Doctor Thesis

A Study of Continuous Sorption and Desorption in Two Connected Fluidized Beds with Organic Sorbent

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Contents

Chapter 1

Introduction

1.1 The background of the present research

Refrigeration system has wider application throughout industrial and agricultural product. This system has practical application recently for a wide variety of fruit, vegetables and some grains. The utilization of desiccant in refrigeration and air conditioning system has been continuously growing during the past several years. This system is considered as a good supplement for air conditioning because it can be a system to overcome the disadvantages of traditional vapor compression air conditioning system. Desiccant can be regenerated (reactivated) by application of heat to release the moisture. Improving the performance of desiccant dehumidification system can be providing more opportunities for this technology.

There are some types of equipment configuration that have been investigated for desiccant dehumidifier system. They are solid packed bed(1-1)-(1-3), rotating honeycomb(1-4), horizontal bed(1-5),(1-6), and fluidized bed(1-7)-(1-10). The process air flows through the desiccant bed giving up its moisture to the bed particles. After the desiccant bed has saturated with the moisture, the bed is heated and purged of its moisture for regeneration. For the system working continually, water vapor adsorbed/absorbed must be driven out of the desiccant material (regeneration) so that it can be dried enough to adsorb water vapor in the next cycle.

Desiccant cooling consists in dehumidifying the incoming air stream by forcing it through a desiccant material and then drying the air to the desired indoor temperature. To make the system working continually, water vapor adsorbed/absorbed must be driven out of the desiccant material (regeneration) so that it can be dried enough to adsorb/absorb water vapor in the next cycle(1-11). Comfort air conditioning requires efficient control of both temperature and humidity.

Sorption and desorption are the mutually contrary processes of the moisture condensation or evaporation out/into the air stream. Hence, the dehumidifier and regenerator are similar to each other. A desiccant system removes moisture from the process air stream, but for every Btu of latent heat (moisture) removed, it adds more than one Btu of sensible heat. That is, air leaving the process side of the system is dry (at low dew point) but hot. Therefore, most applications include a cooling coil downstream of the system to recool the process air(1-12).

Since relative humidity (RH) is a function of vapor pressure, the direction of moisture transfer can be characterized by the difference between the relative humidity of the process and regeneration air streams. The desiccant can retain little moisture when the regeneration air RH is low, so water vapor will migrate from the desiccant to the regeneration air. When the RH of the process air is high, the desiccant can adsorb more moisture from that air stream. Maintaining an adequate difference between the relatives humidity of the process air and regeneration air streams is essential to dehumidify effectively using a desiccant system. Lowering the relative humidity allows the desiccant to reject more water vapor to the regeneration air, thus enabling it to sorb more water vapor from the process air. In many cases, the modest amount of heat added by the preheat coil can be recovered from the condensing process of the refrigeration equipment.

One of the advantages of fluidized bed is that the rate of heat and mass transfer between gas and particles is high compared with other modes of contacting because interaction contact between particles and gas is high(1-13). This can be very useful in increasing the characteristic of adsorption and desorption of adsorption material in a desiccant chamber. Fluidization is the operation by gas or liquid which solids are transformed into a fluid like state through contact with a gas or liquid when a gas or liquid is passed upward through a layer of solid particles. The operation of circulating fluidized bed systems requires that both the gas flow and the solids circulation rate are controlled. Desiccant cooling technology provides a tool for controlling humidity (moisture) levels for conditioned air spaces. Desiccant systems work in conjunction with conventional air conditioning systems to dehumidify the air.

The dynamic sorption characteristics of the organic sorbent have been previously investigated in our laboratory for single process either sorption or desorption process in one chamber (1-1), (1-7)-(1-9). In order to reduce the influence of heat capacity of the vessel when the processes switch from sorption to desorption and for stable amount of dehumidification and strict humidity control, we proposed fluidized bed with two chambers. One chamber is for sorption and the other for desorption which are working continuously. Sorbent powder is transferred by spiral tubes that connected the two chambers. Differently from the previous works. The present research deals with sorption polymers as an organic sorbent (HU720PR) are used as a desiccant material and circulated by the spiral tubes between the two chambers in continuous fluidized bed. In order to increase heat and mass transfer between the sorbent material and moist air, the heating pipe and the cooling pipe are immersed inside the two chambers is also investigated in this work.

1.2 The main purpose of the present research

Fluidized bed dehumidification is one of the most complex and least understood operations which involve simultaneous heat and mass transfer and coupled multiphase flow, and there are deficiencies and difficulties in the mathematical description of the phenomenon of simultaneous and coupled heat, mass, and momentum transfer in sorption particle. The objective of this study is to investigate the operation of continuous sorption and desorption process in two connected fluidized beds with and without cooling pipe which is immersed in sorption chamber and heating pipe is immersed in desorption chamber. In this study heat and mass transfer were considered to evaluate the effect of spiral revolution speed, air velocity, desorption and sorption inlet air temperature, and initial bed height in the chamber to dehumidification rates.

In the first part (Chapter 2 and Chapter 3) of this thesis is literature study to review the background theory of dehumidification, sorption and desorption in fluidized bed, desiccant and sorption material. In the second part is experimental study (Chapter 4 and Chapter 5) of this thesis, the objective is to study the dynamic sorption characteristics of organic sorbent materials in sorption and desorption chambers by using continuous fluidized bed without cooling and heating pipe (Chapter 4) and with a cooling pipe in sorption chamber and a heating pipe immersed in desorption chamber (Chapter 5). The last part (Chapter 6) is mathematical modeling and numerical simulation to provide a better understanding of the sorption process in continuous fluidized bed for dehumidification process.

1.3 The main content of the present research

The study of heat and mass transfer of sorption material in continuous sorption and desorption process in two connected fluidized beds are described and analyzed in this work. An experimental investigation of a continuous fluidized bed is conducted to study sorption characteristics of a new organic sorbent desiccant material with circulated by spiral tubes. Various aspects of heat and mass transfer of sorption and desorption process in two continuous fluidized bed chambers with and without cooling pipe and heating pipe are analyzed in this research.

