

Numerical Simulation of the Voltage Drop with Different Bubbles under the Anode

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Abstract

During the operation of the aluminum reduction cell, bubbles are continuously generated under the anodes. As a result, they combine as a gas layer which isolates the anode from the electrolyte and current path from the anode is prolonged and an extra voltage drop is needed for the normal operation of the cell. In the present work, a numerical model was developed to address the additional voltage drop caused by these bubbles. Other than presented by numerical approximation, the real bubbles were created in the model. The influence of bubble size, bubble area coverage and bubble gap on the voltage drop is comprehensively discussed.

Keywords: Bubble, Voltage drop, Bubble shape, Finite element model, Aluminum reduction cell.

1. Introduction

Carbon dioxide bubble behavior has become one of the hot issues in recent years in the aluminum industry. Carbon dioxide is generated under the anode working surface during the electrolysis process. Due to its big electrical resistance, the bubbles have influence on the local current distribution during its generation, growth and coalescence. When the bubbles gather in the bottom of the anode to form a large bubble layer, this bubble layer blocks the transmission of current, which results in a significantly increased cell voltage, and the increased energy consumption. Moreover, the bubble movement is one of the main driving forces that promote the circulating flow of the electrolyte, which greatly affects the alumina concentration equilibrium and heat transfer in the electrolysis cell. Hence, it is significant to carry out the research on the bubble behavior in aluminum reduction cell. Though the industry also has great interest in directly measuring the bubble behavior in industrial cell, due to the extreme corrosiveness of the high temperature molten salt, direct observation of anode bubble behavior is difficult to achieve. Haupin [1] measured the contribution of bubbles to voltage drop to be in the range of 0.15-0.35 V in industrial cell at an anodic current density of 0.8 A/cm². And the bubble layer was about 5 mm thick with a maximum value of 2 cm. Hyde and Welch [2] studied the influence of accumulated gas under the anode on the bubble resistance by putting ceramic objects as the bubbles in a lead smelting cell. The results showed that the resistance increase caused by the presence of the ceramic objects primarily depends on the bubble volume, and it increases linearly with the accumulated gas. With a lab-scale see-through cell, Youjian Yang [3] found that bubbles tended to generate and adhere to certain regions on the anode surface due to the heterogeneity of the carbon material, and the adhering regions moved when current density was increased. Nikolina Stanic [4] found that an anode slot lowered the actual current density on the anode significantly by reducing the anode bubble coverage.

In order to give an insight into the bubble behavior, as a powerful tool, the numerical simulation has been applied in the industry. The detailed current flow around individual bubbles can be addressed in the numerical modeling, and it provides an excellent opportunity to quantitatively assess the effect of bubbles on induced voltage drop. There are a few numerical works that

investigate the electrical resistance within the presence of bubbles under the anode. Zoric [5] developed a two-dimensional (2D) model to calculate the current distribution and voltage drop induced by bubbles. When the bubbles were treated as a homogeneous layer (thickness of 5 mm) with constant resistivity, an extra voltage drop of 0.4 V was measured at average current density of 0.75 A/cm². Using a 2D geometry of part of a real cell as the testing bed in a computational fluid dynamics model, Kaiyu Zhang [6] predicted bubble-induced voltage drop for a current density of 0.7 A/cm² of about 0.11 V for bubble coverage of 37 % and 0.29 V for bubble coverage of 50 %.

The 2D study may not fully represent the real case which is indeed three dimensional (3D). The aim of this work was to construct a 3D model to investigate the contribution of bubbles to voltage drop.

2. Modeling

2.1 Geometry of the Model

The bubbles were generated under the anode bottom surface. And the current passed from the anode bottom to the aluminum pad. In the physical model, the interested domain of this work was the region between the anode bottom and the top surface of the aluminum pad. And the distance from the anode bottom surface to the aluminum pad top surface was 0.04 m. For simplification, the rectangular slice in this region was selected for the numerical simulation. Therefore there were electrolyte and bubbles in the physical model without the anode carbon and cathode carbon.

2.1.1 Single Bubble Model

Under the vertical projection of the carbon anode in the single bubble model, the electrolyte layer was sliced into a block as shown in Figure 1. One bubble was placed under the anode bottom surface. In order to improve the simulation accuracy, the real entity of the bubble was created in the model.

