Diffuser characterization using a mechanical sampler for high density clouds of bubbles

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Vigneault, C., Panneton, B., Orsat, V. and Raghavan, G.S.V. 1992. Diffuser characterization using a mechanical sampler for high density clouds of bubbles. Can. Agric. Eng. 34:353-357. The development of a high pressure water scrubber requires the determination of the volume-to-surface ratio of the bubbles generated at the bottom of a water column. The technique developed so far to measure the diameter of bubbles was inadequate to measure dense populations of bubbles. A mechanical bubble sampling technique which enables isolation of a representative sample of the population was developed and tested. Bubble size distributions and Sauter mean diameter (d32) measured using the bubble sampler were not significantly different from those obtained without the help of the sampler. The sampling technique along with air flow and pressure measurement made possible the characterization of a bubble generator used in the high pressure water scrubber.

Lors de la mise au point d'un lessiveur à l'eau à haute pression, où des bulles étaient produites à la base d'une colonne d'eau, il était nécessaire de mesurer le ratio volume/surface de ces bulles. La technique de mesure correspondante du point de vues principaux ne permettait pas de mesurer des quantités de bulles de grande densité. La fabrication d'un échantillonneur mécanique a permis l'isolation d'un échantillon représentatif de la population de bulles mais de densité plus faible. L'évaluation de l'échantillonneur montra que celui-ci permettait d'isoler un échantillon dont la distribution des diamètres des bulles et le ratio volume/surface ne différaient pas significativement de ceux de la population. L'utilisation de cette technique de mesure ainsi que les mesures de la pression et du débit d'air ont permis de caractériser un générateur de bulles qui sera utilisé dans le lessiveur de gaz.

INTRODUCTION

The experimental evaluation of a high pressure water scrubber (HPWS) presented by Vigneault and Raghavan (1991) requires the determination of the mean diameter of the cloud of bubbles generated at the bottom of a water column, since it has a potentially large influence on the solubilization process involved in the HPWS. The mean diameter is not usually supplied with other specifications of commercially available bubble generators. It appears to be a function of the pressure loss of the bubble generator.

To be efficient, the HPWS has to function with a high air flow rate generating a fairly dense cloud of bubbles. Pai et al. (1988) conducted trials to characterize microbubble activity by optical and photographic surveys. Their experimental setup consisted of a water tunnel in which a porous section produced microbubbles. Photographs were taken of the clouds of bubbles generated under different sets of conditions. It was difficult to obtain quantitative information on individual bubble characteristics whenever the measurements were taken in a dense population of bubbles. Nevertheless general qualitative characteristics were derived. For example an increase in air flow rate created an increase in bubble size. But the measurement system did not permit the determination of the rate of this increase. At low air flow rates and corresponding low population density quantitative analyses could be achieved from photographs.

A real-time digitizing image analysis system, similar to the system developed by Tsukada and Horio (1990), was considered for the characterization of the bubble population generated in the HPWS. This system could be automated but had the drawback of restricting the dispersion of the bubbles to two dimensions (Lim et al. 1990). When dealing with a dense bubble population, the existing imaging system did not perform well, hence it was limited to a fairly low density bubble population (Vigneault et al. 1992a).

The first objective of this research was to develop and test a mechanical sampling technique which isolates a sample of the bubble population for image analysis. Such a sample should have a size distribution which is representative of the population. The second objective was to characterize the three selected air diffusers and to determine the most suitable diffuser for use in an experimental HPWS.

MATERIALS AND METHODS

Bubble generator

Many techniques for microbubble production have been investigated and reported. Techniques such as multistage bubble fractionation (Leonard and Blacyki 1978), cavitation induced by asymmetric distorted pulses of ultrasound (Aymé and Carstensen 1989), electrostatic atomization of a gas in a liquid medium (Sato 1980), and utilization of a column packed with uniform microbead (Bowley and Hammond 1978) were studied but have not been utilized commercially. Equipment for these techniques was considered too sophisticated and expensive for our application. The most appropriate technique described in the literature is the injection of the gas into the liquid phase through a porous material cast in tube or plate shape. This system required only a compressed air supply and the initial investment was reasonable.
Porous materials can be used to obtain smaller bubbles than would be feasible using a nozzle tip. The porous materials are made by bonding or sintering together fine particles of carbon, ceramic, polymer, or metal. They can be used for gas dispersion or generating foam. The diameter of the generated bubbles (spherical equivalent diameter) can be of the order of 100 μm or larger. In practice, the size of bubbles produced depends on both the size of the pores of the material and the imposed pressure drop. The efficiency of dispersion of the gas is a function of the pore size, the structure and the surface roughness of the material, the liquid medium, the pressure difference, and the turbulence (Fair et al. 1984).

