STUDY OF CARBONATION REACTIONS OF Ca-Mg OXIDES FOR HIGH TEMPERATURE ENERGY STORAGE AND HEAT TRANSFORMATION

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Storing and temperature upgrading of heat energy at 773 K by means of a CaO-CO₂ reaction seems very attractive. One way of storing the reaction product CO₂ gas is in the form of an other carbonate by letting it react with a metal oxide, such as MgO or ZnO. Two metal oxides, MgO and (CaMg)O₂ were selected for CO₂ storage, with the CaO-CO₂ energy storage system as CaO-CO₂-MgO and CaO-CO₂-CaMgO₂ systems, and studies on CaO-CO₂, MgO-CO₂ and CaMgO₂-CO₂ reactions over the temperature range 773-1073 K were carried out. As the CaO-CO₂ system is used not only for storing the heat energy but is also expected to perform as a heat transformer, verification of the temperature upgrading ability is made by means of a lab-scale adiabatic reactor. Pseudo-steady state temperature and pressure existed during the experiments, which correspond quite well with Haul's equilibrium dissociation values of CaCO₃, illustrating that upgraded temperatures of above 1273 K can be achieved by adjusting the carbonating CO₂ gas pressure to around 500 kPa.

Introduction

Efficient methods of storing and temperature upgrading of high temperature heat energy will bring about the widened use of solar energy in industrial process heating, and even in power generation. Thermal energy can be stored by means of sensible heat, latent heat and thermochemical reaction. Among them, thermochemical reaction can not only store large amounts of energy per unit mass, but it also can upgrade the temperature of the heat energy. There are many candidate reactions that can be used for energy storage, such as the ammonia system, the hydroxide system, and the carbonate system. In our previous paper (Kyaw Kyaw *et al.*, 1995), the applicability of the CaO-CO₂ reaction for high temperature storing and temperature upgrading of thermal energy at high temperatures has been investigated. The thermal efficiencies of storing and upgrading heat energy of 773 K with a CaO-CO₂ system with three different CO₂ storage methods: (i) storing of CO₂ as a compressed gas, i.e., a CaO-CO₂-compressor system, (ii) storing of CO₂ in the form of other carbonate substance by reacting with a metal oxide, i.e., a CaO-CO₂-MgO system, and (iii) storing of CO₂ as an adsorbed gas by adsorbing with an appropriate adsorbent, i.e., a CaO-CO₂-zeolite system; have been evaluated. Among them, it is found that the CaO-CO₂-MgO system is the highest in thermal efficiency if the systems upgrade heat at 773 K to temperatures above 1273 K. The thermal efficiency of the CaO-CO₂-Zeolite system is greatly influenced by the adsorptivity of the Zeolite material: the higher the adsorptivity, the higher the efficiency. In order to use the

CaO-CO₂-metal oxide system for high temperature heat upgrading, it is required to understand the behavior and heat generating properties at elevated temperatures of metal oxide/CO₂ reactions: such as CaO/CO₂, MgO/CO₂, ZnO/CO₂, and CaMgO₂/CO₂.

Although many studies have been made on CaO-CO₂ reaction (Barker, 1973, Barker, 1974, Bhatia *et al.*, 1983, Criado *et al.*, 1992, Dedman *et al.*, 1962, Oakeson *et al.*, 1979), study on carbonation of CaO as well as (Ca,Mg)O₂ in the temperature range 773-1073 K is still rare. In this paper, carbonation reactions of CaO, CaMgO₂ and MgO are studied and the temperature upgrading properties of these reactions at elevated temperatures are evaluated by using a lab scale adiabatic reactor.

1 Study of Carbonation Reactions of CaO, MgO and CaMgO₂ under Isothermal and Atmospheric Conditions

1.1 Sample

Calcite (Hiroshima, Japan), dolomite (Tochigi, Japan) and magnesite (China) of particle size 5 μ m, 74 μ m and 0.7 mm were used in this work. The chemical compositions of the materials are shown in Table 1.

