Optimum operating conditions of DIR-MCFC without vapor-phase carbonate pollution

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Abstract

In direct internal reforming-molten carbonate fuel cells (DIR-MCFC), deterioration of catalytic activity takes place in the anode channel due to both liquid-phase pollution and vapor-phase pollution. Although the liquid-phase pollution can be solved by installing protective barrier, an effective defense method and a reactivation method of vapor-phase polluted catalyst have not established yet. In order to study the reactivation method, the adhesion form of potassium compounds in the polluted catalyst under the various gas conditions was evaluated by using a thermogravimetric analyzer in which water vapor can feed. Additionally, the activity of the treated catalyst was also tested by a differential reactor. As a result, KOH changes to K_2CO_3 under a CO_2 concentration of 25% or more. KOH becomes a solid-phase from the liquid-phase when it is changed into K_2CO_3. Therefore, the catalyst can not be reactive because K_2CO_3 chokes pores of the catalyst. However, the activity of the polluted catalyst is revived to 80% of the initial activity by controlling the gas species concentration, especially CO_2. Moreover, the catalytic activity can be revived under a steam–carbon ratio of 2.0 or more. Based on the results obtained by these fundamental experiments, the reactivation methods of catalyst polluted are proposed as follows: (i) catalyst should be loaded more upstream in the anode; (ii) in order to reactivate the polluted catalyst, the DIR-MCFC should maintain a steam–carbon ratio of 2.0 or more; (iii) gas conditions to activate the catalyst should be applied regularly.
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1. Introduction

In direct internal reforming-molten carbonate fuel cells (DIR-MCFC), deterioration of catalytic activity takes place in the anode channel due to both liquid-phase pollution and vapor-phase pollution [1–5]. The liquid-phase pollution meant that catalytic activity is deteriorated by the molten salt's ($62Li_2CO_3/38K_2CO_3$) adhering to the catalyst [6]. It can be solved by installing protective barrier in the pollutant pathway [7]. On the other hand, the vapor-phase pollution meant that that catalytic activity is deteriorated by KOH adhering to the catalyst [8]. Because the vapor-phase pollution is caused in the entire electrode, an effective defense method has not yet been established. Moreover, a reactivation method of a vapor-phase polluted catalyst has not yet been developed. In the vapor-phase pollution, the adhesion form of content potassium in the polluted catalyst is decided depending on the various gas conditions. Generally,

potassium changes the form to KOH or K_2CO_3 by CO_2 and H_2O concentration as shown in Eq. (1).

$$2KOH + CO_2 \Leftrightarrow K_2CO_3 + H_2O \tag{1}$$
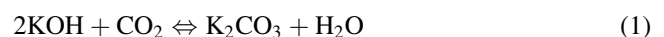
Though KOH is the liquid-phase at the cell temperature, K_2CO_3 is the solid-phase. Although the supplying inert gas can volatilize KOH from the polluted catalyst, it can not volatilize K_2CO_3. Therefore, if the influence of the gas compositions on KOH in the polluted catalysts is evaluated, a reactivation method for the vapor-phase polluted catalyst is proposed. The adhesion form of the potassium content in the polluted catalyst was evaluated by using a thermogravimetric analyzer in which water vapor can be fed. Additionally, a differential reactor also tested the activity of the treated catalyst [9]. Moreover, the influence of the steam–carbon ratio, which is the operating condition of the DIR-MCFC, on the KOH form is examined. Finally, this paper proposes a reactivation method for catalyst polluted by vapor-phase carbonate and the optimum the conditions operating a DIR-MCFC without vapor-phase carbonate pollution.

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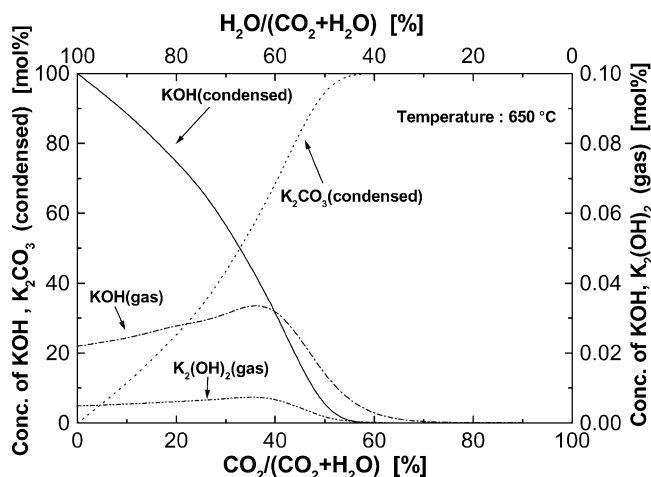*E-mail address:* sugiura@sys.osaka-pct.ac.jp (K. Sugiura).

Fig. 1. Chemical equilibrium calculation of KOH–K_2CO_3.

