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Letter to the Editor

Reply to "Comments on 'Role of bubble size for the performance of continuous foam fractionation in stripping mode'"

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ABSTRACT

A commenting letter on a recent publication challenges the measurement technique developed for optically determining bubble size distributions in foams of continuous foam fractionation in stripping mode. The author assumes an effect of bubble distortion at the glass wall leading to a misinterpretation of the experimental results. In this reply letter it will be shown that bubble distortion is of less relevance in the measurement technique considered confirming validity and reliability of the bubble size measurement method developed. Thus, the correlations between the bubble size and the liquid fraction in the foam and the operating conditions as well as the separation performance in the original publication are seen to be valid.

1. Introduction

The comment of Li [1] on a recently published study of Hofmann et al. [2] concerning the role of bubble size for the performance of continuous foam fractionation in stripping mode addressed the bubble size measurement method, bubble formation and the drift-flux theory describing gas–liquid two-phase flows. Obviously, the comment of Li [1] mainly challenges the measurement technique developed for optically determining bubble size distributions in foams based on digital images (see original publication of Hofmann et al. for convenience [2]). As a result of this, the relations between the bubble size, the liquid fraction, the operating conditions and the separation performance are challenged as well. In addition, although beyond the scope of the original publication, a force balance on a bubble during its formation at a single orifice in the liquid pool and an exemplary drift-flux analysis were presented for explanatory and illustrative purposes. On the basis of the supposed erroneous bubble size measurement, Li criticized the conclusion that the superficial liquid velocity determines the bubble size since the distortion of the bubbles at the column wall led to a false interpretation of the results. First of all, such a conclusion ('liquid velocity determines the bubble size') was not drawn in the original publication. Instead, in [2] it was found that the ratio of superficial feed to gas velocity (or the combination of feed and gas flow) seemed to be an important factor affecting the foam structure (in terms of liquid fraction ε_L and mean sauter diameter $d_{32,\mathrm{mean}}$) and thus influencing the separation efficiency. The relationship between these influencing factors was not discussed in the literature before especially for the case of the stripping mode (see Introduction of [2]).

As we have based our work on Cheng and Lemlich [3] we will discuss this paper in more detail in this reply letter, especially to clarify the issue of optically measuring bubble sizes through the column wall. Therefore, in this reply letter the four sources of errors in optically measuring bubble sizes based on the work of Cheng and Lemlich [3] will be discussed again for the experimental conditions of the original foam fractionation measurements reported by Hofmann et al. in [2]. It will be shown that Li's main argument of bubble distortion affecting the bubble size measurements is not valid for the experimental setup used. Consequently, it will be demonstrated that the originally presented results in the work of Hofmann et al. [2] were not misinterpreted. Furthermore, although of minor relevance to the original paper comments on the bubble formation and the drift-flux analysis by Li [1] will be discussed.

2. Bubble size measurement

According to Cheng and Lemlich [3] four sources of errors can occur affecting photographically measured bubble size distributions of foams:

(1) Statistical sampling bias which discriminates against the inclusion of small bubbles,
(2) Bubble distortion at a fixed boundary, such as the glass wall of a foam column, leading to a change in the observable bubble diameter,
(3) Bubble segregation describing larger bubbles being wedged away from the glass wall by smaller bubbles,
(4) Differences in stability of small and large bubble due to gas diffusion and rupture of bubble films.

In his comment [1], Li concluded that the error sources (1), (3) and (4) can be safely neglected for the measurements conducted in the work of Hofmann et al. [2]. Differences in stability of small and large bubbles (4) should not be apparent due to the nature of the stripping mode in which the counter-currently downflowing

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liquid stabilizes the rising foam bubbles. Further, Li excluded statistical sampling bias and bubble segregation for the case of using the perforated plate as gas sparger since the bubble size distributions generated were very narrow [1]. Consequently, only one of the four sources of errors, namely the distortion (2), was assumed to be important in the bubble size measurements of the foam fractionation experiments reported by Hofmann et al. leading to incorrect measured bubble sizes and thus a misinterpretation of the results.