Three samples out of twelve commercial porous materials were selected to determine suitability for the HPWS application. Selection criteria were the availability of the product, the mechanical strength, and the expected bubble size. The three samples were 125 mm long tubes made from sintered stainless steel, having nominal orifices of 0.5 μm. One tube was supplied by the manufacturer Warco1 (Warco Equipment Ltd., 2057 Chartier Ave., Dorval, PQ) and was 12.7 mm nominal outside diameter. The two other tubes were supplied by the manufacturer Newmet (Newmet Krebsöge, Inc., P.O. Box 68, Terryville, CT), and were respectively 12.7 mm and 20 mm nominal outside diameter (O.D.).

**Bubble size measurement method**

The image analysis system was described in detail by Vigneault et al. (1992b). It consisted of a CCD camera mounted on a two-axis positioner allowing movement in an horizontal plane to capture images of rising bubbles generated at the bottom of a glass aquarium. The signal from the camera was digitized using a video board mounted in a microcomputer. For each camera position, the system took a prescribed number of images. Each image represented a cubic sample from the bubble population. The camera was positioned to capture, one by one, the cubes covering the entire surface through which the bubbles circulated without overlap of cubic samples. The cubic samples had an edge of 6.67 mm corresponding to the depth of field of the camera (Vigneault et al. 1992a). The bubble size results obtained from all the cubic samples were classified in eighty classes numbered from 0 to 79 with corresponding diameters varying from 0.275 mm to 4.225 mm with 0.050 mm increments.

**Bubble mechanical sampler**

A bubble mechanical sampler was designed to sample a small portion of the bubble population to decrease the density of bubble population in the field of view of the camera (Fig. 1). It had two main components, a frame and a pair of sliding gates. The two sliding gates were used to define a rectangular channel through which a sample of the bubble cloud passed. The gates were supported by a v-shaped frame which also directed the portion of the bubble cloud which was not sampled outside the field of view of the camera. By adjusting the position of the gates, the depth of the slice of sampled bub-

![Fig. 1. Mechanical bubble sampler.](image)

Different gate covering materials, including aluminum, copper, stainless steel, glass, and paper, were tried in an effort to prevent bubbles from sticking to the gate. If the bubbles stuck to the gate, they were likely to coalesce and disturb the real diameter distribution of the bubble population. Visual observations were made to determine the effectiveness of each material. The bubble generators were installed 5 mm below the lowest part of the bubble sampler and were located in the center of the aquarium. The camera axis was perpendicular to the gates to capture images of the bubbles that had circulated between them.

**Mechanical bubble sampling effect on the bubble size distribution**

A 5 mm O.D. sintered stainless steel diffuser, having nominal pore size of 2 μm, was used to evaluate the effect of the mechanical sampling on a cloud of rising bubbles. The size distribution of the bubble population was measured using the

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1 Mention of specific trade names does not imply endorsement of those products by Agriculture Canada or McGill University. Similarly, omission of product names is not intended as discrimination against those not mentioned.
image analysis system. To determine the effect of the sampling technique, the bubble population distribution was measured for a constant air flow rate with five replications with and without using the sampler. Non-overlapping samples were taken by positioning the camera to cover the entire horizontal surface through which the generated bubbles flowed. Ten images were analyzed at each camera position.

From the raw bubble diameter data, the Sauer mean diameter ($d_{3,2}$) and the bubble diameter distribution were calculated. The $d_{3,2}$ is a measure of the volume to surface ratio of the population of bubbles generated and is expressed by:

$$d_{3,2} = \frac{n}{\sum_{i=1}^{n} \frac{d_i^3}{n}}$$

where:
- $d_{3,2}$ = Sauer mean diameter (mm),
- $d_i$ = diameter of the bubble $i$ (mm), and
- $n$ = number of bubbles in sample.

**Diffuser characterization**

The minimum pressure drop across the diffuser required to generate bubbles offers a simple means to select maximum pore size applicable to the diffusers (Anon 1990). Each diffuser was immersed in a wetting liquid, e.g., ethyl alcohol, and air pressure inside of the diffuser was increased so that the liquid could gradually be pressed out of the pores. The differential pressure was measured as soon as the first bubbles were observed. The pressure is a measure of the surface tension which is related to the pore diameter as:

$$d^* = \frac{4\gamma}{\Delta P}$$

where:
- $d^*$ = apparent diameter of largest pores (mm),
- $\gamma$ = surface tension of liquid (mN*m$^{-1}$), and
- $\Delta P$ = differential pressure on diffuser at which bubbling first occurs (Pa).