The literature reviews of fluidized bed sorption process are given in Chapter 2. This chapter provides a brief review with respect to the fluidized bed and desiccant dehumidification system. It is needed to have an understanding of previous works in these areas so that we can build upon these contributions to develop a better and more precise system for this type of dehumidification with a new sorbent. Fluidized bed and dehumidification system are very broad area and there have been many researchers and publication paper appeared in the literature regarding those subjects.

Background of desiccant is introduced and reviewed in Chapter 3, the desiccants are natural or synthetic substances capable of absorbing or adsorbing water vapor due to the difference of water vapor pressure between the surrounding air and the desiccant surface(1-12). They can be categorized by their ability to attract and hold water vapor at specific temperatures and relative humidity(1-1). The essential characteristic of desiccants is their low surface vapor pressure. After the desiccant becomes wet and hot, its surface vapor pressure is high, and it will give off water vapor to the surrounding air. Vapor moves from the air to the desiccant and back again depending on vapor pressure differences.

The organic sorbent is a bridge complex of sodium polyacrylate. This bridge complex containing the carboxyl group as water vapor adsorption site has a larger adsorption abilities as compared with silica gel. In this study, sorption polymers powder type as an organic sorbent (HU720PR) are used as a desiccant material. Mean diameter of the sorbent is 113 μm with density 931 kg/m^3. Each desiccant has unique sorption characteristics which affect the performance of the dehumidifier.

The experiments have been carried out to investigate the heat and mass transfer behavior in the sorption and desorption process in two connected fluidized beds. In Chapter 4, study heat and mass transfer parameters were considered to evaluate the effect of spiral revolution speed, air velocity, desorption inlet air temperature, and initial bed height in the chamber to sorption and desorption rates. In the last part of this chapter, the non dimensional correlations that exert an influence on the Sherwood number were derived by using the dimension analysis method and considering the various factors is proposed. The following in Chapter 5, the dehumidification characteristics of organic powder sorption materials have been studied by using continuous fluidized bed with cooling and heating pipe. Sorption rate of water vapor and the variation of temperature in the sorbent bed with time were measured under various conditions.

In Chapter 6, mathematical modeling and numerical simulation are proposed to provide a better understanding of the sorption process in continuous fluidized bed. The model is derived by applying mass and heat balances to the chamber for continuous dehumidification process in the fluidized bed. Dehumidification experiments were carried out on the sorbent to obtain complete and reliable experimental results for comparison with the results of mathematical model. The entire contents of this thesis are summarized in Chapter 7 as the concluding remarks at the end of the thesis.

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Chapter 2

Literature Review

This chapter provides a brief review with respect to the fluidized bed and desiccant dehumidification system. It is needed to have an understanding of previous works in these areas so that we can build upon these contributions to develop a better and more precise system for this type of dehumidification with a new sorbent.

2.1 Fluidized Bed Overviews

Gas-solid fluidization is a process of contact between the two phases, the solid phase and gas or liquid phase. Fluidization is the operation by gas or liquid which solids are transformed into a fluid like state through contact with a gas or liquid when a gas or liquid is passed upward through a layer of solid particles. Geldart(2-1) investigated the behavior of solid particles of various sizes and densities fluidized by gases. The behavior of solids fluidized by gases falls into four clearly recognizable groups, as can be seen in Fig. 2.1, characterized by density difference $(\rho_s - \rho_f)$ and mean particle size. The most easily recognizable features of the groups are(2-1):

- Group A: Solid particle having a small mean size $30 < d_p < 100$ μm and/or low particle density less than about 1.4 g/cm^3. Typical examples of this class of solid particles are catalyst used for fluid catalytic cracking processes. These solids fluidized easily, with smooth fluidization at low superficial gas velocities and slugging conditions when the superficial gas velocities is sufficiently high. As the gas velocity further increased, slug flow breaks down into a turbulent regime. The velocity at which this occurs appears to decrease with increase particle size.
- Group B: Contains most solid particles of mean size 100 μm $< d_p <$ 800 μm and density in the range 1.4 g/cm^3 $< \rho_s <$ 4 g/cm^3. In contrast with group A powders, naturally bubbles occurring start in Group B powders at only slightly above minimum fluidization velocity. These solids fluidized vigorously with formation of

bubbles that may grow in size. Sand particles are representative for this group of solids.

- Group C: This group of solids includes very fine and cohesive powders. For most cases $d_p < 20\mu m$. With these particles normal fluidization is extremely difficult because inter particle forces are greater than those resulting from the action gas. Cement, face powder, flour and starch are representative for this group of solids.
- Group D: These solid particles are large $d_p > 1$ mm and/or dense, and spoutable. Large exploding bubbles or severe channeling may occur in fluidization of this type of solids. Drying grain and peas, roasting coffee beans, gasifying coals, and some roasting metal ores are representative for these solids.

Apart from density and particle size, several other solid properties, including angularity, surface roughness and compositions may also significantly affect the quality of fluidization. However, in many cases Geldart's classification chart is still a useful starting point to examine fluidization quality of a specific gas solid system.

