Drop behavior and energy consumption for CO_2 ocean disposal using a new injection process via a static mixer

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Introduction

Several scenarios of CO_2 disposal into the ocean have been proposed for a long-term sequestration as a counteraction measure for global warming. In the disposal process of liquid CO_2, especially, liquid CO_2 would be released from a pipeline through a nozzle to the ocean at the depth deeper than 500 m.[1] Since the density of liquid CO_2 is smaller than that of seawater at the depth shallower than 3000 m, the released CO_2 drops would ascend to the ocean surface. During the drop ascending process, the CO_2 would be dissolved into the seawater from the drops, and the ascending speed would decrease by the reducing size of the drops. The dissolution process should be completed before reaching the sea surface. Since the ascending and dissolution behavior depends on the size of the released CO_2 drops, the releasing size of the drop should carefully designed and controlled on the injection. On the other hand, the effect of CO_2 hydrate should be considered in the disposal process of liquid CO_2, because the thermodynamic condition of CO_2 hydrate formation would normally be satisfied in the ocean at depths greater than 500 m ($T < 283$ K and $p > 44.5$ bar).[2] The nozzle of the CO_2 pipeline could be blocked by the formation of solid CO_2 hydrate upon injection and sequent the agglomeration of the hydrates, and the blockage should be prevented for a continuous and stable injection process.

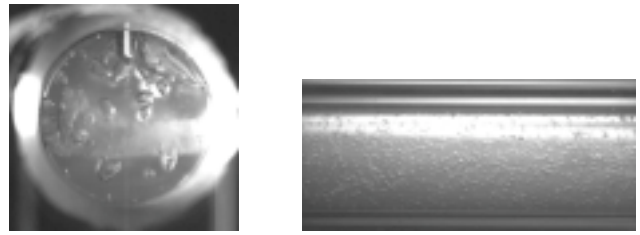
Then, we have proposed a novel injection process of liquid CO_2 into the ocean by utilization of a static mixer as a possible solution for the above difficulties.[3] In this research, behavior of released CO_2 drop from the injection process with static mixer was studied, and estimation of energy consumption was conducted for the scale-up of the injection process.

Experimental

The typical experimental pressure and temperature were, respectively, 7.0 MPa and 277 K. The typical flow for liquid CO_2 was 46.6-93.4 ml/min, and liquid CO_2 flow was installed into deionized water flow (0.47-2.98 L/min). The two-phase flow was injected into the Kenics-type static mixer (Noritake Co. Ltd., Japan) by the high-pressure pump at once. In the experiment, before injected into the mixer and after released from the mixer, the two-phase patterns of the mixture could be observed in the observation section made of polycarbonate, and it was recorded by the high-speed video camera (FOR.A Co. Ltd., VFC-1000 and Photron Ltd.).

Results and Discussion

Figures 1-3 shows typical experimental results for the mixture of liquid CO_2 and water. Liquid CO_2 always dispersed in water flow as drops covered with hydrate film. For the mixture flow before injected into the static mixer, the drop size distributions seemed to conform to the logarithmic normal distribution. On the other hand, the drop size distributions and mean drop diameters for the mixture after released from the static mixer are well characterized by the normal distribution and the Sauter mean diameter. The experimental results suggested that the static mixer is effective for producing liquid CO_2 drops with relatively uniform size distribution. Moreover, the pipe-blockage by the hydrate formation could be prevented in the present system due to an effective mixing process in the static mixer. Thus, the utilization of static mixer in the injection process of liquid CO_2 into the ocean would be advantageous over simple nozzle injection methods.



a) before injected into the mixer b)after released from the mixer

Figure 1. Typical results of the mixture of liquid CO_2 and water. Conditions; CO_2 = 93.4 ml/min, Water = 2.03 L/min.

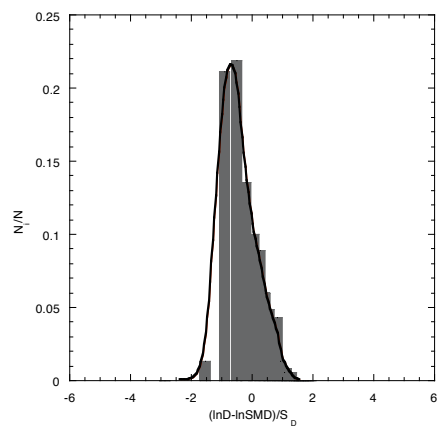


Figure 2. Drop size distribution for Fig.1-a

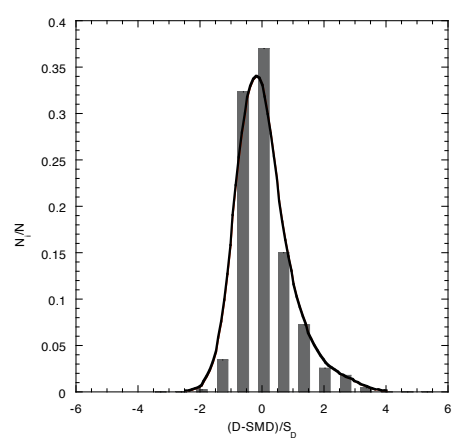


Figure 3. Drop size distribution for Fig.1-b

To examine the feasibility of the present process, a numerical simulation on the fate of the released CO_2 droplets after released from the static mixer was conducted. The fate of the liquid CO_2 in the ocean is one of key information for estimation of the environmental impact caused by the disposed CO_2. The several assumptions were made for the calculations; (1) the released drop is a sphere with uniform initial size, (2) the contribution of the surface hydrate film was ignored because the film thickness is considered much thinner than the drop diameter, (3) the density of liquid CO_2 was constant for simplicity,(4) the drop released would ascend to the sea surface with the terminal velocity determined by the size, density of the drop, (5) the each drop would move independently (no merge or breakup would occur). The dissolution distance of liquid CO_2 drop covered with CO_2 hydrate film, is expressed as a function of dissolution rate[4]. However, this equation is only valid for the drop smaller than 0.4 mm (Stokes region). Then the equation of dissolution distance was extended to the higher Reynolds number region.