1.2 Experimental apparatus

A TG apparatus (SHIMADZU TGA-50H) which can weigh with an accuracy of 0.01 mg was used for thermogravimetric analysis. The schematic diagram is shown in Fig. 1. A sample pan (Pt, 6 mm ϕ $\times$ 2.5 mmH) is housed in a ceramic tube of 20 mm diameter, which is set in the TG apparatus. The temperature is measured with a thermocouple (Pt-Pt/Rh 10%), which is placed underneath the

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Table 1 Composition [%] of the carbonate materials that are used in the experiment

	CaO	MgO	SiO ₂	Fe ₂ O ₃ (Al ₂ O ₃)	Ig. Loss
Calcite (Hiroshima)	55.74	0	0	0	43.74
Dolomite (Tochigi)	34.37	18.2	0.12	0.04 (0.05)	46.78
Magnesite (China)	0.66	46.2	2.51	0.24 (0.06)	49.82

Fig. 1 Schematic diagram of the Shimadzu TGA-50H thermogravimetric analyzer

weighing pan.

1.3 Experimental procedure and conversion calculation

A sample of about 10 mg is put in the sample pan and set in the TGA, and then heated to a certain temperature T until decomposition is achieved with a heating rate of 50 K.min⁻¹ under N₂ atmosphere. After 15 minutes, it is cooled down at a rate of 30 K.min⁻¹. At a predetermined temperature, the gas is switched to CO₂, and the carbonation reaction is started. The flow rate of gases into the TGA is kept at 6.6×10^{-3} m³.hr⁻¹ at 293 K in order to minimize the effect of gas-film diffusion resistance for both carbonation and decarbonation reactions.

Conversion X of the metal oxide to carbonate is calculated as:

$$X = \frac{\frac{W_t - W_o}{W_o}}{\frac{M_{CO_2} \times \frac{Y_{CaO}}{M_{CaO}} + M_{CO_2} \times \frac{Y_{MgO}}{M_{MgO}}}{Y_{CaO} + Y_{MgO} + Y_{Impurities}}} \quad (1)$$

where W_t is the weight of sample during carbonation at any

Fig. 2 Conversion of 5 μ m calcined calcite when carbonated at 673-1073 K under 20-100 vol. % of CO₂ for 1 hr

time [kg], W_o is the weight of calcined sample [kg], Y_{CaO} is the content of CaO in the sample [%], Y_{MgO} is the content of MgO in the sample [%], $Y_{Impurities}$ is the content of silica, Fe₂O₃, Al₂O₃, and other impurities, in the sample [%], M_{CaO} , M_{MgO} and M_{CO_2} are molecular weights of CaO, MgO and CO₂ [kg.mol⁻¹], respectively.

1.4 Results and discussion

1.4.1 Effect of pressure and temperature on the carbonation of CaO

Carbonation of CaO particles of 5 μ m diameter was carried out at 673-1173 K under various CO₂ partial pressures. Conversion curves for carbonation at 673, 873 and 1073 K under CO₂ partial pressures of 20-101 kPa are plotted in Fig. 2. It can be seen that reaction rate and conversion are nearly the same for each temperature, regardless of the difference in CO₂ pressure. A similar finding, that the reaction is zero order with respect to CO₂ at pressures between 1.4-101 kPa (10-760 mmHg) over the temperature range 373-873 K has also been reported by Dedman and Owen (Dedman *et al.*, 1962).

With the carbonation experiment at 1123 K, reaction rate and conversion values are found to be almost the same only for CO₂ pressures of 60, 80 and 101 kPa. No reaction and conversion occur for carbonation with 20 and 40 kPa CO₂ pressures. A very slight weight increase of the calcined sample is noted when the carbonating CO₂ pressure is adjusted up to about 57 kPa. The same phenomena of CO₂ sorption by CaO is noted when CaO is carbonated at 1073 K with CO₂ pressure of 18 kPa. Thus, it can be concluded that a CaO-CO₂ reaction will take place if the pressure of the CO₂ gas is a few kPa higher than that of the CO₂ pressure in the equilibrium state of CaO-CO₂ reaction. Also, the reaction rate is almost to be of zero order with respect to CO₂ pressures under 101 kPa, if the loaded CO₂ pressure for carbonation is much higher than that of the equilibrium pressure.

However, reaction rate and conversion are greatly

Fig. 3 Conversion of 5 μm calcined calcite when carbonated at 673-1073 K under 101 kPa of CO_2 for 1 hr

influenced by the temperature; conversion for carbonation at 1073 K for 1 hr is about 90%, whereas, for 873 K it is 70% and for 673 K it is a mere 35%. Data from carbonation experiments at 673-1173 K with pure CO_2 gas at a pressure of 101 kPa are plotted in **Fig. 3**, and it is found that reaction rate and conversion are fastest and highest at temperatures of 923-1123 K, and they drop with the decrease in temperature. Conversion is almost zero at 1173 K. The form of the curves show that the reaction can be considered as occurring in two stages, the first being a rapid reaction with CO_2 and the second being a much slower interparticle reaction which falls off with time.

