Chemical Engineering Journal 322 (2017) 90–101

Contents lists available at ScienceDirect

Chemical Engineering Journal

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

# Development of an advanced imaging technique for dynamic emulsion stability

Amit V. Patil [a], Xavi Sole Marti [b], Pål Tetlie [c], Stein T. Johansen [a,*]

[a] Flow Technology Group, Oil and Gas Process Technology Department, SINTEF Materials and Chemistry, S.P. Andersens vei 15b, 7031 Trondheim, Norway
[b] Department of Chemical Engineering and Materials Science, HiST, Trondheim, Norway
[c] Solar Cell Silicon Group, Sustainable Energy Technology Department, SINTEF Materials and Chemistry, Alfred Getz vei 2, 7034 Trondheim, Norway

## HIGHLIGHTS

- Experimental study of oil-water emulsion stability in an impeller stirred tank.
- Development of imaging technique for dynamic droplet size analysis.
- Theoretical assessment of droplets for the inertial and viscous sub ranges.
- Measurement of parameters characterizing the droplet stability.

## ARTICLE INFO

*Article history:*
Received 2 December 2016
Received in revised form 27 February 2017
Accepted 28 February 2017
Available online 9 March 2017

*Keywords:*
Liquid-liquid flow
Oil-water emulsions
Interfacial stability
Inertial and viscous subrange
PVM probe
Droplet size relaxation coefficients

## ABSTRACT

Oil-water emulsions consist of droplets that are approximately spherical in shape and with a distribution in size. An image processing technique that can be used for studying emulsion droplet stability behaviour in multiphase flow has been developed. In this work, the developed technique is used to study a model system, comprising Nexbase (with and without SPAN 80 surfactants) oil and saline water emulsion in a stirred tank system. A state of the art stirred tank experimental set up was constructed that measured dynamic droplet size evolution with varying impeller speed and torque. The equilibrium droplet size measurement and torque data were used to validate with theoretical inertial (Hinze model) and viscous subrange models. Besides, this method was successfully used to obtain droplet size relaxation coefficients with varying impeller speeds.



## 1. Introduction

The transport of crude oil and water emulsions is a key element in the flow assurance sector of the upstream oil and gas industries. We should notice that in pipe flows the droplet sizes and volume fractions vary significantly, due to flow regime changes and passage through choke valves. As a result the system may at certain times and conditions be more correctly characterized as dispersion rather than emulsion. In the context of the currently paper this distinction is not relevant and we use the term emulsion for both true emulsions and liquid-liquid dispersions.

The cost of crude oil production is strongly related to pressure drop produced in transport pipes. It is well known that pressure drop is strongly dependent on the rheological behaviour which is strongly influenced by emulsion stability. Therefore oil-water emulsion stability has long been a major field of study in the past [1]. Emulsion stability or droplet size evolution is strongly characterized by interfacial tension and surface chemistry [2,3]. So there has been a need to quantify the droplet size evolution behaviour for given characteristics of oil-water emulsions. This work introduces a novel method to do this with an advanced imaging technique.

For water-in-oil emulsions it is important to quantify droplet size for assessing risk of gas hydrate formation. The interfacial area of the water-hydrocarbon interfaces is a critical parameter, controlling the transport of hydrocarbons to the water phase, and in the last instance the possibility for reliable flow [4]. In the past many transient hydrate models were developed [5,6] without having the critical capability to predict the droplet size. In these studies experimental imaging were used to study hydrate formation in controlled pressurized tank or flow loop environment [7–9]. This technique can also be applied to quantify dynamic particle size distribution in hydrate forming flows. Such measurements would be

* Corresponding author.
*E-mail address:* S.T.Johansen@sintef.no (S.T. Johansen).

http://dx.doi.org/10.1016/j.cej.2017.02.156
1385-8947/© 2017 Published by Elsevier B.V.

very valuable in order to validate flow models for cold flow applications [10].

In turbulent regimes the eddies play a pivotal role in emulsion droplet stability. The smallest eddies, characterized by the Kolmogorov length scale control the droplet size depending on the spectral regime [11]. In turbulent regimes where inertial forces dominate, the droplet size is larger than the smallest eddies. The stresses caused by the turbulent fluctuations are responsible for break up of droplets. The ability of velocity fluctuations to break droplets is a function of a critical Weber number ($We_{cri}$) [12].

On the contrary, if viscous stresses are higher then turbulent stresses, the droplet size is smaller than the Kolmogorov length. In this case viscous forces dominate due to higher kinematic viscosity relative to interfacial tension. The droplet break up due to viscous shear was derived by Taylor [13]. In locally isotropic flow, the droplet break up criteria under viscous forces domination is given by Shinnar [14].

Many previous works have validated these equilibrium droplet scaling criteria for emulsions and evaluated scaling coefficients for various types of emulsions [15–17,6]. In current work also equilibrium droplet measurements are fitted with the above theoretical models and scaling coefficients are presented.