However, according to [3], the argumentation of Li in [1] contradicts the results and conclusion of the work of Cheng and Lemlich in which the contribution of bubble distortion as possible error source played an inferior in any case. For the case of a homogeneous foam, Cheng and Lemlich found that "the effect of bubble distortion on planimetric measurement of bubble radius is slight. The results closely approximate the true bubble size." [3]. Furthermore, one of their conclusions was: "For a homogeneous foam, the unadjusted measurement of bubble size at a wetted boundary wall is a reliable way of determining true bubble size." [3]. Thus, on the basis of the narrow bubble size distributions found in the work of Hofmann et al. [2] which was confirmed by Li [1] the bubble size measurement method is not affected by bubble distortion and the results were not misinterpreted. Even for non-uniformly sized bubbles in the foam (inhomogeneous foam) "bubble distortion was found to may not seriously affect the mean" bubble size [3]. In this case, bubble segregation was pointed out to affect the bubble size measurement leading to an underestimation of the true bubble size [3]. Note, that this underestimation leads to an opposite effect in the measured bubble size compared to the effect of bubble distortion explained by Li [1].

With respect to the work of Cheng and Lemlich [3] exemplary digital foam images to each of the conducted foam fractionation experiments in stripping mode reported in the work of Hofmann et al. [2] are taken into account to evaluate the presence of possible error sources. Note, that these images were not included in the original publication but are shown now as supplementary data. The influence of superficial feed velocity varying from $j_f = 0.023\ \mathrm{cm\,s^{-1}}$ to $0.117\ \mathrm{cm\,s^{-1}}$ (corresponding images (a)–(g)) on the foam structure at a fixed superficial gas velocity $j_g = 0.196\ \mathrm{cm\,s^{-1}}$ is shown in Fig. 1. The results for the liquid fraction ε_L and the determined mean sauter diameter $d_{32,\mathrm{mean}}$ which are related to these exemplary foam images can be found in Fig. 8 in the original publication [2].