The tests were repeated six times for each diffuser and the mean of these results was used to calculate the $d^*$ of the diffuser.

The air flow rate was measured using a volumetric displacement measuring device. A manometer was connected to the gas inlet line to monitor the pressure at every gas flow rate measured to determine the effect of the pressure on the air flow rate.

The image analysis system was used to measure the diameter of the bubble generated by the three porous diffusers. The tests were conducted from the lowest pressure required to generate bubbles to the maximum flow rate which still permitted measurements using the mechanical sampler. At low gas flow rates, the mechanical sampler was not used since the bubble cloud density was low. The mechanical sampler was essential to the analysis at higher gas flow rates which produced more dense bubble populations. The camera captured images at four different positions over the length of the diffusers to obtain a bubble size distribution representative of the population produced. Ten images were analyzed at each camera position. The $d_{3,2}$ was calculated using Eq. 1 for the results obtained over the four positions of the camera and a relationship between the $d_{3,2}$ and the air flow rate per unit of length of the diffuser was determined.

**RESULTS AND DISCUSSION**

**Mechanical sampler**

The visual trials on the effect of different materials used for covering the gate walls showed that bubbles stuck to all materials except paper (common photo copier paper). With paper, bubbles did not appear to stick on the gate of the sampler and the flow of the bubbles through the gates of the sampler was virtually undisturbed. The paper was cut to protrude approximately 1 mm all around the gates. The paper rectangles were able to withstand the wet conditions for one day before any visible deterioration.

**Bubble sampling technique effect on the bubble size distribution**

A chi-square goodness-of-fit test described by Daniel (1978) was conducted on the hypothesis that the frequency distribution of the population measured using the mechanical bubble sampler would be the same as that of the population measured without the mechanical sampler. Figure 2 shows the histograms of the volumetric distribution of the bubble clouds for the 2 μm diffuser measured with and without the sampler. The chi-square test conducted on the two distributions showed no significant difference in the two populations measured ($X^2 = 16.055, P = 0.762$).

**Fig. 2. Mean bubble size distribution measured with and without the mechanical sampler for a 2 μm diffuser.**

Table I presents the $d_{3,2}$ for the characterization of the 2 μm diffuser at a nominal air flow of 350 μL*s$^{-1}$. The averaged $d_{3,2}$ of 1.047 mm and 1.059 mm were obtained for the population measured with and without the mechanical sampler respectively. An F-test conducted on these $d_{3,2}$
showed no significant difference between the two sets of measurements ($F_{1,4} = 0.23699, P = 0.6377$).

Trials were conducted using a higher flow rate but it was impossible for the image analysis system to determine the bubble population distribution without using the mechanical bubble sampler. No other reliable method was found to evaluate the effect of the mechanical bubble sampler. Based on these results, it was considered that no bubble agglomeration occurred on the paper surface and the sampler used was adequate for mechanical sampling of a cloud of bubbles without affecting its size distribution.

Table I. Sauter mean diameter ($d_{3,2}$) of bubbles produced by a sintered stainless steel diffuser measured with and without a bubble sampler

<table>
<thead>
<tr>
<th>Using the sampler</th>
<th>Replicate #</th>
<th>Air flow ($\mu L \cdot s^{-1} \cdot mm^{-1}$)</th>
<th>$d_{3,2}$ (mm)</th>
<th>Average of $d_{3,2}$ (mm)</th>
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**Diffuser characterization**

The minimum differential pressures measured were 11.56 kPa, 13.28 kPa, and 19.10 kPa which corresponded to $d'$ of 7.78 $\mu m$, 6.78 $\mu m$ and 4.71 $\mu m$ respectively for the Warco 12 mm, Newmet 12 mm, and the Newmet 20 mm diffusers. The values $d'$ obtained this way, however, are not equal to the actual pore size because the correlation is only valid for circular capillaries. By correlating the results of a glass bead test and the bubble point test, Anon (1990) determined a correction factor. The shape of the pore influences the correction factor. It is approximately 0.2 for very irregular pores and 0.4 for pores which are formed by spherical particles. These figures are only to be considered as approximate and valid for a range of wall thickness of the diffusers ranging from 1 to 4 mm (Anon 1990). Even if it was not possible to have the exact value of the correction factor applicable to the tested diffusers, it was clear that the largest pores of the Warco and the Newmet 12 mm diffusers were larger than the ones of the Newmet 20 mm diffuser.