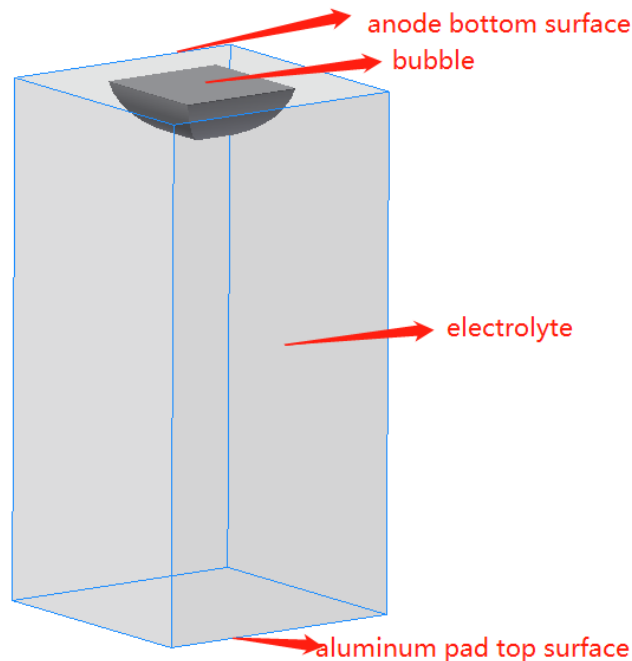


Figure 1. Physical model of a single bubble.

2.1.2 Multi-Bubble Model

Several bubbles were placed under the anode bottom surface as shown in Figure 2.

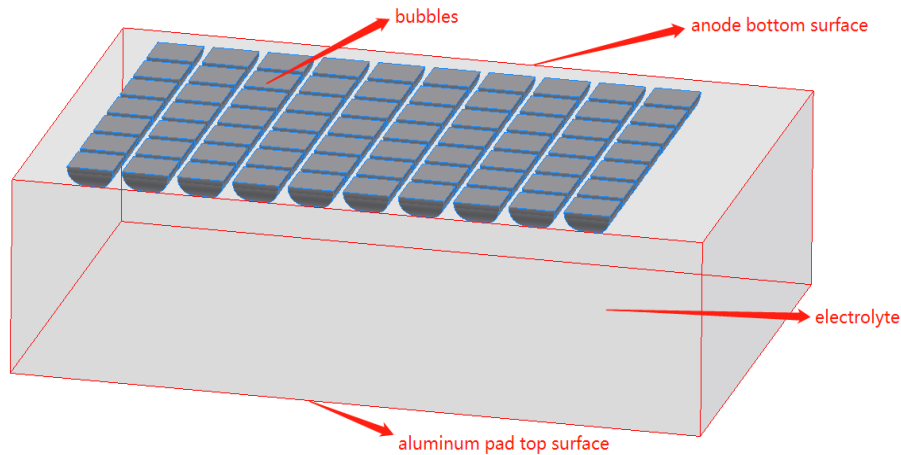


Figure 2. Multi-bubble model.

2.2 Assumptions and Boundary Conditions

The bubble was assumed to be a cube and squeezed by the hydraulic pressure of the molten electrolyte as shown in Figure 3. Unless the height of the bubble was clearly set, the default height of the bubble was 0.005 m as measured by Haupin[1] in an industrial cell. In multi-bubble model, the spaces between bubbles were evenly distributed.

Zero electrical potential was assumed at the top surface of aluminum pad and current flew into the model at the anode bottom surface with the current density of 0.73 A/cm². The electrical resistance of the electrolyte was 0.0045 Ωm and that of air was 9.0 x 10⁶ Ωm. Another significant assumption was that anodic overvoltage was ignored. Ideally, the total volume of bubble gathered under the anode was the result of the current, the flow pattern of electrolyte and the surface status of the anode bottom. To find the answers to different ‘what if’ scenarios in the simulations presented here, some bubble sizes and bubble volumes were greater than the actual value.

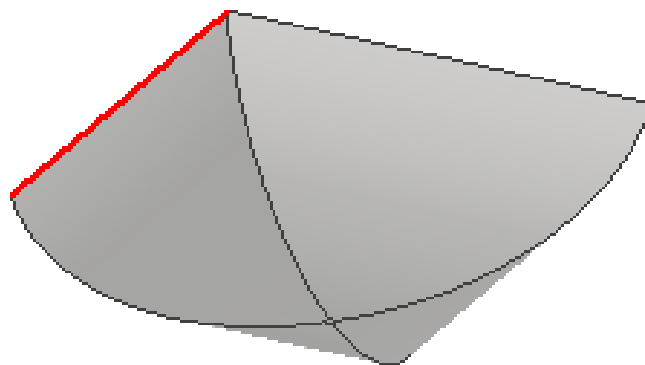


Figure 3. The appearance of bubble under the anode bottom.

