Numerical Analysis of Heat and Moisture Transfer in Desiccant Wheel for Dehumidification

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SUMMARY

In the desiccant dehumidifier using adsorbent such as silica gel and zeolite, moist outdoor air is dehumidified by the adsorbent, and the damped adsorbent needs to be dried (regenerated) by giving heated air. Utilizing solar thermal energy as a heat source for the regeneration of the adsorbent leads to large energy conservation. We aim to develop the high efficiency desiccant dehumidification system using solar thermal energy. For this development, we investigated numerical analysis method of heat and moisture transfers in desiccant wheel in order to carry out the optimal design of this desiccant system. In this paper, the heat and water vapor transfer phenomena inside a desiccant wheel were formulated, and the algorithm of numerical calculation for the formulated equations was investigated. Its validity was checked by comparing the calculation results with the results of the repeated adsorption-desorption experiment for a fixed desiccant wheel (the wheel is not rotating), and with the experiment using an actual desiccant machine (the wheel is rotating). With regard to the numerical calculation targeted at the repeated adsorption-desorption experiment, the periodic change in moisture content was accurately reproduced by the calculation. However, with regard to the actual desiccant machine, this numerical analysis could not accurately predict the air temperature after passing through the desiccant wheel, although it could evaluate the amount of dehumidification fairly well.

INTRODUCTION

In Japan, solar heat systems have been introduced in mainly detached houses. In fiscal 2002, the quantity of these amounted to 740,000 kL in crude oil equivalent. The scheme for achieving the goals of the Kyoto Protocol [1], which was approved at a Cabinet meeting in April 2005, also includes the aim to further promote the introduction of solar heat systems. In order to achieve the goals, it is necessary to promote the use of solar systems for the public buildings, housing complex, and industrial fields, and so it is imperative to develop the technology for application in these fields. In order to spread the heating and the hot water supply systems that utilize solar heat, it is one key to find how to use the excessive solar heat during summer and spring/autumn seasons, and we started on a research project of "the floor heating & cooling, ventilation, and hot water supply system using solar heat" (Fig.1). For this system, we are developing a wheel-type solid desiccant air-conditioning system (Fig. 2) using this excessive solar heat. In the desiccant system that uses absorbents, such as silica gel and zeolite, outdoor moist air is dehumidified in absorbents, and heated up by adsorption heat, to become low-humidity high-temperature air, and then it passes sensible heat exchanger and evaporative cooling, to be supplied as cool and dry air. By utilizing solar heat as the heat source for regenerating (dehumidifying) the damped absorbents, it is possible to gain a great degree of the energy-saving effect. In addition, this is not dehumidification by the dew condensation method, and so it is possible to inhibit the growth of mold and fungi. As mentioned above, the desiccant system is an air-conditioning technology attracting people's attentions as an environmentally-friendly air-conditioning system from the perspectives of energy saving, air quality, and chlorofluorocarbon issues. But for the popularization of this system, we need to pursue higher efficiency, miniaturization, weight reduction of devices, the methods for utilizing solar heat effectively, and the technique for post-cooing at low energy costs.

In this study, in order to develop a high-efficiency desiccant system utilizing solar heat, we are examining the pre-cooling technique of the adsorbing part of the desiccant wheel, unique post-cooling methods, and the application of new adsorbing materials. We are also intended to optimize a variety of parameters that influence the performance of the desiccant system. There are a large number of parameters that determine the performance of a desiccant system—desiccant material's moisture adsorption/desorption characteristics, size of the wheel, air volume, process/regeneration splitting ratio, rotation speed, temperature of regeneration, void ratio, and the degree of pre-cooling. Therefore, it costs an enormous amount of time and labor to discover the desirable combination of parameters.

In this circumstance, we developed a technique for numerical analysis of heat and moisture transfers, considering the rotation of a desiccant wheel in order to carry out the optimal design of a desiccant system. The heat and moisture transfer phenomenon inside a desiccant element was formulated, and the algorism of numerical calculation for the formulated equations was investigated. First, we measured the equilibrium moisture content, which is used as the input value of the adsorption/desorption characteristics of a desiccant material for numerical calculation. Secondly, in order to confirm the validity of the numerical analysis method, we compared the results of the experiment of repeating the adsorption and desorption when a wheel is fixed with the results of the numerical calculation, and then compared the results of the measurement in the actual desiccant machine and the results of the numerical calculation that took the rotation of the wheel into account.