The effect of pressure on the gas flow rate is given in Fig. 3 for the three diffusers tested. Equations 3, 4, and 5 were obtained by regression and corresponded to the curves presented on Fig. 3 for the Warco 12 mm, Newmet 12 mm, and Newmet 20 mm, respectively:

$$Q = 1.886 + 0.418 P, \quad 5 \leq P \leq 40, \quad R^2 = 0.992 \tag{3}$$

$$Q = \left( \frac{P - 16.45}{5.09} \right)^{2.5}, \quad 18 \leq P \leq 42, \quad R^2 = 0.995 \tag{4}$$

$$Q = \left( \frac{P - 12.73}{14.69} \right)^{2.6}, \quad 10 \leq P \leq 82, \quad R^2 = 0.997 \tag{5}$$

where:

$Q =$ flow rate per unit of length of diffuser ($\mu L \cdot s^{-1} \cdot mm^{-1}$),

$P =$ pressure drop through the wall of diffuser (kPa), and

$R =$ correlation coefficient.

**Fig. 3. Gas flow rate per unit of length expressed as a function of pressure for the three 0.5 $\mu m$ diffusers tested.**

Figure 4 shows the $d_{3,2}$ as a function of the gas flow rates for the three diffusers tested. The upper limit of the gas flow rate was imposed by the excessive size of the bubbles produced. In fact, bubbles having a diameter larger than 4.0 mm were not measurable using the imaging system. The gate of the sampler had to be opened too large to permit those bubbles to circulate and the cloud of bubbles seen by the camera was too dense to differentiate between bubble boundaries. The measurements were terminated when bubbles of this size were produced.

At low air flow rates, the results showed a decrease in the
d₃₂ with an increase in the air flow rate for the 12 mm
diffusers. After reaching a minimum, the d₃₂ increased with
an increase in the air flow rate. This decrease at the low air
flow rate might be explained by a non-uniform pore size
which correlates to the larger d calculated from the data for
the two 12 mm diffusers. Since pressure and flow rate are
directly correlated, only the larger pores produce bubbles at
low pressure. As the pressure increases, the smaller pores
begin to produce smaller bubbles which decreased the d₃₂.
With further increase in pressure and flow rate, the bubbles
produced increased in diameter. Datta et al. (1950) suggested
that a part of the kinetic energy of the gas stream emerging
into an expanding bubble may be converted into pressure
energy which might help to inflate the bubble but they could
not demonstrate it. This increase in diameter with the in-
crease of the air flow rate was also noticed by Pal et al.
(1988). The decrease in the d₃₂ at low pressure and flow rate
was not present for the Newmet 20 mm diffuser which could
indicate more uniform pore size.

Equations 6, 7, and 8 correspond to the curves presented in
Fig. 4 for the Warco 12 mm, Newmet 12 mm and Newmet
20 mm, respectively:

\[
d_{3,2} = 0.875 Q^{0.6} - 0.1, \quad 3 \leq Q \leq 11, \quad R^2 = 0.944 \quad (6)
\]
\[
d_{3,2} = 0.751 + (0.143 Q - 0.245)^{0.6}, \quad 2 \leq Q \leq 14, \quad R^2 = 0.994
\]
\[
d_{3,2} = 0.4 Q^{0.37} + 0.4, \quad 0 \leq Q \leq 58, \quad R^2 = 0.989 \quad (8)
\]

For the development of a HPWS, the Newmet 20 mm dif-
funser was considered as the most appropriate for the
following two reasons. First, the largest pores of this diffus-
er were fairly small in d and its d₃₂ did not decrease as the air
flow increased which produced a smaller d₃₂ than the two
other diffusers at low air flow rate. Secondly, the rate of
change of the d₃₂ with the flow rate was smaller for this
diffuser compared to the other two. This helped to produce a
relatively low d₃₂ at high air flow per unit of length which
reduced the length of the diffuser required to produce a given
total air flow, while keeping the d₃₂ low.

CONCLUSION

A mechanical means of sampling a small bubble population
from a dense cloud of bubbles was developed. Bubble agglom-
eration was not visually detected on the surface of the sampler.
Bubble size distributions and Sauter mean diameter (d₃₂) mea-
sured using the bubble sampler were not significantly different
from the ones obtained without the help of the sampler.

The sampler could therefore be used to characterize the
three diffusers. It permitted selection of the most suitable
diffuser to test the high pressure water scrubber presented by
Vigneault and Raghavan (1991). The d₃₂, the air flow per
unit of length of the diffuser and the ratio of air flow to the
differential pressure through the wall of the diffuser were all
determined.

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