1.4.2 Effect of temperature on the decomposition and carbonation of magnesite

In carrying out the experiments with magnesite of 5 μm , it is found that magnesite decomposes very slowly, even at temperatures 673-823 K, which are very much higher than the equilibrium dissociation temperature of 623 K (Britton *et al.*, 1952a, Perry and Green, 1984). Temperatures higher than 923 K are necessary to achieve complete decomposition of magnesite within 15 minutes. Conversion is found to be maximum at about 14% when the calcined magnesite is carbonated at 523 K [see **Fig. 4**]. The conversion drops to 3% when the carbonation temperature is increased to 573 K. No conversion is recorded for carbonation at 673 K.

1.4.3 Effect of pressure and temperature on the carbonation of CaMgO_2

When carbonation experiments are carried out with 5 μm particles of dolomite, it is found that the reaction rate and conversion for carbonation at temperatures, of 673-1073 K is almost independent of CO_2 pressure between 20-101 kPa. Since this phenomena is exactly similar to that of carbonation of CaO , it is concluded that the carbonation reaction of CaMgO_2 will occur if the charged CO_2 pressure

Fig. 4 Conversion of 5 μm calcined dolomite when carbonated at 773-1073 K under 101 kPa of CO_2 . Calcined magnesite is carbonated at 523 K

is higher than the reaction equilibrium pressure and the reaction rate is of zero order with respect to CO_2 pressure.

Data of carbonation at 773-1073 K under CO_2 pressure of 101 kPa are plotted in **Fig. 4**. It can be seen that carbonation in the temperature range 873-1073 K is fastest, reaching a conversion of about 55% in 10 minutes, whereas, carbonation at 773 K reached a conversion of about 50%. However, in all the carbonation experiments, even though the carbonation temperatures are different, ranging between 873 K and 1073 K, the conversion values reached after 1 hr of carbonation are almost the same—about 56%. Carbonation over the temperature range 873-1073 K reached about 54% conversion in a few minutes and produced a relatively brief second stage reaction. All the reactions virtually ceased in the range of 56-58% conversion, and this indicates that the rest of the chemical substances, like MgO , involved in the calcined dolomite are not so reactive toward CO_2 at temperatures of 773-1073 K.

Britton *et al.* (1952b) reported that dolomite is a specific substance having a distinct crystal lattice different from that of calcite and magnesite and that decomposition gives a solid solution $(\text{Ca,Mg})\text{O}_2$ which soon breaks up into separate crystallites of CaO and MgO . Since MgO from the decomposition of magnesite shows no tendency to recombine with CO_2 at temperatures higher than 673 K, it can be concluded that only crystallites of CaO will react with CO_2 when calcined dolomite is carbonated at 773-1073 K.

1.4.4 Reaction rate constant of CaO , MgO and CaMgO_2 under CO_2 pressures of 101 kPa

Since the particles used for the carbonation experiments are smaller than 5 μm , it is assumed that the calcined particle is porous and is composed of oxide of uniform spherical grains and that the reaction of each grain proceeds from the outside towards the center, and the rate

Fig. 5 (a) dX/dt vs. $(P-P_e)$ for carbonation of CaO in the temperature range 773-873 K

Fig. 5 (b) Reaction rate constant k_x vs. $1/T$ for the carbonation of calcite and dolomite in the temperature range 773-1073 K

at which each grain reacts is proportional to the surface area of the reaction front at a given time. Accordingly, we will calculate the reaction rate constant by using the initial growth stage reaction rate expression developed by Nitsch (1962) for the CO_2 -lime reaction

$$\frac{dX}{dt} = k_x (1 - X)^{2/3} (P - P_e)^n \quad (2)$$

where the dX/dt is the rate of conversion [s^{-1}], t is the time of reaction [s], k_x is the reaction rate constant [$\text{kPa}^n \cdot \text{s}^{-1}$], X is the conversion at time t [-], P is the pressure of CO_2 [kPa] and P_e is the equilibrium pressure of CO_2 [kPa].

