

Critical Parameters to Determine Mean Bubble Size of Generated Foams from a Foam Generator

Jeong-Uk Kim,^{1,2} Byung Hyun Park,¹ Myong-Hwa Lee¹

¹Korea Institute of Industrial Technology, 89 Yangdaegiro-gil, Ipjang-myeon, Cheonan, Chungnam 331-822, Republic of Korea

²School of Mechanical Engineering, Yonsei University, 50 Yonsei-ro, Seodaemun-gu, Seoul 120-749, Republic of Korea

Correspondence to: M.-H. Lee (E-mail: myonghwa@kitech.re.kr)

ABSTRACT: The filtration performance of filter media fabricated by foam coating technology is highly dependent upon their pore sizes. Therefore, we investigated the effect of the mixing ratio of combined coating components (PTFE emulsion, a foam stabilizer, a foaming agent, and a thickener) and operating parameters (feed rate of coating solution, air flow rate, mixing speed, and cooling temperature) on the bubble size distribution of generated foams in a foam generator. The mean bubble size and bubble size distributions were observed through microscopic observations with an optical microscope. We found that viscosity was the most critical parameter in preparing a coating solution, and the entire series of operating parameters as mentioned above influenced the bubble size in a foamed solution. The bubble size decreased with an increasing ratio of thickening agent up to 1.8%, mixing speed, and with decreasing solution feed rate, and cooling temperature. Furthermore, we had a minimum bubble size for the condition of air flow rate at 200 mL/min. © 2013 Wiley Periodicals, Inc. *J. Appl. Polym. Sci.* 130: 2062–2067, 2013

KEYWORDS: membranes; foams; coatings

Received 16 January 2013; accepted 10 April 2013; Published online 14 May 2013

DOI: 10.1002/app.39401

INTRODUCTION

A dust collector, following a selective catalytic reactor (SCR) and a heat exchanger, is generally used in a power plant and a boiler facility as an air pollution control device (APCD). However, this APCD has some disadvantages, namely, particle deposition on the catalyst layers in a SCR, resulting in a decrease of NO_x removal efficiency, and on heat exchanging tubes in a heat exchanger, resulting in a decrease of heat exchanging efficiency. These problems can be overcome by installing a high temperature bag house upstream of the SCR and heat exchanger.

Recently, the authors have developed an inexpensive bag filter media using a foam coating technology that is effective in the high temperature region around 300°C, and have reported their filtration characteristics.^{1,2} The manufacturing method has several advantages, which are reduced amount of wastewater, decreased consumption of coating solution, and, especially, a simple process. The filtration performance of the filter media is highly dependent upon the pore size.^{3–5} As the pore size decreases, the particle collection efficiency increases due to inertial force and interception.⁵ However, the small pore size also influences the increase of pressure drop across the filter media, due to flow resistance. Therefore, we need to optimize the internal morphology to maximize collection efficiency of the filter media.

The foam coating processes consist of a coating solution preparation, coating solution foaming process, coating process, drying process, and curing process. Foam generation is the most critical process of all the manufacturing processes, for determining the pore size of the filter media. There are several studies about how to mix the coating solutions and how to control the foaming process inside a mixing chamber in order to control pore size.^{6–8} Yen and Yeh⁶ have reported that the viscosity of a coating solution had an effect on foam stability and foam size. Kroezen and Wassink⁷ and Hanselmann and Windhab⁸ have shown that bubble size distribution was highly influenced by mixing speed, and a distribution with a larger mean diameter had relatively greater standard deviation. However, these studies are limited to polyethylene glycol, starch ether, and protein solution. Therefore, we investigated the effect of the mixing ratio of combined coating solutions, including a PTFE emulsion, and operating parameters, on bubble size distribution in this study.

