ELSEVIER

Chemical Engineering Journal 86 (2002) 3–10

Chemical Engineering Journal

www.elsevier.com/locate/cej

Effects of heat exchange condition on hot air production by a chemical heat pump dryer using $CaO/H_2O/Ca(OH)_2$ reaction

Hironao Ogura [a,*], Tetsuya Yamamoto [a], Hiroyuki Kage [a], Yoshizo Matsuno [a], Arun S. Mujumdar [b,1]

[a] Department of Applied Chemistry, Kyushu Institute of Technology, 1-1, Sensui-cho, Tobata, Kitakyushu 804-8550, Japan

[b] Department of Mechanical and Production Engineering, National University of Singapore, 10 Kent Ridge Crescent, Singapore 119260, Singapore

Abstract

Results of an exploratory experimental study of a chemical heat pump (CHP) assisted convective dryer are presented. The $CaO/H_2O/Ca(OH)_2$ gas–solid reversible hydration/dehydration reaction is used to store and recover heat from the dryer exhaust air to enhance the thermal efficiency of the dryer. The CHP unit can be operated to increase the temperature level and also to dehumidify the air, which is a particularly attractive feature for drying. Results are presented for a single cylindrical reactor to study the effects of the heat exchange conditions on hot air production. The results show that the hot air production is improved by enlarging the heat exchanger, increasing the heat transfer rates by use of stainless mesh and increasing the air flow rate. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Novel dryer; Chemical heat pump; Convective dryer; Heat and mass transfer; Heat recovery; Efficiency

1. Introduction

Effective thermal energy utilization has become increasingly important from the viewpoints of energy and environmental problems. Drying, which is a highly energy intensive process in most industrial sectors, is no exception. Although some options to save energy in drying, such as the use of a mechanical heat pump are available, the results of such options are often limited to specific applications [10].

A chemical heat pump (CHP) is proposed as one of the potentially significant technologies for effective energy utilization in drying. The CHP can store thermal energy such as the waste heat from dryer exhaust, solar energy, geothermal energy, etc. in the form of chemical energy, and release the energy at various temperature levels during the heat-demand period. The CHP is basically driven by only thermal energy, and thus does not release any contaminating gases. The authors proposed and studied the CHP system using the widely studied calcium oxide/calcium hydroxide hydration/dehydration reversible $CaO/H_2O/Ca(OH)_2$ reaction for heat storage and high/low-temperature heat generation. We have confirmed experimentally and theoretically that the CHP could operate in the temperature upgrading mode [3], the heat storing mode [4], the heat enhancement mode [1] as well as the refrigeration mode [5–7].

We have proposed a new concept: a chemical heat pump dryer (CHPD) system for ecologically friendly effective utilization of thermal energy in drying [8,9]. The CHPD concept has been discussed from the viewpoint of coupling the CHP and a direct dryer. The efficiencies of various types of CHPD systems were evaluated on the bases of energy and energy consumption.

This paper presents an experimental study focusing on the heat and mass transfer performance in batch drying using the heat enhancement mode of the CHP. The effects of heat exchanging conditions such as the heat exchanger design and the air flow rate on the hot air production performance. A single cylindrical reactor was built as the key component of a CHPD system utilizing the calcium oxide/calcium hydroxide hydration/dehydration reversible reaction. This study was performed in the heat-releasing step of the CHP to heat up the air to around 100 °C. The hydration reactor temperature rises to over 300 °C while the evaporator temperature is kept at the 17 °C level. The evaporator temperature is at a reasonable level because it is obtained from the ambient air. However, operation at this level has heat and mass transfer problems as reported in an earlier study [6]. The results of this experimental study are discussed from the viewpoints of heat and mass transfer in/out of the reactor for improving the magnitude and temperature levels of

* Corresponding author.
E-mail addresses: ogura_h@hotmail.com (H. Ogura), mpeasm@nus.edu.sg (A.S. Mujumdar).

[1] Adjunct Professor, Department of Chemical Engineering, McGill University, 3610 University Street, Montreal, Que., Canada H3A 2B2.

1385-8947/02/$ – see front matter
PII: S1385-8947(01)00265-0

Nomenclature

A	heat exchange area (m^2)
C	specific heat (kJ/kg K)
h	heat transfer coefficient (W/m^2 K)
P	pressure (kPa)
P_P	reaction equilibrium pressure of CaO/$Ca(OH)_2$ particle (kPa)
P_W	saturated vapor pressure calculated from water temperature in evaporator (kPa)
Q	thermal energy (kJ)
r	radial distance in cylindrical coordinate (mm)
R	radius (mm)
T	temperature (K)
W	air flow rate (min^{-1})
X	conversion of CaO (–)
Y	absolute humidity (kg water/kg dry air)
z	axial distance from bottom (mm)
Z	bed height (mm)

Greek letters

ε	heat recovery efficiency (–)
θ	time (min)

Subscripts

A	air
C	condenser
C*n*	convective
Ev	evaporator
Ex	heat exchanger
g	steam gas
G	gas
H	high
L	low
M	medium
P	particle in reactor
R	heat releasing step
s	solid
S	heat storing step
W	water in evaporator/condenser
0	initial
1–2	consecutive stage

the stored/discharged heat considering the characteristics of the hot dry air produced.