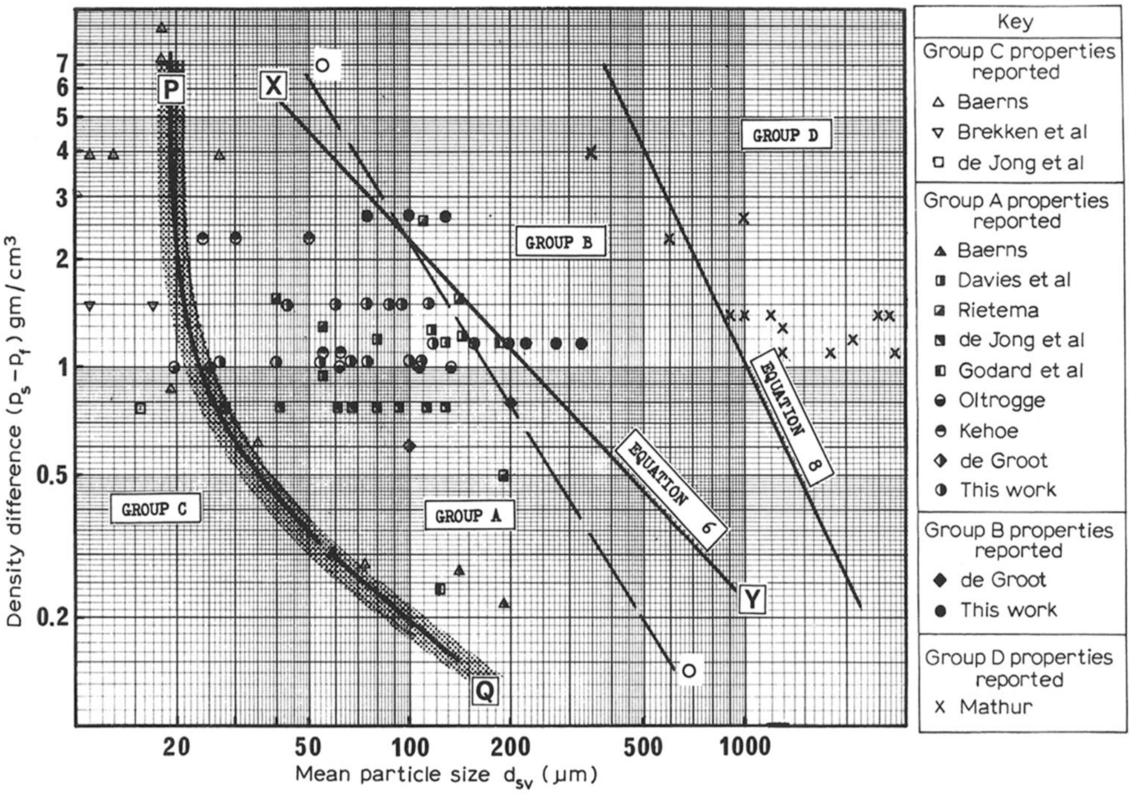


Fig. 2-1 Powder classification diagram for fluidization by air$^{(2-1)}$

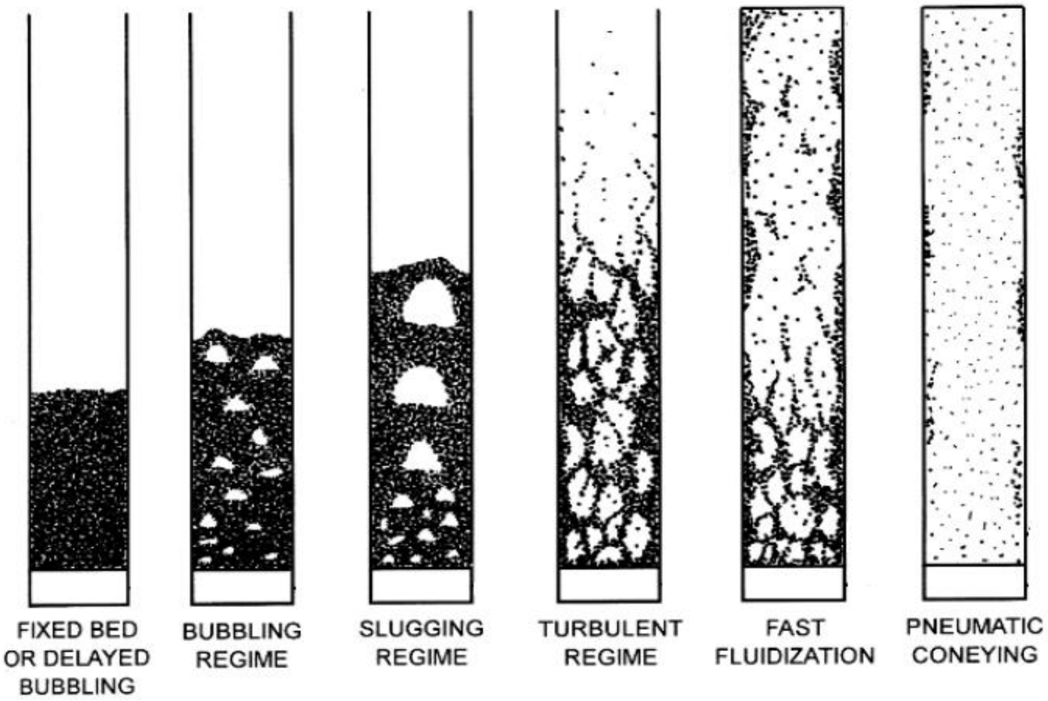


Fig. 2-2 The primary gas solid flow regimes(2-2)

Most gas solid system experience a range of flow regimes as the gas velocity is increased. Figure 2-2 presents several important gas solid fluidization regimes for the process industry(2-2). In dense fluidized beds regions of low solid density may be created. This gas pockets or voids are frequently referred to as bubbles.

Each of the fluidization regimes has characteristic solids concentration profiles. A plot of the profile showing the solid concentration versus the height above the distributor for the bubbling bed regime of fluidization takes a pronounced s-shape. The main characteristics of the pertinent gas solid flow regimes are:

- Fixed bed: When a fluid is passing upward through a bed of fine particles at a low flow rate, and the fluid merely seeps through the void spaces between stationary particles.
- Minimum fluidization: At a still higher velocity, a point is reached where all the particles are just suspended by the upward flowing gas. At this point, the frictional force between particle and fluid just counterbalances the weight of the particles, and the particle component of the compressive force between adjacent particles disappears. The pressure drop through any section of the bed thus balances (approximately) the weight of fluid and particles in that section. Further increase in the gas velocity flow rate will not change the pressure drop noteworthy.
- Smooth fluidization: In fine particle beds (Group A powder), a limited increase in gas flow rate above minimum fluidization can result in smooth, progressive expansion of the bed. Bubbles do not appear as soon as the minimum fluidization state is reached. There is a narrow range of velocities in which uniform expansion occurs and no bubbles are observed. Such beds are called a particulate fluidized bed, a homogenously fluidized bed, or a smoothly fluidized bed. However, this regime does not exist in beds of larger particles of type B and D, in this case bubbles do appear as soon as minimum fluidization is reached.
- Bubbling fluidization: An increase in flow rate beyond the point of minimum fluidization results in large instabilities with bubbling and channeling of gas. At higher flow rates, agitation becomes more violent and the movement of solids becomes more vigorous. Bubbles coalescence and breakage take place, and with

increasing gas velocity the tendency of bubble coalescence is normally enhanced. However, the bed does not expand much beyond its volume at minimum fluidization.