MATERIALS AND METHODS

Figure 1 shows a schematic diagram of a PTFE foaming process. The PTFE coating solution which consisted of PTFE emulsion (TE3893, Dupont), foam stabilizer (Maxcoat FS-300, Maxchem), foaming agent (Maxcoat FA 20, Maxchem), and thickening agent (TT-935, Youngwo Chemtech), was introduced into a

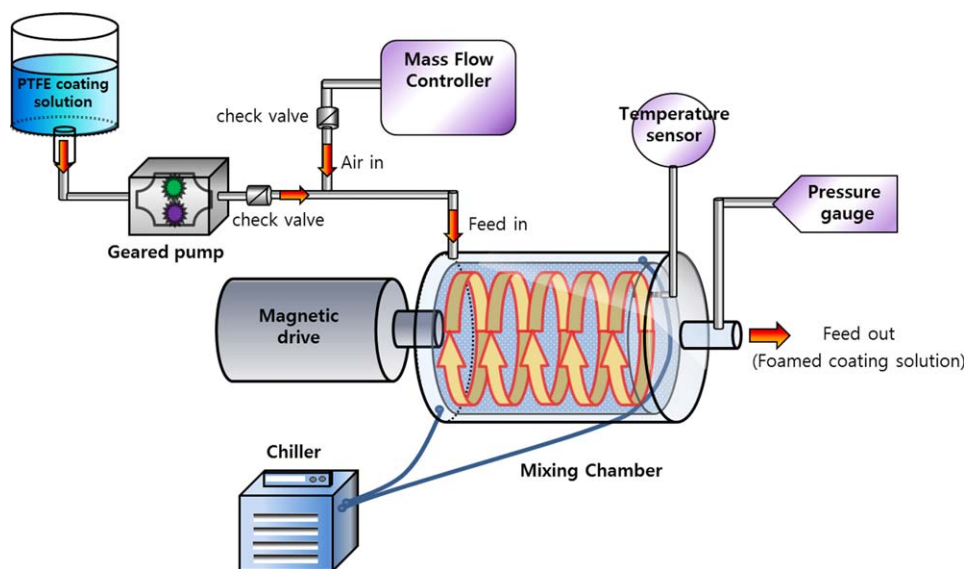


Figure 1. Schematic diagram of a foam generator. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Table I. Mixing Ratio of Coating Components

PTFE emulsion (%)	Foam stabilizer (Ammonium soap) (%)	Foaming agent (Fatty acid amide derivative) (%)	Thickening agent (TT935-acrylic emulsion) (%)
Determined	5.5	1.0	0.6
by other components	5.9	1.4	1.0
	6.3	1.8	1.4
	6.7	2.2	1.8
	7.1	2.6	2.2

cylindrical storage tank and pumped into a mixing chamber (internal volume: 1 L) in a foam generator. Purified air with a flow rate (0.05–1 L/h) was supplied upstream of a mixing chamber and used to increase the blow ratio of the coating solution. Check valves were installed to prevent the coating solution from flowing back. In addition, the temperature of the coating solution was controlled by supplying cooling water in an outer chamber covering the mixing chamber. The solution

Table II. Operating Parameters to Determine the Optimum Foaming Conditions

Solution feed rate (L/h)	Air flow rate (mL/min)	Mixing speed (rpm)	Cooling temperature (°C)
1	50	100	15
2	100	200	20
4	200	300	25
6	400	400	30
	600	500	40
	800		
	1000		

was foamed in a mixing chamber with a number of cylindrical blades and internal pressure of atmospheric pressure, which plays the role of fragmenting the bubbles. The foamed coating solution was received in a beaker and the bubble sizes were immediately observed with an optical microscope (EGVM 35B, EG Tech). The number of bubbles with more than 100 was counted to measure the bubble size distribution.

An optimum combination of coating components and operating conditions in a foam generator are required to make the best quality filter media. We prepared coating components with various combinations as shown in Table I. Reference values shown in bold characters were used as guideline values, which were mixing conditions in our previous work.¹ Furthermore, operating parameters used to determine the optimum foaming conditions are listed in Table II.