2. Proposed CHPD system

Many types of CHPs have been developed and reported in the literature. The calcium oxide hydration/dehydration system was considered in the early study to be the most feasible for CHPD systems from the viewpoints of temperature level, safety, corrosion and cost [8,9].

The $CaO/H_2O/Ca(OH)_2$ CHP reaction is expressed by the following set of equations [2]:

$$CaO(s) + H_2O(g) \Leftrightarrow Ca(OH)_2(s) + 104.2\,\mathrm{kJ/mol} \quad (1)$$

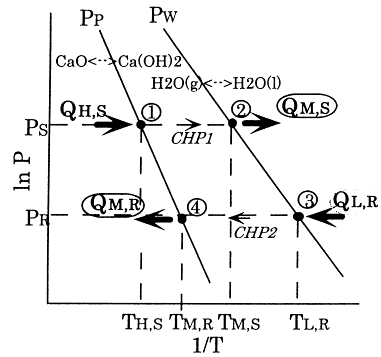
$$H_2O(g) \Leftrightarrow H_2O(l) + 41.7\,\mathrm{kJ/mol} \quad (2)$$

We need to select the appropriate operating modes for the reactions. The heat enhancement mode has the highest energy efficiency of all the possible modes of CHP operation because useful heat is released even in the heat-storing step.

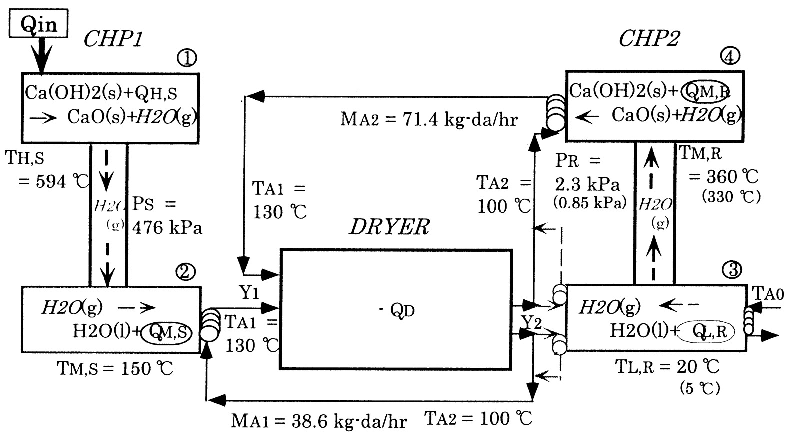
Fig. 1 shows one of the CHPD systems, which we proposed for a CHPD in an earlier study [9]. In this system, we assumed a compact dryer with 100 kg dry air/h flow rate and constant rate of drying. The CHPD system design and the operating temperature levels were chosen so that the energy efficiencies of the CHPD are as high as possible. Other potentially interesting systems will be examined in later works.

Fig. 1a shows the operating line for this CHPD indicating the relationships between the reaction equilibrium pressure and temperature. P_P is the reaction equilibrium pressure of water vapor at the reaction temperature of CaO. P_W denotes the saturation vapor pressure calculated from the water temperature at the evaporator/condenser. This system of two CHPs works in the heat enhancement mode. The two CHPs, CHP1 and CHP2, operate concurrently; CHP1 is in the heat-storing mode and CHP2 is in the heat-releasing mode. These CHPs switch their operating modes with each other every hour or so; the switching time is decided by experiments such as those reported in our previous study [3]. Fig. 1b shows a flowsheet of the corresponding CHPD. In CHP1, high temperature heat $Q_{H,S}$ is stored in the CaO reactor using a suitable heat source with Q_{in} at $T_{H,S} > 594\,°C$. Water vapor in the reactor is released from the reactor and is condensed in the condenser. The condenser releases medium temperature heat $Q_{M,S}$ around $T_{M,S} > 150\,°C$ by controlling the heat transfer rate. On the other hand, CHP2 also releases medium temperature heat $Q_{M,R}$ around $T_{M,R} > 360\,°C$ in the CaO reactor by controlling the evaporator temperature at around $T_{L,R} > 20\,°C$ with room temperature heat. In short, this CHP system stores 600 °C heat and releases heat at 150 and 360 °C continuously by switching between the two CHPs. Furthermore, CHP2 can produce "cold" heat at the evaporator for cooling/dehumidification of air by using the latent heat of evaporation. For example, in the case of an evaporator temperature around $T_{L,R} > 5\,°C$, medium temperature heat $Q_{M,R}$ around $T_{M,R} > 330\,°C$ is released in the CaO reactor as shown in the figure.