2. Chemical equilibrium calculation of KOH–K_2CO_3 reaction

Fig. 1 shows the result of calculating the chemical equilibrium of the KOH–$_2CO_3$ reaction shown in Eq. (1). The thermodynamic data was quoted from JANAF Thermo-chemical Tables [10]. Here, "condensed" means the coexistence of both of the solid-phase and the liquid-phase. A reactive temperature is the cell temperature of 650 °C. The chemical equilibrium is calculated by changing $CO_2/(CO_2 + H_2O)$, which is arranged with the mole fractions. KOH (liquid-phase) is changed into K_2CO_3 (solid-phase) by the addition of CO_2. In the condensed-phase, the concentration of KOH and K_2CO_3 correspond when the CO_2 concentration is about 33%. In the vapor-phase, KOH and $K_2(OH)_2$ exist a little, and they are changed into K_2CO_3 (solid-phase) with increasing CO_2, too. Here, K_2CO_3 (vapor-phase) is negligible under this

calculated condition because it is about 2×10^{-8} mol%. Therefore, if the DIR-MCFC could be operated under CO_2 of 33% or less, the catalytic activity may be able to be revived to volatilize KOH by supplying an inert gas. Moreover, the concentration of each gas species hardly influences the reaction temperature (range of 400–650 °C).

3. Experimental apparatus and procedures

From the above-mentioned chemical equilibrium calculation, steam and the CO_2 concentration greatly influence the form of KOH in the catalyst. If the mass change of the polluted catalyst can be measured under various gas compositions, the form of KOH in the polluted catalyst can be confirmed because the mass of KOH and K_2CO_3 is greatly different. However, steam can not be supplied to the reactor because the sensor is in the reactor of a conventional thermogravimetric analyzer. Therefore, the thermogravimetric analyzer in which water vapor can be fed employed in this study as shown in Fig. 2. The mass change of the polluted catalyst filled to the sample basket, which is made of a stainless mesh, can be measured by being hung from an electronic balance within the reactor. The temperature of the polluted catalyst is also measured by thermocouple (type: K, diameter: 0.5 mm) that is installed in the basket so as not to interfere in the mass measurement. The computer continuously takes these data under the temperature rise with electric furnace. The supply gases, which are mixed H_2, N_2, and CO_2 by mass flow controller, are fed to the reactor through the humidifier. The supply gas temperature rises by passing the alumina ball layer that is installed within the reactor. The experimental conditions are shown in Table 1. The reactor is heated up until 800 °C at 5 °C/min of heating rate. Gas flow rate is 4.17×10^{-5} m³/s. In order to study the
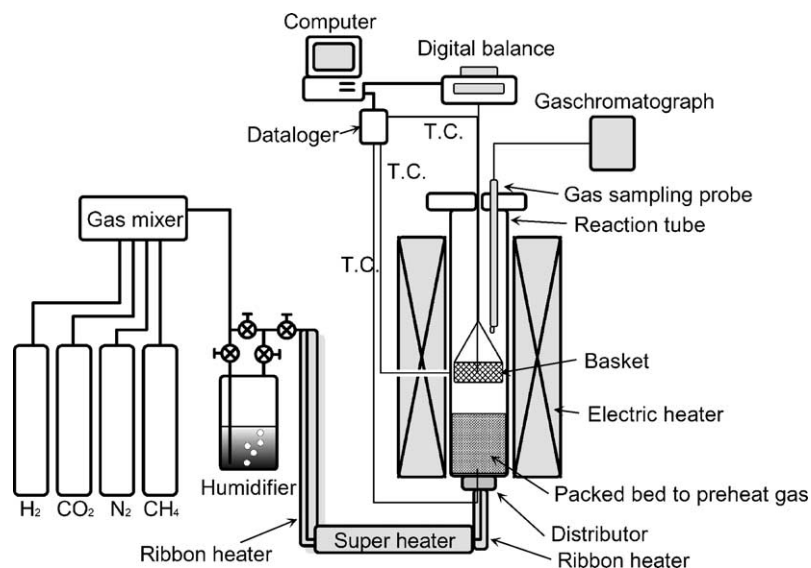

Fig. 2. Schematic diagram of experimental apparatus.

Table 1
Experimental conditions

Concentrations (vol.%)				
N_2	CO_2	H_2O	CH_4	S/C
100	0	0		
90	10	0		
75	25	0		
50	50	0		
25	75	0		
0	100	0		
50	0	50		
25	0	75		
0	10	90		
0	20	80		
0	25	75		
0	40	60		
0	80	20		
		75	25	3.0
		67	33	2.0
		60	40	1.5
		50	50	1.0

Gas flow rate: 4.17×10^5 m^3/s; heating rate: 5.0 °C/min; final temperature: 800 °C; mass of catalyst: 5.0 g; pollution fractions : 0, 1.6, 3.0 mass%.

effect of gas species on the mass change of the polluted catalyst, gas species compositions are widely varied.

The catalyst polluted by vapor-phase carbonate is made according to the following procedures: (1) Ni/MgO catalyst (TOPSOE: type: RKNR) is soaked in the KOH solution of an arbitrary concentration; (2) The catalyst taken out of an aqueous solution is dried in N_2 atmosphere of 250 °C during 24 h. The catalytic activity and the specific surface area of the polluted catalyst made like this are almost the same as those of the polluted catalysts are gathered from DIR-MCFC. Therefore, the catalyst polluted made by this making procedure can imitate the polluted catalyst by vapor-phase carbonate in DIR-MCFC. Here, the pollution fraction of the polluted catalyst are 0, 1.6, 3.0 mass%.

