Feasibility Study of Air Conditioning System With Separated Dehumidification Process Using Low Temperature Exhaust Heat of Ice Storage

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ABSTRACT

The aim of this study is to develop an advanced air conditioning system. The dehumidification process of this system is separated from the cooling process and combined with an ice storage system. We use Wakkanai siliceous shale as a desiccant material. This is a natural meso-porous material produced in the northern area of Hokkaido, Japan. A honeycombed desiccant material made of the shale is cheaper than the one with silica-gel, and it can release vapor easily even by using low-temperature air. It was found that the desiccant process by using the shale honeycomb enables the temperature of regeneration to decrease to 40ºC, whereas the desiccant process using silica-gel needs the temperature of 80ºC.

1. INTRODUCTION

Recently the demand for cooling is increasing for comfortable conditions, especially in the urban areas. Because of this demand, energy consumption in the daytime is very large and causes the shortage of electricity. Therefore, a peak shaving using night power for a cold storage is effective for energy saving and the electric load leveling.

On the other hand, the humidity control is one of the key factors for indoor comfort. As a comfortable indoor condition, 26ºC and 50–60%RH is recommended in the summertime in Japan. The average temperature and relative humidity of summer in Tokyo is shown in Fig. 1. This shows that dehumidification is necessary. However, the conventional air-conditioning system needs a lot of energy for dehumidification. It cools the humid air to remove moisture condensing the humidity into a droplet. Briefly it spends much energy for removing latent heat.

As a result, a desiccant cooling system attracts increasing attention. The desiccant system is an open heat driven cycle, and it consumes less energy for dehumidification. A typical desiccant system is shown in Fig. 2. Because a desiccant wheel absorbs moisture from the humid air, this system doesn’t need supercooling for condensation. Furthermore, we can use the desiccant wheel repeatedly by regenerating with high temperature air. As the regenerating air, waste heat of micro gas turbine, solar energy, and other exhaust heat are useful. In Japan, the solid desiccant systems using silica gel or zeolite filter are mainly used. Although they
have high adsorption performance, they are not familiar to the air-conditioning market because of their prices and high regeneration temperature around 80ºC.

In this paper, as an effective utilization of exhaust heat from the refrigerator for the ice storage, the combination with a desiccant system was introduced (Fig. 3). Part of the cooling load is shifted from peak hours to off-peak hours like midnight. And the exhaust heat is used for regenerating the desiccant material. Authors developed a desiccant wheel using Wakkanai siliceous shale as a new desiccant material. Performance evaluation and numerical calculation were achieved.

2. WAKKANAI SILICEOUS SHALE

Wakkanai siliceous shale (WSS) is a kind of siliceous mudstone. Figure 4 shows the appearance of this shale. It is widely distributed in northern part of Hokkaido (Soya area) in Japan as shown in Fig. 5, and laid down in layers more than 1,000 meters below the surface. This shale is natural meso-porous material, and it has characteristic pore size distribution as
shown in Fig. 6. The pores in the range from 4 to 20 nm contribute to the moisture adsorption. The primary constituent of this shale is silicon dioxide (SiO₂). This shale’s specific surface area calculated by BET equation is 149 m²/g, and the fine pore volume is 0.382 cm³/g. Figure 7 shows the water adsorption isotherms of WSS at 25°C. WSS adsorbs a lot of water vapor when the relative humidity of air is higher than 70%, however it doesn’t adsorb well under the dry condition.

Compared with silica gel (type A), WSS starts to adsorb the moisture in the range of higher relative humidity. Although the maximum adsorption amount of WSS is about 3/4 of silica gel (type A), WSS is easier to be regenerated than silica gel because WSS releases the moisture simply when the relative humidity decreases. And the price is about 1/10 of that of silica gel.
3. DESICCANT WHEEL CONTAINING WAKKANAI SILICEOUS SHALE

To develop a desiccant wheel containing WSS, we made paper using pulp and the WSS powder. WSS powder was obtained by a ball-milling treatment. The highest-frequent diameter of WSS particle was 3.1 µm. The WSS paper was formed into a corrugate-structure filter as shown in Fig.8. The diameter is 150 mm, and the length is 200 mm just for a test production. Two types of pulp were used as WSS filters.

For analyzing the adsorption performance, short-term cyclic test was carried out. The experiment condition is shown in Table 2. A condition of term A –adsorption- was the simulation of the outside air in the daytime of summer in Tokyo. The other, term B -regeneration- was simulated the return-air from the room (26ºC, 60%RH) heated to 40ºC by using the exhaust heat of the refrigerator. Figure 9 shows the experimental setup and its picture. Summary of the test pieces is shown in Table 3.

Figure 7: Water adsorption isotherms of Wakkanai siliceous shale and silica gel (type A) analyzed at 25ºC.

Figure 8: Appearance of the test production of the desiccant filter containing WSS
The weight changes of these filters in the first and second cycles are shown in Fig. 10. It was confirmed that Filter C –silica gel (type A)- and Filter D –zeolite- adsorbed moisture in the first cycle, but they couldn’t be regenerated enough by 40°C air. Then, in the second cycle, they couldn’t adsorb the same amount of moisture as in the first cycle.