In order to supply dry hot air at $T_{A1} > 130\,°C$, $T_A >$ 100 kg dry air/h, air is recirculated as shown in Fig. 1b. Other parameters were calculated in the earlier study [9] as follows: amounts of heat $Q_{H,S} > Q_{M,R} = 595\,W = 2.14\,MJ/h$, $Q_{H,S} > Q_{L,R} = 238\,W = 0.86\,MJ/h$, mass flow rates $M_{A1} > 38.6$ kg dry air/h, $M_{A2} > 71.4$ kg dry air/h, amounts of reactants needed CaO = 1.15 kg, H_2O = 0.37 kg. For energy used for drying $Q_D = 833\,W = 3\,MJ/h$, the evaporation rate is $\Delta Y = 0.0125$ kg water vapor/kg dry air



a) Operating line



b) Flowsheet

Fig. 1. CHPD system using $CaO/H_2O/Ca(OH)_2$ reaction operating in heat enhancement mode.

or $M_{\mathrm{Ev}} = 1.25$ kg water vapor/h neglecting the sensible heat of the solid material. In this case, the energy consumed in this CHPD system for evaporation is calculated using Eq. (3) as

$$Q_{\mathrm{Ev}} = \frac{Q_{\mathrm{H,S}}}{M_{\mathrm{Ev}}} \tag{3}$$

The result is $Q_{\mathrm{Ev}} = 1.71$ MJ/kg for water evaporation. This is much less than the latent heat of evaporation of water which is about 2.4 MJ/kg. Furthermore, when the outlet air needs to be dehumidified, evaporator cooling can dehumidify the air as shown by the dotted line in Fig. 1.

3. Experiments

3.1. Experimental apparatus

Fig. 2 shows a schematic diagram of the CHP unit employed. This unit is designed for standard tests to measure the rates of hot air production. It is composed of two cylindrical stainless vessels connected to each other horizontally. The right side of the unit is the reactor, which has an inside diameter of 60 mm and a height of 288 mm. The reactor has a single particle bed filled with CaO or $Ca(OH)_2$ particles to a height of around 200 mm. The outside of the reactor is a heat exchanger between the reactant bed and the air, which is made by two types of acrylic cylinders. The left side of the unit is the evaporator/condenser, which has an inside diameter of 60 mm and a height of 288 mm. The evaporator/condenser is supplied with a fixed amount of water. The vessel has a copper heat exchanger. The reactor and the evaporator/condenser are insulated with glasswool.

3.2. Sample

The CaO particles employed in this experiment were prepared by calcining limestone at about 1223 K in an electric furnace. The purity of $CaCO_3$ is 99% and the mean particle diameter is 0.7–1.0 mm. A mass of 0.4 kg CaO particles was packed to a height of 200 mm in the cylindrical bed reactor for all the experiments reported here.

3.3. Experimental procedure

The experimental procedure is based on the schematic diagram of the operating principle of the CHPD in the heat