3. Results and Discussion

3.1 Effect of Bubble Size

A single bubble model with anode length of 0.05 m, anode width of 0.05 m was built. Considering the wettability between anode surface and bath and the bubble surface tension, the bubble was placed 0.0001 m under the anode bottom surface in the electrolyte. And cell voltage drop caused by the pure resistance of electrolyte and bubble between the anode bottom surface and the top surface of aluminum pad was measured at different bubble sizes. Without bubble presence, the cell voltage drop was constant at 1.314 V. The bubble-induced voltage drop was the difference between the cell voltage drop with bubble presence and that without bubble presence. At the fixed bubble height, cell voltage was obtained with bubble at different size placed under the anode. The results of bubble size and the bubble-induced voltage drop are shown in Figure 4. In the simulation, in order to keep the bubble area coverage fixed at 69.4 % and at 25 %, the anode size changed with the bubble size from 0.012 m to 0.022 m. The bubble-induced voltage drop increased when the bubble size increased. At the bubble area coverage of 69.4 %, the bubble-induced voltage drop was in the range of 0.210 V to 0.250 V, which was in the range of 0.15 V to 0.35 V that Haupin [1] measured in an industrial cell but lower than the range of 0.24 to 0.45 V that Solheim [7] measured in physical modeling cell. At bubble area coverage of 25 %, the bubble-induced voltage drop was in the range of 0.050 V to 0.065 V.

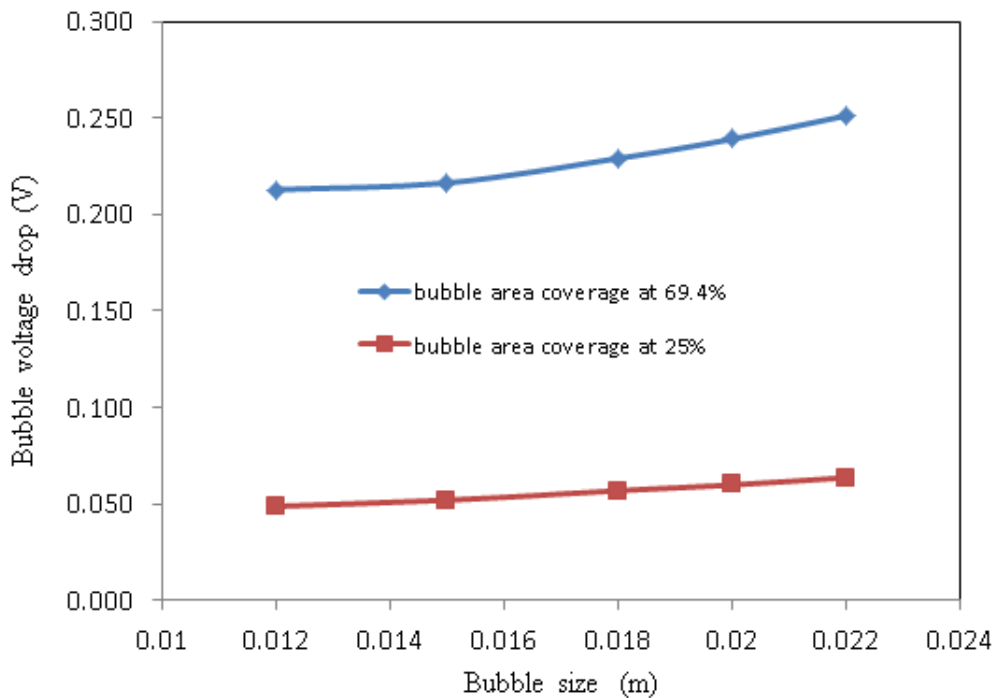


Figure 4. The bubble-induced voltage drop changes with bubble size at fixed bubble area coverage.

