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Importance of flow stratification and bubble aggregation in the separation zone of a dissolved air flotation tank

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ABSTRACT

The importance of horizontal flow patterns and bubble aggregation on the ability of dissolved air flotation (DAF) systems to improve bubble removal during drinking water treatment were explored using computational fluid dynamics (CFD) modeling. Both analytical and CFD analyses demonstrated benefits to horizontal flow. Two dimensional CFD modeling of a DAF system showed that increasing the amount of air in the system improved the bubble removal and generated a beneficial stratified horizontal flow pattern. Loading rates beyond a critical level disrupted the horizontal flow pattern, leading to significantly lower bubble removal. The results also demonstrated that including the effects of bubble aggregation in CFD modeling of DAF systems is an essential component toward achieving realistic modeling results.

1. Introduction

Dissolved air flotation (DAF) is growing in popularity as a method of drinking water treatment (Haarhoff, 2008). Early models of flow in the separation zone of DAF systems assumed vertical plug flow from the surface to the underdrain system. Based on this assumption, the maximum surface loading rate to avoid bubble washout was calculated to be in the order of 5–10 m/h (Haarhoff and Van Vuuren, 1995). More recent pilot plant testing demonstrated that higher loading rates were possible, with excellent solids removal efficiency at rates as high as 41 m/h, but with increased bubble carryover to downstream processes (Edzwald et al., 1999). Based on the experimental results of Lundh et al. (2000, 2001), Haarhoff and Edzwald (2004) and Edzwald (2007) attributed the concept of stratified flow to explain the higher loading rates observed in practice. Stratified flow was explained as water traveling in a horizontal flow layer along the top of the tank to the far end, and then traveling back toward the front in a second horizontal layer below the first layer. However, based on the study by Lundh et al. (2000, 2001), the stratified flow was only present at certain flow conditions, and the second horizontal layer was disrupted as the loading rate increased or as the air fraction decreased, leading to short-circuiting of the flow. Several studies using computational fluid dynamics (CFD) models of DAF systems have also predicted stratified flow, however, they did not identify limiting conditions required to create the desirable stratified flow conditions, and did not predict the quantitative impact of the stratification on bubble removal (Ta et al., 2001; Hague et al., 2001; Bondelind et al., 2010).

While flow stratification is one important phenomenon that should be better understood to improve bubble removal

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efficiency in DAF systems (and hence, implicitly, particle removal), bubble aggregation is another factor that may be associated with better bubble removal. Empirical studies by Hedberg et al. (1998) and Amato et al. (2001) suggested that increasing bubble aggregation in the separation zone by means of adding internal plates (such as lamella plates) can improve removal of free bubbles in the separation zone by producing larger bubbles that have a larger rise velocity. Leppinen and Dalziel (2004) also reported that large bubble aggregates (clusters) in the separation zone improved removal efficiency. Previous CFD models of DAF, such as those reported by Kwon et al. (2006) and Amato and Wicks (2009), were based on the assumption of a uniform bubble size and neglected bubble aggregation. CFD studies from other applications have included bubble coalescence and break-up models by using a population balance algorithm (Chen et al., 2004), and it is hypothesized that implementation of bubble aggregation in a CFD model of a dissolved air flotation system would make the model more accurate.

In this work, a simple theoretical model was first developed to understand the effect of horizontal flow layers on bubble removal; with and without bubble aggregation. Then, CFD was used to predict conditions under which the flow stratification pattern happens and its effect on bubble removal. The model was then enhanced with a population balance model to account for bubble aggregation and break-up. The enhanced model was used to understand how changes in air fraction and flow rate affect bubble removal by affecting bubble aggregation and creating a stratified flow. It was expected that the optimal air fraction and maximum flow rate could be determined for a prototype DAF system based on the developed model.

Note that the effects of solid particles and the presence of a coagulant on bubble aggregation were not included in this model. It is expected that these components will be included in future work.

2. Methodology

The geometric dimensions of the pilot DAF tank used by Lundh et al. (2001) were chosen for modeling, so that obtained CFD results could be compared qualitatively to their observations. The configuration of the flow domain modeled in CFD is shown in Fig. 1. A two-dimensional model, capable of representing the flow characteristics in the separation zone (Bondelind et al., 2010), was used to reduce the computational demand. The two-dimensional model did not allow for complete modeling of the recycle air/water injection system, so a pre-blended mixture of air/water was introduced into the contact zone through the water flow inlet. All of the simulations were performed for a water temperature of 20 °C. The governing equations and details of the modeling set-up can be found in Appendix A.

For the case with no bubble aggregation, a uniform bubble size of 80 μm was used (average bubble size in the contact zone is reported to be in the range of 40–80 μm; Edzwald, 2010). For models that included bubble aggregation and break-up, a discrete population balance model was used. Two different initial inlet bubble sizes (i.e. at the inlet to the contact zone) of 20 and 80 μm were tested in the presence of bubble aggregation. These initial bubble sizes were then allowed to grow in the model as the bubbles aggregated. The bubble size distribution was divided into four discrete groups for each inlet bubble size, as shown in Table 1. The details of the model can be found in Appendix A.

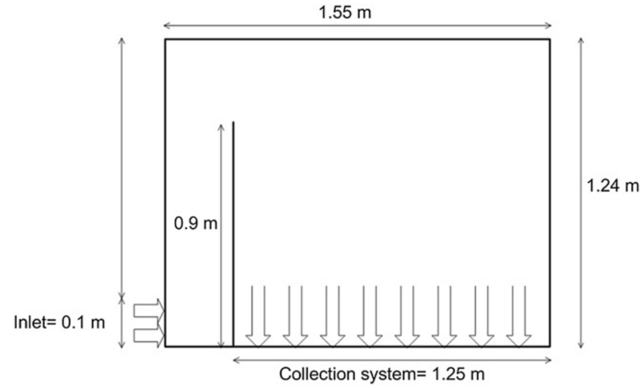

Fig. 1 – Configuration of the modeled DAF system.

3. A conceptual model for bubble removal in the separation zone

A study by Edzwald (2007) commented on the importance of horizontal flow layers on bubble removal. Edzwald (2007), however, assumed that each additional horizontal layer is of equal importance in improving bubble removal (i.e. the presence of two horizontal layers triples the maximum loading rate), and did not evaluate the importance of bubble aggregation. In this section, a similar conceptual model of flow in the separation zone is followed, but bubble removal from each horizontal layer is evaluated independently by also looking at the effects of bubble aggregation. This simple model will show that in the absence of bubble aggregation, bubble removal only occurs from the first layer. In the presence of bubble aggregation, the addition of multiple layers will be demonstrated to be beneficial, but with diminishing returns for each subsequent horizontal layer.

3.1. *Bubble removal model in the absence of bubble aggregation*

The importance of the horizontal flow layers is first assessed, starting with a simplistic scenario with two perfect plug flow horizontal back-and-forth layers as shown in Fig. 2.

The bubble removal efficiency of the top layer (with length L and thickness of H) for a bubble rise velocity of V_b can be

Table 1 – Bubble size groups for each inlet bubble size.

Bubble size groups	Group 1 (μm)	Group 2 (μm)	Group 3 (μm)	Group 4 (μm)
Inlet bubble size 20 μm	20	40	80	160
Inlet bubble size 80 μm	80	160	320	640