- Slugging fluidization: The gas bubble coalescence and grow as they rise, and in a deep enough bed of small diameter they may eventually become large enough to spread across the vessel. Fine particles flow smoothly down by the wall around the rising of void gas. These voids are called axial slugs. For coarser particle beds, the portion of the bed above the bubble is pushed upward. Particles fall down from the slug, which finally disintegrates. Then another slug forms, and this is unstable oscillatory motion is repeated. This is called a flat slug. Slugging normally occurs in long, narrow fluidized beds.
- Lean phase fluidization: As the gas flow rate increases beyond the point corresponding to the disappearance of bubbles, a drastic increase in the entrainment rate of the particles occurs such that a continuous feeding of particles into the fluidized bed is required to maintain a steady solid flow. Fluidization of this state is generally denoted lean phase fluidization.

2.2 Continuous Fluidized Bed

The operation of circulating fluidized bed systems requires that both the gas flow and the solids circulation rate are controlled, in contrast to the gas flow rate only in a dense phase fluidized bed system. The solids circulation is established by a high gas flow.

The integral parts of a Continuous Fluidized Bed (CFB) loop are the riser, gas solid separator, down comer and solid flow control device. The CFB is thus a fluidized bed system in which solid particles circulates between the riser and the down comer, as depicted in Fig. 2-3(2-2)-(2-4). The riser is the main component of the system. The name riser is generally used to characterize a tall vessel or column that provides the principal reaction zone. On average, the particles travel upwards (or rise) in the riser, though the motion at the wall may be downwards. The fluidized gas is introduced at the bottom of the riser, where solid particles from the downcomer are fed via a control device and carried upwards in the riser. The fast fluidization regime is the principal regime under which the CFB riser is operated. The particles exit at the top of the riser into the gas solid separators which are normally cyclones. In lean phase fluidized beds, the rate of entrainment is far larger than in turbulent fluidized beds, and bigger cyclone collectors outside the bed are necessary. The separated particles then flows to the downcomer and return to the riser. The entrance and exit geometries of the riser often significantly affect the gas and solid flow behavior in the reactor. The efficiency of the cyclones determines the particles size distribution and solids circulation rate in the system. The downcomer provides holds volume and static pressure head for particle recycling to the riser. The downcomer can be a large reservoir which aids in regulating the solids circulation rate, a heat exchanger, a spent solid regenerator, hopper or standpipe. The main task in achieving smooth operation of a CFB system is to control the solid recirculation rate to the riser. Several designs of valves for solids flow control are used. The solid flow control device serves two main functions, namely to seal the riser gas flow to the downcomer and to control the solids circulation rate. Rotary valves are effective sealing devices for solids discharge. The L valve can act as a seal an as a solid flow control valve. There are many other valve designs available to suit specific conditions. The riser can not be considered as an isolated entity in the CFB loop because the pressure drop over the riser must be balanced by that imposed by the flow through its accompanying component such as the downcomer and the circulation device(2-4).

In general, the high operating gas velocities for lean phase fluidization yield a short contact time between the gas and solid phases. Fast fluidized beds and co-current pneumatic transport are thus suitable for rapid reactions, but attrition of catalyst may be serious.

However, it is not always easy to distinguish between the flow behavior encountered in the fast fluidization and the transport bed reactors. The transport reactors are sometimes called dilute riser reactors because they are operated at very low solid mass fluxes. The dense riser transport reactors are operated in the fast fluidization regime with higher solid mass fluxes. The transition between these two flow regimes appears to be gradual rather than abrupt(2-4).

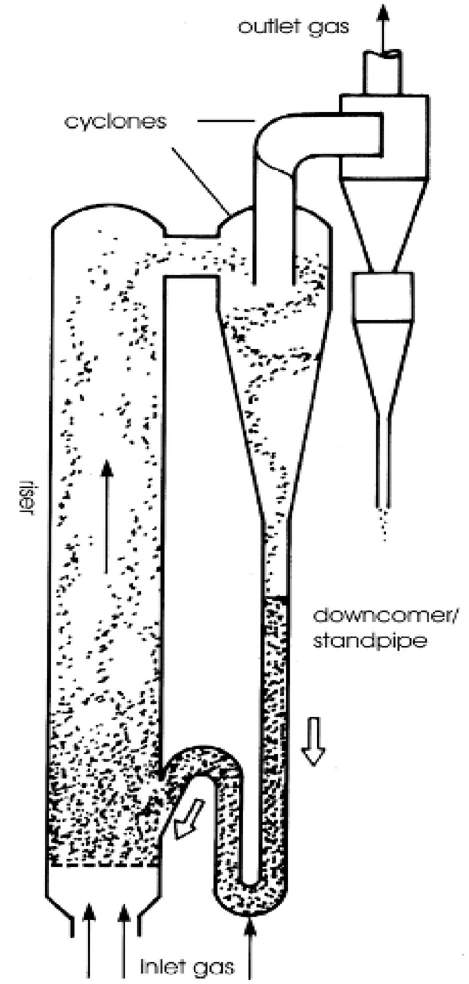


Fig. 2-3 A schematic representation of a circulating fluidized bed(2-4).

2.3 Desiccant Dehumidification System Overviews

Desiccant technology provides a tool for controlling humidity (moisture) levels for conditioned air spaces. Desiccant systems work in conjunction with conventional air conditioning systems to dehumidify the air. Desiccant material are those of that attract moisture due to differences in vapor pressure(2-5). Most people are familiar with desiccant such as silica gel packages that are included with new electronics or textile products. Desiccant can be in the form of a solid or a liquid. People have identified types of desiccant that are appropriates as a component of commercial heating, ventilation and air conditioning (HVAC) systems. These desiccants have been selected base on their ability to hold large quantities of water vapor, their ability to be reactivated, and cost.