On the other hand, Filter A –WSS and natural pulp- adsorbed about the same amount of moisture as Filter C, and it could be completely regenerated by 40°C air. Filter B didn’t have a good ability of the moisture adsorption though it contained WSS. The amount of contained WSS was supposed to be less than that of Filter A.

This cyclic test showed that Filter A had the best performance for the moisture adsorption in this condition. However, this amount was not enough for a dehumidifying in the humid season in Tokyo. So we must improve the adsorption ability of this filter.

In the next section, the numerical calculation program for Filter A was constructed by using the result of this cyclic test.
4. NUMERICAL SIMULATION MODEL

Feasibility study of the desiccant wheel containing WSS (Filter A) was simulated with a numerical model shown in Fig.11. It was assumed that heat and mass transfer occurred at the same time at each element of the honeycomb. In addition, a micro element was replaced by the slab model. Equations of heat and mass transfer were solved by dividing a micro element into 5 parts along the flowing direction (z-direction).

In the airflow path, the pressure and the velocity of air were assumed to be constant. And advection flow was singly considered in the one-dimensional direction. Furthermore, heat and mass transfer in the desiccant material was neglected. It was assumed that the distribution of temperature and adsorption amount was homogeneous in the direction of thickness.
The dominant equations are as follows:

<Mass balance at the layer of air>
\[
\rho_a \frac{\partial x}{\partial t} + \rho_a u_a \frac{\partial x}{\partial z} + m_a = 0
\]  
(1)

<Mass balance at the adsorption layer>
\[
m_{ad} = \rho_d \frac{\partial q}{\partial t} a_d
\]  
(2)

<Heat balance at the layer of air>
\[
\rho_a c_{pa} \frac{\partial T_a}{\partial t} + \rho_a u_a c_{pa} \frac{\partial T_a}{\partial z} + \frac{\alpha_s}{a_a} (T_a - T_d) = 0
\]  
(3)

<Heat balance at the adsorption layer>
\[
\rho_d c_{pd} \frac{\partial T_d}{\partial t} = \rho_d \frac{\partial q}{\partial t} q_h + \frac{\alpha_s}{a_d} (T_a - T_d)
\]  
(4)

<Boundary conditions>
\[
x = x_{in}, \ T_a = T_{ain} \ at \ z = 0
\]

<Initial conditions>
\[
x = x_0, \ T_a = T_{ain}, \ T_d = T_{ain} \ at \ t = 0
\]

<Symbols>
- \(a\): thickness [m], \(c_p\): specific heat [kJ/kg/K], \(L\): length [m], \(m\): mass transfer amount [kg/m²/s],
- \(q_h\): heat of adsorption [W/m²], \(q\): adsorption amount [kg/kg], \(T\): temperature [ºC],
- \(t\): time [s], \(u\): velocity [m/s], \(x\): absolute humidity [kg/kg], \(z\): position of z-axis direction [m]
- \(\alpha_s\): heat transfer coefficient [W/(m²-K)], \(\rho\): density [kg/(m³)]

<Subscripts>
- \(a\): air, \(d\): desiccant, \(in\): inlet, \(out\): outlet, \(s\): surface, \(0\): initial condition ,\(ad\): adsorption

## 5. RESULTS AND DISCUSSION

Figure 12 shows the comparison of the results of the numerical simulation with those of the experimental measurement about the temperatures of the inlet and the No. 2 point (about 6 cm from the filter’s entrance) in Fig. 9, and the inlet and the outlet absolute humidity.

As a result, it was confirmed that this numerical model could reproduce the temperature rising immediately after the start of ventilating. And a falling tendency of temperature was approximately reproduced.

Furthermore, when the filter length was changed in this simulation, the half length of the 200mm-filter resulted in 75% of the total adsorption amount. It meant the latter half of the filter didn’t fully contribute to the adsorption.

Next, by using this Filter A model, the outlet absolute humidity was calculated according to the changes of the air flow rates. It was assumed that the diameter of the desiccant wheel was 900 mm and the length was 100 mm. Adsorbing condition (T: 30ºC, AH: 20.1 g/kg) and regenerating condition (T: 40ºC, AH: 12.6 g/kg) recurred every 6 minutes.

The result of the numerical simulation is shown in Fig. 13. The outlet humidity became lower with the reduction of the air flow rates.
This study shows that Wakkanai siliceous shale is introduced as a new desiccant material. The filter containing the shale can be regenerated by using 40°C air from the experiment. Thus, an exhaust heat from the refrigerator of the ice storage is reasonable to regenerate this filter. However, the adsorption amount is still the pending issue.

6. CONCLUSION

This study shows that Wakkanai siliceous shale is introduced as a new desiccant material. The filter containing the shale can be regenerated by using 40°C air from the experiment. Thus, an exhaust heat from the refrigerator of the ice storage is reasonable to regenerate this filter. However, the adsorption amount is still the pending issue.

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