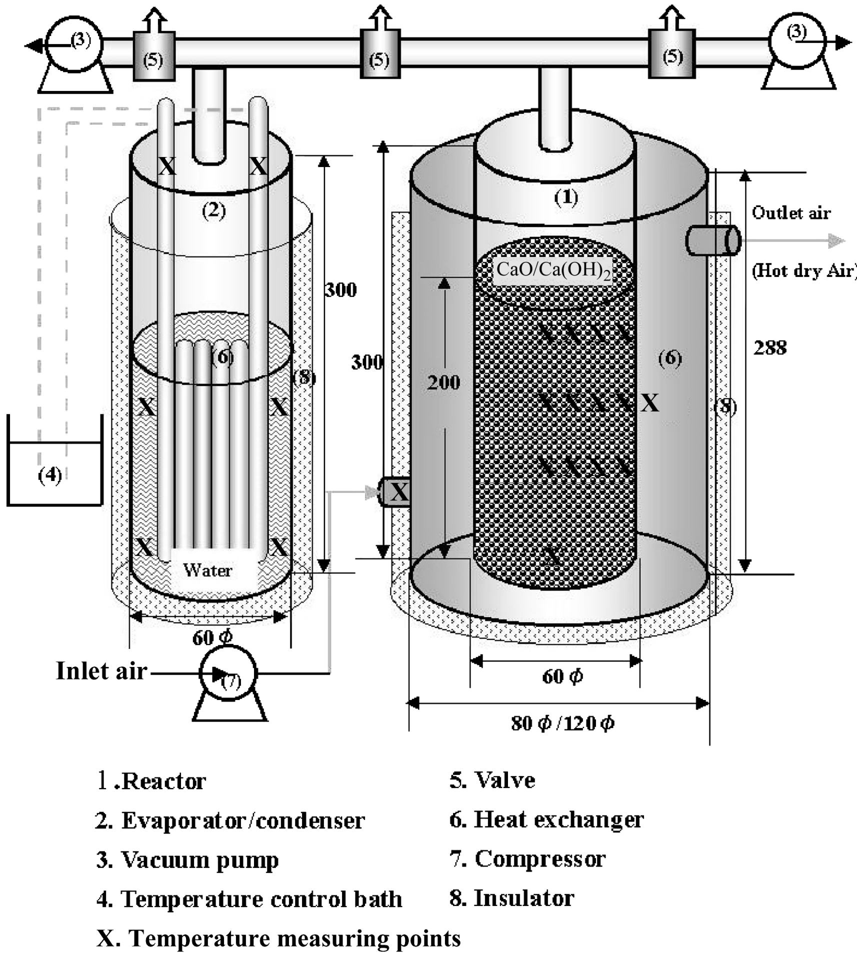


Fig. 2. Standard-type CHP unit.

enhancement mode as shown in Fig. 1. In this study, characteristics of hot air production by CHP2 in the heat-releasing step were examined by following experimental procedure.

The water in the evaporator is insulated so that $T_{L,R} = T_{W,0}$. The particles in the reactor are kept at $T_{M,R} = T_{P,0}$. When the two vessels are connected, steam flows from the evaporator to the reactor ($3 \rightarrow 4$) due to the pressure difference between P_W and P_P. In this way, medium-temperature-level heat ($Q_{M,R}$) at $T_{M,R}$ and low-temperature-level heat ($Q_{L,R}$) at $T_{L,R}$ are obtained simultaneously. The resulting medium-temperature-level heat ($Q_{M,R}$) at $T_{M,R}$ is recovered by an air heat exchanger to produce hot air. The air at the inlet of the heat exchanger at $T_{Ex,H\,Inlet}$ is upgraded to the outlet temperature of the heat exchanger $T_{Ex,H\,Outlet}$. The low-temperature-level heat ($Q_{L,R}$) generated at $T_{L,R}$ is normally recovered by a water heat exchanger. In the case of this standard experiment, the water in the evaporator is kept at a constant temperature of $T_{L,R}$ (3) by a temperature-controlled bath.

The temperature and the pressure changes in both vessels were measured with sheathed thermocouples and pressure gauges, respectively. The change of water level in the evaporator/condenser was also measured for calculating the conversion of CaO particles.

3.4. Experimental conditions

The effect of the heat exchange condition is examined for hot air generation/recovery. In order to enhance the heat transfer rate of the heat exchanger, a larger acrylic cylinder (120φ) is used (termed as a wide heat exchanger) and a stainless mesh is packed between the reactor and the larger acrylic cylinder (named here as a wide mesh heat exchanger). Furthermore, the air flow rate was changed to examine the effect.

4. Results and discussion

Fig. 3 shows the effect of the heat exchanger design on the temperature changes of the heat exchanger air at the inlet and the outlet for hot air heat exchange experiments by our standard CHP apparatus. It is found that hot air is produced and the air temperature rises rapidly in every experiment. It

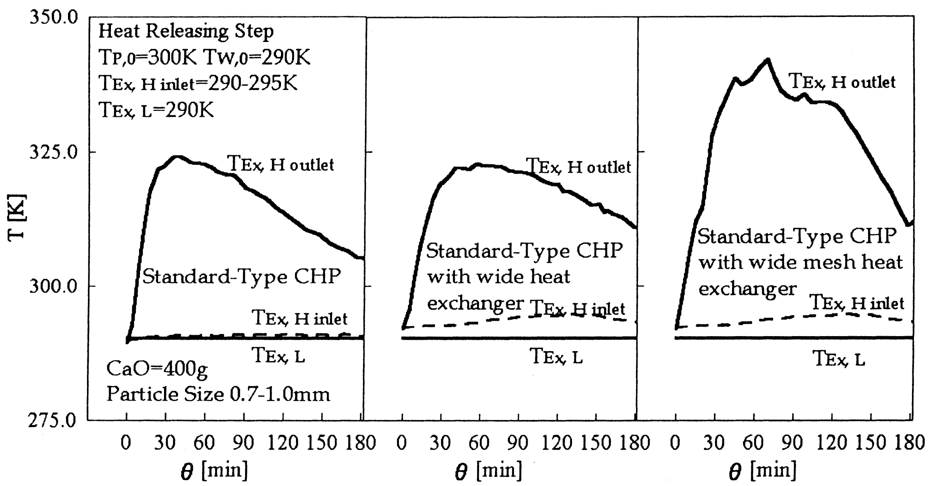


Fig. 3. Effect of heat exchanger design on temperature changes of heat exchanging medium.

is shown from that the enhanced wide mesh heat exchanger is a good candidate design for hot air production for drying.

