CHEMICAL ENGINEERING TRANSACTIONS

VOL. 86, 2021

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Sauro Pierucci, Jiří Jaromír Klemeš

ISBN 978-88-95608-84-6; **ISSN** 2283-9216

DOI: 10.3303/CET2186103

Computational Fluid Dynamic Modelling of Optimal Water Level in Low-Pressure Microbubbles Scrubbers

Hyundo Park[a,b], Yup Yoo[a,b], Yeongryeol Choi[a,b], Jiwon Roh[a,b], Juwon Lee[a,b], Junghwan Kim[a,*], Hyungtae Cho[a,**]

[a]Green Materials and Porcesses R&D Group, Korea Institute of Industrial Technology, Ulsan 44413, Republic of Korea
[b]Department of Chemical and Biomolecular Engineering, Yonsei University, Seoul 03722, Republic of Korea
* kjh31@kitech.re.kr ; ** htcho@kitech.re.kr

Currently, there are many issues related to air pollution worldwide and many countries are tightening their emission regulations on fine dust-causing substances to address these problems. Thus, the removal of these substances is becoming increasingly important. Low-pressure microbubble (LPMB) scrubbers are hybrid scrubbers that combine the advantages of general scrubbers with those of microbubbles. LPMB scrubbers can be used to simultaneously remove particulate matter (PM), SO_X, and NO_X using microbubbles. Microbubbles are small bubbles with a diameter of 10-50 μm and play a key role in simultaneous removal of PM, SO_X, and NO_X. The performance of LPMB scrubbers depends on the amount of water inside them. Therefore, the initial water level is an extremely important operating condition in LPMB scrubbers. This study used computational fluid dynamics modelling to determine the optimal initial water level in LPMB scrubbers by conducting an experiment based on the initial water level. The results indicate that, with a pressure difference of 5,000 Pa, the LPMB scrubbers performed best (producing a flow rate of 16.58 m3/min) when the initial water level was the same height as the atomizer.

1. Introduction

Recently, many health-related problems, such as respiratory disease, have been caused by particulate matter (PM). This is because PM is so small that it can penetrate deep into the lungs, and some particles can even enter the bloodstream. Exposure to such particles can affect both the lungs and the heart. Numerous scientific studies have linked particle pollution exposure to a variety of problems, such as premature death in people with heart or lung disease, nonfatal heart attacks, irregular heartbeat, aggravated asthma, decreased lung function, and increased respiratory symptoms, including irritation of the airways, coughing, and difficulty breathing (US EPA 17, 2017).

PM is classified into PM_{10} and $PM_{2.5}$ depending on particle diameter; PM_{10} is dust less than 10 μm in diameter, while $PM_{2.5}$ is dust less than 2.5 μm in diameter. PM is mainly produced by artificial sources such as fuel burning, boilers, automobiles, and power generation facilities. $PM_{2.5}$ is mainly secondary pollution caused by atmospheric reactions with the substances, such as SO_X and NO_X, contained in primary pollutants emitted from automobiles and thermal power plants. Therefore, emission regulations on PM-causing substances, such as SO_X and NO_X, are being tightened in many countries to reduce damage caused by particulates pollution, and the removal of these substances is becoming increasingly important.

There are various methods of removing fine dust-causing substances such as PM, SO_X, and NO_X, but not many of these methods remove PM, SO_X, and NO_X simultaneously. Low-pressure microbubble (LPMB) scrubbers are microbubble-based scrubbers that exploit the advantages of microbubbles to simultaneously remove PM, SO_X, and NO_X. Microbubbles are small bubbles with a diameter of 10-50 μm and are already widely used in water treatment processes. A typical example of a water treatment process using microbubbles is the dissolved air floatation process (Lee et al., 2020). Microbubbles, which are negatively charged in water, electrostatically attract positively charged PM, SO_X, and NO_X (Sumikura et al., 2007). Owing to the pyrolytic decomposition that takes place within the collapsing bubbles, OH radicals and shock waves can be generated at the gas–liquid interface (Agarwal, Ng, & Liu, 2011).