4. Results and discussion

4.1. The effect of adsorbing water on the catalyst

In order to evaluate the effect of adsorbing water on the catalyst and on the mass change of the polluted catalyst, the mass change of the soak/dry catalyst, which is soaked in pure water and dried by furnace, and the dry catalyst, which is only dried under N_2 atmosphere, are measured. Fig. 3 shows the effect of H_2O adsorption in mass change of catalyst. From this figure, the mass change of the dry catalyst decreases by about 2 mass% at 100 °C. On the other hand, the mass change of the soak/dry catalyst decreases by about 2 mass% at 100 °C and decreases by about 5 mass% in the temperature range from 300 to 400 °C. As the reason for these mass decrements is desorption of chemical absorption water and physical absorption water, it has to be considered
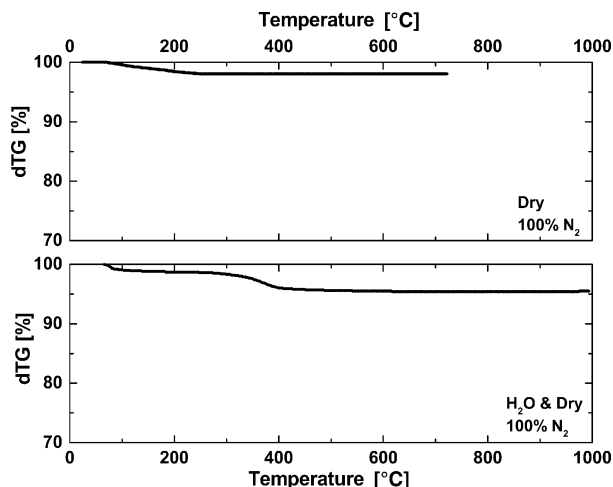

Fig. 3. Effect of H_2O adsorption in mass change of catalyst.

that these mass decrements are included in the experimental data.

4.2. CO_2 concentration dependence of KOH–K_2CO_3 reaction

Fig. 4 shows the mass change of the polluted catalyst by increasing the catalyst temperature in various CO_2 concentrations. The mass decreases by 2–4% at 100 °C and decreases by 10–15% in the temperature range from 300 to 400 °C. The former decrement is desorption of water, the latter decrement is the sum of: desorption of water, the volatilizing of KOH, the evaporation of the absorbed water by KOH and the mass increment to change from KOH into K_2CO_3. Thus, the mass decrement between 300 and 400 °C is defined to ΔM as shown in Fig. 5. The relation between this ΔM and CO_2 concentration is shown in Fig. 6. Here, ΔM is plotted as a decrement from 100%. ΔM decreases by increasing CO_2 concentration and is saturated when CO_2 concentration is 25% or more. In the case of the polluted catalyst of 1.6 mass% of pollution fraction, there must be only 1.6 mass% mass change when all KOH evaporates. However, the mass change is about 13 mass%. The reason is
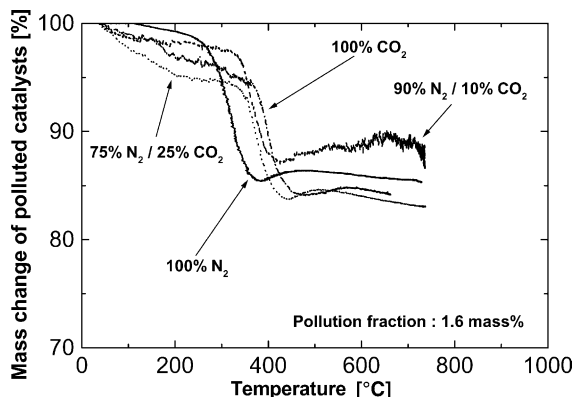

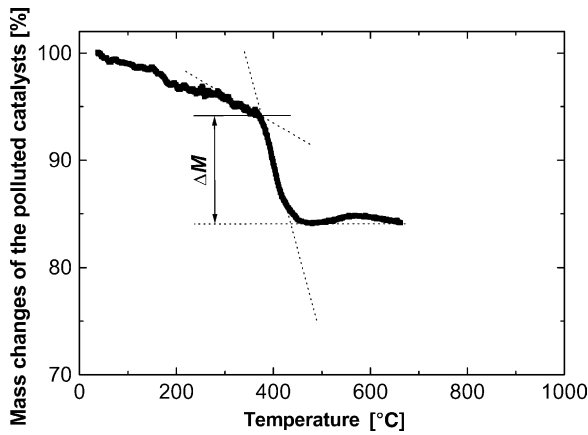Fig. 4. Mass change of polluted catalysts in CO_2/N_2 gas atmosphere.

Fig. 5. The definitions of mass decrement (ΔM) between 300 and 400 °C.

that the mass change of 0% CO_2 corresponds to the sum of: the evaporation of water, the volatilizing of KOH and the evaporation of the absorbed water by KOH. Therefore, the KOH content of ΔM is 1.6 mass% and the remainder is water. On the other hand, all KOH is changed into K_2CO_3 under 100% CO_2. In this case, KOH of 1.6 mass% becomes K_2CO_3 of 1.97 mass% from Eq. (2), and the mass of the polluted catalyst increases, but it decreases about 10%. The reason is that the mass change of 100% CO_2 corresponds to the sum of: the evaporation of water, the evaporation of water absorbed to KOH and a mass increment to change from KOH into K_2CO_3.