3.2 Effect of Bubble Area Coverage

As commonly used in the literature, the bubble-induced voltage drop was used as a function of bubble area coverage. By converting the bubble-induced voltage drop at current density of 0.7 A/cm² to that at current density of 0.73 A/cm², the results obtained by Kaiyu Zhang [6] using 2D simulation and this research using 3D simulation are compared in Figure 5. Both of the bubble-induced voltage drops were within the range of 0.1 V to 0.35 V from the bubble area coverage of 26 % to 60 %. At bubble coverage of

36 %, there is little difference between the predicted value by the present 3D simulation results and that by Kaiyu Zhang's 2D simulation. However, the bubble voltage drop in the present model is greater than that of 2D simulation at bubble coverage of 46 %. The difference between the present 3D simulation results and Kaiyu Zhang's 2D simulation results is obvious. A possible reason is that when the bubble area coverage is larger, the current needs to travel a longer distance to bypass the bubble region. For a 2D simulation, the bypass distance was longer than that in 3D simulation, leading to higher voltage drop.

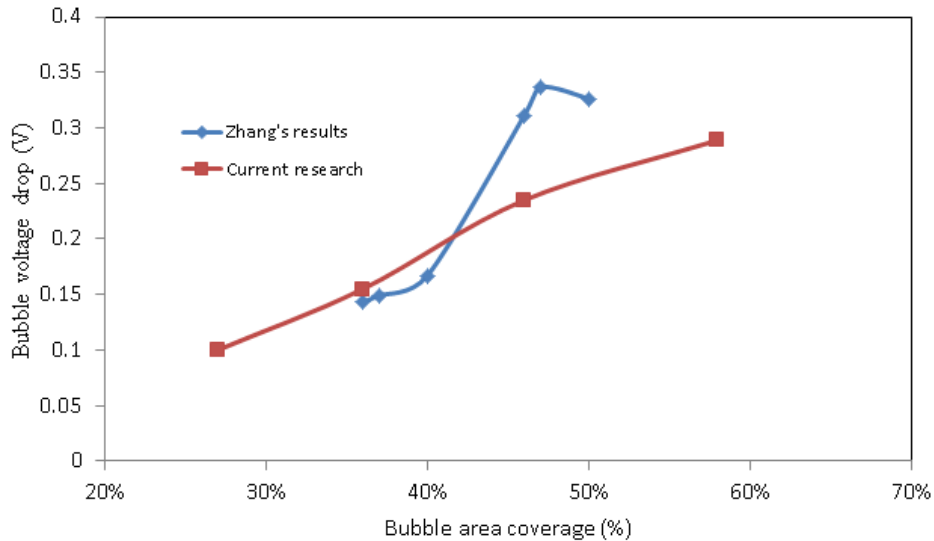


Figure 5. The simulation results of bubble-induced voltage drop from 2D and 3D.

In reference [6], existing bubble resistance equations derived from both experimental work and theoretical investigation were summarized. According to these equations, the bubble-induced voltage drops were calculated with the same parameters as in the present research and the results are shown in Figure 6. The predicted bubble voltage drop is similar to that predicted by these equations, but the trend does not fit to any particular equation. At the lower bubble coverage of less than 10 %, the predicted value agrees well with Equation 3 and Equation 5. At the middle bubble coverage of 10 % to 50 %, the predicted value agrees with Equation 2 and Equation 4. When the bubble coverage exceeds 79.4 %, Equation 5 is not applicable. At higher bubble coverage exceeding 70 %, the predicted value is greater than Equation 1 and Equation 3 and smaller than Equation 2, Equation 4 and Equation 5. Anyway, at lower bubble area coverage, the curves of the published equations and current research reveal that the bubble-induced voltage drop slowly increases as the bubble area coverage increases. And it increases significantly when the bubble area coverage exceeded 60 %.

3.3 Effect of Bubble Layer Thickness

In order to study the effect of bubble layer thickness, a single bubble model with anode length of 0.012 m, anode width of 0.012 m with one bubble under the anode bottom surface was built. At bubble area coverage of 69 % and 25 %, the bubble-induced voltage drops at different bubble layer thickness were investigated separately as shown in Figure 8. At bubble area coverage of 25 %, the bubble-induced voltage drop was very small and slightly increased with increasing bubble layer thickness. At bubble area coverage of 69.4 %, the bubble-induced voltage drop was very big and significantly increased with increasing bubble layer thickness.