Paper Received: 3 September 2020; Revised: 22 February 2021; Accepted: 4 April 2021
Please cite this article as: Park H., Yoo Y., Choi Y., Roh J., Lee J., Kim J., Cho H., 2021, Computational Fluid Dynamic Modelling of Optimal Water Level in Low-pressure Microbubbles Scrubbers, Chemical Engineering Transactions, 86, 613-618 DOI:10.3303/CET2186103

These OH radicals can remove PM, SO_X, and NO_X through oxidation-reduction reactions. These features make microbubbles highly effective at removing PM, SO_X, and NO_X. In this study, we observe microbubbles from LPMB scrubbers and determine the optimal initial water levels for increased gas capacity. A computational fluid dynamics (CFD) model was developed to test various initial water levels. The CFD model was used to observe the efficiency of LPMB scrubbers, according to the initial water level; the flow rate of the exhaust gas flowing into the inlet was obtained.

2. Low-pressure microbubble scrubber

LPMB scrubbers use the same equipment as conventional scrubbers that remove pollutants in exhaust gasses, but microbubbles are included as the main pollutant removal substance. Unlike conventional scrubbers which remove only SO_X, LPMB scrubbers can be used to remove PM, SO_X, and NO_X simultaneously. Another important feature of LPMB scrubbers is the generation of microbubbles at low or negative pressures using the suction pressure of the blower rather than high-pressure compressed gas, which is the conventional method of generating microbubbles.

Figure 1 shows a schematic diagram of an LPMB scrubber. LPMB scrubbers consist of an inlet and an outlet, two venturi meters, an atomizer, three barriers, a wall, and a blower. A pressure difference is generated between the inlet and outlet using the blower installed near the outlet. This pressure difference leads to the exhaust gas being sucked into the inlet of the scrubber. The exhaust gas passes through two venturi meters and then through an atomizer. The increased velocity of the air as it passes through the narrow atomizer causes collisions with the barriers and the water to form microbubbles. Too much water makes it difficult for high-velocity gas to collide with the barriers because of the weight of the water, while too little water prevents the formation of bubbles because the gas only and collides with the barriers. Therefore, the initial water level is a vital operating condition which must be determined in LPMB scrubbers. This study uses a CFD model of an LPMB scrubber to determine the optimal initial water level conditions and describes an experiment based on various initial water levels.