$$\frac{K_2CO_3}{2KOH} = \frac{138}{2 \times 56} \cong 1.23; \ 1.6 \, \text{mass}\% \times 1.23 = 1.97 \, \text{mass}\%$$

(2)

It is assumed that the water content in the polluted catalyst is the same if it is a catalyst of the same pollution fraction. Then, the difference between the mass change of 0% CO_2 and the mass change of 100% CO_2 corresponds to the sum of mass increments caused when all KOH is changed into K_2CO_3 and water absorbed to K_2CO_3. The content of ΔM
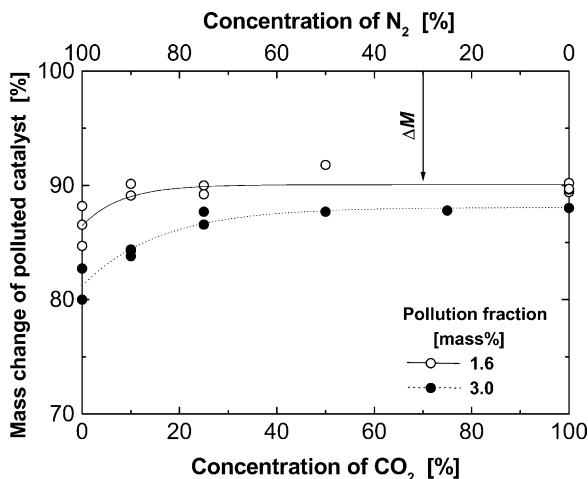

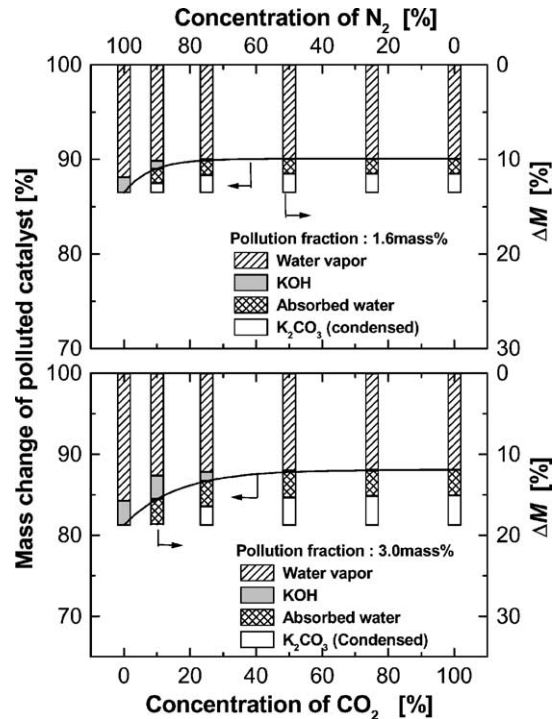Fig. 6. Effect of CO_2 concentration on mass change of polluted catalysts.

Fig. 7. Contents of the mass change in CO_2/N_2 gas atmosphere.

was arranged based on such an idea. Fig. 7 shows the contents of ΔM. Although the absorbed water is evaporated with KOH in 0% CO_2, it is absorbed to K_2CO_3, which is changed from KOH, as CO_2 concentration increases. When the CO_2 concentration becomes 25% or more, KOH has been almost changed into K_2CO_3. Therefore, if the CO_2 concentration is 25% or less, KOH can volatilize from the polluted catalyst and the catalytic activity might be able to be reactivated.

From the above-mentioned result, $\Delta M_{100\% \, N_2} - \Delta M$ based on ΔM of 100% N_2 is arranged to exclude these water influence from ΔM and to be represented by the mass change of the KOH reaction only. Because $\Delta M_{100\% \, N_2}$ shows the mass of KOH and the adsorbed water in the catalyst, K_2CO_3 is hardly generated in the catalyst if $\Delta M_{100\% \, N_2} - \Delta M$ is zero. On the other hand, KOH changes into K_2CO_3 and remains in the catalyst if ΔM is a plus value. Therefore, the data is shown as $\Delta M_{100\% \, N_2} - \Delta M$.

4.3. CO_2/H_2O mixed gas dependence of the KOH–K_2CO_3 reaction

The gas atmosphere around the catalyst in the DIR-MCFC is a CO_2/H_2O mixed gas because CO_2 and H_2O are generated with the cell reaction. Fig. 8 shows effect of CO_2/H_2O gas atmosphere on the mass change of the polluted catalysts. Here, $\Delta M_{100\% \, N_2} - \Delta M$ is arranged to evaluate the variation to K_2CO_3 of KOH. $\Delta M_{100\% \, N_2} - \Delta M$ is saturated when the CO_2 concentration is 30% or more. Although $\Delta M_{100\% \, N_2} - \Delta M$ under CO_2/N_2 atmosphere steadied with 25% or more of CO_2, it under CO_2/H_2O atmosphere it steadied with 30% or
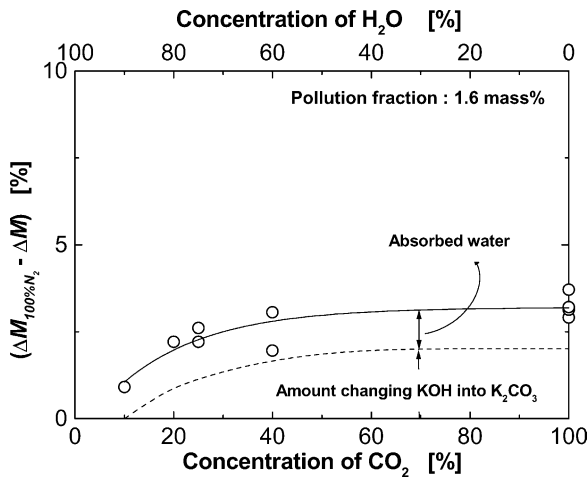
Fig. 8. Effect of CO_2/H_2O gas atmosphere on mass change of polluted catalysts.

more of CO_2. Therefore, as water addition is effective in controlling the changing of KOH into K_2CO_3, the catalytic activity of the polluted catalyst might be able to be reactivated if CO_2 concentration can be suppressed to 30% or less under the high steam atmosphere.