Figure 4 shows the ascending behavior of the drop with various initial diameters, assuming the releasing depth of liquid CO_2 500 m. In this condition, the initial diameter should be smaller than 9.1 mm to be dissolved completely before reaching the sea surface. However, liquid CO_2 would be vaporized when the pressure is lower than the saturated vapor pressure, then the ascending rate would be accelerated drastically due to the larger difference in the density between the seawater and gaseous CO_2. To avoid the vaporization, the initial diameter of the drop should be smaller than 4.0 mm to be dissolved completely before reaching the depth of 390 m, where the water pressure equals to the vaporization pressure for 277 K (about 3.9 MPa).

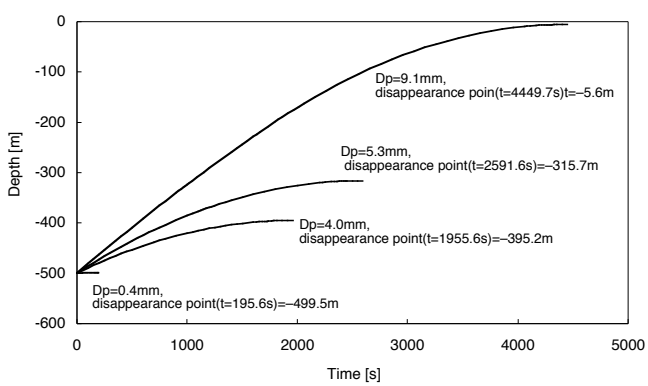


Figure 4. Ascending behavior of the drop with various initial diameters

Energy consumption is also one of important factors to discuss the feasibility of the new injection process. The energy required for the injection process is the pressure drop along the static mixer. The pressure drop is given by the Fanning equation including the individual frictional coefficient of the present static mixer. In the experimental conditions, the maximum energy consumption was estimated to be 0.83 J/g-CO_2. Of course, the energy consumption becomes smaller than this value as a ratio of liquid CO_2 flow rate to water increase.

For the scale-up of the injection process besed on the experimental conditions, we assumed a capture and disposa l process of CO_2 from 100 MW thermal power plant (CO_2 emission rate = 22.9 kg/s, energy generation per unit CO_2 emission = 4365 kJ/kg-CO_2 generation[1]). Because it is known from the experiments that the ratio of the drop mean diameter to the diameter of the mixer is expressed as a function of Weber number, the energy consumption can be estimated by setting up a drop mean diameter. In here, we assumed that the ratio of liquid CO_2 to water flow rate is same to the experimental condition. As summarized in **Table 1**, when the mean diameter of CO_2 drop made to generate in the static mixer was set up in 4.0 mm, the diameter of the mixer was the range of 1.91 from 0.75 m, and the maximum of the energy consumption was 0.406 kJ/kg-CO_2. This is less than 0.01% to the energy generation per unit CO_2 emission. Even if the diameter was set up in 0.1 mm, the rate of the energy consumption was 3.14% of the maximum. Therefore, it can be said that the static mixer is a uniform size CO_2 drop generator of which the energy consumption is very small, and the injection process is very useful for CO_2 ocean disposal.

Table 1. Estimated results of energy consumption for the injection process via the static mixer

SMD [mm]	Partial Ratio of CO2 [kg/kg-total flow]	Mixer Diameter [m]	Mean Flow Velocity [m/s]	We Number [-]	Energy Consumption [kJ/kg-CO2]	Ratio to Power Generation [%]
4.0	0.0136	1.912	0.562	1913	0.406	0.0093
	0.0265	1.462	0.486	1118	0.165	0.0038
	0.0251	1.494	0.492	1168	0.178	0.0041
	0.0480	1.148	0.426	689	0.074	0.0017
	0.0750	0.952	0.385	474	0.041	0.0009
	0.1307	0.747	0.338	292	0.019	0.0004
SMD [mm]	Partial Ratio of CO2 [kg/kg-total flow]	Mixer Diameter [m]	Mean Flow Velocity [m/s]	We Number [-]	Energy Consumption [kJ/kg-CO2]	Ratio of Power Generation [%]
0.1	0.0136	0.422	11.56	93	238.8	3.14
	0.0265	0.322	10.00	54	110.1	1.28
	0.0251	0.330	10.11	57	117.2	1.37
	0.0480	0.253	8.77	34	55.3	0.58
	0.0750	0.210	7.92	23	32.9	0.31
	0.1307	0.165	6.95	14	17.1	0.15

Conclusions

For the new injection process of liquid CO_2 into the ocean using a static mixer, behavior of liquid CO_2 in water and estimation of energy consumption to examine the feasibility were studied. The experimental results suggested that the static mixer is effective for producing liquid CO_2 drops with relatively uniform size distribution. For a simple numerical simulation on the fate of the released CO_2 drops after released from the static mixer, the initial diameter of the drop should be smaller than 4.0 mm to make it dissolve completely when the depth to release liquid CO_2 is supposed 500 m. The distribution of the drop must be taken into consideration to examine in detail. Assuming that the CO_2 injection process was installed in the disposal process of emission CO_2 from 100MW thermal power plant, energy consumption to generate drop with mean diameter 4.0 mm was much smaller than the energy generation per unit CO_2 emission. The static mixer was a very energy consumed device for the generation of uniform size drops. These results indicate that the injection process via a static mixer is a feasible option for the CO_2 disposal process.

References

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