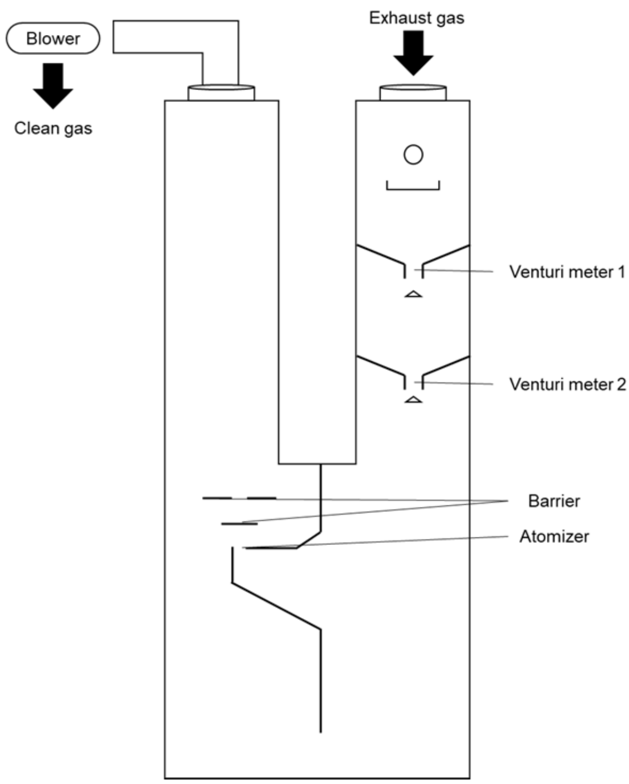
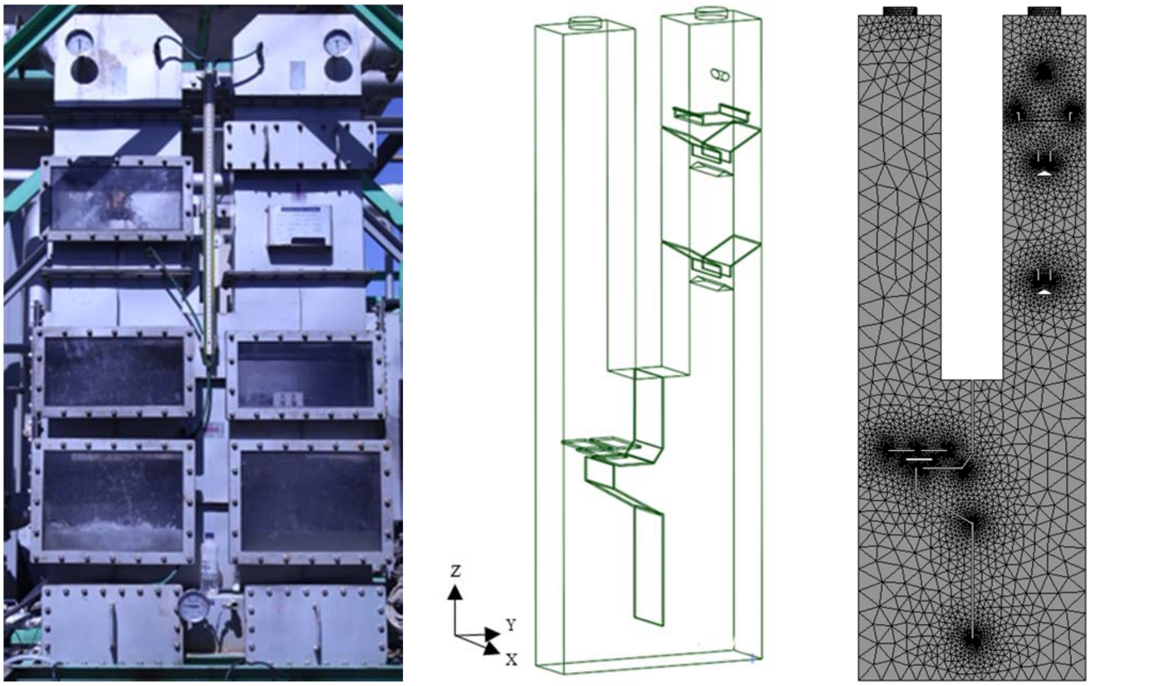


Figure 1: Schematic diagram of a low-pressure microbubble scrubber

3. CFD simulation

3.1 Geometry and mesh

An experiment was conducted using CFD to determine the optimal initial water level. Prior to conducting the experiment, an actual LPMB scrubber was rendered as a CFD model. Figure 2 shows the LPMB scrubber, as well as the geometry and mesh implemented using CFD. The geometry was created using ANSYS FLUENT Spaceclaim. The LPMB scrubber was 1,290 mm, 392 mm, and 4,031 mm in width, length, and height, respectively. We implemented venturi meters, an atomizer, and barriers, similar to those in the real LPMB scrubber. Figure 2 (c) shows the mesh of the implemented geometry. The number of mesh nodes in CFD model was 1,023,894. Although there are various indices that can be used to evaluate mesh quality, we only calculated two indices: skewness and orthogonal quality. Table 1 shows the mesh rating according to the skewness and orthogonal quality values (Fatchurrohman & Chia, 2017). The mean skewness value of the mesh was 0.23363, corresponding to the highest grade "Excellent", and the average orthogonal quality value was 0.76512, corresponding to "Very good", the grade below "Excellent". Thus, the CFD model grid was well organized, and it was deemed acceptable for use in the experiment.



(a) (b) (c)

Figure 2: The appearance of (a) the low-pressure microbubble scrubber, (b) its geometry, and (c) the applied mesh.

Table 1: Skewness and orthogonal quality ratings

Skewness					
Unacceptable	Bad	Acceptable	Good	Very good	Excellent
0.98-1.00	0.95-0.97	0.80-0.94	0.50-0.80	0.25-0.50	0-0.25
Orthogonal quality					
Unacceptable	Bad	Acceptable	Good	Very good	Excellent
0-0.001	0.001-0.14	0.15-0.20	0.20-0.69	0.70-0.95	0.95-1.00

3.2 Governing equations

The fluid dynamics are described by Navier-Stokes equations with multiphase model (Cho et al., 2013, 2017). LPMB scrubbers contain two phases: gas and liquid. Therefore, a multiphase model is essential for the analysis. Although there are a variety of multiphase models, the volume of the fluid multiphase model was chosen in this study.