4.4. Evaluation of catalytic activity of the reactivation catalysts

Until Section 4.3, it was considered that the mass reduction was due to evaporation of KOH, and a mass increment was due to a change from KOH to K_2CO_3. The potassium quantity in the catalyst before and after experimenting was measured by atomic absorption spectrochemical analysis to confirm these considerations. Table 2 shows the analysis result. Here, potassium quantity is converted into KOH quantity and the polluted catalyst of the pollution fraction 3.0 mass% was used for the analysis. The pollution fraction (KOH) from the polluted catalyst under the 0% CO_2 condition was detected as about 0.65 mass%. On the other hand, the pollution fraction in the polluted catalyst under the 100% CO_2 condition was detected as about 3.25 mass%; this value corresponds to the pollution fraction of the polluted catalyst before experimenting. In 100% CO_2 experimenting, it is judged that KOH changes into K_2CO_3 and remains in the catalyst because the pollution fraction has hardly changed before and after the experiment. On the other hand, it can be judged that KOH evaporated from the polluted catalyst because the pollution fraction has decreased to one-fifth

Table 2
Comparison of concentration of KOH in polluted catalyst in N_2 with CO_2 gas atmospheres

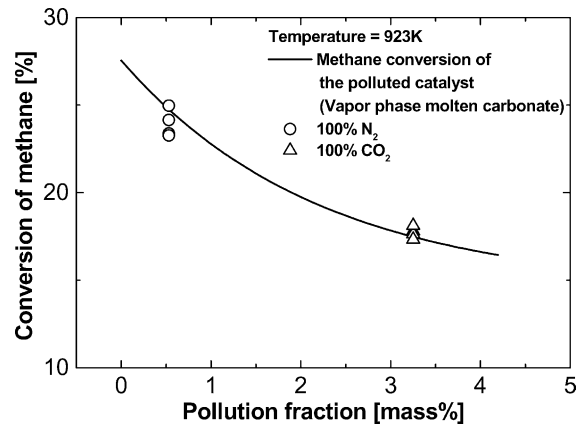|	Before experiment	After experiment	
		100% N_2	100% CO_2
Pollution fraction (mass%)	3.02	1.53	3.25

Fig. 9. Evaluation of catalytic activity of the reactivated catalysts.

of its original value after the experiment of 100% N_2. Here, KOH and K_2CO_3 in the polluted catalyst could not be identified in an X-ray structure analysis because the KOH and K_2CO_3 in the polluted catalyst are little.

Moreover, the differential reactor evaluates the catalytic activity (methane conversion and reaction rate constant) of both catalysts after experimenting under 100% N_2 and 100% CO_2 conditions. Here, the experimental method and the analysis technique have been already published in another paper [8]. Fig. 9 shows the comparison between methane conversion of polluted catalyst by vapor-phase carbonate (solid line) from another paper and methane conversion of catalyst after experimenting. The activity of the catalyst after experimenting under the 100% CO_2 condition is same as catalytic activity of the polluted catalyst (3.0 mass% of pollution fraction). However, the catalytic activity of the polluted catalyst after experimenting under the 100% N_2 (0% CO_2) condition is revived to 80% of the initial activity. Fig. 10 shows the reaction rate constant of the reactivation catalysts. Here, each lines means the reaction rate constant of the catalyst polluted by vapor-phase carbonate from another paper [8]. The catalytic activity of the catalyst after experimenting under the 100% CO_2 condition is not improved, but after experimenting under 100% N_2 condition
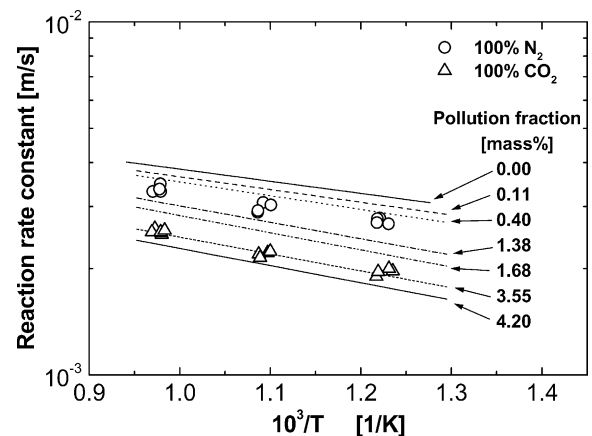

Fig. 10. Reaction rate constant of the reactivated catalysts.

it has been improved. As the slopes of these reaction rate constants are similar to the slope of the reaction rate constant of the catalyst polluted by vapor-phase carbonate, the reaction mechanism does not change even if the polluted catalyst is reactivated. Therefore, the catalytic activity of the polluted catalyst can be revived by controlling the gas composition in operating the DIR-MCFC. From the viewpoint of the catalyst loading, as CO_2 concentration is low and H_2O concentration is high upstream at the anode catalyst is not easily polluted. However, as CO_2 concentration rises by generation with the cell reaction in the downstream anode catalyst is polluted easily.

