Transport Process of Carbon Dioxide in Seawater and Synthetic Seawater*

Qiusheng LIU**, Katsuya FUKUDA** and Yongwei YANG**

**Graduate School of Maritime Sciences, Kobe University,

5-1-1, Fukaeminami, Higashinada, Kobe 658-0022, Japan

E-mail: qslu@maritime.kobe-u.ac.jp

Abstract

Carbon dioxide (CO₂) ocean sequestration technologies, such as dissolution into seawater, are important to mitigate global warming. In this study, solution processes of CO₂ gas in seawater and synthetic seawater were experimentally and theoretically studied under various pressures and temperatures to evaluate the transport process of CO₂ in seawater. The solubilities of CO₂ in seawater and synthetic seawater were measured by a change in pressure due to absorption at temperatures ranged from 277 K to 333 K near atmospheric pressures, and ranged from 277 K to 298 K at pressures of 1 MPa, 2 MPa, and 3 MPa. It was obtained that the solubilities of CO₂ increase with an increase in pressure, but decrease with an increase in temperature. The solubility of CO₂ in synthetic seawater decreases with an increase in salt concentration. An empirical correlation for solubility of CO₂ in seawater at various temperatures and pressures was obtained based on the experimental data. In the theoretical analysis for the solution of single CO₂ bubble in seawater, the single CO₂ bubble was assumed to be stationary and surrounded by infinite liquid seawater. The rate of solution of bubble in liquid is affected strongly by various parameters, such as solubility, diffusion coefficient, bubble radius, and temperature.

Key words: Solution Process, Carbon Dioxide, Seawater, Synthetic Seawater, Solubility, Henry's Law Constant, Salt Concentration, Diffusion Coefficient, Bubble, Solution Time

1. Introduction

It is known that every year 20 billion tons of carbon dioxide (CO₂) is emitted from the industrial works and power plants, and disposed into the atmosphere due to the consumption of fossil fuel by human beings. The increasing concentration of carbon dioxide in the atmosphere is one of the causes of greenhouse effect. In order to control the concentration of CO₂ in the atmosphere, technologies such as effective use of fossil fuel and conversion to clean energy are important. On the other hand, the technology of recovering the emitted CO₂ and isolating from the atmosphere is also considered to be effective ⁽¹⁾. For example, as shown in Fig.1, after separating and collecting the CO₂ gas produced from thermal power plant by the chemistry absorbing method or the physical adsorbing method, it then can be disposed into the ocean. One of the methods is to put carbon dioxide directly into the deep sea, and it is stored in the ocean by dissolving in it. It is considered that the

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carbon dioxide gas supplied to the deep sea is isolated from the atmosphere over about 1000 years. In order to absorb and dispose the CO₂ in the ocean, it is required to dissolve it into seawater, and it is necessary to investigate the solubility of CO₂ in seawater at various pressures and temperatures. Furthermore, in order to analyze global-scale circulation of CO₂ gas, the detailed fundamental data of solubility and diffusion coefficient are required.

Many researches ^{(2), (3)} were reported about the solubility of the CO₂ gas in pure water. However, the data of the solubility in seawater is seldom reported and not completely understood. Stewart and Munjal ⁽⁴⁾ reported their results of solubility of CO₂ in distilled water, artificial seawater in the temperature ranged from -5 °C to 25 °C under the pressures ranged from 10 to 45 atm. The solubility decreased with an increase in salt concentration in seawater. However, the temperature is limited and the correlation for solubility was not obtained. Weiss ⁽⁵⁾ obtained the solubility at the temperatures ranged from -1 °C to 40 °C, the effect of pressure was not reported. Nighswander et al. ⁽⁶⁾ obtained the experimental data of solubility for CO₂ in water and 1wt% NaCl solution. However, the data for general seawater (3.4% NaCl solution) was not reported.

In this study, solution processes of CO₂ gas in seawater and synthetic seawater were experimentally studied under various pressures, temperatures, and salt concentrations to evaluate the solubilities of CO₂ in seawater. The solubilities of CO₂ in seawater were measured by a change in pressure due to absorption at pressures. An empirical correlation for solubility of CO₂ in seawater at various temperatures and pressures was obtained based on the experimental data. Furthermore, solution process of single CO₂ bubble in seawater was theoretically studied to investigate the effects of temperature, pressure, diffusion coefficient, and initial bubble diameter on the complete solution time.

