sparger with a pore size of 20 μm (Waters Chromatography, Bedford, MA, USA), placed underneath the impeller. A single Rushton or Smith turbine (half tube section blades), with d = 0.5 T, was placed at $c = d/1.1$ from the tank bottom, under power inputs of 0.25, 0.3 and 0.50 kW/m^3.

2.2. Continuous and dispersed phases

Continuous phase was distilled water or a salts solution, as described by Galindo et al. (2000). For the organic dispersed phases, two kinds of oils were used: food-grade castor oil (Cosmopolita, Mexico) at 5% (v/v) (ρ = 960 kg/m^3; μ = 560 mPa s) and food-grade corn oil (ACH Food Companies, Inc.) at 10% (v/v) (ρ = 920 kg/m^3; μ = 44 mPa s). A non-Newtonian continuous phase was also prepared by adding 0.6% (w/v) of carboxymethylcellulose (CMC, Aldrich Chemical, Co., USA), a pseudoplastic thickener (shear thinning) with the following rheological characteristics: n = 0.77; K = 0.11 Pa s^n expressed by the power law model ($\tau = K\gamma^{n-1}$). In this last case, 1% (v/v) of corn oil was used as the second liquid phase.

2.3. Image analysis equipment

The experimental rig consists of a high-speed digital video camera (Redlake Motion Pro HS-4, FL, USA, capacity for recording up to 5130 fps of 512 × 512 pixels), which was coupled to a stereomicroscope with variable magnification (Olympus SZ1145ESD). A high intensity direct light 230 V to 50 Hz, Arc Xenon, 180 W (SX200, Fort Imaging Systems, Inc., France) was used, which feeds a light guide submerged upright inside the vessel, placed facing the stereomicroscope and from 0.9 up to 11 cm from the wall (see Fig. 1). Sequences of 200–400 images were acquired from the dispersion at magnifications up to 11× with the camera software Motion Pro-central. Image resolution was of 512 × 384 pixels in all the cases. Image recording was carried out during the first 10 min of mixing, time interval which the events to be characterized were more evident and clear. Sequences of images were analyzed with the scientific software Image-Pro® Plus V. 5.2 (Media Cybernetics, USA) following the image processing procedure that has been described in detail in previous reports (Galindo et al., 2005; Taboada et al., 2006). Circular objects were manually, one by one, traced in every frame selecting three points of each bubble or drop to measure the diameter of at least 500 drops and/or 300 bubbles per sample to ensure an error lower than 10% in size measurements.

On the other hand, the images showing true-trapped or overlapped bubbles were segmented in order to estimate the Q values (ratio between projected pattern size and embedded sphere diameter by measuring the extent of the bright and dark areas) (Córdova-Aguilar et al., 2008). The data were transferred to an Excel worksheet to calculate the Q values and carry out an ANOVA analysis with an uncertainty level of 5% to confirm the differences that actually exists between free and trapped bubbles.

2.4. Calibration procedure and evaluation of the system accuracy

The system was calibrated for different magnifications (6× to 22×) with the acquired images of a micrometer immersed into the solution (to avoid errors due to light refraction effects). The values were validated using polymeric beads (Duke Scientific Corp., Palo Alto, CA, USA) of certified size diameters (200 ± 4 μm, NIST). All values were not statistically different (confidence of 95%) to the ones quoted by the particle manufacturer.