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Energy Efficient Microbubble Generation Mediated by Oscillatory Flow for Water Treatment

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Abstract **-Development of modern industrial process, especially gas – liquid, requires improvement of heat and mass transfer phenomena. One of the ways for such processes intensification is to increase the interfacial surface area and contact time by gas bubbling into liquid in form of micro-bubbles.**

Traditional bubble generation techniques rely on constant gas flow through a micro-porous bubble generating components which results in larger bubbles compare to a pore size. Modern micro-bubble generation techniques require high energy input for operation.

Energy efficient bubble generation technique under oscillatory flow with use of the Tesař-Zimmerman fluidic oscillator has been investigated. Mesoporous diffuser has been tested in order to study single bubble and bubble cloud dynamics at different formation conditions.

Bubble cloud dynamics have been observed using high speed photography to garner the bubble size distribution. The results of the study showed a significant drop in engendered bubble size when compared to constant flow approach.

Keywords **- equipment design, flow oscillation, microbubbles, process intensification.**

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I. Introduction

Microbubbles (MBs) range in size from 1 µm to 1000 µm [1]. Bubble characterisation and visualisation has been previously carried out using several techniques including photonic, acoustic and optical [2].

MBs have wide industrial application in water treatment [3] including separation, de-emulsification, aeration, micro algal flotation and electrofloatation [4]. MBs provide high surface area to volume ratio, fast heat and mass transfer as well as longer residence time. This gives higher efficiency in a multiphase process realisation [5].

Energy intensive MBs generation is not widespread in industry. Nevertheless high demand for gas-liquid process intensification has driven development of new MBs generation techniques.

MBs generation via fluidic oscillation has shown a remarkable improvement in bubble throughput and dramatic reduction in bubble size without the concomitant expenditure of high energy. This process therefore can be seen as a highly sustainable and economic way to generate MBs. A fluidic oscillator has been described in Tesař et al [6] --a no moving part synthetic hybrid jet microfluidic device.

In this report, we present data on MBs generation via fluidic oscillation. The micro bubbles discussed herein are uncoated and therefore have a water-air interface. It is important to note that air can be replaced by any gas or a mixture of gases resulting in a widening of application fields and change of bubble dynamics thereby changing the bubble formation characteristics and behaviour.

II. Materials and Methods

The MBs generation was performed with application of a bespoke setup attached downstream to the fluidic oscillator (FO), Fig. 1. The gas flow through the system was controlled by pressure regulator (Norgren, 0-6 bar) and the flow controller (Key Instruments 0-140 slpm). The FO at a given flow rate is oscillated at known frequency. Flow down to diffuser was controlled by bleeding line with control valves installed. The inlet flow rate to FO was controlled so that it can be compared to non oscillatory flow.

The ceramic mesoporous membrane was tested as diffuser.

The experimentation has been done by bubbling air to the water with flow rate through diffuser varied at 0.5 – 3 L/min with oscillation frequency at 284 Hz. The diffuser system was adopted from [7]. The ceramic plate has averaged pore size 20 µm and made from 80% alumina:20% silica (w/w).

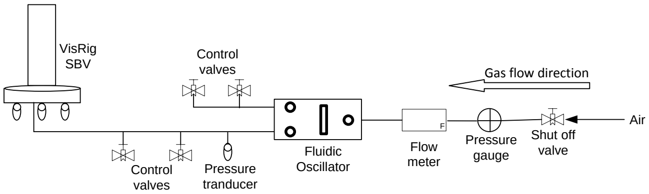

Fig 1. Flow diagram of the experimental Set Up

To characterise bubble cloud dynamics, a high speed photography is typically used [8], [9] and [10]. For our work the FastCam HS3 Photron camera equipped with Nikon AF Lens was used to collect the bubble size distribution. The camera was computer controlled by the PFV PhotronFastcam software. A typical image of the ceramic diffuser and microbubbles cloud formed is presented on a Fig 2.

III. Results and Discussion

We have selected six flow rates to characterise the ceramic diffuser. The top flow rate limit was set at the level when a single bubble in the cloud can still be distinguished from the cloud. The bubbles size distributions were determined for each flow rate and studied in comparison between non oscillated flow, fig. 3; oscillated flow, fig. 4.

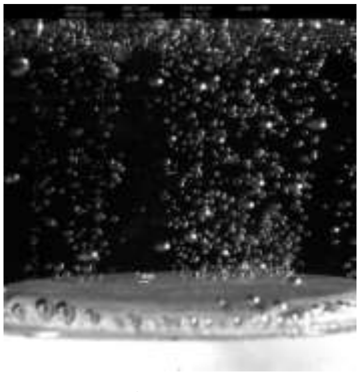

Fig 2. General view of microbubble cloud generated with the ceramic diffuser

We have found that increment of the flow rate at non oscillated flow conditions resulted in complex behaviour of the bubble formation mechanism. Figure 3 presents the bubble distribution at steady flow, without presence of fluidic oscillator. At low flow rate, 0.5 L/min, bubble distribution is normal and relatively narrow; from 0.46 to 0.86mm with majority of bubbles formed have 0.5mm in size. Flow rate 1 L/min has generated similar range for the bubble size distribution. The distribution obtained does not have a sharp mode in compare to 0.5 L/min flow rate and it is wider spread in 0.56 to 0.75mm range. Spreading of the distribution continues at higher flow rates. From the 2.5 L/min flow rate the bubble size distribution is no longer "bell shaped" and has relatively flat shape over the full range.