Fig.1 CO₂ ocean sequestration technology.

Nomenclature

c	density ratio of the gas to the liquid
D_{if}	diffusion coefficient, m ² /s
$\dot{G}$	mass flux at the wall of bubble
H	Henry's law constant, Pa
n	mole numbers, mole
P	pressure, Pa
R	radius of bubble, m
R_0	initial radius of bubble, m
$\dot{R}$	decreasing rate of radius.
r	coordinate along the radius, m

S	solubility, mol/m ³
T	temperature, K
t	time, s
V	volume, m ³
x	solubility (mole fraction)
ρ	density, kg/m ³

Subscripts

l	liquid
g	gas
w	surface of bubble

2. Experimental Apparatus and Method

Figure 2 shows the schematic diagram of the experimental apparatus. The experiments were conducted in a stainless steel vessel which is 60 mm in diameter, 170 mm in height, and 480 cm³ in volume. The gas solubilities were determined by a barometric method reported by Luhning and Schumpe⁽⁷⁾ and Liu et al.⁽⁸⁾, which involves the measurements of the volumes of the gas and liquid, the temperature, and the total pressure change due to gas absorption. Glass windows were installed for the observation and measurement of the liquid level by a CCD camera. The pressure was measured by a strain gauge pressure transducer and could be read to ± 0.1 kPa. The temperature was measured by K-type thermocouples with a precision of ± 0.5 deg. The temperature of the liquid was controlled by electric heaters installed outside of the vessel. The liquid temperature was kept constant within ± 1 deg by a PID (proportion-integration-differentiation) controller. A cooling coil in the test vessel was used to lower the temperature or to obtain the experimental data at temperatures lower than room temperature.

Experiments were carried out using the following procedures: (a) the required amount of liquid (seawater or synthetic seawater) was put into the vessel; (b) the liquid was degassed by using a vacuum pump and a magnetic agitator; (c) when the temperature reached the desired value, the agitator was stopped and the CO₂ gas was added slowly to reach a desired pressure; (d) when the temperatures of liquid and gas phases were equal, thermal equilibrium was reached; (e) the initial pressure, temperature, and the level of liquid were recorded; (f) agitation was started; (g) after about 10 min, the agitation was stopped;

Fig.2 Schematic diagram of experimental apparatus for solubility measurement.

the pressure would not change at the saturation state for a definite temperature; (h) the pressure and temperature were recorded, and the amount of dissolved gas was calculated.

The moles of dissolved gas were calculated by

$$n_2 = \frac{\Delta P_{CO_2} V_2}{R' T} \quad (1)$$

where P_{CO_2} is the partial pressure of CO_2 gas which was obtained by subtracting the seawater vapor pressure from the total pressure, P (P_{abs}), ΔP_{CO_2} is the difference of partial pressure of CO_2 gas between the initial state and the final solution (saturation solution) state, V_2 is the volume of gas, R' is the gas constant (8.314 J/(mol·K)), and T is the absolute temperature.

The moles of seawater are

$$n_1 = \frac{\rho_1 V_1}{M_1} \quad (2)$$

where ρ_1 , V_1 , and M_1 are the density, the volume, and the molecular weight of seawater, respectively. Physical properties of seawater are shown in the literatures ^{(3), (9)}.

The mole fraction of dissolved gas (n_2) in seawater (n_1) is,

$$x = \frac{n_2}{n_1 + n_2} \quad (3)$$

The solubility of CO_2 expressed as moles of CO_2 per cubic meter of seawater (in the unit of mol/m³) is

$$S = \frac{n_2}{V_1} \quad (4)$$

Then, Henry's law constant is

$$H = \frac{P_{CO_2}}{x} \quad (5)$$

The measurement errors for pressure, volume, and temperature were 0.2%, 0.2%, and 0.75%, respectively. Then, the measurement errors for n_2 , x , and H were estimated to be about 1.5%. The reproducibility of solubility was with $\pm 5\%$ for triplicate measurements.

3. Experimental Results and Discussion

The experimental data were obtained at temperatures ranged from 277 to 298 K, and the pressures ranged from around 1 MPa to 3 MPa. Moreover, the temperatures ranged from 277 K to 333 K at pressures near atmospheric pressures.