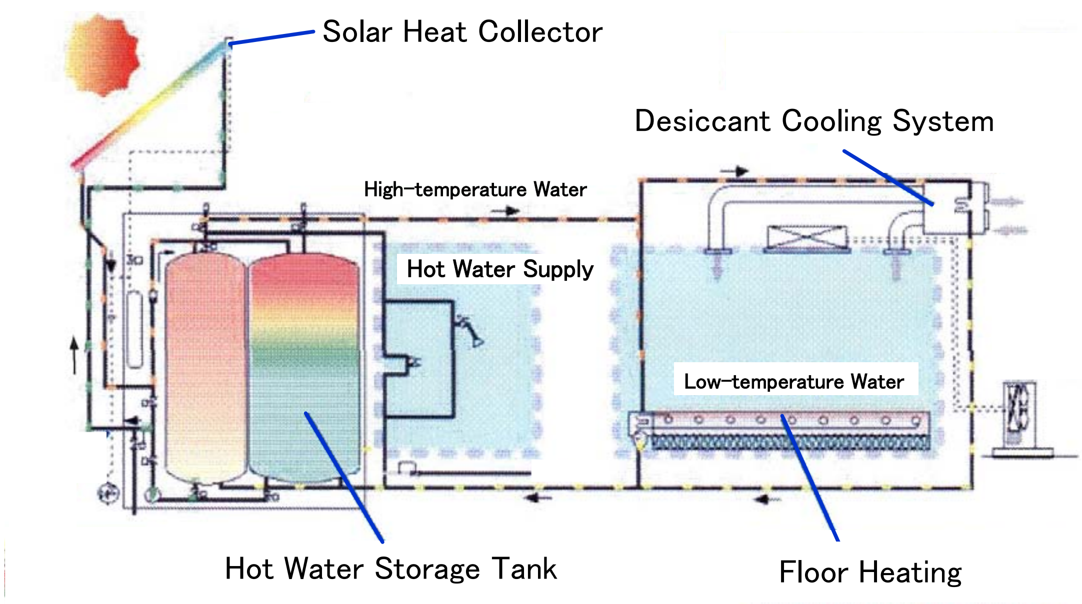

Figure 1. Schematic diagram of the floor heating & cooling, ventilation, and hot water supply system using solar heat.

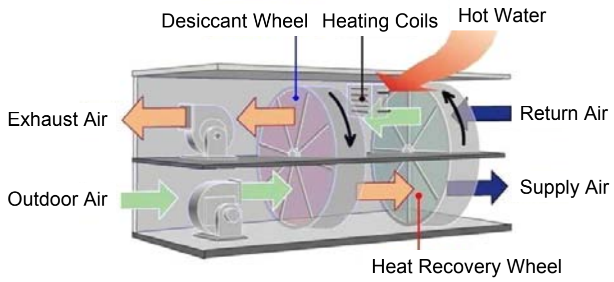

Figure 2. Desiccant cooling system

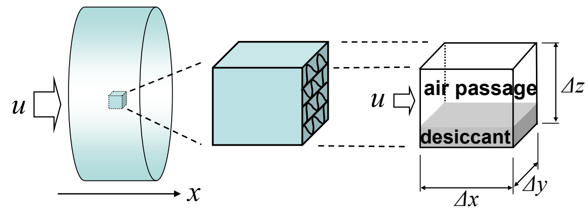

Figure 3. Modeling of desiccant wheel

TRANSPORT EQUATIONS OF HEAT AND WATER VAPOR INSIDE A DESICCANT ELEMENT

As shown in the left diagram of Fig. 3, a parallelepiped infinitesimal volume is taken from the wheel and modeled, as shown in the right diagram of Fig. 3. Considering the balances of water vapor and heat quantity inside this infinitesimal volume, the three transport equations (1), (4), and (5), as shown in Table 1, can be obtained. Equation (2) indicates that the moisture content of a desiccant material changes due to the water vapor transfer on the desiccant material's surface. Equation (3) is based on the assumption of local equilibrium in which the relation between the absolute temperature and moisture content of the desiccant material's surface (adsorption/desorption phase) instantaneously follows the adsorption isotherm. This formulation was conducted with reference to the theory of simultaneous transfer of heat and water vapor proposed by Matsumoto and Hokoi et al.[),)]. The adsorption isotherm of Equation (3) varies significantly according to materials, and so in this study, we measured this for the target desiccant wheel.

