# Chemical and Foaming Stability of Foam Decontaminating Agents - 16137

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## ABSTRACT

This study conducted experiments to evaluate the stability of nano foaming agents by adding various types of surfactants, silica nanoparticles, and viscosifiers with the aim of enhancing the stability of foaming agents containing nanoparticles. Nonionic surfactants such as EM100 showed higher stability as compared to the Sodium Dodecyl Sulfate (SDS) anionic surfactant, and the foam stability decreased as the surfactant concentration increased. The cosurfactant addition did not significantly affect the foam stability, but the addition of Xantan gum-one of the various viscosifiers tested in this study-resulted in the highest foam stability. When silica nanoparticles were added to the surfactant EM100, the foam stability improved further. In particular, the foam stability of the nano foaming agent was observed to be the maximum when a partially hydrophobic nanoporous silica such as KAERI 1 was added, as compared to the addition of a hydrophilic dry silica such as M5. This is because the partially hydrophobic particles were distributed over the liquid film between the foams, thereby preventing drainage and increasing the stability of the foaming agent fluid.

The manufactured nano foaming agent can be used not only for the effective decontamination of large-sized equipment or large facilities but also for overcoming the problem of production of a large amount of radioactive waste during chemical decontamination.

## INTRODUCTION

Facilities that handle radioactive materials become aged after a long period of operation. Hence, the maintenance, repair, and decommissioning of the facilities are periodically required. Consequently, decontamination technology has been developed to prevent the proliferation of radioactive materials and to reduce the radiation exposure of operators during work [1,2].

Currently, chemical solution decontamination technology is being widely used as it exhibits a high decontamination effect achieved through chemical dissolution as well as oxidation and reduction reactions. However, this technology has a drawback in that a large amount of radioactive liquid waste is produced, which means that the amount of liquid waste produced by the application of decontamination technology needs to be reduced. Foam decontamination technology can significantly reduce the radioactive waste produced after decontamination, since more than 90% of the decontaminating materials used in this technology consist of gases. It can also be used in the decontamination of large-sized equipment or large facilities where application of decontamination technology is difficult. It also allows for remote decontamination [3,4,5]

Decontamination efficiency generally increases with an increase in the contact time between the contaminated surface and the chemical decontaminant. Therefore, maintaining without breaking the foam for a certain time period is required for increasing the decontamination efficiency of the decontaminant. To improve the stability of the foam, surfactants and polymers or inorganic materials such as nanoparticles can be added [6,7].

The present study evaluated the stability of a foaming agent containing nanoparticles by using various types of surfactants and silica nanoparticles. This evaluation will contribute to an increase in the stability of the foam decontaminant as part of the development of an efficient foam decontaminant that can replace chemical solution decontaminant.

## EXPERIMENTAL

## Experiment Material

The present study used nonionic surfactants such as  $Elotant^{TM}$  Milcoside 440N (EM440N, LG Household & Health Care) and  $Elotant^{TM}$  Milcoside 100 (EM100, LG Household & Health Care) and an anionic surfactant such as sodium dodecyl sulfate (SDS, Sigma-Aldrich), which are widely used for commercial purposes, as surfactants consisting of foaming agents [8].

Hydrophilic dry silica (fumed silica, M-5, Cabosil) and hydrophobic silica nanoparticles (K-P20, OCI Co.) were used as commercially available nanoparticles. Spherical mesoporous silica nanoparticles (KAERI 1), which are partially hydrophobic and less than 200 nm in size, are manufactured synthetically using M-5 silica nanoparticles with ethanol and tetraethylorthosilicate (TEOS, Sigma-Aldrich).

Furthermore, Xantan gum (XG, Sigma-Aldrich), carboxymethylcellulose (CMC, Sigma-Aldrich), hyaluronic acid (HA, IPKN), glycerin (Sigma-Aldrich), and gelatin (J. T. Baker<sup>®</sup>) were used as viscosifiers to increase the stability of the foam, whereas dodecanol (Sigma-Aldrich) and decanol (Sigma-Aldrich) were used as cosurfactants.

## **Experiment Method**

Nonionic surfactants, e.g., EM100 and EM440N, and anionic surfactants, e.g., SDS, were manufactured for measuring the foam stability of resulting from the use of different types of surfactants with a 1% concentration. In addition, the foam stability, with respect to the change in concentration of the surfactant, was studied by varying the concentration of EM100 between 0.05 and 3 wt%. The effect of cosurfactant type on foam stability was investigated by adding 0.05 wt% each of dodecanol and decanol, separately to 1 wt% EM100. To determine the effect of viscosifier type on the foam stability, 0.05 wt% each of Xantan gum, CMC, HA, glycerin, and gelatin were added to 1 wt% EM100. Additionally, to determine the effect of the nanoparticles on the foam stability, 1 wt% each of M5, K-P20, and KAERI 1 were separately added to 1 wt% EM100 to perform an experimental comparison of the foam stability with these different nanoparticles.