In the measurement of solubility, to clarify the reliability of the experiment and procedure, the solubility for CO_2 in pure water was also measured and compared with

previous data. Figure 3 illustrates the Henry's law constants calculated from the experimental data of solubility for CO₂ in pure water under pressures from near atmospheric pressure up to 200 kPa. The dashed line shows the data reported by Hodgman⁽¹⁰⁾. It can be seen that the experimental data of pure water shows good agreement with the data tabulated by Hodgman⁽¹⁰⁾; they are increasing with the increase of temperature. On the other hand, the Henry's law constants of CO₂ in pure water show lower values compared with those in seawater near atmospheric pressure as shown in the figure.

Fig.3 Henry's law constants of CO₂ in pure water and seawater.

Table 1 Solubility of CO₂ in seawater at pressures from 101 kPa to 157 kPa.

P_{abs} [kPa]	T [°C]	P_{CO_2} [kPa]	x [10 ⁻³]	S [mol/m ³]
103.8	4.2	102.9	0.93	52.3
105.7	4.2	104.8	0.92	51.6
103.8	4.1	102.9	0.93	52.4
107.3	10.5	105.9	0.88	49.4
106.3	10.5	104.9	0.81	45.2
106.7	9.8	105.5	0.82	46.0
102.4	19.8	100.0	0.56	31.6
103.4	19.9	101.0	0.56	31.4
101.4	19.8	99.0	0.60	33.9
109.4	24.6	106.3	0.57	31.8
109.4	24.8	106.2	0.53	29.8
107.6	25.0	104.1	0.48	38.6
139.6	31.4	134.9	0.67	37.7
157.2	38.7	150.4	0.65	36.5
142.5	40.2	135	0.56	31.4
139.6	47.3	129.1	0.49	27.2
136.6	48.6	125.6	0.45	25
139.6	54.5	124.7	0.41	22.8
153.3	59.5	135.7	0.46	25.7
134.7	62.2	114	0.34	19.1

Table 2 Solubility of CO₂ in seawater near 1MPa.

P_{abs} [kPa]	T [°C]	P_{CO_2} [kPa]	x [10 ⁻³]	S [mol/m ³]
1034.0	4.2	1033.0	8.24	476.1
1025.1	4.4	1024.2	8.10	468.1
997.7	4.4	996.7	7.84	451.9
1103.6	10.2	1102.2	7.42	423.5
1029.1	10.0	1027.7	7.74	443.0
1005.5	10.2	1004.2	7.55	433.1
1031.6	20.0	1029.2	5.37	304.8
1045.3	20.1	1042.9	5.40	308.2
1020.8	20.1	1018.4	5.31	300.6
995.4	25.2	992.1	4.54	258.5
983.6	25.2	980.3	4.55	258.2
972.8	25.2	969.5	4.47	253.4

Table 3 Solubility of CO₂ in seawater near 2MPa.

P_{abs} [kPa]	T [°C]	P_{CO_2} [kPa]	x [10 ⁻³]	S [mol/m ³]
2026.0	4.0	2025.2	12.6	730.8
2072.1	4.3	2071.2	12.3	713.8
1974.0	4.3	1973.2	12.0	693.3
2004.7	10.2	2003.4	10.2	593.1
1947.1	10.3	1945.8	10.4	614.3
2007.0	10.3	2005.6	10.0	586.2
1945.0	19.9	1942.6	8.44	487.8
1942.0	20.0	1939.6	8.27	477.0
1962.6	20.0	1960.2	8.23	474.6
1945.6	25.4	1942.4	7.72	441.2
2072.5	25.2	2069.2	7.78	447.6

Table 4 Solubility of CO₂ in seawater near 3MPa.

P_{abs} [kPa]	T [°C]	P_{CO_2} [kPa]	x [10 ⁻³]	S [mol/m ³]
2890.2	9.6	2888.9	11.4	671.3
2875.5	9.7	2874.2	11.6	684.2
3043.1	9.6	3041.8	11.3	659.8
3043.3	20.0	3040.9	9.97	567.0
3024.7	20.3	3022.2	9.58	558.0
3012.9	20.1	3010.4	9.81	570.5
2982.9	25.2	2979.6	9.39	543.3
2960.3	25.3	2957.0	9.09	526.3
3084.9	25.2	3081.6	9.13	533.4

Table 1 shows the solubility, S , in the unit of mol/m^3 , and the mole fraction solubility, x , of CO_2 in seawater at pressures from 101 kPa to 157 kPa at temperatures ranged from 4.1 °C to 62.2 °C (277 K to 335 K). All the pressures are taken from values at saturated solution condition. The mole fraction solubility increases from 0.34×10^{-3} to 0.93×10^{-3} with decreasing temperatures from 335 K to 277 K. The solubility per unit volume, S , shows the same trend with mole fraction solubility, it increases from 19.1 mol/m^3 to 52.4 mol/m^3 with the decrease of temperature. Tables 2, 3, and 4 show the solubilities of CO_2 in seawater at pressures near 1 MPa, 2 MPa, and 3 MPa, respectively.