It can model two or more immiscible fluids by solving a single set of momentum equations and tracks the volume fraction of each fluid throughout the domain. Typical applications include the prediction of jet breakup, the motion of large bubbles in a liquid, the motion of liquid after a dam break, and the steady or transient tracking of any liquid-gas interface (ANSYS INC., 2019).
The tracking of the interface(s) between the phases is accomplished by solving a continuity equation for the volume fraction of one (or more) of the phases. For each phase, this equation has the following form (ANSYS INC., 2019):

$$\frac{1}{\rho_q}\left[\frac{\partial}{\partial t}\left(\alpha_q\rho_q\right)+\nabla\cdot\left(\alpha_q\rho_q\vec{v}_q\right)=\sum_{p=1}^{n}\left(\dot{m}_{pq}-\dot{m}_{qp}\right)\right] \quad (1)$$

where $\dot{m}_{qp}$ is the mass transfer from phase *q* to phase *p*, $\dot{m}_{pq}$ is the mass transfer from phase *p* to phase *q*, $\vec{v}_q$ is the velocity of phase q, and α_q is the volumetric fraction value of the q^{th} fluid in the cell. Based on the local value of α_q, appropriate properties and variables are assigned to each control volume within the domain.

3.3 Simulation conditions

Table 2 shows the set conditions of the CFD model. This model sets the pressure difference between the inlet and outlet to 5,000 Pa. There were five scenarios tested in this study. The differences between the initial water level and the height of the atomizer from case 1 to case 5 were -0.2 m, -0.1 m, 0.0 m, 0.1 m, and 0.2 m, respectively. Figure 3 shows cases 1 through 5 before LPMB scrubber operation. Figure 3 is a contour representation of the water volume fraction. In the figure, red (for 1) indicates water and blue (for 0) indicates air. The initial water level increases from case 1 (Figure 3 (a)) to case 5 (Figure 3 (e)).

Table 2: Summary of the computational fluid dynamics model conditions

Domain	Case 1	Case 2	Case 3	Case 4	Case 5
Model			VOF multiphase Realizable k-epsilon Pseudo transient		
Gravity			-9.81 m/s^2		
Δ Pressure			5,000 Pa		
Initial water level	-0.2 m	-0.1 m	0 m	+0.1 m	+0.2 m

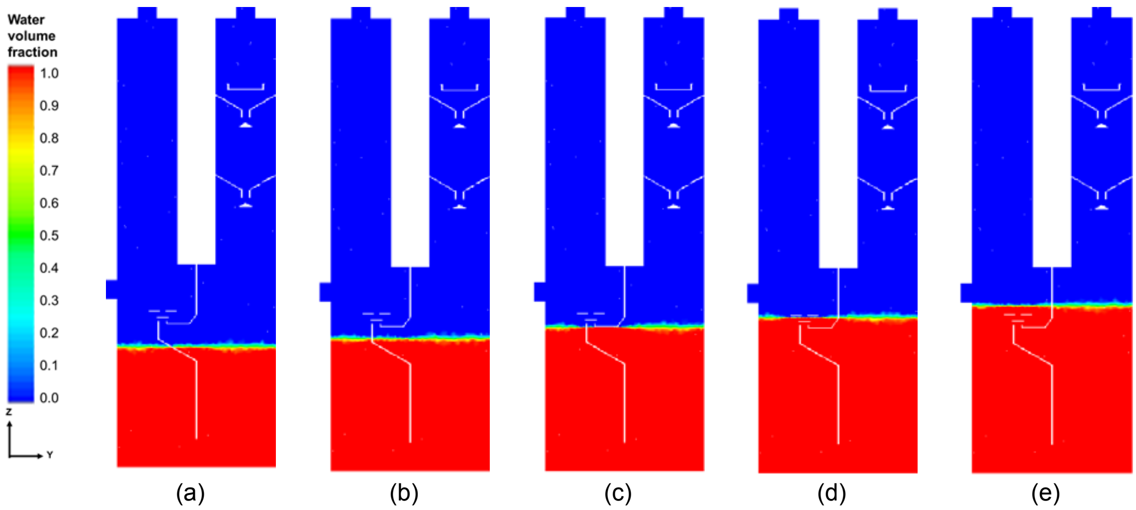


Figure 3: Initial conditions of the low-pressure microbubble scrubber (a) case 1, (b) case 2, (c) case 3, (d) case 4, and (e) case 5