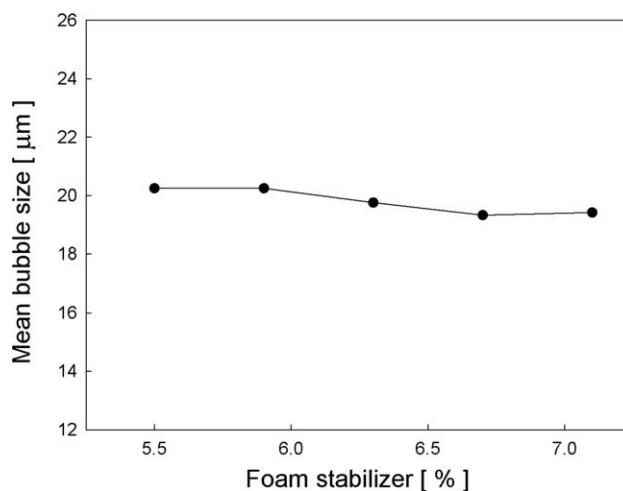


Figure 2. Effect of a foam stabilizer on bubble size distribution when added to a coating solution.

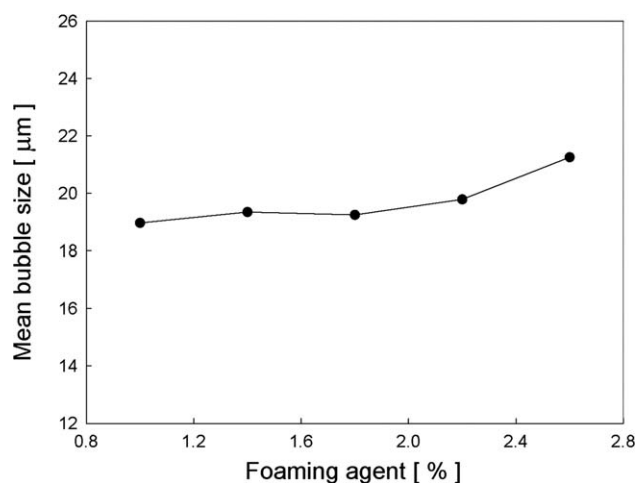


Figure 3. Effect of a foaming agent on bubble size distribution when added to a coating solution.

RESULTS AND DISCUSSION

Bubble sizes in a foamed solution to be coated onto a glass fiber mat are determined by both the mixing ratio of coating components and the operating parameters in a foam generator. Therefore, the individual effect on the bubble size in a foamed solution was investigated in terms of the mixing ratio of coating components and operating parameters in a foam generator.

Optimum Mixing Ratio of Coating Components

To begin with, the influence of mixing ratio of coating components on bubble size distribution in a foamed solution was analyzed. Operating parameters in the foam generator (solution

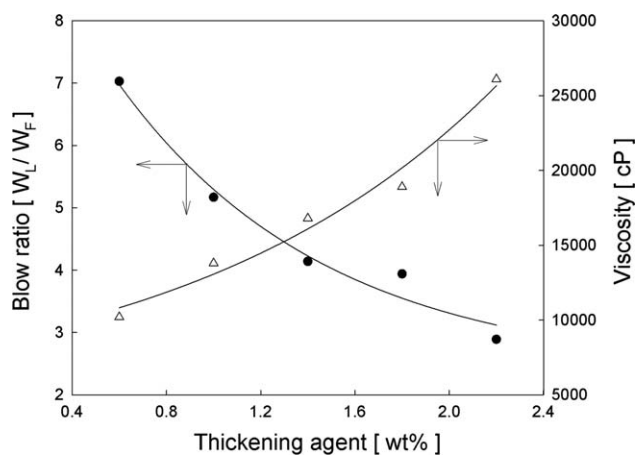


Figure 4. Effect of a thickening agent on blow ratio and viscosity when added to coating solution.

feed rate: 1 L/h, air flow rate: 200 mL/min, mixing speed: 300 rpm, cooling temperature: 20°C, and chamber internal pressure: atmospheric pressure) were fixed to clarify the effect of mixing ratio.