Obviously, different sizes of bubbles could be observed (Fig. 1). Starting at the superficial feed velocity $j_f = 0.117\ \mathrm{cm\,s^{-1}}$ (Fig. 1(g)) the apparent bubbles in the foam showed a quite narrow bubble size distribution with a mean sauter diameter of about $d_{32,\mathrm{mean}} = 1500\ \mu\mathrm{m}$ and a liquid fraction of about $\varepsilon_L = 17\%$. With decreasing superficial feed velocity j_f down to a value of $j_f = 0.047\ \mathrm{cm\,s^{-1}}$ (corresponding images Fig. 1(c)–(g)) the bubble size distribution stayed narrow whereas the mean sauter diameter increased to a value of about $d_{32,\mathrm{mean}} = 2000\ \mu\mathrm{m}$ at $j_f = 0.047\ \mathrm{cm\,s^{-1}}$. As previously mentioned for homogeneous foam bubble distortion does not or only slightly affect the measured bubble size with a maximum error of about 5% [3]. Comparing the range of measured mean sauter diameter $d_{32,\mathrm{mean}} = 1500$–$2000\ \mu\mathrm{m}$ and the maximum error of about 5%, bubble distortion cannot explain the increase in mean sauter diameter. Thus, as previously concluded by Cheng and Lemlich [3] the optical measurement method constitutes a reliable method for determining the true bubble size in the foam in case of homogeneous foam. A further decrease of superficial feed velocity j_f had a quite large effect on the foam structure which can be seen in Fig. 1(a) and (b) leading to a larger mean sauter diameter $d_{32,\mathrm{mean}}$ and broader bubble size distributions. As described before, the influence of bubble distortion would lead to an increase of the measured bubble diameter whereas bubble segregation would cause an underestimation of the larger bubbles at the column wall which are in turn opposite effects. As known from Cheng and Lemlich [3] bubble distortion only slightly affects the measurements in case of inhomogeneous foam. Thus, the only error in bubble sizes measured for low superficial feed velocities could be a slight underestimation of the bigger bubbles leading to the conclusion that the true bubble size would be larger. Nevertheless, the trend of increasing mean sauter diameter with decreasing ratio of superficial feed to gas velocity j_f/j_g is still valid even if segregation occurs and thus the statements of Hofmann et al. are still correct. The visual impression of the digital images seemed to support the validity of the measurement method to be reliable and representative since especially at low superficial feed velocities (e.g. Fig. 1(a)) the translucent bubbles which are located in the bulk foam and which can be observed through the bubbles at column wall are likely to have the same bubble size distribution as those measured at the column wall. As described in Fig. 8 in [2] the liquid fraction increases with increasing ratio of superficial feed to gas velocity which also can be found in the digital foam images in Fig. 1 from (a) to (g) from about $\varepsilon_L = 4\%$ to 17%. These values indicate a transition between dry and wet foam since a foam commonly is called dry for liquid fractions below 5% [4]. Thus, the assumption of Hofmann et al. [2] that the counter-currently added feed liquid superimposes phenomena like drainage and coalescence should be slightly attenuated such as the stabilizing effects of the downflowing feed liquid depend on the ratio of superficial feed to gas velocity. Thus, in a dry foam destabilizing effects are much higher than in a relatively wet foam leading to a broader bubble size distribution in case of dry foams. Furthermore, different operating conditions adjusted by the ratio of superficial feed to gas velocity j_f/j_g cause different liquid pool concentrations leading to a change in foam and bubble film stability at its formation at the liquid level. For low ratios j_f/j_g as shown in Fig. 1(a) and (b) the concentration in the liquid pool is relatively low leading to a lower foam stability and thus to a drier foam with bigger bubbles and a broader bubble size distribution. With increasing superficial feed velocity (and increasing ratio of superficial feed to gas velocity) the foam stability increases and the importance of destabilizing effects vanishes resulting in narrow bubble size distribution as observed in the digital foam images presented.

Additionally, as comparison to the influence of superficial feed velocity on the foam structure, digital images of foam fractionation experiments with varying superficial gas velocity of $j_g = 0.157$–$0.257\ \mathrm{cm\,s^{-1}}$ (corresponding images (a)–(d)) and fixed superficial feed velocity $j_f = 0.047\ \mathrm{cm\,s^{-1}}$ are presented in Fig. 2.

Obviously, the superficial gas velocity j_g had an effect on the bubble size in the foam bed. An increase in superficial gas velocity j_g led to an increase of mean sauter diameter $d_{32,\mathrm{mean}}$ and a decrease of the liquid fraction ε_L in the foam (compare Fig. 8 in [2]). Additionally, comparing Fig. 1(b)–(g) to Fig. 2(a)–(d), the digital foam images with varying superficial gas velocity j_g almost show the same results as for the influence of superficial feed velocity j_f. This increase in $d_{32,\mathrm{mean}}$ is not due to bubble distortion since the bubble size distributions are narrow as shown in Fig. 6 in the original publication [2] leading to the conclusion that the bubble size measurement method is reliable for determining the true bubble size in foams. Thus, as stated by Hofmann et al. it can be confirmed that the ratio of superficial feed to gas velocity j_f/j_g had an effect on the foam structure leading to different bubble sizes and thus varying liquid fractions. Consequently, the conclusion that the bubble size, the liquid fraction and the performance parameter are correlated is supported.

To sum up, it was shown that bubble distortion does not or only slightly affect the bubble size measurements especially for homogeneous foams as originally found by Cheng and Lemlich [3] leading to the conclusion that the bubble size measurements were not affected by distortion of the bubbles. Consequently, Li's theory of bubble distortion affecting the measurement is refuted. Moreover,