4. Results and discussion

4.1 Contours of water volume fraction

The experiment was conducted based on the simulation conditions specified earlier. Figure 4 shows the LPMB scrubbers during operation. As in Figure 4 water volume fraction is presented with 0 for air (blue) and 1 for water (red). Usually, a water fraction of 0.3-0.4 is determined to be a bubble. Figure 4 (a)-(c) show water fractions of 0.3-0.4, which were determined to be microbubbles, but these values are rare in Figure 4 (d) and (e). In Figure 4 (a), the water level near the wall changed little immediately before and after LPMB scrubber operation. This means that the exhaust gas entering the inlet passed through the atomizer without affecting the water. In the remaining cases, the water surface on the right side of the wall was lowered by gas before LPMB scrubber operation. However, Figure 4 (e) shows that, even though the right water surface was lowered, it still filled to the height of the atomizer. Owing to this phenomenon, the exhaust gas could not easily pass through the atomizer. In addition, Figures 4 (d) and (e) show that there was a large volume of water in the upper area of the atomizer. This would also make it difficult for the exhaust gas to pass through the atomizer.

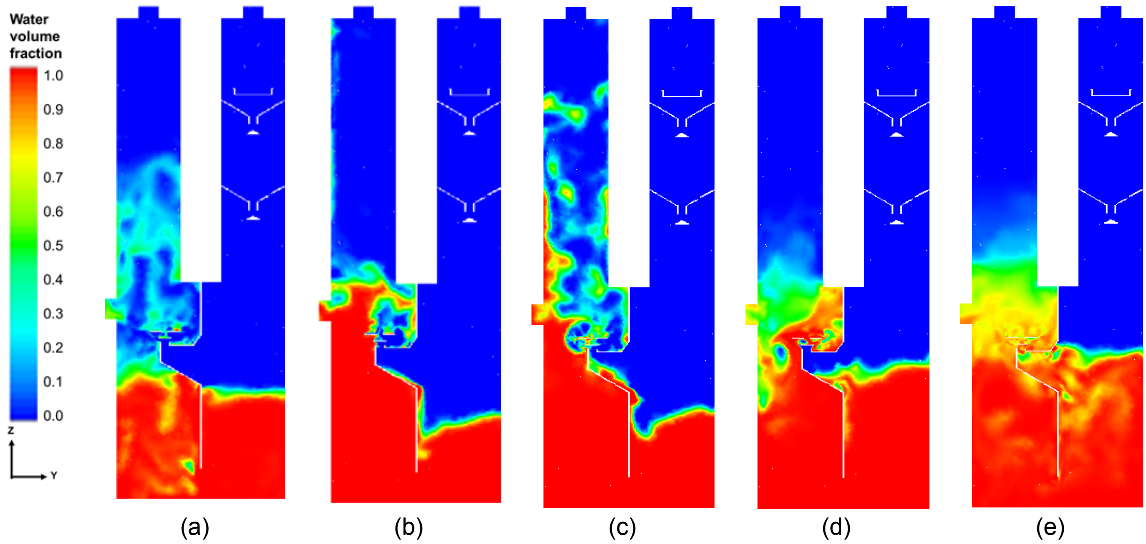


Figure 4: Water volume fraction results of the low-pressure microbubble scrubber (a) case 1, (b) case 2, (c) case 3, (d) case 4, and (e) case 5

4.2 Gas flow rate

The main driving force for LPMB scrubber operation is the suction power of the blower installed on the outlet side. The pressure difference between the inlet and outlet is caused by the inhalation of the blower. This draws the exhaust gas into the inlet. The exhaust gas entering the inlet is finally discharged as clean gas after passing through the venturi meters and atomizer of the LPMB scrubber. The velocity of the incoming exhaust gas determines how much gas the LPMB scrubber handles.