Fig. 4 shows the effect of the heat exchanger design on changes of the overall conversion of CaO for hot air heat exchange experiments. From this figure, it is noted that the conversions are not high because of the depth of the bed of CaO. The conversion can be increased only by enhancing the heat transfer condition. This means that the heat transfer enhancement is important for hot air production by CHPD.

Fig. 5 shows the effect of the heat exchanger design on hot heat recovery efficiency in CHPDs. The efficiency of energy recovery is defined here as follows:

$$\text{Efficiency of heat recovery} = \frac{Q_{\text{Ex,H}}\,(\text{recovered hot heat amount})}{Q_{\text{H}}\,(\text{generated hot heat amount})} \tag{4}$$

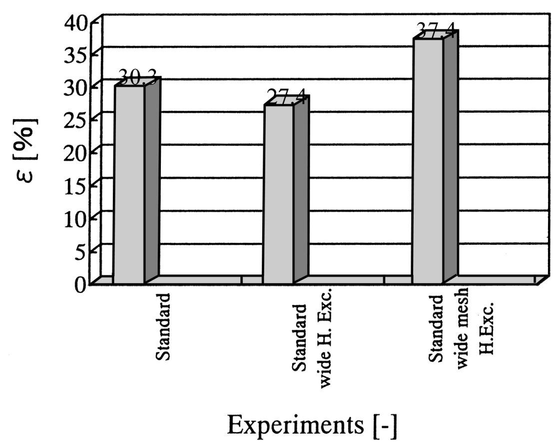


Fig. 5. Effect of heat exchanger design on hot heat recovery efficiency.

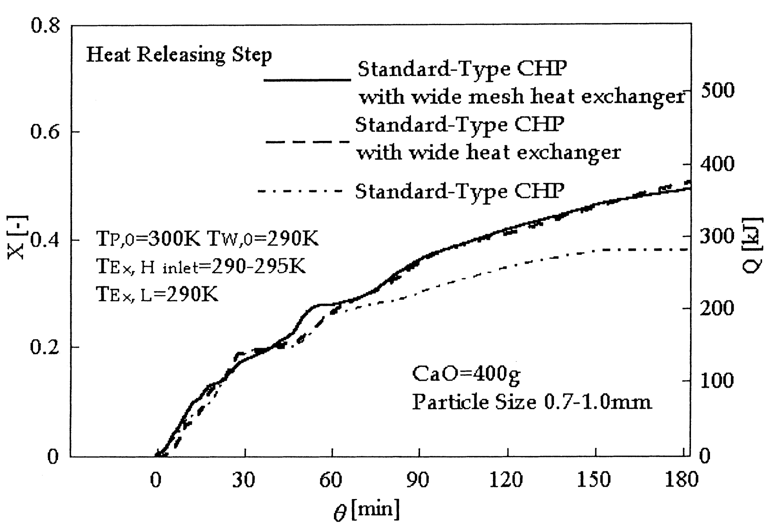


Fig. 4. Effect of heat exchanger design on overall conversion of CaO bed.

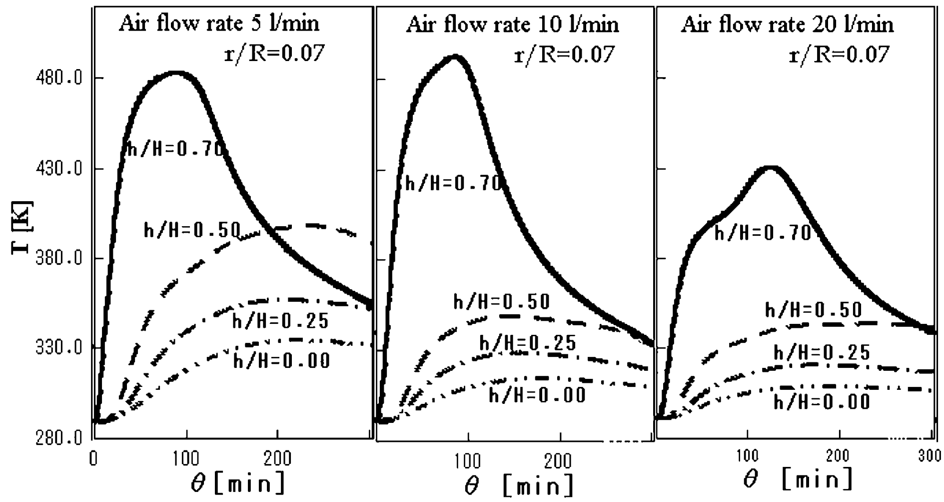


Fig. 6. Effect of air flow rate on temperature distribution in the reactor.