Table 1. Transport equations of heat and water vapor

Water vapor transport equation in air passage

$$\varepsilon\rho_a\frac{\partial X_a}{\partial t}=-\varepsilon u\rho_a\frac{\partial X_a}{\partial x}+\varepsilon\frac{\partial}{\partial x}\left(\lambda_a'\frac{\partial X_a}{\partial x}\right)-\gamma\frac{\partial w}{\partial t}\quad(\mathrm{kg/m^3s})\qquad\mathbf{(1)}$$

Equation of moisture content

$$\gamma\cdot\frac{\partial w}{\partial t}=\alpha' S\left(X_a-X_b\right)\quad(\mathrm{kg/m^3s})\ \mathbf{(2)}\qquad w=f\left(X_a,\theta_a\right)=f\left(X_b,\theta_d\right)\quad(\mathrm{kg/kg_d})\ \mathbf{(3)}$$

Heat transport equation in air passage

$$\varepsilon C_a\rho_a\frac{\partial\theta_a}{\partial t}=-\varepsilon u\rho_a C_a\frac{\partial\theta_a}{\partial x}+\varepsilon\frac{\partial}{\partial x}\left(\lambda_a\frac{\partial\theta_a}{\partial x}\right)-\alpha S\left(\theta_a-\theta_d\right)\quad(\mathrm{J/m^3s})\qquad\mathbf{(4)}$$

Heat transport equation in desiccant material

$$\left(1-\varepsilon\right)C_d\rho_d\frac{\partial\theta_d}{\partial t}=\left(1-\varepsilon\right)\frac{\partial}{\partial x}\left(\lambda_d\frac{\partial\theta_d}{\partial x}\right)+L\alpha' S\left(X_a-X_b\right)+\alpha S\left(\theta_a-\theta_d\right)\quad(\mathrm{J/m^3s})\qquad\mathbf{(5)}$$

ε : porosity (-), ρ : air density (kg/m^3), X : absolute humidity (kg/kg'), t : time (s)
x : coordinate along air passage (m), u : air velocity (m/s), λ' : water vapor conductivity {kg/ms(kg/kg')}
γ : density of desiccant material (desiccant mass per volume including air passage) (kg$_d$/m^3)
w : moisture content (kg/kg$_d$), α' : water vapor transfer coefficient on desiccant surface {kg/m^{2}s(kg/kg')}
α : convective heat transfer coefficient on desiccant surface (J/sm^{2}K)
S : Surface Area of desiccant material per volume including air passage (m^2/m^3)
$f\left(X_a,\theta_a\right)$: adsorption isotherm (kg/kg$_d$), C : specific heat (J/kgK), θ : temperature (K)
λ : thermal conductivity (J/smK), L : latent heat of vaporization (J/kg)

Suffix $_a$: air $_d$: desiccant material $_b$: desiccant material's surface (adsorption/desorption phase)

MEASUREMENT OF THE EQUILIBRIUM MOISTURE CONTENT OF A DESICCANT WHEEL

The experimental apparatus and measuring methods adopted in this study follow the JIS's method for measuring the equilibrium moisture content of building materials [2] and the Environmental Standards of the Architectural Institute of Japan [3].

Fig. 4 shows the experimental apparatus. This apparatus is composed of a temperature-controlled bath, an air control unit, which automatically adjusts the mixing ratio of dry air and saturated air to a specified relative humidity and sends air to the measurement chamber, and an air handling unit (AHU), which supplies the air with steady temperature to the temperature-controlled bath. The weight change of the desiccant wheel during moisture adsorption or desorption was gauged by an electronic balance, and the dew-point temperature of the influx/outflux air was measured by a chilled-mirror dew-point thermometer. The temperature inside the temperature-controlled bath was measured by a PT100.

Firstly, a desiccant wheel with a diameter of 150 mm and a thickness of 100 mm was put into an oven, and dried sufficiently at 110 degrees Celsius, and then the reference dry mass was measured. Next, the desiccant wheel was put into the measurement chamber, air with a specified relative humidity of 10% was supplied, and measurement was carried out until the desiccant wheel reached the constant weight (equilibrium state). The relative humidity was increased in a stepwise manner, and the above weight measurement was conducted (adsorption process). After the specified relative humidity was increased to 95%, the relative humidity was decreased in a stepwise manner, and the above weight measurement was conducted until the specified relative humidity reached 10% (desorption process).