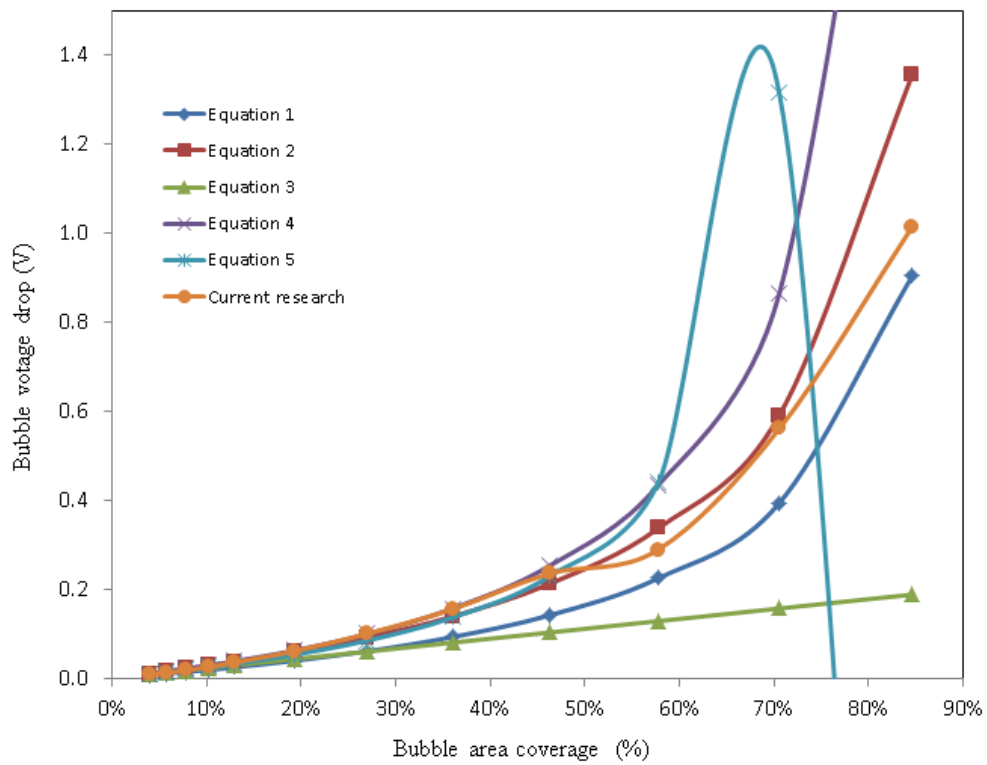


Figure 6. Comparison between the simulation bubble-induced voltage drop and calculated by published equations.

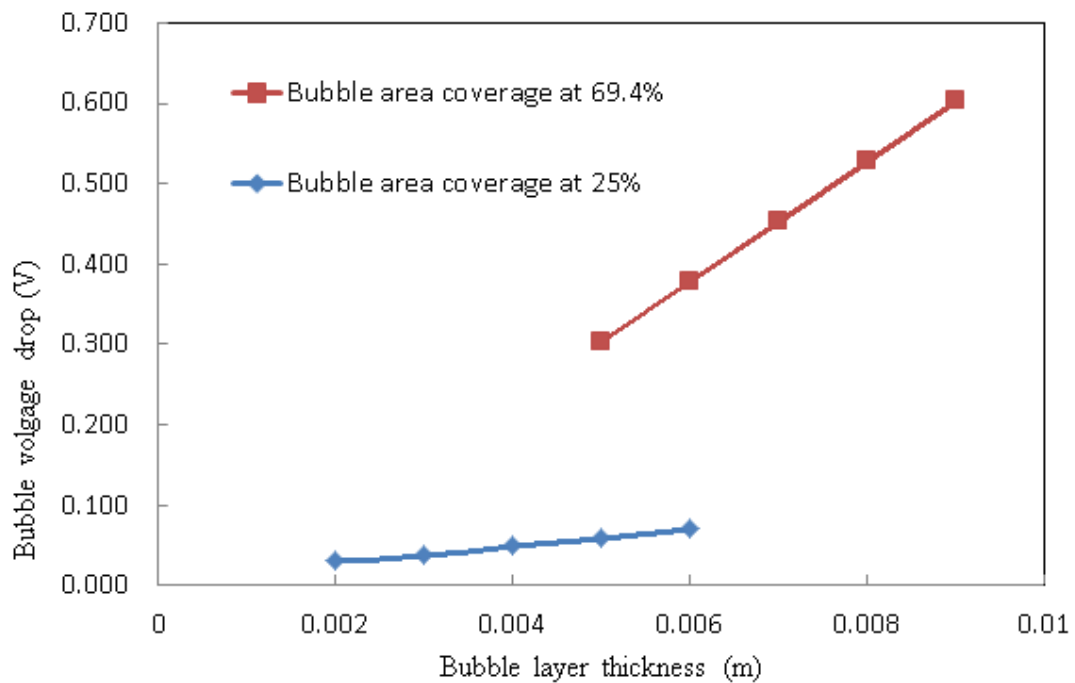


Figure 7. Bubble layer thickness and the bubble induced voltage drop.