A glass was filled with 60 mL of the manufactured liquid foaming agent and subsequently filled with nitrogen gas to produce approximately 200 mL of foam. Then, as shown in Fig. 1, the foamability and foam stability were measured over 3,600 s using FoamScan® (TECLIS, France) via image analysis and electrical conductivity measurements.

The change in foam volume, or the fraction of liquid remaining within the foam (liquid fraction), and the volume flowing into liquid as the foam collapsed over time (foam drainage), were analyzed to study the foam stability in real time.



Fig. 1. Scheme of Foamscan instrument.

## **RESULTS AND DISCUSSION**

To study the foam stability with respect to surfactant types, 1 wt% EM100, EM440N, and SDS were used. Fig. 2 shows the results of the foam stability experiment over time. The foam volume decreased by 60 mL and 50 mL when using the SDS anionic surfactant and the nonionic surfactants (such as EM100 or EM440N), respectively.

On the basis of the results listed in Table I, in which the foam volumes over time were compared according to the integration area of its curve, the use of nonionic surfactants such as EM100 and EM440N provided 3.7% and 3.4% higher foam stability, respectively, with respect to SDS.

Thus, nonionic surfactants such as EM100 and EM440N showed higher stability as compared to SDS, whose foamability and stability are already known to be high [8]. However, EM440N is sensitive to temperature and cannot be used over a wide temperature range, whereas EM100 is not sensitive to temperature and the foam produced can be stably maintained, making it an excellent principal surfactant for a nano foaming agent.

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Fig. 2. Variation of foam volume in foam of 1% EM100, SDS, EM440N.

TABLE I.	Integration	area fo	r foam	volume	curve	in	foam	of	1%	EM100	, S	DS,
				EM440N								

	1% SDS	1% EM100	1% EM440N
Integration area for foam volume curve	533,025	552,725	550,934

On the basis of the foam stability experiments on the above surfactant types, an experiment on foam stability with respect to the EM100 concentration was conducted to determine the appropriate concentration of EM100 suitable for manufacturing and applications, as well as for securing an excellent foam stability performance.

As shown in Fig. 3, the results of the experiment, conducted over 3,600 s and using an EM100 concentration in the range of 0.05–3 wt%, indicated that the foamability increased with an increase in the surfactant concentration as expected, but the foam stability decreased at the same time. That is, the foam volume decreased by 40 mL with 0.05 wt% of EM100, by 46 mL with 0.1 wt% EM100, by approximately 50 mL with 0.5 wt% and 1 wt% EM100, and by 54 mL with 3 wt% of EM100.



Fig. 3. Variation of foam volume in foam of 0.05, 0.1, 0.5, 1, 3% EM100.

To determine the effect of the cosurfactant on the foam stability, an experiment was conducted in which decanol and dodecanol of 0.05 wt% concentration were added to a nonionic surfactant such as 1 wt% EM100. As shown in Fig. 4, when the cosurfactant was not added, the foam volume decreased by 49 mL, and after decanol was added, the volume decreased by 57 mL, indicating that the performance was worse with the cosurfactant than without it. The foam volume decreased by approximately 43 mL after dodecanol was added. Thus, it was observed that the cosurfactant did not significantly affect the increase in foam stability.



Fig. 4. Variation of (a) foam volume and (b) liquid fraction in foam of 1% EM100 with 0.05% decanol, dodecanol.

To determine the effect of the viscosifier on the foam stability, an experiment was conducted in which a 0.05 wt% of viscosifier was added to nonionic surfactants such as 1% EM100. The viscosifiers used in this experiment were Xantan gum, CMC, HA, glycerin, and gelatin. According to the results shown in Fig. 5, the foam volume

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decreased by 48 mL when 0.05% Xantan gum was added to 1 wt% EM100, by 50 mL when CMC was added, by 51 mL when HA and gelatin were added, and by 57 mL when glycerin was added. The foam volume of Xantan gum was observed to be the highest at up to 1,000 s; thereafter, CMC and HA showed a nearly similar change in foam volume. In contrast, in the case of glycerin, the foam stability was lower than in the case when the viscosifier was not added.



Fig. 5. Variation of (a) foam volume and (b) liquid fraction in foam of 1% EM100 with Xantan gum, CMC, HA, Glycerin, Gelatin.