4.5. Effect of the simulation gas of DIR-MCFC on KOH–K₂CO₃ reaction

As fuel gas of DIR-MCFC is likely to be natural gas, $25CH_4/75H_2O$ has been generally adopted as a gas composition for research. Recently, ratio of steam and methane (S/C) has been decreased from about 1.5 to 2 to improve the power generation efficiency. Therefore, the effect of the simulation gas of DIR-MCFC on the KOH–K₂CO₃ reaction is examined by changing S/C. Fig. 11 shows the mass change of the polluted catalyst by increasing the catalyst temperature in various S/C. The mass for all experimental conditions increases at about 150 °C and decreases in the temperature range from 300 to 400 °C. An increment at 150 °C is adsorption of supplied water because this increment is almost proportional to H_2O concentration. Moreover, this increment is unrelated to the KOH–K₂CO₃ reaction, because the mass change of the catalyst has returned to zero before the catalyst temperature reaches the melting temperature of KOH. On the other hand, a decrement from 300 to 400 °C is related to KOH–K₂CO₃ reaction. Therefore, this decrement is related to ΔM as shown Fig. 12. ΔM increases by increasing S/C (H_2O concentration increases) and it saturates when S/C is 1.5 or more. ΔM is the same tendency as ΔM of the methane even if the methane is replaced with nitrogen. Because the reforming reaction is not caused in the temperature range from 300 to 400 °C as shown in Table 3,
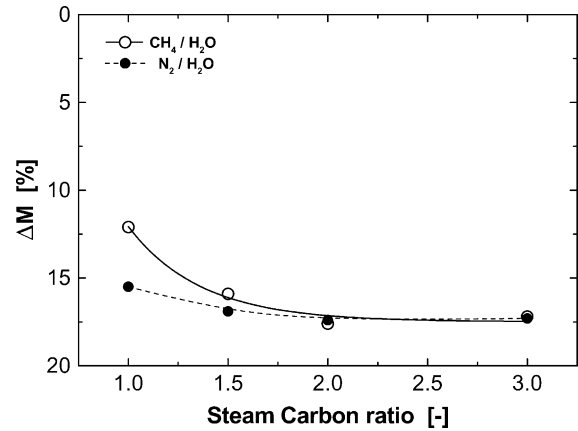

Fig. 12. Effect of CH_4/H_2O gas atmosphere on mass change of polluted catalysts.

Table 3
Dry gas composition under CH_4/H_2O gas atmosphere

Temperature (°C)	Concentration (vol.%)								
	S/C = 3.0			S/C = 2.0			S/C = 1.5		
	CO₂	H₂	CH₄	CO₂	H₂	CH₄	CO₂	H₂	CH₄
350	1.12	0	98.88	1.11	0	98.89	0.78	0.01	99.21
400	1.19	0	98.81	1.08	0.02	98.9	0.86	0.03	99.1
450	1.77	0.12	98.11	1.22	0.09	98.69	0.33	0.14	99.53
500	1.66	0.40	97.94	1.45	0.37	98.18	1.92	0.42	97.65
550	3.57	1.04	95.39	3.45	1.40	95.15	3.71	1.12	95.17

it is thought that the change in ΔM greatly influences H_2O concentration. On the other hand, ΔM decreases when S/C is 1.0, because the carbon deposition occurs. Therefore, the catalytic activity might be reactivated if S/C is 1.5 or more.

Moreover, the methane conversion and reaction rate constant, which are measured by the same method as in Section 4, were added to Figs. 9 and 10, respectively. These results are shown as Figs. 13 and 14, respectively. The catalytic activity of the polluted catalyst experimented on with S/C is of 3.0 almost revived to the initial activity. On the
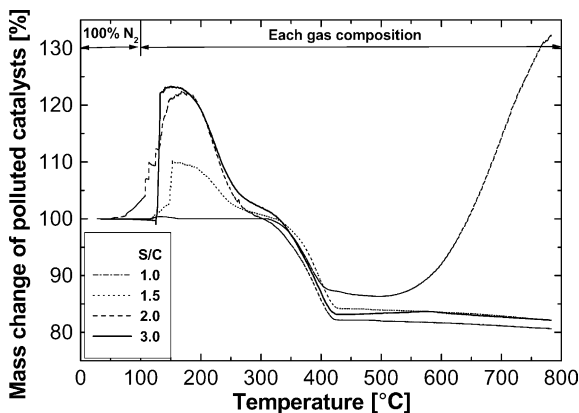

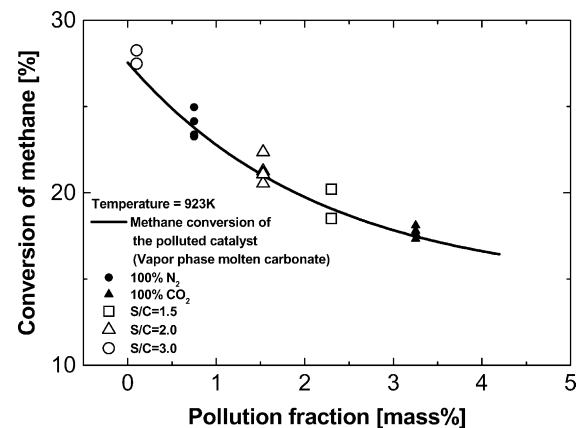Fig. 11. Mass change of polluted catalysts in CH_4/H_2O gas atmosphere.