Air conditioning loads can be divided into two components, namely sensible and latent loads. An air conditioner must counterbalance the two sort of load in order to maintain the desired indoor condition. In order to remove the latent heat, the traditional refrigerant vapor compression system, cools the process air down below its dew point in order to condense out water vapor contained therein(2-6). One of the ways to remove moisture from air is by passing the air over a desiccant, which pulls moisture from the air through differences in vapor pressure.

In order to be effective, the desiccant must be capable of addressing the latent cooling load in a continuous process. In order to accomplish this, commercial desiccant systems consist of a process air path and a reactivation air path. The desiccant that is in the process air path has been prepared to have a lower vapor pressure than the air passing over it. Thus, the moisture in the air is transferred onto the desiccant material. As the desiccant vapor pressure increases due to the presence of the moisture that is attracted, the desiccant material is transferred to a reactivation process. In the reactivation process, hot air is passed over the desiccant. The vapor pressure of the hot air is lower than the desiccant surface which forces the moisture to transfer from the desiccant surface into the hot air stream. The moist hot air is then exhausted from the system into the outdoor air. The desiccant material that has had the trapped moisture removed is now prepared to attract moisture as it is transferred back into the process air path. The dry process air leaving the desiccant is then passed over a conventional cooling coil which addresses the sensible cooling work required to meet the air specification of the conditioned space.

The design and operation of a desiccant system is based on the desiccant material used to accomplish the dehumidification. Desiccant material attract moisture through the process either adsorption or absorption and sorption (2-6). Adsorption is the process of trapping moisture within the desiccant material similar to the way a sponge holds water through capillaries. Most adsorbents are solid materials. Absorption is the process of trapping moisture through a chemical process in which the desiccant undergoes a chemical change. Most absorbent are liquids. Sorption behavior of both absorption and adsorption occur simultaneously. These phenomena clearly depicted in Fig.2-4. Each of liquid and solid desiccant systems has its own advantages and shortcomings. Liquid desiccant have lower pressure drop on air side. Solid desiccant are compact, less subject to corrosion and carryover (2-7).

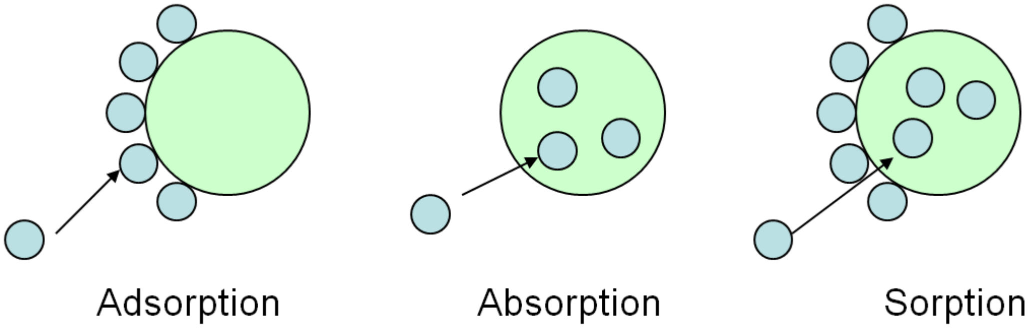


Fig.2-4 Mechanism of adsorption, absorption and sorption

Commercially available desiccant systems are based on five configuration or technologies(2-5), (2-6)

- Liquid spray tower
- Solid packed tower
- Rotating horizontal bed
- Multiple vertical bed
- Rotating desiccant wheel

2.3.1 Liquid spray towers

Spray tower dehumidifiers function much like an air washer, except instead of water, the units spray liquid desiccant into the air being dried, which is called the process air. The desiccant absorbs moisture from the air and falls to a sump. The liquid is sprayed back into the air, and continues to absorb moisture until a level control indicates it should be dried out and reconcentrated. Then part of the solution is drained off and circulated through a heater. The warm desiccant is sprayed into a second air stream, called the reactivation air. Moisture leaves the desiccant and moves to the air.

Liquid spray tower dehumidifiers have some uniquely favorable characteristics. Dehumidification is thermodynamically quite elegant, because the desiccant is only heated or cooled to the minimum necessary to accomplish the required dehumidification. Also, the process requires a constant humidity and the inlet air is dry, water can be added to the desiccant solution so the conditioner will act as a humidifier instead of a dehumidifier. Extra liquid can also be regenerated and sent to a holding tank, providing energy storage in less than 20 % of the floor space of an equivalent ice-storage system. Further, since the liquid desiccant contacts the air, particles are removed as well as water vapor. Liquid spray dehumidifiers are frequently arranged in large, central systems rather than small, free standing units for small spaces. This is partly because they tend to be somewhat more complex than solid desiccant units, but also because large systems can be designed with several conditioner units connected to a single regenerator. This configuration is similar to a mechanical refrigeration system with multiple evaporators connected to a single condenser. For large buildings with several dehumidification systems, this can have advantages of first cost, at the expense of complexity of controls. Potential disadvantages of liquid systems include response time, maintenance, and first cost for smaller units. Because the desiccant solution may be distributed throughout a long piping system and large reserve sump, the system can take time to respond to fast changing internal moisture loads or different necessary outlet conditions; such as occur in environmental simulation chambers. But slow response on the outlet conditions also means slow response to inlet changes; which can be advantage. A large mass of recirculation desiccant protects an internal process from rapid changes in weather moisture.

Maintenance varies, but some liquid desiccants are corrosive, and therefore need more attention. Also, at low humidity levels, some liquid desiccants can dry out rapidly, which means liquid levels must be carefully watched to avoid desiccant solidification.