From this figure, it is found that the heat recovery efficiency can be promoted by designing the CHP and the heat exchanger for hot air production. We need to design better and more efficient heat exchangers for hot air production in CHPDs. This is an area for further development of the technology proposed.

Fig. 6 shows the changes of temperature distribution in the z direction of the reactor for hot air production experiments, which display the effect of air flow rate. The temperatures rise rapidly in the initial period, and fall slowly because of the decrease of the reaction rate and the heat recovery by the heat exchanger. The temperatures rise with decrease of the air flow rate. It is important to know this effect to keep the reactant bed in desired reactive temperature zone. It is also found that the axial temperature distribution exist because of the mass transfer resistance for water vapor diffusion in the bed.

Fig. 7 shows the effect of air flow rate on the hot heat recovery efficiency. By increasing the air flow rate by about four times, the hot heat recovery efficiency is also found to increase more than four times. This means that the air flow rate is not high enough to recover the generated heat in the reactor in these experiments although the recovery efficiency reaches more than 50%.

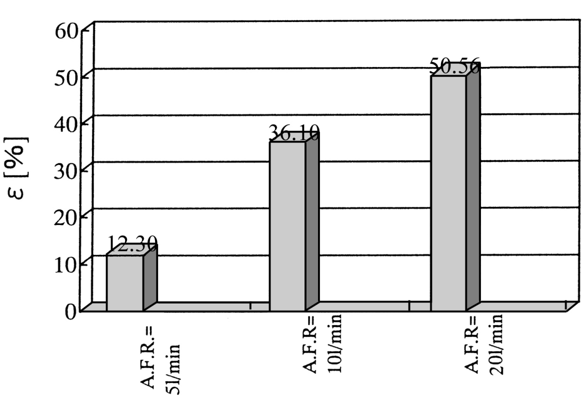


Fig. 7. Effect of air flow rate on hot heat recovery efficiency.

In order to determine the reason for the low conversion of the CaO bed and the low heat recovery efficiencies mentioned above, we examine the heat and mass transfer characteristics of the reactor as follows. Fig. 8 shows the changes of temperature distribution of the reactor for hot air production. The temperatures rise rapidly in the initial period. Then they fall slowly because of the decrease of the reaction rate and the heat recovery by the heat exchanger in the r direction. The temperatures at higher levels in the bed are higher than those at lower positions. This shows that a significant mass transfer resistance exists in the z direction for water vapor diffusion. The result agrees with the theoretical results of an earlier study [7]. It is found that the reactant bed needs to be shallow in the water vapor flow direction to reduce the mass transfer resistance.

Fig. 9 shows changes of the thermal output from the CHPD apparatus. Q_{H} and $Q_{\mathrm{Ex,H}}$, denote the generated "hot" heat in the reactor and the recovered "hot" heat by the air heat exchanger. $Q_{\mathrm{P,H}}$ is the transferred heat in the r direction of the particle bed defined as follows. Here, the value of the effective thermal conductivity λ_{P} is assumed to be 3 W/m K based on our earlier data [7].

$$Q_{\mathrm{P,H}} = \lambda_{\mathrm{P}} A \frac{(\Delta T_{\mathrm{P}})_{\mathrm{ln}}}{\Delta r} \tag{5}$$

$Q_{\mathrm{C1,H}}$ and $Q_{\mathrm{C2,H}}$ are convective heat transfer rates from the air reactor wall to the air heat exchanger defined by

$$Q_{\mathrm{C}n,\mathrm{H}} = h_n A (\Delta T_{\mathrm{Ex}})_{\mathrm{ln}} \tag{6}$$

The convective heat transfer coefficient h_n is determined as h_1: the total transferred heat $Q_{\mathrm{C1,H}}$ equals the generated hot heat Q_{H} and as h_2: the total transferred heat $Q_{\mathrm{C2,H}}$ equals the recovered hot heat $Q_{\mathrm{Ex,H}}$. The values of the heat transfer coefficients are $h_1 = 9.0\,\mathrm{W/m^2\,K}$ and $h_2 = 4.5\,\mathrm{W/m^2\,K}$.