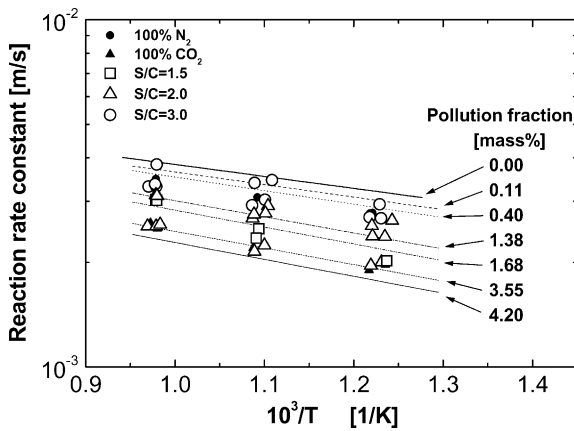Fig. 13. Evaluation of catalytic activity of the reactivated catalysts.

Fig. 14. Reaction rate constant of the reactivated catalysts.

other hand, the methane conversion decreases by decreasing S/C. If the catalytic activity in 100% CO_2 was defined a 0% and the initial activities was defined 100%, the catalytic activity when S/C is 2.0 is revived only 36% of initial activity. As the catalytic activity is revived only 16% of initial activity at 1.5 of S/C, it is difficult to reactivate the polluted catalyst if S/C is 1.5 or less. Moreover, the reaction rate constant with S/C of 3.0 is similar to the one of pollution fraction 0.11 mass%, and the reaction rate constant in with of S/C 1.5 is similar to the one of pollution fraction 3.55 mass% from which the catalytic activity can not be reactivated. Therefore, catalytic activity can be reactivated safely if S/C is two or more.

4.6. Verification of reactivation method by DIR-MCFC

The proposed reactivation method is verified by applying it to the DIR-MCFC. Evaluation method is that the polluted catalyst is loaded in anode channel of DIR-MCFC, and DIR-MCFC is supplied by various gas compositions during start-up procedure. Here, DIR-MCFC made by National Institute of Advanced Industrial Science and Technology—Kansai (AIST) a is 16 cm^2 single cell; the electrodes were sintered nickel as shown in Table 4. The electrolyte eutectic is a mixture of lithium carbonate (Li_2CO_3), by 62 mol%, and potassium carbonate (K_2CO_3), by 38 mol%. The electrolyte matrix is lithium aluminum oxide. A fresh catalyst, which has not been polluted, and the polluted catalyst were used for the catalyst of the DIR-MCFC. The catalyst loading density is 65 mg/cm^2. The operating condition is shown in Table 4. Here, the proposed reactivation method is used as a start-up gas. Fig. 15 shows initial cell performance used by the experiment under the standard condition (STD) and DIR mode condition (DIR). In all conditions, the cell performance in the STD condition is better than cell performance in the DIR condition. Moreover, the gas in the start-up does not influence cell performance because cell performance in the STD condition is the same in most cells. Because there is an individual difference in each cell, cell performance should be arranged by the difference between voltage in

Table 4
AIST's DIR-MCFC components and experimental conditions

Materials	
Cathode	NiO (in situ)
Anode	Ni/Al
Matrix	LiAlO$_2$
Electrolyte	62% Li$_2$CO$_3$/38K$_2$CO$_3$
Electrode area	16 cm^2
Temperature	923 K
Pressure	0.1 Mpa
Current density	0–150 mA/cm^2
Gas utilization	40%
Standard gas composition	
Cathode	70% Air/30 CO$_2$
Anode	70.4% H$_2$/17.6CO$_2$/12H$_2$O
DIR mode gas composition	
Cathode	70% Air/30 CO$_2$
Anode	25% CH$_4$/75H$_2$O (S/C = 3.0)
	40% CH$_4$/60H$_2$O (S/C = 1.5)
Start-up gas composition	
RT to 220 °C	100% Air
220–650 °C	
Cathode	100% CO$_2$
Anode	
CO$_2$	100 ([N$_2$] = 0)
N$_2$	0 ([CO$_2$] = 100)
CH$_4$	25
H$_2$O	75
S/C	3.0
CH$_4$	40
H$_2$O	60
S/C	1.5