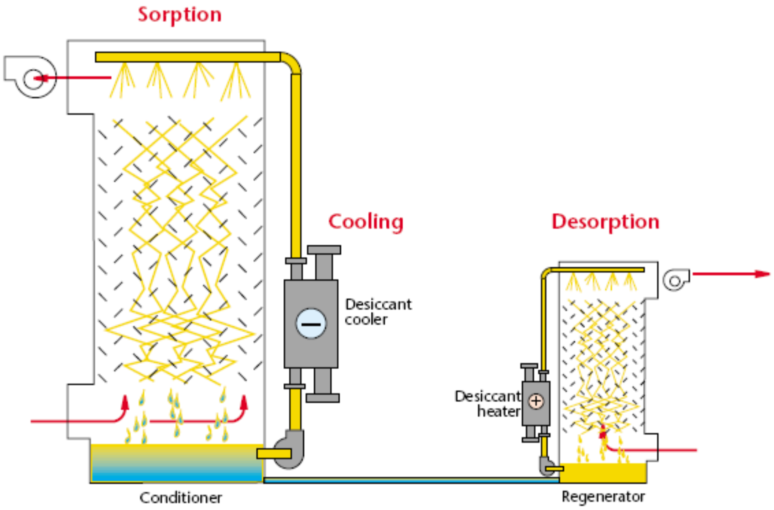


Fig. 2-5 Liquid spray towers$^{(2-5)}$

Dai$^{(2-8)}$ studied the use of liquid desiccant cooling to improve the performance of vapor compression air conditioning. Experimental investigation demonstrates that cooling production and COP of the new hybrid system can be increased significantly, when they are compared with those of vapor compression system (VCS) alone. Assuming that the outlet temperature and humidity of the system are constant, psychrometric analysis at The Air-conditions and Refrigeration Institute (ARI) conditions has been conducted under three different cases. The benefits are represented by lower electricity consumption of the compressor, higher COP of the system, less flow rate of condensation air, and reduced size of VCS, etc. The reason that hybrid system is superior in performance to conventional systems lies in that desiccant dehumidification and evaporative cooling changes the inlet states of the air entering into VCS. Furthermore, the effects of dehumidification and evaporative cooling are analyzed.

2.3.2 Solid packed tower

In the packed tower dehumidifier, solid desiccant like silica gel or molecular sieve is loaded into a vertical tower, giving up its moisture to the dry desiccant. After the desiccant has become saturated with moisture, the process air is diverted to a second drying tower, and the first tower is heated and purged of its moisture with a small reactivation airstream.

The thermal energy that drives the desiccant cycle in a solid desiccant tower is added to the process by heating and cooling the reactivation and process airstreams. In other words, when the saturated desiccant must be heated to raise its surface vapor pressure, the heat is carried to the desiccant by hot reactivation air. Likewise, when the hot dry desiccant must be cooled to lower its vapor pressure, the cool process air removes the heat from the bed.

Since drying and reactivation take place in separate, sealed compartments, the packed tower dehumidifier is frequently used to dry pressurized process gases. In fact, the same configuration is used to dry liquid chemicals as well as gases. When large amount of desiccant are loaded into the towers, the process can be achieve very low dew point temperature. Desiccant dehumidifiers for compressed air are frequently the packed tower type.

While the configuration allows very low dew points, the packed tower design can also result in a changing outlet condition. When the desiccant is first exposed to the process air stream, it can dry the air deeply. Later, as its moisture capacity fills up, the air is not dried quite so much. If a changing outlet condition would cause problems in a process, controls could be provided to ensure the towers are changed before the process air condition becomes too wet.

As process air flow requirements get larger, packed tower dehumidifiers get very large because air velocities are generally kept quite low. Low air velocities are necessary for two reasons. High velocities would lead to uneven air distribution through the bed because moist air would ‘tunnel’ through the desiccant. Also the air velocity must remain low to avoid lifting the desiccant, which would then impact against other particles and the walls of the dehumidifier vessel. The impact would fracture the desiccant, which would blow out of the unit in the form of a fine dust.

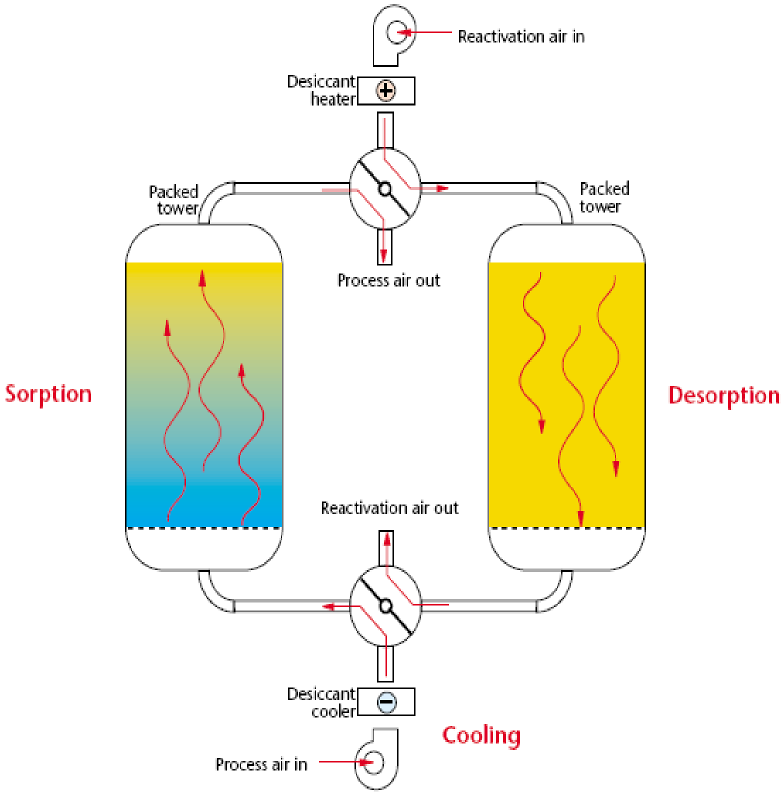


Fig.2-6 Solid packed tower(2-5)

Kabeel(2-9) has theoretically and experimentally investigated the effect of design and operating parameters on the performance of a multilayer desiccant packed bed. In the experimental work, a silica gel packed bed of eight layers has been studied. The transient value of the mass of adsorbed water and desorbed water was measured for different values of the bed length. The theoretical model shows the dependence of the dimensionless values of water content in the bed on the dimensionless time. Also the model shows that the dimensionless temperature depends on the bed characteristics and the bed water content. The effect of inlet air humidity and velocity on the adsorption process for each bed layer was studied at different inlet velocities and at different air humidities. The effect of inlet temperature on desorption process for each packed bed layer was also studied at different inlet temperatures. The theoretical model also introduces an equation which can be used to predict the optimum bed length. Also, the optimum length of the bed can be recommended from the experimental results according to the operation time.