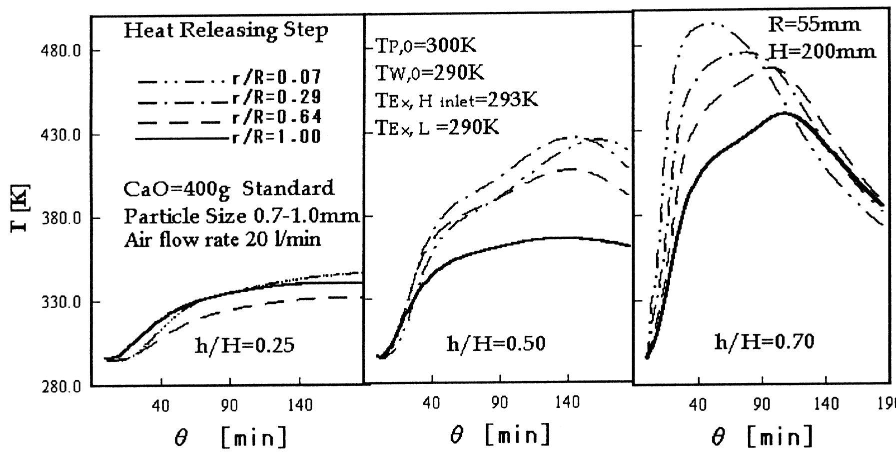


Fig. 8. Changes of temperature distribution in the reactor.

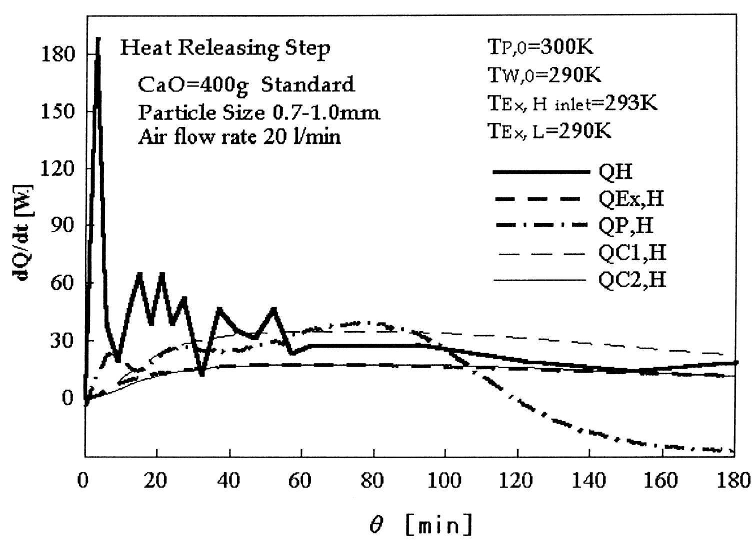


Fig. 9. Changes of thermal output from the CHPD apparatus.

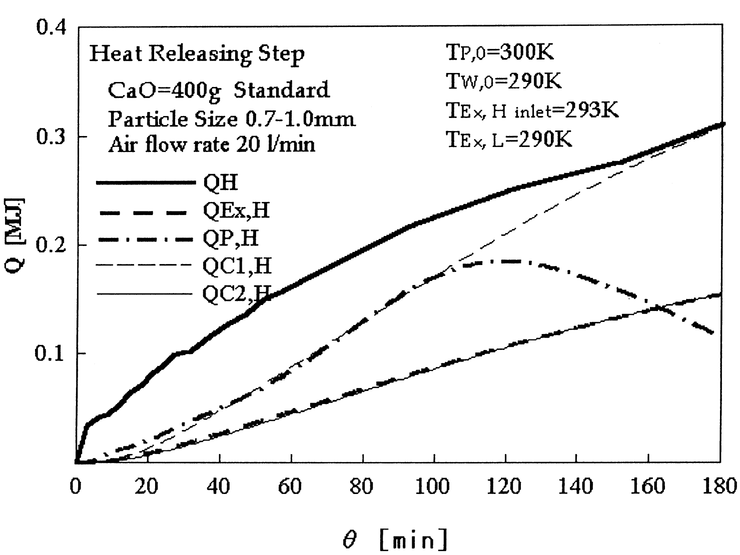


Fig. 10. Changes of generated and recovered heat from the CHPD apparatus.

It is found that the output of the generated hot heat Q_H is very high in the initial period. The output of the transferred heat in the r direction of the particle bed $Q_{P,H}$ rises with some time delay because of the heat transfer resistance in the particle bed. $Q_{P,H}$ falls down to a negative output finally.

Fig. 10 shows the changes of the generated and recovered heat from the CHPD apparatus. It is found that the convective heat transferred from the reactor wall to the air heat exchanger $Q_{C1,H}$ increases late in comparison with the generated hot heat Q_H similar to the change of the heat transferred in the r direction of the particle bed, $Q_{P,H}$. This implies that the convective heat transferred from the reactor wall to the heat exchange air, $Q_{C1,H}$, depends on the heat transfer rate in the reactant bed. Later, the heat flow in the bed becomes more complicated and the calculated $Q_{P,H}$ falls and does not match the experimental measurements. On the other hand, the change of the convective heat transferred from the reactor wall to the heat exchange air, $Q_{C2,H}$, h_2: the total heat transferred $Q_{C2,H}$ equals the recovered hot heat $Q_{Ex,H}$, agrees with the change of $Q_{C2,H}$. Thus, the magnitude of the recovered heat by heat exchange, $Q_{Ex,H}$, is governed by the heat released from the reactor wall, $Q_{C2,H}$. As noted earlier, the convective heat transfer needs to be enhanced as the value of convective heat transfer coefficient is calculated to be only about 4.5 W/m^2 K.