Foam Stabilizer. Figure 2 shows the mean bubble size as a function of the ratio of a foam stabilizer added to a coating solution at a fixed ratio of other ingredients (foaming agent: 1.8%, thickening agent: 1.4%). We could see that mean bubble size in the foamed solution was not changing in the range of 5.5–7.1% of added foam stabilizer. Therefore, we decided to increase the ratio of foam stabilizer to 6.3%, which was the same value in our previous work.¹

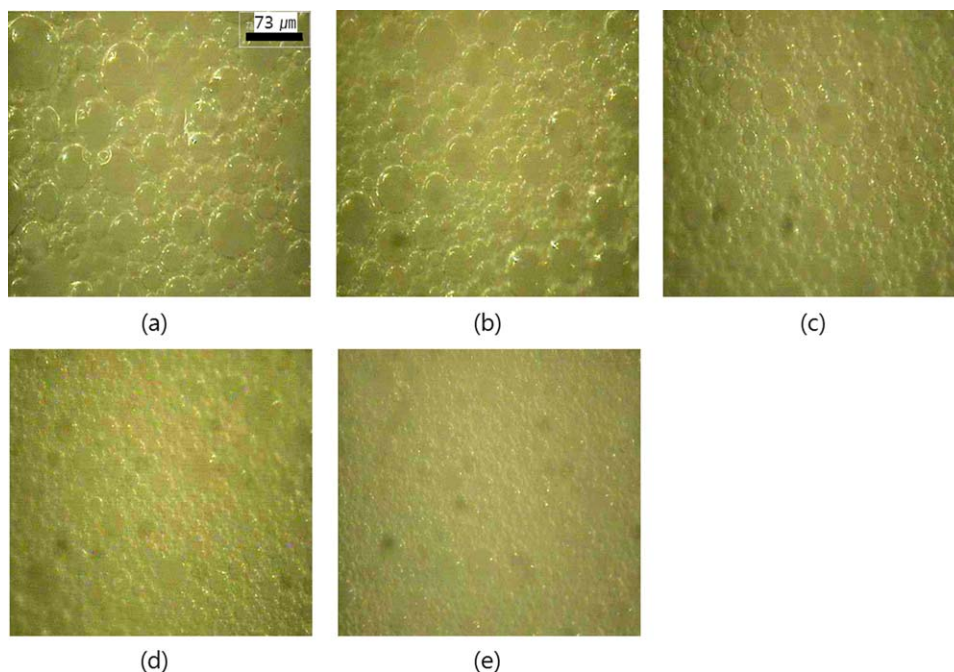


Figure 5. Optical microscope images of foams showing the effect of thickening agent: (a) thickener: 0.6% (mean bubble size: 26.30 μm), (b) thickener: 1.0% (mean bubble size: 23.86 μm), (c) thickener: 1.4% (mean bubble size: 19.40 μm), (d) thickener: 1.8% (mean bubble size: 15.91 μm), (e) thickener: 2.2% (mean bubble size: 15.50 μm). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

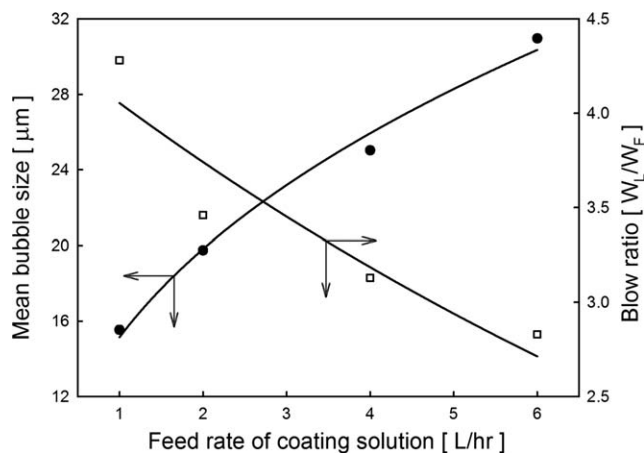


Figure 6. Effect of coating solution feed rate on bubble size distribution and blow ratio.