2.3.3 Rotating horizontal bed

In this device, dry, granular desiccant is held in a series of shallow, perforated trays that rotate continuously between the process and reactivation airstreams. As the tray rotates through the process air, the desiccant adsorbs moisture. Then the trays rotate into the reactivation airstream, which heat the desiccant, raising its vapor pressure and releasing the moisture into the air.

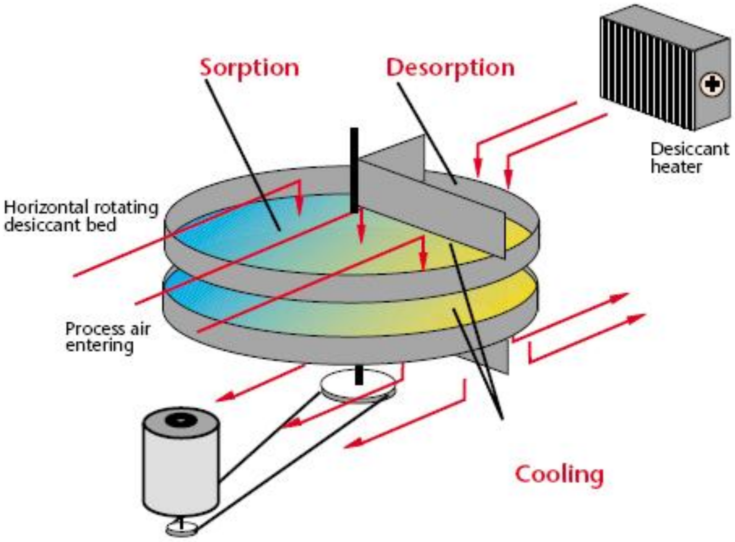


Fig.2-7 Rotating horizontal bed(2-5)

The design is modular. To increase capacity, the manufacturer can be either increase the diameter of the rotating trays so they will hold more desiccant, or increase the number of beds stacked on top of one another. If the desiccant is evenly loaded through the trays, the rotating horizontal bed provides a fairly constant outlet moisture level, and a high airflow capacity can be achieved in less floor space than with a dual tower unit. On the other had, since the trays can never be filled absolutely to the top of the bed; the desiccant settles slightly in use; air leaks from the moist reactivation side to the dry process side within the tray just above the desiccant.

To avoid this leakage, rotating bed designs generally arrange the process and reactivation airflow in a parallel rather than a counterflow configuration. This keeps he pressures more equal between the process and reactivation sides of the unit, which reduces leakage and improves performance. The technique still has limitations, and such units are more sensitive to the moisture condition of the entering reactivation air than some other designs. Also the parallel arrangement of process and reactivation airflows is not as energy efficient as a counterflow arrangement. As a result, reactivation energy consumption can be very high for these units compare to the other designs.

Against the limitations, the rotating horizontal bed design offers a low first cost. The design is simple, expandable and easy to produce. Although the desiccant can fracture and carry over into the air stream, it can be replaced by disassembling the beds to refill them. In situations where energy cost is not high, or where it does not represent a great deal of money in absolute terms, the low first cost of these units may offset their high operating cost.

2.3.4 Multiple vertical beds

In recent years manufacturers have combined the better features of packed tower and rotating horizontal bed designs in an arrangement that is well suited to atmospheric pressure dehumidification applications, yet can achieve low dewpoints. The single or double tower is replaced by circular carousel with eight or more towers that rotate by means of ratcheting drive system between the process and reactivation airstreams.

Like the packed tower, this design can be achieve low dewpoints because leakage between process and reactivation air circuits is minimized. Also because the beds are separate and sealed from one another, the pressure difference between process and reactivation is not so critical, so airstreams can be arranged in the more efficient counterflow pattern for better heat and mass transfer. Like the rotating bed, the ratcheting, semi continuous reactivation of the desiccant provides a relatively constant outlet air moisture condition on the process side, reducing the saw tooth effect that can occur in packed tower units.