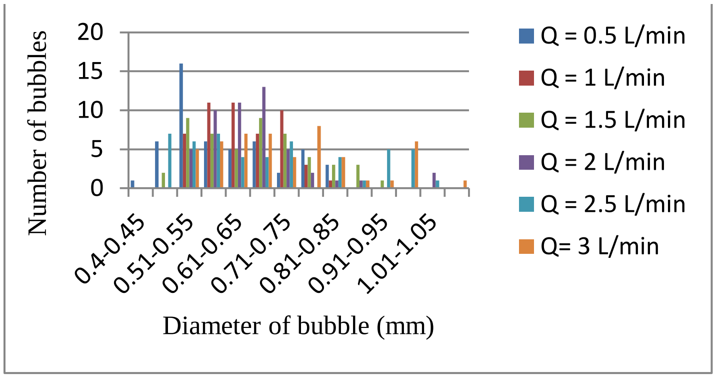

Fig 3. Bubble Distribution at Non Oscillated Flow (Q is air flow rate)

This effect can be described by the fact that for hydrophobic porous materials and constant gas flow, the bubble formation process is governed mainly by wetting properties of bubble forming surface and pressure drop across diffuser. It important to note that once engaged to the bubble formation a pore continues to form bubbles. As result a limited fixed number of pores with the smallest pressure drop were involved in bubble formation at the low flow rate. This makes bubble distribution narrow.

At higher flow rate pressure builds up under the diffuser plate and at the same pressure drop over diffuser more pores of different diameters became involved in the bubble formation. This effect reflects in deformation of bubble size distribution from normal to a flat type observed from the 2.5 L/min flow rate.

FO does not change averaged flow rate but alters a pressure field within a flow. A steady pressure transforms to a sequence of pressure waves approaching a diffuser. Rising pressure initiates bubble formation from wide range of pores. Bubbles to be formed have very large surface curvature and require small pressure of air to continue growing. Nevertheless a gas-liquid interface surface curvature decreases rapidly and pressure of air has to be higher to continue a bubble grow, as it follows from the

Young-Laplace law. At this moment a pressure wave experiences a negative phase.

Physically there are two main complex competing processes to take into account for a bubble formation mechanism. First is gas diffusion from the half way formed bubble back to the feeding pore due to higher pressure in the volume of attached bubble in compare to other side of diffuser experiencing negative phase of a pressure wave. As gas from the big pores with a low pressure drop withdraws, the bubble formation process terminates. Bubbles initiated on the pore with higher pressure drop cannot get bigger due to pressure reduction in the pore. Second is a strong adverse affect of surface tension at higher curvature to complete and detach bubble. For a given surface properties and wide set of feeding pores this results to narrow set pores which will be able to form bubbles. This situation repeats for every wave arriving to a membrane. This is one of the reasons why bubble distribution obtained significantly differs from the case of steady flow.

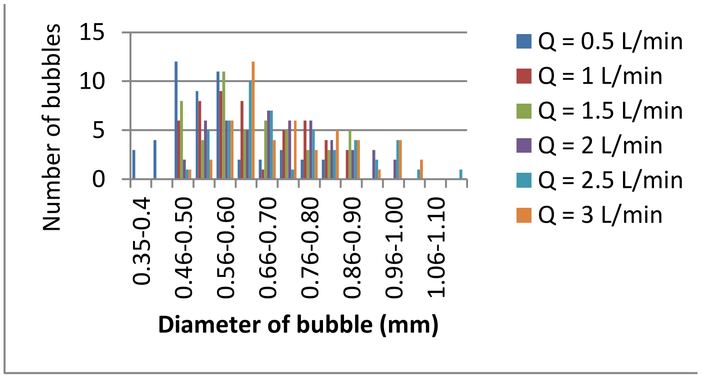

Fig 4. Bubble Distribution at Oscillated Flow (Q is air flow rate)

Figure 4 shows the bubble distribution with the presence of fluidic oscillator. At low flow rate, 0.5 L/min, bubbles have a normal distribution on their sizes with maximum on 0.46-0.5mm. In contrast to a steady flow at 1 L/min flow rate, the two modes distribution was observed at this flow rate for FO application case. Maximums were located at 0.56-0.6 and 0.76-0.8 mm ranges. Further on the distribution has developed to the flat shape at 1.5 L/min of flow rate. It is interesting to note that bubble distribution became normal at 2 L/min flow rate and the process on distribution normalisation progressed at higher flow rates with well formed normal distribution at 3 L/min, maximum location at 0.61-0.65 mm.

IV. Conclusions

We have investigated bubble formation processes for cases of steady and oscillatory flows. Application of the same membrane and flow rates permitted to distinguish effect of fluidic oscillation to the bubble formation mechanism from mesoporous membrane. It was found that two cases selected for investigation differs at every flow conditions on the positions of distribution maximum and shapes. The results of the study showed a significant drop in resultant bubble size with FO application and have significant importance for aeration technology development.

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