Foaming Agent. Figure 3 shows the mean bubble size as a function of the ratio of a foaming agent added to a coating solution at the fixed ratio of other ingredients (foam stabilizer: 6.3%, thickening agent: 1.4%). As we could see in the graph, there was no difference of mean bubble size in the range of 1.0–2.6% of added foaming agent. Therefore, we also determined the ratio of foaming agent to 1.8%, which was the same value in our previous work.¹

Thickening Agent. Figure 4 shows the blow ratio and viscosity as a function of the ratio of a thickening agent added to a coating solution at a fixed ratio of other ingredients (foam stabilizer: 6.3%, foaming agent: 1.8%). As the ratio of thickening agent increases, the viscosity of the foamed solution drastically increases. However, the blow ratio which stands for the weight per unit volume of an initial coating solution versus the weight per unit volume of a foamed solution, decreases with the increasing ratio of thickening agent.

Optical images of bubbles in the foamed solution are shown in Figure 5. Mean bubble size was decreased by increasing the ratio

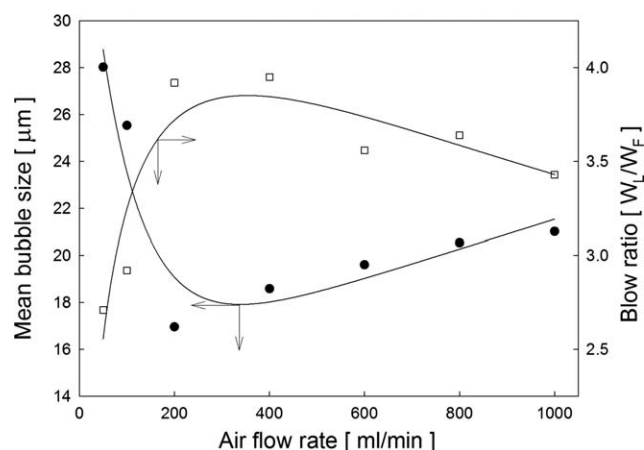


Figure 7. Effect of air flow rate on bubble size distribution and blow ratio.

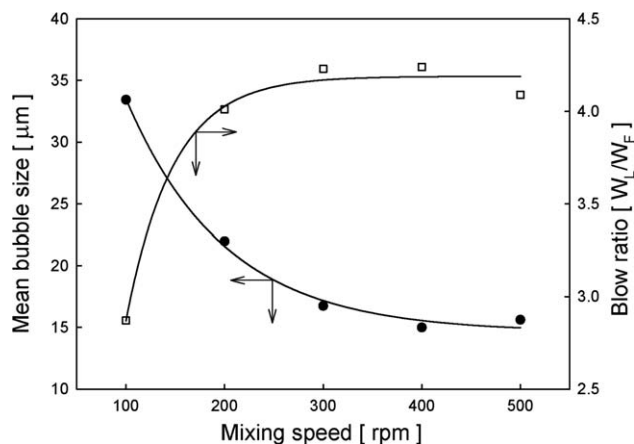


Figure 8. Effect of mixing speed on bubble size distribution and blow ratio.

of thickening agent. We could see that the mean bubble size was 26.30 μm at a thickening agent ratio of 0.6%, however, it drastically decreased to 15.5 μm at 2.2%. Summarizing these results, the mean bubble size was almost same for the ratio of thickening agent ranging from 1.8% to 2.2%, so we could decide the ratio of thickening agent to be 1.8%, resulting from a higher blow ratio.

Optimum Operating Conditions in a Foam Generator

The optimum combination of coating components (PTFE emulsion: 90.1%, foam stabilizer: 6.3%, foaming agent: 1.8%, and thickening agent: 1.8%) was determined by the above-mentioned experimental procedure. The solution was then used to figure out the effect of operating parameters (feed rate of a coating solution, air flow rate, mixing speed, and cooling temperature) on bubble size distribution in a foam generator.

Feed Rate of a Coating Solution. Figure 6 shows the effect of coating solution feed rate on mean bubble size and blow ratio. We adopted the same optimization procedure as above using the reference values (air flow rate: 200 mL/min, mixing speed: 300 rpm, and cooling temperature: 20°C). As the feed rate increased, bubble size was increasing and blow ratio was decreasing. The result could be attributed to the fact that a higher feed rate caused a shorter residence time in the chamber, resulting in larger bubble size.⁹ In addition, blow ratio of a coating solution decreased from 4.3 to 2.8.