Fig. 5 shows measurement results of the equilibrium moisture content. Here, the moisture content higher than 45%RH for 70 degrees Celsius condition was not measured because the measuring limit of dew-point temperature was 50 degrees Celsius, and so the humidity limit was 45% in the 70 degrees Celsius condition. This has no problems because the relative humidity of the air inside the actual desiccant wheel never becomes higher than 45 %RH in the high-temperature condition.

Under the 25 degrees Celsius condition, the moisture content during the desorption process was higher than that during the adsorption process, under the medium humidity condition (20%RH-80%RH). This hysteresis phenomenon, which is commonly seen in porous materials, was observed. In addition, when the ambient temperature was set to be 70 degrees Celsius, the moisture content became lower than that under the 25 degrees Celsius condition, for the same relative humidity. This indicates that the relation between relative humidity and equilibrium moisture content varies according to temperature.

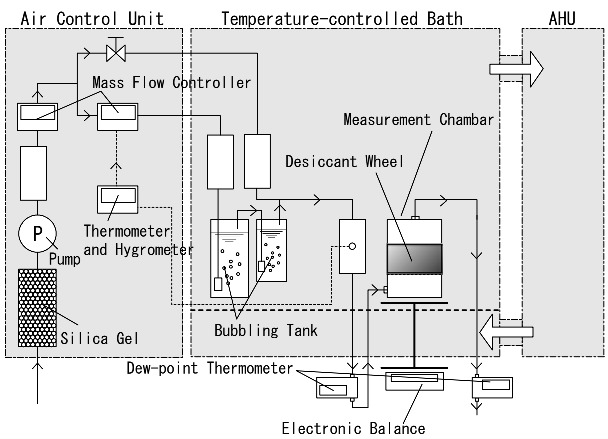

Figure 4. Experimental apparatus for measuring the equilibrium moisture content

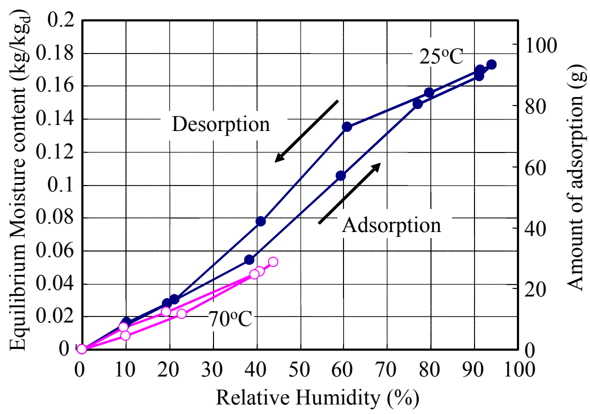

Figure 5. Adsorption isotherm

ALGORITHM OF NUMERICAL CALCULATION

The five equations shown in Table 1 are solved, to obtain the five unknown quantities: $X_a, X_b, \theta_a, \theta_d, w$. This algorithm is such that each variable is set at an initial value, Equations (1), (4), (5), and (2) are solved through time evolution, to obtain the values of $X_a, \theta_a, \theta_d, w$ at the next time step, and then a convergent calculation between Equations (2) and (3) is carried out to determine w and X_b. If the explicit method was used to solve Equations (1), (4), and (5), it is necessary to discretize time extremely finely in order to obtain stable solutions, and so the full-implicit method is adopted in this study. Namely, each of Equations (1), (4), and (5) is solved with TDMA (tri-diagonal matrix algorithm) [4] and then a convergent calculation is conducted between Equations (2) and (3), to determine provisional values of $X_a, X_b, \theta_a, \theta_d, w$ at the next time step. Using these updated provisional values, the above procedures are repeated with the Gauss-Seidel method [4] until convergence, to determine the values at the next time step. When the values at the next time step are determined, the time step proceeds to the next one. The control volume method is used for the discretization of space, and the upwind scheme is adopted for the advection term [4].