By plotting dX/dt value vs. $(P-P_e)$ for carbonation

Fig. 6 (a) Conversion of calcined calcite of various sizes when carbonated at 773 K under 101 kPa of CO_2

Fig. 6 (b) Conversion of calcined dolomite of various sizes when carbonated at 773 K under 101 kPa of CO_2

reactions at 773-873 K as in Fig. 5 (a), it is found that n is about 0.1. The reaction rate constants k_x of calcite and dolomite for carbonation over the temperature range of interest 773-923 K are calculated and are plotted against $1/T$ as in Fig. 5 (b). It is also estimated that the activation energy of carbonation is about 78 kJ/mole for calcite and 35 kJ/mole for dolomite. It can be seen that, for temperatures above 823 K, the reaction rate constant of calcite is higher than that of dolomite, but on the other hand at temperatures below 823 K, the order is opposite with the reaction rate constant of dolomite higher than that of calcite. The reaction rate constant of these two materials is almost the same at 823 K. Accordingly, it can be concluded that around 823 K, the reaction rates of CaO-CO_2 and $\text{CaMgO}_2\text{-CO}_2$ reactions are quite comparable.

Fig. 7 Schematic diagram of the lab-scale adiabatic packed bed reactor used for verification of the temperature upgrading ability of the CaO-CO₂ reaction

1.4.5 Effect of particle size of Calcite and Dolomite on reaction rate and conversion

In Figs. 6 (a) and 6 (b), conversion values of carbonation of calcite and dolomite particles of 5 μm , 74 μm and 0.7 mm at 773 K under CO₂ pressure of 101 kPa are plotted. It can be seen for calcite that the rates of the initial rapid reaction stage are almost the same for all the sizes, with the diffusion controlled slower second stage coming into effect earlier than the other sizes at 0.7 mm. For dolomite, not so much difference is observed compared to calcite for the initial reaction rates as well as final conversions for all sizes, indicating that CO₂ is quite liable to diffuse into the particle because of the presence of MgO which does not take part in the reaction. This is in good agreement with the result obtained from the carbonation of 5 μm dolomite at 773-1073 K where the reaction attains 50% conversion within a few minutes, followed by a very brief second stage reaction. Thus, it is concluded that the initial reaction stage of carbonation of calcite and dolomite of sizes 5 μm to 0.7 mm can be expressed by the same equation used for 5 μm particles.

2. Verification of Heat Upgrading Ability of CaO/CO₂ Reaction by Means of Adiabatic Reactor

2.1 Sample preparation

Calcite of 0.7 mm is calcined at 1123 K for 3 hr under atmospheric conditions in a muffle furnace. When the furnace has cooled down to 773 K, the calcined sample is withdrawn and is placed in a desiccator where it is cooled down to room temperature.

2.2 Apparatus

A reactor of 50 mm ϕ x 230 mmH is placed in a molten salt bath at 773 K. The salt bath is equipped with a temperature controlling device and is well insulated. A schematic diagram of the reactor is shown in Fig. 7. Three

Fig. 8 Temperature profiles of the CaO reactant bed when adiabatically carbonated under CO₂ pressures of 200-608 kPa. Initial bed temperature is 773 K

thermocouple leads are placed along the central axis at 20, 55 and 90 mm height from the bottom of the reactor. The lid of the reactor is connected to a vacuum pump, a pressure recorder and a CO₂ supply.

2.3 Procedure

Calcined sample is loaded into the reactor to a height of about 150 mm. Then, the reactor is sealed off and the air trapped inside the reactor is removed by vacuum pump. Pressure inside the reactor is maintained at 0.1 kPa until the readings from the thermocouples placed inside the reactor are equal to that of the molten salt bath. Then, CO₂ gas is slowly introduced into the reactor until it reaches a desired pressure, which is then maintained throughout the experiment.

2.4 Results and Discussion

It is assumed that during the course of reaction, adiabatic conditions prevail at the center of the reactant bed and the temperature recorded by the middle thermocouple is equal to the temperature that is in equilibrium with CO₂ gas pressure used for carbonating the CaO.