Air Flow Rate. Figure 7 shows the effect of air flow rate on bubble size distribution and blow ratio at fixed operating conditions (coating solution feed rate: 1.0 L/hr, mixing speed: 300 rpm, and cooling temperature: 20°C). We could see that mean bubble size was drastically decreasing with increasing air flow rate for the condition of less than 200 mL/min, however, it was readily increasing for the condition of more than the value. It was conceivable that the relatively low fragmentation by cylindrical blades, due to a low bubble population density, generated larger bubbles in a low air flow rate, and the shorter residence time resulted in a relatively larger bubble size in a high air flow rate. In addition, blow ratio of a coating solution increased drastically from 2.7 to 4.0 and maintained plateau.

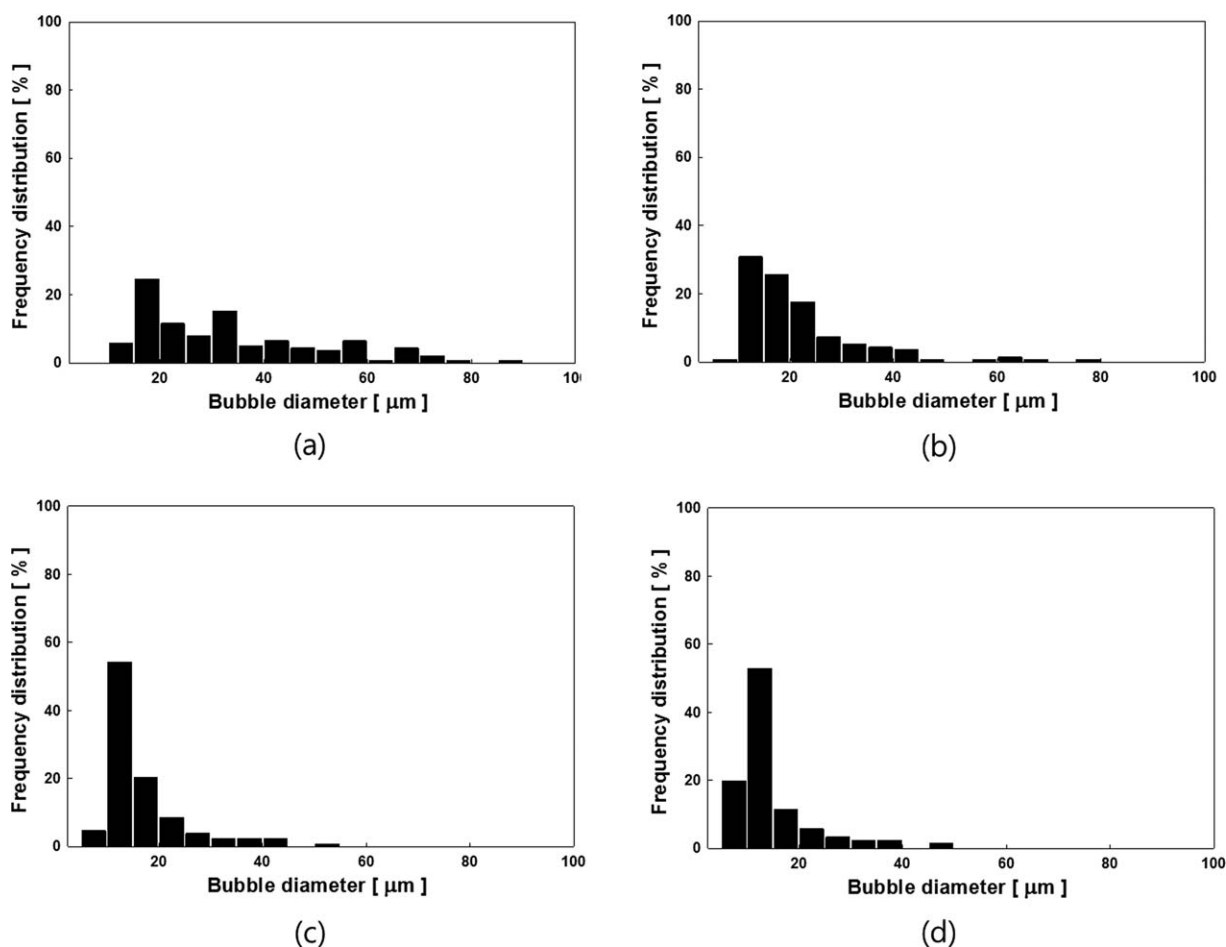


Figure 9. Change in bubble size distribution by mixing speed: (a) mixing speed: 100 rpm (mean bubble size: 33 μm), (b) mixing speed: 200 rpm (mean bubble size: 22 μm), (c) mixing speed: 300 rpm (mean bubble size: 17 μm), (d) mixing speed: 400 rpm (mean bubble size: 15 μm).

Mixing Speed. Figure 8 shows the effect of mixing speed on mean bubble size and blow ratio for the fixed operating conditions (coating solution feed rate: 1.0 L/h, air flow rate: 200 mL/min, and cooling temperature: 20°C). We could see that mean bubble size was decreasing with increasing mixing speed.