Fig. 6 shows the graph drawn by converting the horizontal axis in Fig. 5 from relative humidity to absolute humidity. The curves in Fig. 6 correspond to the function $f(X_a, \theta_a)$ in Equation (3). Here, the moisture content was defined as the average values of the adsorption and desorption processes, and the unmeasured temperature condition was obtained through the interpolation based on the measurement results at 25 degrees Celsius and 70 degrees Celsius. In the numerical analysis for the Equation (3), the temperature and the absolute humidity on the desiccant surface θ_d and X_b are substituted into the function that was produced by approximating adsorption isotherms in Fig. 6 with a quartic function, to obtain moisture content w in the Equation (3).

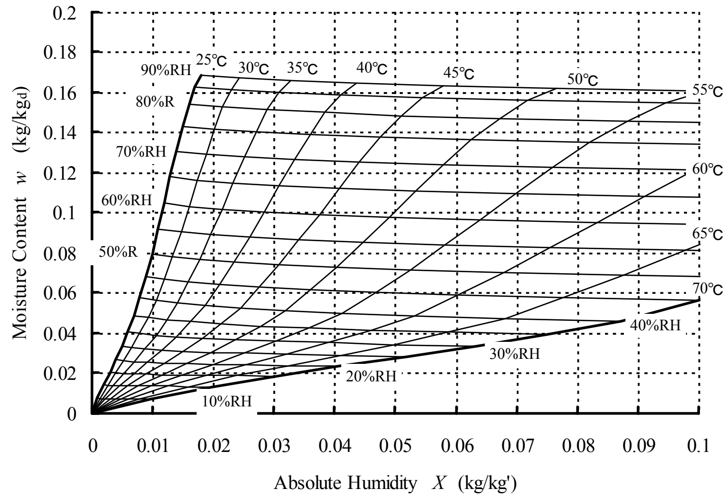

Figure 6. Adsorption isotherm used for the calculation

VALIDATION OF NUMERICAL CALCULATION

In order to check the validity of the formulated equations and the numerical calculation method for solving them, the repeated adsorption-desorption experiment was conducted for comparison. Fig. 7 shows the experimental apparatus. In the experiment, the air of 25 degrees Celsius and 70 degrees Celsius were supplied to a desiccant wheel by turns every two minutes, by operating manual dampers. The desiccant wheel with a diameter of 150 mm and a thickness of 100 mm was fixed so as not to rotate. The air volume was adjusted to 100 m^3/h with an orifice flow meter. In order to insulate heat, glass wool was wrapped around the Y pipe, the straight pipe, and the orifice. The desiccant wheel was placed on an electronic balance, separated from the straight pipe and the chamber box. The both sides were covered with lightweight, thin vinyl film, so as to prevent air leakage and not to receive loads from the both sides as much as possible. The mass of the desiccant wheel was measured with the electronic balance, and the dew-point temperatures at the upstream and the downstream of the wheel were measured with the chilled-mirror dew-point hygrometer.

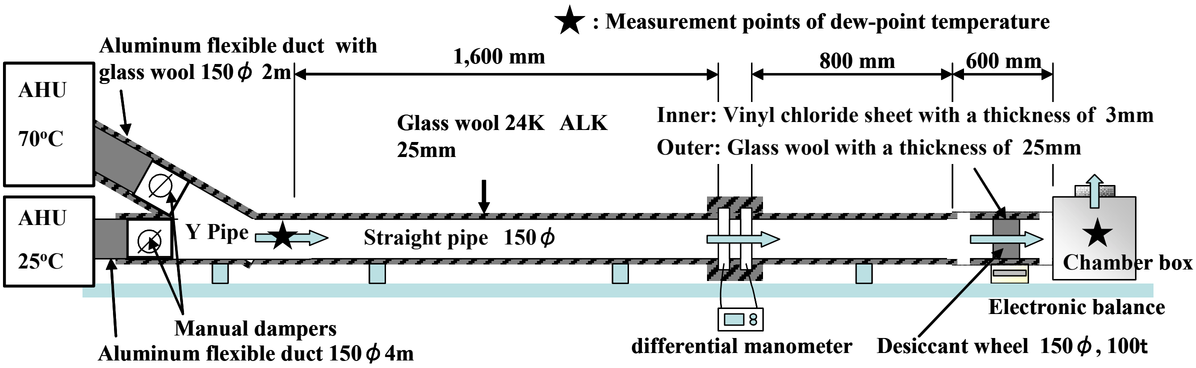

Figure 7. Experimental apparatus for repeated adsorption-desorption experiment

Table 2 tabulates properties used for the numerical calculation. For the computational grid, the 100 mm-thick element was divided equally into 20 parts, and time interval was set at 0.1 seconds.