Figure 4 shows the mole fraction solubilities, x , at various pressures for the temperatures ranged from 277 K to 298 K. It is understood that the solubilities increase with an increase in pressure, and decrease with an increase in temperature.

Figure 5 shows the solubilities, S , at temperatures of 283 K and 298 K under various pressures. The data by Stewart and Munjal⁽⁴⁾, and Broecker⁽¹¹⁾ are also shown in the figure for comparison. As shown in the figure, almost all the experimental data agree well with the data by Stewart and Munjal⁽⁴⁾, and Broecker⁽¹¹⁾ within -4% to 8% except the data at 283 K under 2 MPa: the experimental data are 16% lower than Stewart and Munjal's data⁽⁴⁾ at 283 K and 2 MPa. As reported by Stewart and Munjal⁽⁴⁾, they used an experimental apparatus

Fig.4 Solubilities at various pressures and temperatures.

Fig.5 Comparison of the author's experimental data with the data by Stewart and Munjal⁽⁴⁾, and Broecker⁽¹¹⁾.

Fig.6 Henry's law constants of CO₂ in seawater at various temperatures and pressures.

consisting of an autoclave, a liquid sample-withdrawal and chemical analysis instrument. On the other hand, in the present work, the authors used a barometric method by measuring the changes in pressures due to the absorption of CO₂ in seawater. The difference between authors' data with those by Stewart and Munjal is considered to be arising from the difference in the experimental method.

Figure 6 shows Henry's law constants for CO₂ in seawater at various pressures and temperatures. They are calculated from the experimental data tabulated in Tables 1 to 4. As shown in Fig.6, the Henry's law constants increase with the increases in pressures and temperatures. It should be noted that the correlation for Henry's law constant at a high pressure should take into account the effect of pressure as reported by Liu et al. in the previous paper⁽⁸⁾. An empirical correlation based on authors' experimental data at various pressures and temperatures was obtained as following equation.

$$\ln\left(\frac{H}{H_0}\right) = A\left(1 - \frac{T_0}{T}\right) + B\ln\left(\frac{T}{T_0}\right) + C\left(\frac{T}{T_0} - 1\right) + f(P) \quad (6)$$

where, H (MPa), T (K) are the Henry's law constant and the temperature, respectively. And, $f(P) = m_1 P^2 + m_2 P + m_3$, P (MPa) is system pressure, $A=27.54$, $B=-27.0$, $C=5.60$, $H_0=187.6$ MPa, $T_0=298.15$ K, $m_1=0.025$, $m_2=0.137$, $m_3=-0.0317$.

The calculated values by Eq.(6) are also shown in Fig.6 as solid and dashed lines. They agree with author's experimental data within $\pm 6\%$. The data obtained from Stewart and Munjal⁽⁴⁾ are also shown in the same figure for comparison. It is understood that the correlation can express their data within $\pm 15\%$.

To investigate the effect of salt concentration on the solubility, experiments were carried out using several kinds of synthetic seawater with different weight concentration of NaCl solution. Figure 7 shows solubilities at a temperature of 283 K for salt concentrations ranged from 1 wt% up to 5 wt%. The data for seawater (3.4 wt%) was shown in the same figure for comparison. We can see the solubilities decrease with an increase in salt concentration. It is fruitful to have a check on previous data at other salt concentrations.

Stewart and Munjal ⁽⁴⁾ reported some data at salt concentrations of 3.4 wt%, 10.3 wt%, and 17.2 wt % at a temperature of 283 K under 1 MPa. Their data are shown in Fig.7 by solid symbols for reference. We can see their data show the same dependence on salt concentration: the solubility decreases with an increase in salt concentration. As can be seen from the figure, their data are lower than the authors' data due to their higher salt concentrations. We can obtain the similar result if we compare Stewart and Munjal's data with author's experimental data at other temperatures such as 277 K, 293 K for salt concentration of 4%. It is considered that the solubilities at various salt concentrations and temperatures measured in this work are reasonable.