Figure 5 shows the amount of exhaust gas flowing into the inlet case-by-case. As the initial water level increases, the amount of gas entering the inlet increases, and then the amount of gas entering decreases significantly in cases 4 and 5, where the initial water level is higher than that of the atomizer. The reason for this decrease is the water accumulated in the area above the atomizer, as mentioned earlier, and the water level on the right side of the wall being higher than the atomizer height.

Table 3 is a summary of the amount of gas flowing into the inlet. The higher the initial water level, the higher the amount of gas that can be processed. However, when the water level is above a certain height, it prevents the gas from passing through the atomizer. Under 5,000 Pa pressure difference conditions, the LPMB scrubber performed best, when the initial water level was the same as that of the atomizer, displaying an inflow rate of 16.58 m^3/min, which was 6.4 times higher than the flow rate of case 5.

Table 3: Experimental results

Domain	Case 1	Case 2	Case 3	Case 4	Case 5
Gas inlet flow rate [m^3/min]	7.67	12.75	16.58	2.84	2.58

Figure 5: The results of gas flow rate by case

5. Conclusion

In this study, a CFD model was developed to determine the optimal conditions for the initial water level of the LPMB scrubber, and an experiment was conducted. The results indicate that, the higher the initial water level, the higher the gas flow rate of the LPMB scrubber. However, the gas flow rate decreased rapidly when the initial water level exceeded the height of the atomizer. This shows that, at water levels above a certain height, the excessive amount of water inside the LPMB scrubber prevents the gas from flowing smoothly. Therefore, it is extremely important to determine the optimal initial water level for the conditions of the equipment to increase the gas capacity of LPMB scrubbers.

Acknowledgments

This study has been conducted with the support of the Korea Institute of Industrial Technology as "Development of hybrid model and software to optimization of as removal system in recovery boiler for power generation (kitech JH-21-0006)

References

Agarwal, A., Ng, W. J., & Liu, Y. (2011). Principle and applications of microbubble and nanobubble technology for water treatment. *Chemosphere*, *84*(9), 1175–1180. https://doi.org/10.1016/j.chemosphere.2011.05.054

ANSYS FLUENT 13 User's Guide. (2013). Ansys Fluent Theory Guide. *ANSYS Inc., USA*, *15317*(November), 724–746.

Cho, H., Cha, B., Kim, S., Ryu, J., Kim, J., & Moon, I. (2013). Numerical analysis for particle deposit formation in reactor cyclone of residue fluidized catalytic cracking. *Industrial and Engineering Chemistry Research*, *52*(22), 7252–7258. https://doi.org/10.1021/ie302509q

Cho, H., Kim, J., Park, C., Lee, K., Kim, M., & Moon, I. (2017). Uneven distribution of particle flow in RFCC reactor riser. *Powder Technology*, *312*, 113–123. https://doi.org/10.1016/j.powtec.2017.01.025

Fatchurrohman, N., & Chia, S. T. (2017). Performance of hybrid nano-micro reinforced mg metal matrix composites brake calliper: Simulation approach. *IOP Conference Series: Materials Science and Engineering*, *257*(1), 0–7. https://doi.org/10.1088/1757-899X/257/1/012060

Lee, K. H., Kim, H., KuK, J. W., Chung, J. D., Park, S., & Kwon, E. E. (2020). Micro-bubble flow simulation of dissolved air flotation process for water treatment using computational fluid dynamics technique. *Environmental Pollution*, *256*, 112050. https://doi.org/10.1016/j.envpol.2019.01.011

Sumikura, M., Hidaka, M., Murakami, H., Nobutomo, Y., & Murakami, T. (2007). Ozone micro-bubble disinfection method for wastewater reuse system. *Water Science and Technology*, *56*(5), 53–61. https://doi.org/10.2166/wst.2007.556

US EPA 17. (2017). *Health and Environmental Effects of Particulate Matter (PM) | Particulate Matter (PM) Pollution | US EPA* (pp. 2–3). pp. 2–3. Retrieved from https://www.epa.gov/pm-pollution/health-and-environmental-effects-particulate-matter-pm