Fig. 8 shows the calculation result of the moisture content after it reached periodic steady state, with the experimental result. The calculation reproduced the periodic change of the moisture content with the repeat of adsorption and desorption, and the calculated moisture content was within the range of the variation of the experimental data, as a whole.

Table 2. Calculation conditions

$\varepsilon = 0.71$	$\rho_d = 988$ (kg/m^3)	$\alpha = 60$ (J/sm^{2}K)	$\rho_a = 101.3/((\theta_a + 273)*0.287*(1+1.61*X_a))$ (kg/m^3)	
$u = 1.163$ (m/s)	$\lambda' = 0.000032$ {kg/ms (kg/kg')}	$\alpha' S = 17.0$ {kg/m^3 s(kg/kg')}	$S = 1180$ (m^2/m^3)	
$\gamma = 289$ (kg$_d$/m^3)	$L = 2390000$ (J/kg)	$C_a = 1006$ (J/kgK)	$C_d = 580$ (J/kgK)	
$\lambda_a = 0.022$ (J/smK)	$\lambda_d = 1.0$ (J/smK)			
Inflow Boundary Condition:	$\theta_a = 25$K or 70K	$X_a = 0.0069$ kg/kg'		

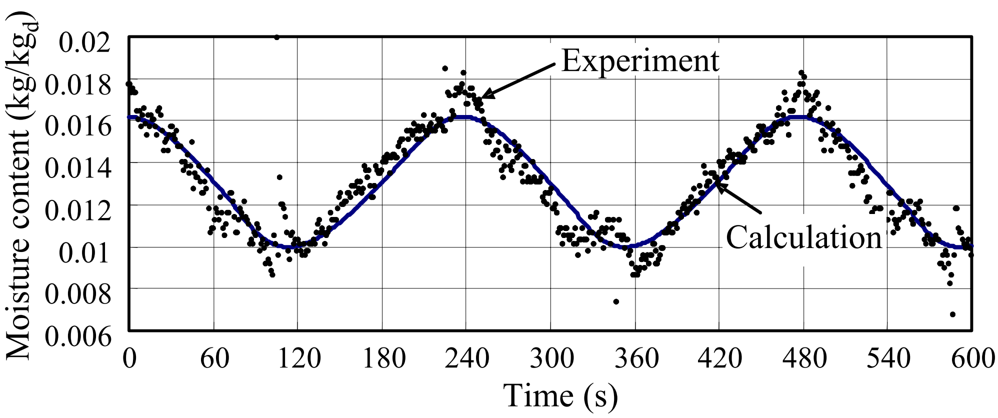

Figure 8. Periodic change of moisture content

NUMERICAL CALCULATION METHOD CONSIDERING THE ROTATION OF A WHEEL

Calculation method

As shown in Fig. 9, the wheel is segmented into each element in the rotational direction, and the above-mentioned numerical calculation is carried out separately. Each segmented element is rotated, and the flow direction and the influx temperature and humidity are switched, according to whether it is located at the adsorption side or the desorption side. By averaging the outflow temperature and humidity of all elements located at the adsorption side, it is possible to obtain the temperature and humidity of the air that has been dehumidified through the wheel at each time step. Until this averaged temperature and humidity become steady, the calculation is continued while rotating the wheel.

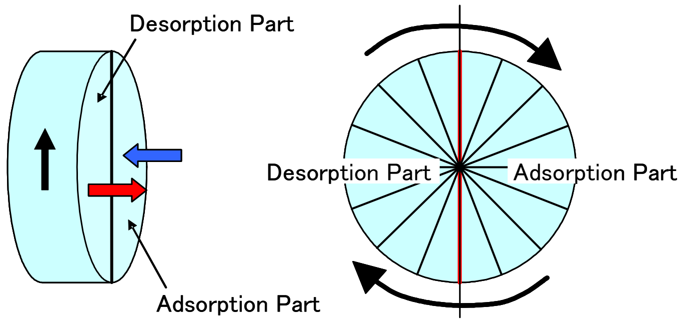

Figure 9. Calculation method for rotating desiccant wheel

Validation of Calculation method

In order to validate the numerical calculation method considering the wheel's rotation, we compared the calculation results with the experimental results for an actual desiccant machine. The actual desiccant wheel had a diameter of 300 mm and a thickness of 100 mm. Table 3 shows the experimental condition. For the inflow boundary conditions of the temperature and the humidity at the process side and the regeneration side, the measurement values were used. The air volume was set at 100 m^3/h, and the rotation speed was set at 30 RPH.