Fig.7 Solubilities of CO₂ in seawater and synthetic seawater at various salt concentrations.

4. Theoretical Study of Solution and Diffusion Process for Single CO₂ Bubble in Liquid Seawater

As explained in the introduction of this research, in order to dispose the CO₂ in the ocean, it is necessary to dissolve it into seawater by a method of bubble solution through a nozzle (see Fig.1). In this section, solution process of single CO₂ bubble in seawater is numerically solved to investigate the effects of parameters such as temperature, pressure, diffusion coefficient, and initial bubble diameters on the complete solution time. As the first stage of this study, we just deal with the normal standard seawater (salt concentration 3.4%) in this solution. The solubilities measured at various pressures and temperatures in this work are used in the numerical solution.

4.1 Basic Equation and Boundary Condition

Figure 8 shows the physical model for single CO₂ bubble solution in seawater. The physical model is the same with that in authors' previous analysis ^{(12), (13)}. Following assumptions are made to obtain theoretical solutions.

- (1) Bubble is spherical and stationary in the liquid.
- (2) The concentration of CO₂ gas at the gas-liquid interface is governed by Henry's law.
- (3) Surface tension in the gas-liquid boundary is neglected.

According to the above assumptions, the mass conservation equation for CO₂ gas in liquid is as follows:

$$\frac{\partial \rho_g}{\partial t} + \frac{1}{r^2} \frac{\partial}{\partial r} (r^2 \rho_g u_g) = 0 \quad (7)$$

Fig.8 Physical model of single CO₂ bubble solution and diffusion in seawater.

where, one-dimensional spherical coordinate is used, r is coordinate along the radius, t is time, ρ_g is density of the gas, and u_g is velocity of gas in the liquid. u_g is expressed by the following equations ^{(12), (13)}:

$$u_g = \frac{R^2}{r^2} \dot{R} - \frac{\rho_l}{\rho_g} Dif \frac{\partial}{\partial r} \left[\frac{\rho_g}{\rho_l} \right] \quad (8)$$

where, ρ_l , R , $\dot{R}$ and Dif are density of liquid, radius of bubble, decreasing rate of radius, and diffusion coefficient.

Substituting Eq.(8) into Eq.(7), and dividing by ρ_l , we have,

$$\frac{\partial c}{\partial t} + \frac{1}{r^2} \frac{\partial}{\partial r} (c \dot{R} R^2 - r^2 Dif \frac{\partial c}{\partial r}) = 0 \quad (9)$$

where, c is the density ratio of the gas to the liquid.

Boundary conditions are:

$$r \rightarrow \infty, \quad c_\infty = 0 \quad (10)$$

$$r=R, \quad c_w = P_{co}/H \quad (11)$$

$$r=R, \quad \dot{G} = \rho_{gi} \dot{R} = \rho_l Dif \left[\frac{\partial c}{\partial r} \right]_w \quad (12)$$

where, H is Henry's law constant evaluated by Eq.(11) when solubility is used as weight concentration, c_w is the density ratio at the wall of bubble, P_{co} is pressure of the bubble, ρ_{gi} is density of the gas within the bubble, and $\dot{G}$ is mass flux at the interface of bubble.

Using dimensionless variables determined by Eq.(13), Eq.(9) is expressed as dimensionless form shown in Eq.(14):

$$t^* = \frac{Dif}{R_0^2} t, \quad R^* = \frac{R}{R_0}, \quad r^* = \frac{r}{R_0}, \quad c^* = \frac{c}{c_w} \quad (13)$$

$$\frac{\partial c^*}{\partial t^*} + \frac{1}{r^{*2}} \frac{\partial}{\partial r^*} (c^* \dot{R}^* R^{*2} - r^{*2} \frac{\partial c^*}{\partial r^*}) = 0 \quad (14)$$

where, R_0 is initial radius of CO₂ bubble. Boundary conditions are transformed into,

$$c_w^* = 1, \quad c_\infty^* = 0, \quad \dot{R}^* = \frac{1}{b} \left[\frac{\partial c^*}{\partial r^*} \right]_w \quad (15)$$

where,

$$b = \frac{\rho_{gi}}{\rho_l c_w} \quad (16)$$

As shown in Eqs.(15) and (16), the solution and diffusion process is governed by the parameter b .

$$c_w = \frac{P_{CO_2}}{H} = \frac{\rho_{gi} R^* T}{H}, \quad b = \frac{H}{\rho_l R^* T}$$

then c_w is proportional to ρ_{gi} , and the process is governed by various variables such as temperature, diffusion coefficient, solubility, and initial radius.