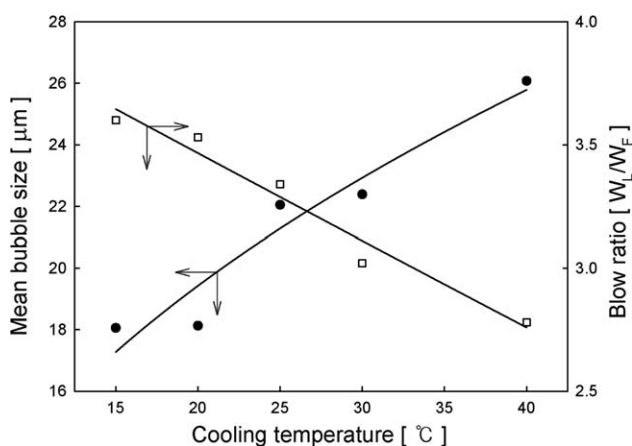


Figure 10. Effect of cooling temperature on bubble size distribution and blow ratio.

However, bubble size was less influenced by a mixing speed higher than 300 rpm. The bubble size distribution is shown in Figure 9. The mean bubble size was 33 μm at a mixing speed of 100 rpm and decreased to 15 μm at 400 rpm. Furthermore, we could also observe that the distribution was getting narrower with increasing mixing speed. We can imagine that generated bubbles would collide with cylindrical blades in the mixing chamber and be easily fragmented with increasing mixing speed. In addition, blow ratio of a coating solution increased drastically from 2.9 to 4.2 and maintained plateau.

Cooling Temperature in a Chamber. Figure 10 shows the effect of cooling temperature on bubble size distribution and blow ratio at fixed operating conditions (coating solution feed rate: 1.0 L/h, air flow rate: 200 mL/min, and mixing speed: 300 rpm). We could see that mean bubble size was increasing with increasing temperature. Bubble growth is usually related to gas diffusion inside. Therefore, we could infer that cooling of a coating solution resulted in lowering diffusivity which prevented the expansion of bubbles.¹⁰ In addition, blow ratio of a coating solution increased from 2.8 to 3.6.

Summarizing the experimental observations, we can imagine the following possibility as described in Figure 11. Stable coating