Fig. 10 plots the calculated result and measured result on a psychrometric chart. The air temperature that has passed through the wheel increased from 30 degrees Celsius to 54 degrees Celsius in the experiment, while the calculated temperature became 49 degrees Celsius, which was about 5 degrees lower than the experimental value. The absolute humidity after passing through the wheel was 0.01 kg/kg' in the experiment, while the calculated one was 0.0093 kg/kg'; these values are almost the same. Namely, the amount of dehumidification was evaluated quite accurately by the calculation. As for the regeneration side, there was also some difference in temperature between the experimental and the calculated results, but the results of the absolute humidity were almost the same. With regard to the discrepancy in temperature, this calculation method did not take the heat transfer among the segmented elements into account, but in actual wheels, it is considered that there is heat transfer at the boundary surface between the regeneration and process sides. This is expected to be improved by considering the heat transfer at the boundary surface between the regeneration and process sides in the model of the numerical calculation.

Table 3.
Calculation conditions

Geometry of desiccant wheel	300φ×100 t
Inflow Condition of process air	Temperature 30 K Absolute humidity 14.7 g/kg’
Inflow Condition of regeneration air	Temperature 70 K Absolute humidity 10.7 g/kg’
Air volume	100 m^3/h
Rotation speed	30 RPH

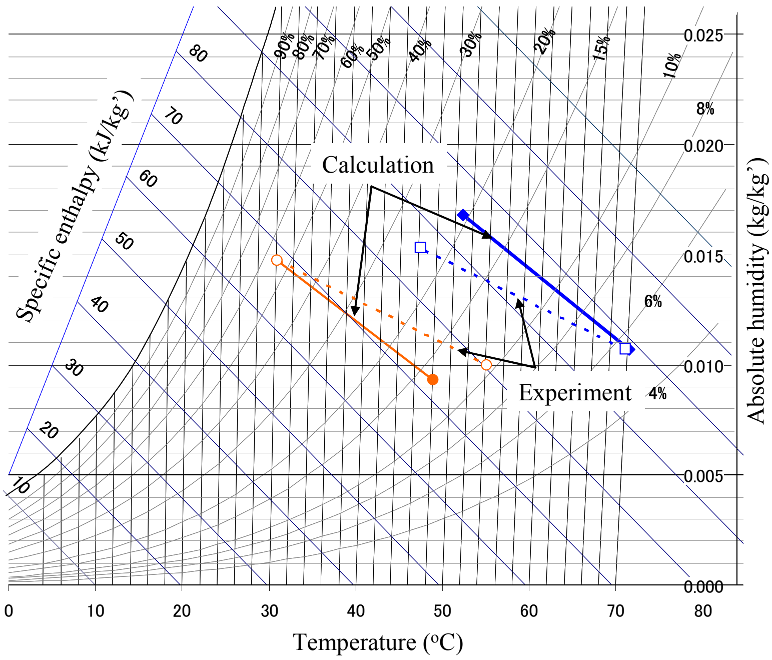

Figure 10. Comparison between calculated results and experimental results for an actual desiccant machine

CONCLUSIONS

The heat and water vapor transfer phenomena inside a desiccant wheel were formulated, and the algorithm of numerical calculation was investigated. Its validity was checked by comparing the calculation results with the results of the repeated adsorption-desorption experiment and the experiment using an actual desiccant machine. With regard to the numerical calculation targeted at the repeated adsorption-desorption experiment, the change in moisture content was accurately reproduced. However, the comparison with the experiment using an actual desiccant machine indicates that this numerical analysis could not accurately predict the air temperature after passing through the desiccant wheel, although it could evaluate the amount of dehumidification quite accurately. The prediction of air temperature is expected to be improved by considering the heat transfer at the boundary surface between the regeneration and process sides in the model of the numerical calculation.

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