Many methods for droplet size measurement have been developed in the past [18]. Most commonly used methods are the in situ measurement methods like particle video microscope (PVM) probe and Focused beam reflectance measurement (FBRM). FBRM has largely been more popular than PVM because of its ease to work with. Its focussed moving point beam measures directly providing distribution data online [19–21]. However it is known that this instrument provides cord length distribution measurement and hence requires a recalibration to get real droplet size distribution [22,10]. PVM probe has commonly been used to get real droplet size using manual methods. Till now PVM probes have been largely limited to calibration measurements use [22].

The manual analysis of PVM probe images is tedious and hence an image processing technique is essential for large scale dynamic measurements. Here we present the use of a newly developed imaging technique for processing images from the PVM probe as a direct droplet size measuring method. This technique involves detection of specific shapes, in this case, circles of varying size in images and statistically managing the extracted size distribution data.

Detection of circular or any other given shape objects in images has long been a scientific field called pattern recognition study [23–27]. Images with clear sharp circular objects can be easily detected with traditional Hough methods [26]. However this becomes difficult in images of highly heterogeneous systems like emulsions. Here we present an adapted method that can be used for droplet detection in emulsions. Using this method we could directly use the PVM probe for dynamic droplets size distribution measurements. Large scale images of dynamic droplet variations in a stirred tank were obtained and processed. These processed data provide detailed variations in droplet mean size and droplet size distribution directly using a strong and accurate method.

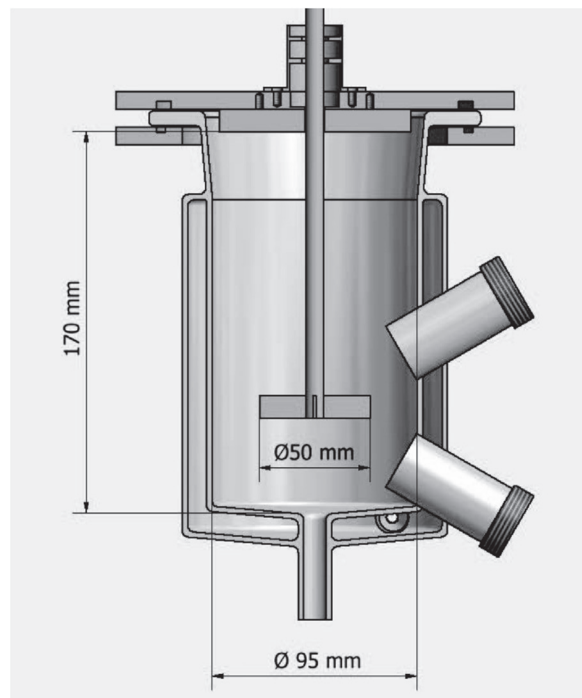
In this work we further present the use of this technique to study emulsion stability in model oils (Nexbase) and water (brine). In this study we use a stirred tank set up where the impeller speed is varied to observe droplet size variation and derive relaxation parameters characteristic for a given emulsion system. Many works in the past have used surfactants to introduce the effect of asphaltenic emulsion stability behaviour [28]. Here we make use of Span 80 to introduce this effect in one of our experiments.

Using the newly developed technique unique studies are presented on dynamic droplet size relaxation. Similar relaxation research have been done previously in gas-liquid bubbly flow systems [29,30]. But for liquid-liquid systems this is a first of its kind presented.

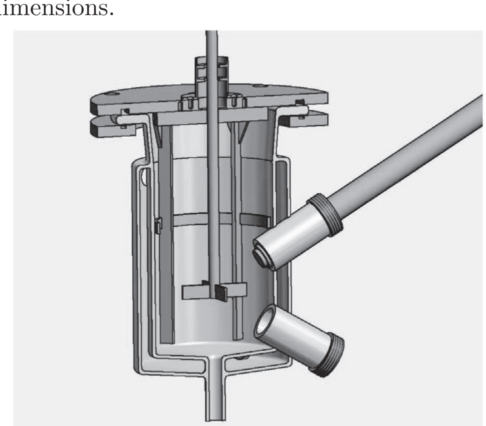
## 2. Experimental method

### 2.1. Experimental set up

A simple stirred tank set up made of 1290 mL size silica glass is used. This jacketed vessel has an internal diameter of 95 mm and a height of 170 mm. The annular jacket has temperature controlled liquid flowing through it. The input and output of the jacket is connected to an automatic temperature controller, regulating the liquid circulation. The tank has two lateral entrances where the upper one is used for the PVM probe. The projected and cross sectional view of this tank is shown in Fig. 1.




(a) Cut cross sectional front view of the tank presenting the dimensions.



(b) Cut projected view of the tank showing its internal parts: impeller, baffles, flange, probe sockets and drainage.

**Fig. 1.** Diagrams describing the internal structure and dimensions of the tank.