5. Conclusions

An experimental study focusing on the effects of heat exchange condition on the hot air production by a CHPD using the $CaO/H_2O/Ca(OH)_2$ reaction for convective drying as a CHPD was performed for a system the authors proposed in prior studies. As a result, the following conclusions are shown.

The CHP system using calcium oxide/calcium hydroxide hydration/dehydration reaction can be used for hot air production for batch drying using ambient air temperature in the heat-release step. The temperature levels and amount of the hot air produced and the reaction rates/conversions depend on the heat and mass transfer characteristics of the CaO reactor and the heat exchanger. The heat recovery efficiency can be augmented by designing the heat exchanger and the air flow rate appropriately for hot air production. The reactant bed needs to be shallow in the water vapor flow direction. The recovered heat by the air heat exchanger is governed by the released heat from the reactor wall; the convective heat transfer rate needs to be enhanced by designing the reactor and the heat exchanger appropriately. These are the objectives of the follow-up studies planned by the authors.

References

[1] M. Kanamori, H. Ogura, H. Matsuda, M, Hasatani, High-temperature high-density heat storage using $Ca(OH)_2/CaO$ thermochemical reaction, in: Proceedings of the Fifth World Congress on Chemical Engineering, San Diego, USA, 1996, pp. 67–72.

[2] H. Matsuda, T. Ishizu, S.K. Lee, M. Hasatani, Kinetic study of $Ca(OH)_2/CaO$ reversible thermochemical reaction for thermal energy storage by means of chemical reaction, Kagaku Kogaku Ronbunshu 11 (1985) 542–548.

[3] H. Ogura, A. Nagura, H. Matsuda, M, Hasatani, M. Yanadori, M. Hiramatsu, Studies on heat transfer augmentation in chemical heat pump composed of $CaO/Ca(OH)_2$ reversible reaction and evaporation/condensation of water, in: Proceedings of the International Conference on the Analysis of Thermal and Energy Systems, Athens, Greece, 1991, pp. 665–676.

[4] H. Ogura, A. Nagura, H. Matsuda, M. Hasatani, M. Yanadori, M. Hiramatsu, Studies on improving the efficiency of chemical heat pump using $CaO/Ca(OH)_2$ reversible reaction, in: Proceedings of the Fourth World Congress on Chemical Engineering, Karlsruhe, Federal Republic of Germany, Vol. 4, 1991, pp. 1–18.

[5] H. Ogura, M. Kanamori, H. Matsuda, M. Hasatani, Generation of low-temperature heat by chemical heat pump using $CaO/H_2O/Ca(OH)_2$ reaction system, in: Proceedings of the First International Thermal Energy Congress, Marrakesh, Morocco, 1993, pp. 531–534.

[6] H. Ogura, S. Fujimoto, H. Iwamoto, H. Kage, Y. Matsuno, S. Baba, S. Muta, A.S. Mujumdar, Reactor design of $CaO/H_2O/Ca(OH)_2$ chemical heat pump unit for cold/hot heat-generation with night-electric heat storage, in: Proceedings of the 13th International Congress on Chemical and Process Engineering (CHISA'98), Praha, Czech Republic, Vol. 8, 1998, pp. 17–18 (H7.1).

[7] H. Ogura, R. Shimojyo, H. Kage, Y. Matsuno, A.S. Mujumdar, Simulation of hydration/dehydration of $CaO/Ca(OH)_2$ chemical heat pump reaction for cold/hot heat generation, Drying Technol. 17 (1999) 1579–1592.

[8] H. Ogura, H. Kage, Y. Matsuno, A.S. Mujumdar, Application of chemical heat pump technology to industrial drying: a proposal of a new chemical heat pump dryer, in: Proceedings of the Symposium on Energy Engineering (SEE2000), Hong Kong, Vol. 3, 2000, pp. 932–938.

[9] H. Ogura, A.S. Mujumdar, Proposal for a novel chemical heat pump dryer, Drying Technol. 18 (2000) 1033–1053.

[10] I. Strommen, T. Eikevik, O. Alves-Filho, Optimum design and enhanced performance of heat pump dryers, in: Proceedings of the First Asian–Australian Drying Conference, Bali, Indonesia, 1999, pp. 68–80.