Figure 8 shows the temperature profile of the reactant bed for the adiabatic carbonation experiments with 206, 304 and 608 kPa CO₂ pressures. It can be seen that the temperature of the bed is raised from 773 K to about 1273 K within the first two minutes (phase-1) due to heat generated during the fast initial reaction between CaO and CO₂. For CO₂ pressure of 206 kPa, the temperature of the bed is upgraded to about 1200 K, whereas, if the CO₂ pressure is at 608 kPa, the temperature of the bed reaches 1300 K. By using standard heat of formation and heat capacity data (Perry and Green, 1984), it is estimated that during the fast initial reaction, the carbonation reaction attained a minimum of about 35% conversion, so the generated heat of

Fig. 9 Comparison of the steady state temperature and pressure that was observed during the adiabatic carbonation of CaO against the equilibrium dissociation line of CaCO_3 developed by Haul

reaction will be able to upgrade the temperature of the whole reaction medium to 1173 K, whereas about 40% conversion is needed to elevate the temperature of the reactant bed to 1273 K.

The temperature of the reactant bed remains almost constant at the elevated temperature for about 15 minutes (phase-2) due to continued reaction of $\text{CaO}-\text{CO}_2$, but at a much reduced rate. This slower reaction between $\text{CaO}-\text{CO}_2$ in phase-2 can be regarded as carbonation under constant temperature and pressure; the temperature and pressure being the elevated temperature and the charged CO_2 pressure respectively. Also, as the 'pseudo-steady state' exists for a certain period, the temperature and pressure prevailing during phase-2 are considered to be in pseudo-equilibrium. The temperature of the reactant bed later falls gradually (phase-3) to that of the molten salt bath at 773 K.

As presented in **Fig. 9**, the temperature attained during phase-2 and the charged CO_2 pressure agree very well with the data by Haul (Haul and Markus, 1952), indicating that on referring the sets of temperature-pressure existing along the equilibrium line, the $\text{CaO}-\text{CO}_2$ reaction can be made to occur at any desired temperature by adjusting the CO_2 pressure to a value that corresponds to the respective set of equilibrium temperature-pressure. Thus, by heating up CaCO_3 with heat energy available at 773 K, and keeping it under 0.01 kPa (773 K and 0.01 kPa corresponds to one of the sets of equilibrium pressure-temperature condition presented by Haul), and then by carbonating the CaO (produced by the decomposition of CaCO_3 at 773 K) with CO_2 gas of 500 kPa, heat energy at 1273 K will be available during phase-2 of the $\text{CaO}-\text{CO}_2$ reaction as shown in **Fig. 8**. By this means, the $\text{CaO}-\text{CO}_2$ reaction can be made to transform heat energy at 773 K into heat energy at 1273 K.

According to Haul's data as presented in **Fig. 9**, if CaCO_3 and $\text{CaMg}(\text{CO}_3)_2$ are made to decompose under the

same CO_2 pressure, (assuming that decomposition of dolomite also agrees well with Haul's data) it can be seen that the dissociation temperature of $\text{CaMg}(\text{CO}_3)_2$ will be much lower than that of CaCO_3 . Thus, by heating CaCO_3 under 0.01 kPa with the heat from the heat source at T_M (773 K), CaCO_3 at state A will decompose and release CO_2 . The product CO_2 gas is cooled down to T_L and allowed to react with MgO at state B. When the formed MgCO_3 at state B is heated up to T_M (state C), it will decompose and discharge CO_2 at 2 kPa. The discharged CO_2 is made to react with CaO at T_M . Due to generated heat of reaction, the product CaCO_3 will be heated up to T_H and the excess amount of heat at higher temperature ($T_H > T_M$) will be available for use. In this way, with the $\text{CaO}-\text{CO}_2$ reaction pair functioning as a heat absorber/generator and the $\text{CaMgO}_2-\text{CO}_2$ reaction pair functions as a CO_2 storage medium, the $\text{CaO}-\text{CO}_2-\text{CaMgO}_2$ system can be set up as a high temperature thermal energy storage and temperature upgrading system.

Conclusion

CaO and CaMgO_2 can react with CO_2 in the temperature range 773-1073 K, and can achieve conversions higher than 50%, whereas MgO exhibits almost no reactivity at temperatures above 673 K. The carbonation reaction of these oxides is independent of the CO_2 pressure under total pressure of 101 kPa, and will proceed if the charged CO_2 gas pressure is a few kPa higher than the equilibrium pressure of CO_2 .