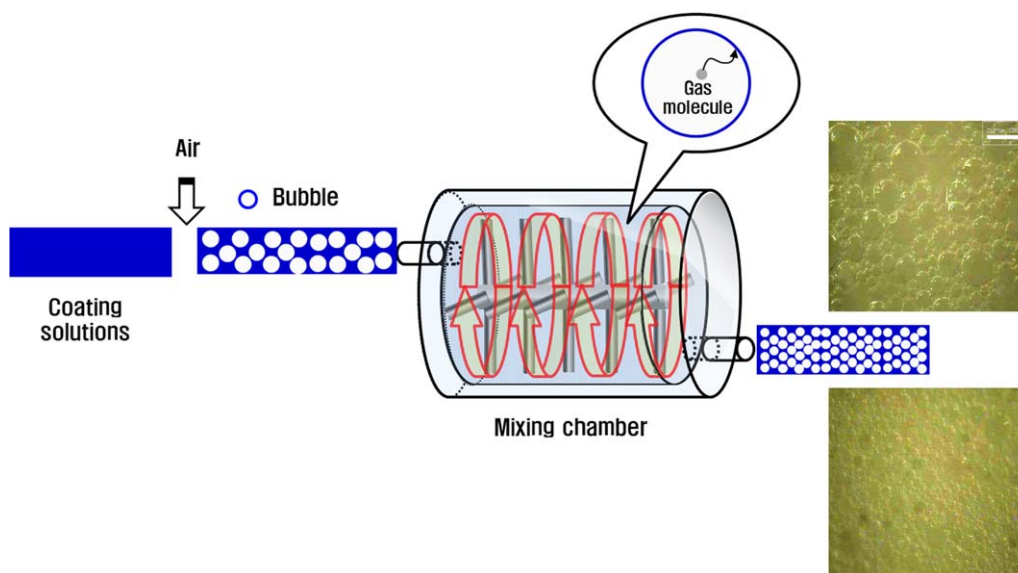


Figure 11. Mechanistic description of bubble formation in the foam coating process. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

solution with the best composition ratio of coating components is introduced. The solution is quite sensitive to fluid viscosity. Bubbles generated by air supply, experience bubble fragmentation, coalescence, and expansion by gas diffusion in the mixing chamber. A short residence time passing through the mixing chamber caused a larger bubble size due to the reduced chance of fragmentation by rotating blades, and a high mixing speed resulted in a smaller bubble size for the opposite reason. In addition, the cooling of a coating solution in a mixing chamber prevented the expansion of foamed bubbles. Furthermore, we could figure out that blow ratio of a coating solution always had an opposite trend with mean bubble size from Figures 6 to 10.

CONCLUSIONS

An experimental approach to find out the critical parameters that determine bubble size in a foamed coating solution was carried out in this study. We found that the ratio of a thickening agent, which determined viscosity, was the most critical parameter in preparing a coating solution, and the entire series of operating parameters, such as solution feed rate, air flow rate, mixing speed, and cooling temperature in a foam generator, influenced the bubble size in a foamed solution. The bubble size decreased with an increasing ratio of thickening agent, mixing speed, and a decreasing solution feed rate, and cooling temperature. Furthermore, we achieved a minimum pore size with an air flow rate of 200 mL/min.

ACKNOWLEDGMENT

This work was financially supported by a commercialization supporting program of the Ministry of Knowledge Economy (Project number: N0000541).

REFERENCES

1. Park, B. H.; Lee, M.-H.; Kim, S. B.; Kim, G. S.; Jo, Y. M. *J. Air Waste Manag. Assoc.* **2010**, *60*, 137.
2. Park, B. H.; Lee, M.-H.; Kim, S. B.; Jo, Y. M. *Appl. Surf. Sci.* **2011**, *257*, 3709.
3. Yamamoto, N.; Fujii, M.; Kumagai, K.; Yanagisawa, Y. *J. Aerosol Sci.* **2004**, *35*, 731.
4. Cyrs, W.; Boysen, D.; Casuccio, G.; Lersch, T.; Peters, T. *J. Aerosol Sci.* **2010**, *41*, 655.
5. De Freitas, N.; Gonçalves, J.; Innocentini, M.; Coury, J. *J. Hazard. Mater.* **2006**, *136*, 747.
6. Yen, M.; Yeh, T. *J. Polym. Res.* **1997**, *4*, 253.
7. Kroezen, A.; Wassink, J. *J. Soc. Dyers Colourists* **1987**, *103*, 386.
8. Hanselmann, W.; Windhab, E. *J. Food Eng.* **1999**, *38*, 393.
9. Elbadawi, A. M.; Pearson, J. S. *Textile Prog.* **2003**, *33*, 1.
10. Naguib, H. E.; Park, C. B. *Polym. Eng. Sci.* **2002**, *42*, 1481.