3.4 Effect of Bubble Gap

In order to study the effect of bubble gap (the gap between the bubbles, expressed by the distance between edges of bubbles), a multi-bubble model with anode length of 0.15 m, anode width of 0.1 m was built. A matrix of bubbles (10 rows and 7 columns) was placed under the anode bottom surface. At the constant bubble area coverage of 46.7 %, bubble-induced voltage drop at different bubble gaps was obtained as shown in Figure 9. As the distance between the bubbles increased, the bubble-induced voltage drop got lower. It decreased from 0.259 V to 0.113 V, a reduction of 56 % as the bubble gap increased from 0.0002 m to 0.004 m. However, the rate of change was getting smaller and smaller, and it tended little change when the bubble gap greater than 0.004 m. This meant that the bubble-induced voltage drop was greatly affected by the bubble gap within 0.004 m.

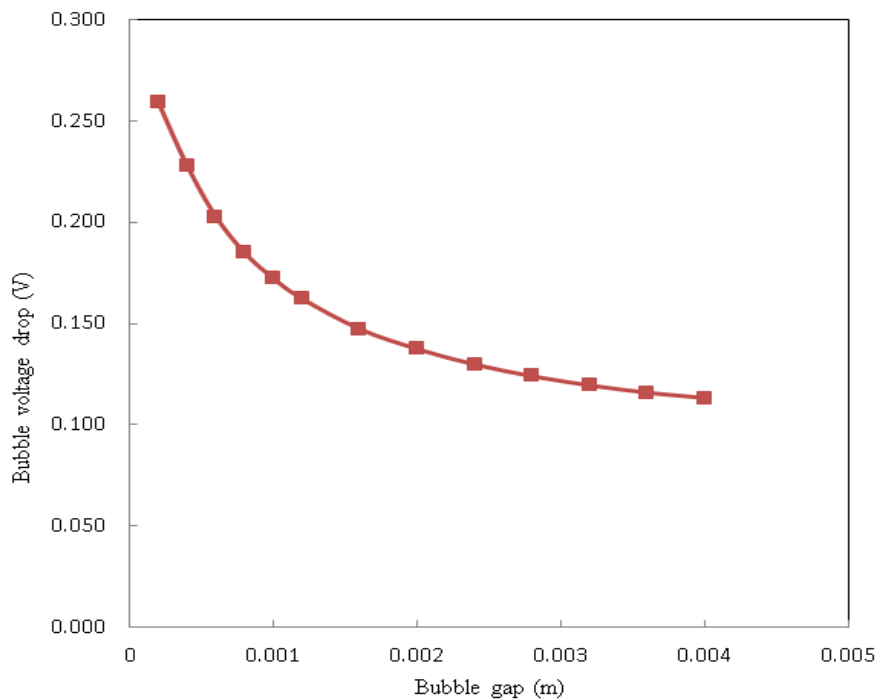


Figure 8. The bubble voltage drop at different bubble gap.

4. Conclusions

Several 3D models with real bubble entity were built to investigate the extra voltage drop caused by bubbles under the anodes. The influence of bubble size, bubble area coverage and bubble gap on the voltage drop was modeled. The main findings from this study are as follows:

- Although the bubble-induced voltage increased as increasing bubble size, the influence of bubble size on voltage drop was greater at higher bubble area coverage and smaller at lower bubble area coverage.
- The bubble area coverage had great impact on the bubble-induced voltage drop when the bubble area coverage was more than 60 %.
- At low bubble area coverage, the bubble-induced voltage drop is very small and slightly increases with increasing bubble layer thickness. But at higher bubble area coverage, the bubble-induced voltage drop is very big and significantly increases with increasing bubble layer thickness.
- For a fixed bubble area coverage, the less the evenly dispersed bubbles aggregated, the lower the voltage drop was.

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