The results of the study for the liquid fraction of the foam showed that when Xantan gum was added, the liquid fraction was observed to be significantly higher, and the other viscosifiers showed a relatively low liquid fraction of foam. Accordingly, when a viscosifier such as Xantan gum, which is eco-friendly and biodegradable, was added to a nonionic surfactant such as 1 wt% EM100, not only did it improve the foam stability but it also made effective in waste treatment after decontamination [9].

To determine the effect of silica nanoparticles on the foam stability, 1 wt% concentration of a hydrophilic dry silica such as M5, hydrophobic nanoparticles such as K-P20, and partially hydrophobic nanoporous silica such as KAERI 1 were added to 1 wt% EM100 to be used for evaluating the foam stability. The results of the foamability comparison showed that K-P20 = M5 > KAERI 1, in that order. The results of the liquid fraction in foam shown in Fig. 6 revealed that adding KAERI 1 to 1 wt% EM100 was the most effective, followed by K-P20, whereas M5 showed nearly the same result as the one without silica nanoparticles.



Fig. 6. Variation of (a) foam volume and (b) liquid fraction in foam of 1% EM100 with M5, KAERI 1,

and K-P20.

The effects of the formulation on the liquid fraction have been investigated by determining the time for the initial liquid fraction ( $\epsilon_0$ ) to halved ( $\tau_{(\epsilon 1/2)}$ ) and for the initial liquid fraction ( $\epsilon_0$ ) to become 1/10<sup>th</sup> ( $\tau_{(\epsilon 1/10)}$ ). As shown in Table II,  $\tau_{(\epsilon 1/2)}$  is almost same, regardless of nanoparticles type, as compared to the case using only EM100, while  $\tau_{(\epsilon 1/10)}$  is improved by a factor of 3.2 with KAERI 1, by a factor of 1.3 with K-P20, than for solely EM100.

Thus, it was shown that the hydrophobicity of the nanoparticles affected the foam stability. In particular, it was shown that nano foaming agents that added partially hydrophobic nanoporous silica such as KAERI 1 had the highest foam stability. This is because hydrophobic silica is aligned with the lamellar side, and hydrophilic silica is distributed over the Plateau border, whereas partially hydrophobic nanoparticles are dispersed over the entire liquid film between the foams, preventing drainage and thereby increasing the stability of the nano foaming agent [10,11]. It was observed that adding partially hydrophobic KAERI 1 to 1 wt% EM100 increased the foam stability more than any other silica particle.

	Initial liquid fraction and its time parameters			
	ε <sub>0</sub> (%)	$T_{(\epsilon 1/2)}$ (S)	$T_{(\epsilon 1/10)}$ (S)	
1% M100	22.8	119.3	409.2	
1% M100+1% M-5	16.5	116.3	396.2	
1% M100+1% KAERI-1	18.0	120.3	1,310.0	
1% M100+1% K-P20	17.2	117.3	547.2	

TABLE II. Characteristic foam drainage data:  $\varepsilon_0$ ,  $\tau(\varepsilon_{1/2})$ , and  $\tau(\varepsilon_{1/10})$ 

#### CONCLUSIONS

The present study conducted experiments on nano foaming agents for evaluating their stability by adding various types of surfactants, silica nanoparticles, and viscosifiers to increase the stability of the foaming agents containing nanoparticles. The results showed that nonionic surfactants such as EM100 showed higher stability as compared to the commercial SDS, whose foamability and stability are known to be high. It was also observed that the foam stability decreased as the surfactant concentration increased. The addition of cosurfactants and viscosifiers in the foaming agent compositions showed that the cosurfactant addition did not significantly affect the foam stability, whereas adding Xantan gum, from among the various viscosifiers, produced the highest foam stability. When silica nanoparticles were added to the surfactant EM100, the foam stability improved further. In addition, the foam stability of the nano foaming agent was observed to be at maximum when a partially hydrophobic nanoporous silica such as KAERI 1 was added, as compared to the addition of a hydrophilic dry silica such as M5. This is because the partially hydrophobic particles were distributed over the liquid film between the foams, thereby preventing drainage and increasing the stability of the foaming agent fluid. Thus, the foaming agent, manufactured using a solution in which 0.05 wt% of Xantan gum was added to 1 wt% EM100 and 1 wt% of KAERI 1 nanoparticles were dispersed showed the effective foam stability.

We conclude that the manufactured nano foaming agent can be used for not only the effective decontamination of large-sized equipment or large facilities but also for overcoming the problem of the production of a large amount of radioactive waste during chemical decontamination.

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#### ACKNOWLEDGMENT

This work has been carried out under the Nuclear R&D Program (2012M2A8A5025655) funded by Ministry of Science, ICT & Future planning.