The Eq.(14) was numerically solved by finite difference method.

4.2 Results of Numerical Solution

Figure 9 shows the solution and diffusion process of the single CO₂ bubble in seawater at temperatures of 277 K, 283 K, and 293 K. The system pressure is 0.1 MPa. Henry's law constants measured by authors at the corresponding temperatures of 277 K, 283 K, and 293 K are 110 MPa, 126 MPa, and 158 MPa, respectively. And the diffusion coefficients at the corresponding temperatures are 1.03×10^{-9} m²/s, 1.24×10^{-9} m²/s, and 1.63×10^{-9} m²/s, respectively ^{(14),(15)}. Densities for seawater are 1028 kg/m³ at 277 K, 1028 kg/m³ at 283 K, and 1026 kg/m³ at 293 K. b are obtained as 0.8574, 0.9616, and 1.1645 at the corresponding temperatures based on Eq.(16).

The ordinate of Fig.9 is the dimensionless radius, and the abscissa is the dimensionless time. The solid line and the dashed lines show the results at various temperatures. As shown in the figure, the total solution time is 30% shorter at 277 K than that at 293 K. This means that the solution process is enhanced by lowering the temperature.

Fig. 9 Theoretical solutions of nondimensional radius-time relation for single CO₂ bubble solution in seawater.

Figures 10(a)-(c) are numerical solution results for dimensionless radius-time relation for single CO₂ bubble solution in seawater at pressures of 1 MPa (a), 2 MPa (b) and 3 MPa (c). It can be seen from Figs. 10(a)-(c) that the dimensionless complete solution time at a definite temperature becomes larger as the pressure increased.

(a) 1 MPa

(b) 2 MPa

(c) 3 MPa

Fig. 10 Theoretical solutions of nondimensional radius-time relation for single CO₂ bubble solution in seawater.

As shown in Eqs.(15), and (16), the solution process is governed by parameter b . Henry's law constant is a function of temperature, and b is also determined by temperature. As shown in Figs.9 and 10, the solution time decreased with a decrease in temperature as can be derived from Eq.(15) because the value of b decreased with the increase of temperature.

On the other hand, according to correlation (Eq.(6)), Henry's law constant increases with the pressure, then the value of b ($b = H/(\rho_l R' T)$) will increase with the pressure. As the result, the solution time increased with the pressure as shown in Figs. 10(a)-(c).

We can derive from Fig.10 that the complete solution time will increase with an increase in initial diameter (or radius) because the dimensional time, t ($t = t^* R_0^2 / D_{if}$), is proportional to the square of bubble radius as well as the nondimensional time, t^* .

Figure 11 shows the comparison of solution time for seawater with pure water. Seawater needs more time because of its lower solubility compared with that of pure water.

Fig. 11 Comparison of solution process with pure water.

5. Conclusions

Solution processes of CO_2 gas in seawater and synthetic seawater were experimentally studied under various pressures, temperatures, and salt concentrations to evaluate the solubilities of CO_2 in seawater. Moreover, solution time for single CO_2 bubble in seawater was numerically obtained. Following results were obtained.

- (1) The experimental data agree well with Stewart and Munjal's data ⁽⁴⁾ within -4% to 8% except the data at 2 MPa and 283 K.
- (2) An empirical correlation for solubilities of CO_2 in seawater at various temperatures ranged from 277 K to 298 K, and pressures ranged from atmospheric pressure to 3 MPa was obtained based on the experimental data. The correlation can express the experimental data within $\pm 6\%$, and express the data by Stewart and Munjal ⁽⁴⁾ within $\pm 15\%$.
- (3) The solubility of CO_2 in seawater was lower than that in pure water. It decreases with the increase in salt concentration.
- (4) The solution rate of bubble in seawater is affected strongly by various parameters, such as solubility, diffusion coefficient, bubble radius, pressure, and especially temperature. The bubble solution process is enhanced by lowering the temperature: the total solution time is 30% shorter at 277 K than that at 293 K under 0.1 MPa.

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