STD and voltage in DIR ($dV = V_{STD} - V_{DIR}$) as shown in Fig. 16. The catalytic activity in the cell will be evaluated by using this arrangement method. As dV where a fresh catalyst is installed is almost constant even if a current density increases, the catalyst is reforming the necessary hydrogen for the cell. However, as dV where the polluted catalyst is installed increases with increasing current density, there is
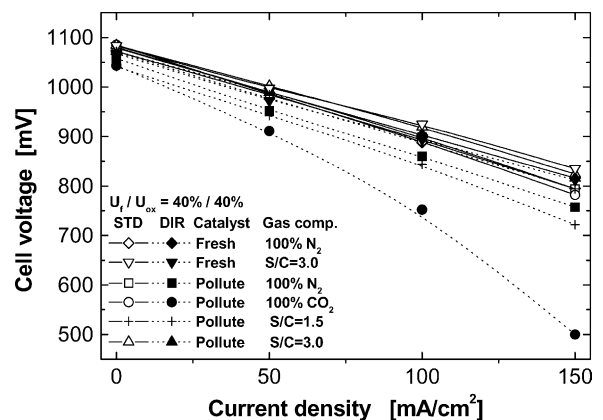

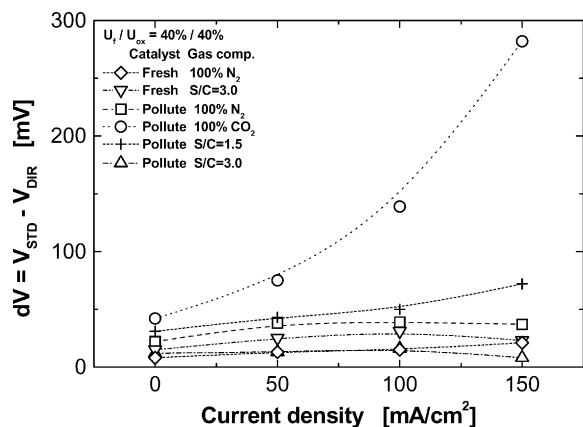Fig. 15. Initial cell performance of AIST's DIR-MCFC.
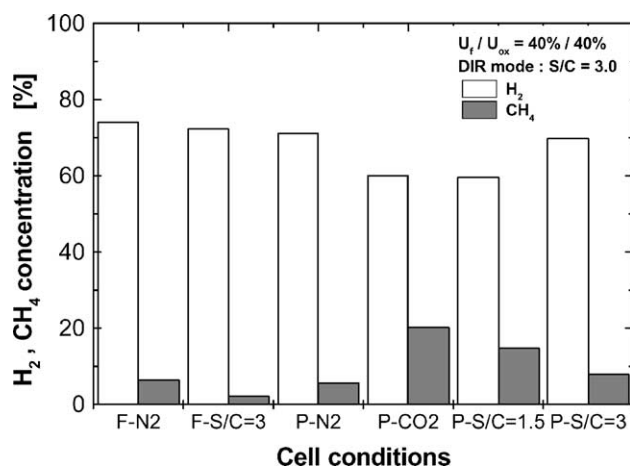
Fig. 16. DIR-MCFC performance.

Fig. 17. Catalytic activity of the reactivated catalyst within DIR-MCFC.

the possibility that the polluted catalyst is not reforming the necessary hydrogen for the cell. Especially, as dV under 100% CO_2 condition increases drastically by increasing the current density, the polluted catalyst can not be reactivated. On the other hand, dV under 100% N_2 and dV under $S/C = 3.0$ are almost the same. dV under $S/C = 1.5$ is poor. The gas composition of the anode outlet is analyzed by gaschromatography, H_2 and CH_4 concentration in anode outlet at OCV are shown as Fig. 17. H_2 and CH_4 concentration that uses a polluted catalyst and uses 100% N_2 and $S/C = 3.0$ as a start-up gas are almost same as the one that uses a fresh catalyst. On the other hand, as H_2 and CH_4 concentration that uses a polluted catalyst and uses 100% CO_2 as a start-up gas are considerably bad, the polluted catalyst can not be reactivated under this condition. Moreover, as H_2 and CH_4 concentration (a polluted catalyst; $S/C = 1.5$) are almost the middle of 100% N_2 condition and 100% CO_2 condition, the polluted catalyst can not be reactivated enough under this condition. Therefore, as the supplied gases, which are 100% N_2 and $S/C = 3.0$, can make KOH volatilize from the polluted catalyst in DIR-MCFC, the proposed reactivation method is appropriate. Moreover, the DIR-MCFC can be operated without vapor-

phase carbonate pollution and the polluted catalyst can be reactivated by using these reactivation methods if the DIR–MCFC is operated under the condition that the ratio of H_2O to CH_4 (S/C) in the fuel is increased.

5. Conclusion

A reactivation method for catalyst polluted by vapor-phase carbonate was developed by elucidating the adhesion form of potassium compounds in the polluted catalyst. Moreover, optimum-operating conditions of the DIR-MCFC without vapor-phase carbonate pollution was proposed by evaluating the reactivation method within the DIR-MCFC. The results obtained in this study are summarized as follows.

(1) The catalytic activity of a catalyst polluted by vapor-phase carbonate is revived to 80% of the initial activity by N_2 flowing into the polluted catalyst.
(2) The catalytic activity of a catalyst polluted by vapor-phase carbonate is not revived for changing KOH into K_2CO_3, if the DIR-MCFC was operated under the condition where CO_2 concentration was larger than 25%.
(3) Catalyst should be loaded more upstream in the anode where the H_2O concentration is high and the CO_2 concentration is low.
(4) The catalytic activity can be reactivated if S/C is two or more.
(5) The DIR-MCFC can be operated without vapor-phase carbonate pollution if the ratio of H_2O to CH_4 (S/C) in the fuel was two or more.

Acknowledgements

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