The reaction rate constants of $\text{CaO}-\text{CO}_2$ and $\text{CaMgO}_2-\text{CO}_2$ reactions are quite comparable. Also, from the adiabatic carbonation experiments of CaO, the temperatures and pressures that exist during the pseudo steady state agree very well with Haul's equilibrium line. As the dissociation temperature of $\text{CaMg}(\text{CO}_3)_2$ is lower than the dissociation temperature of CaCO_3 under the same CO_2 pressure, the $\text{CaMgO}_2-\text{CO}_2$ reaction can act as a CO_2 storage system in the proposed $\text{CaO}-\text{CO}_2-\text{CaMgO}_2$ high temperature thermal energy storage system, in which CaMgO_2 functions as a metal oxide for removing the CO_2 gas that will be produced when CaCO_3 absorbs heat energy from the heat source and decomposes into CaO and CO_2 . By allowing the CO_2 gas that has been recovered by heating the $\text{CaMg}(\text{CO}_3)_2$ produced to react with CaO, heat energy will be delivered again.

From the $\text{CaO}-\text{CO}_2$ adiabatic carbonation experiments, it is found that the temperature of the CaO packed bed can be raised from 773 K to temperatures in the region of 1273 K by adjusting the pressure of the CO_2 gas used for carbonation around 500 kPa. This clearly demonstrates the ability of the $\text{CaO}-\text{CO}_2$ reaction to transform thermal energy at a certain temperature region to thermal energy of a relatively higher temperature region.

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Nomenclature

k_x	= reaction constant	$[s^{-1} \cdot kPa^{-n}]$
M	= molecular weight	$[kg \cdot mol^{-1}]$
n	= exponential constant of $(P-P_e)$ term	[-]
P	= pressure of CO_2	$[kPa]$
P_e	= equilibrium pressure of CO_2	$[kPa]$
t	= time	$[s]$
T	= temperature	$[K]$
W	= weight	$[kg]$
X	= conversion	[-]
Y	= content of material	$[%]$

Literature cited

- Barker, R.; "The reversibility of the reaction $CaCO_3 = CaO + CO_2$," *J. of appl. Chem. Biotechnol.*, **23**, 733-742 (1973)
- Barker, R.; "The Reactivity of Calcium Oxide Towards Carbon Dioxide and its Use of Energy Storage," *J. of appl. Chem. Biotechnol.*, **24**, 221-227 (1974)
- Bhatia, S. K. and D. D. Perlmutter; "Effect of Product Layer on the Kinetics of the CO_2 -lime Reaction," *AIChE Journal*, **29**, 79-86 (1983)
- Britton, H. T. S., S. J. Gregg and G. W. Winsor; "The calcination of Dolomite; Part I - The kinetics of the Thermal Decomposition of Calcite and of Magnesite," *Trans Faraday Society*, **48**, 63-69 (1952)

- Britton, H. T. S., S. J. Gregg and G. W. Winsor; "The calcination of Dolomite; Part II - The Thermal Decomposition of Dolomite," *Trans Faraday Society*, **48**, 70-75 (1952)
- Criado, J. M., M. Macias, and A. Macias-Machin; "Analysis of the System $CaO-CO_2-H_2O$ for Storage of Solar Thermal Energy," *Solar energy*, **49**, 83-86 (1992)
- Dedman, A. J. and A. J. Owen; "Calcium Cyanamide Synthesis; Part 4.- The Reaction $CaO + CO_2 = CaCO_3$," *Trans. Faraday Society*, **58**, 2027-2035 (1962)
- Haul, R. A. W. and J. Markus; "Thermal Decomposition of Dolomite; IV. Thermogravimetric Investigation of the Dolomite Decomposition," *J. appl. Chem.*, **2**, 298-306 (1952)
- Kyaw Kyaw, H. Matsuda and M. Hasatani; "Applicability of Carbonation / Decarbonation Reactions to High-Temperature Energy Storage and Temperature Upgrading System," Submitted to *J. of Chemical Engineering of Japan* (1995)
- Nitsch, Von. W.; "Über die Druckabhängigkeit der $CaCO_3$ -Bildung aus dem Oxyd," *Zeitschrift für Elektrochemie*, **66**, 703-708 (1962)
- Oakeson, W. G. and I. B. Cutler; "Effect of CO_2 Pressure on the Reaction with CaO ," *J. of American Ceramic Society*, **62**, 556-558 (1979)
- Perry, R. H. and D. Green; *Perry's Chemical Engineer's Handbook*, 6th ed., Section 3, McGraw-Hill Book Co. (1984)