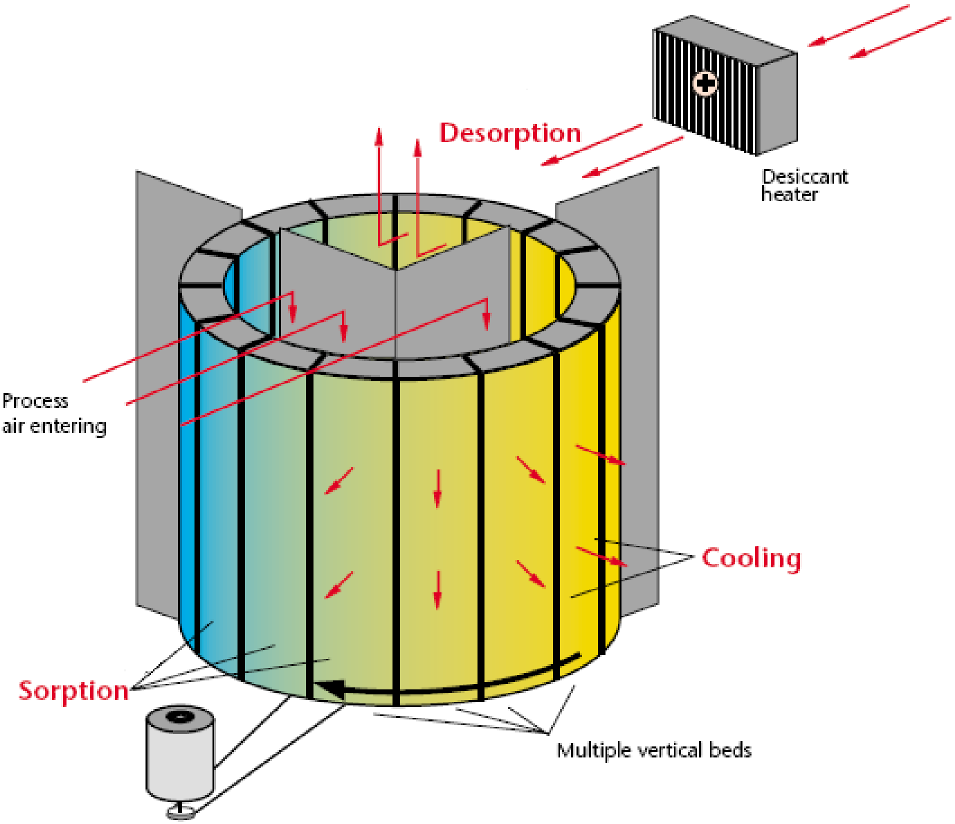


Fig.2-8 Multiple vertical bed(2-5)

These benefits are achieved at the expense of increased mechanical complexity. So compared to rotating horizontal bed units, the vertical bed dehumidifiers tend to be more expensive, and can require more maintenance. Generally, however, these are minor limitations compared to the large savings in energy and performance improvement at low dewpoints.

2.3.5 Rotating honeycomb

Another dehumidifier design uses a rotating honeycomb wheel to present the desiccant to the process and reactivation airstreams. This is sometimes called a DEW (Desiccant Wheel) dehumidifier. They finely divided desiccant is impregnated into the semi ceramic structure, which in appearance resembles corrugated cardboard that has been rolled up into the shape of a wheel. The wheel rotates slowly between the process and reactivation airstreams.

The rotating honeycomb design has several advantages. The structure is very lightweight and porous. Different kind of desiccants, both solid and liquid, can be loaded into the structure, which allows a wheel to be tailored for specific applications. Since the flutes of the structure are like individual, desiccant lined air ducts; the desiccant surface area presented to the air is maximized even while the airflow remains smooth, reducing air pressure resistance compared to packed beds. Low dewpoints and high capacity, normally two mutually exclusive goals, can be achieved by combining different desiccant in the same wheel. And since the total rotating mass is low compared to its moisture removal capacity, the design is quite energy efficient. The design is also quite simple, reliable and easy to maintain. One design concern with honeycomb dehumidifiers is the cost of the rotating wheel. The structure is energy efficient, but cost more to produce compared to granules of dry desiccant. Care should be taken to insure the wheel is not damaged. The first cost is apparently balanced by operational advantages, since the design is the most widely installed of all desiccant dehumidifier configurations in ambient pressure applications.

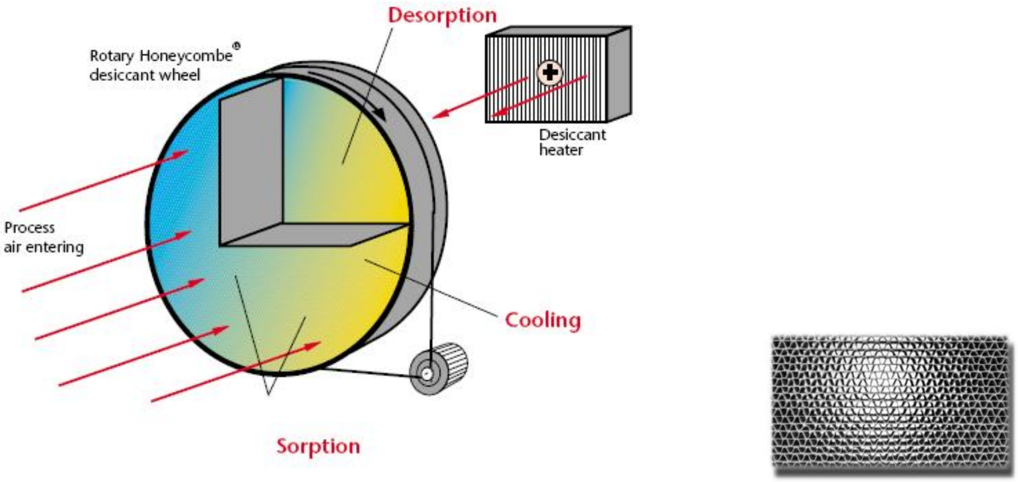


Fig.2-9 Rotating desiccant wheel (2-5)

Sorption characteristics of a honeycomb-type sorption element composed of a new organic sorbent that was composed of the cross-linked polymer of sodium acrylate have been previously investigated in our laboratory (2-10). Transient experiments in which moist air was passed into the honeycomb-type sorption element were conducted under various conditions of air velocity, temperature, relative humidity and the length of honeycomb. As a result, the effective mass transfer coefficient of the organic sorbent adsorbing the water vapor was non dimensionalized as a function of Reynolds number, modified Stefan number and non dimensional honeycomb length.

2.4 Operating Variables

There are eight key parameters which affect the performance of desiccant dehumidifiers and the exact effect of each parameter depends on the type of dehumidifier. These include(2-5):

1. Process air moisture
2. Process air temperature
3. Process air velocity through the desiccant
4. Reactivation air temperature
5. Reactivation air moisture
6. Reactivation air velocity through the desiccant
7. Amount of desiccant presented to the reactivation and process airstreams
8. Desiccant sorption-desorption characteristics

A system designer can consider some implication of inlet moisture changes:

- If moisture entering is greater than expected, the process air will be warmer than expected, so if a constant temperature leaving the system is important, additional cooling is necessary.
- If moisture is less than expected, the air will leave drier than expected, so if a constant moisture leaving the system is important, less air should be processed through the dehumidifier.

Desiccant surface vapor pressure depends on the temperature of the material as well as on its water content. So it is understood that desiccant performance is affected by the temperature of the incoming air. The moisture removal performance is improved because the desiccant is cooler, and therefore has a lower surface vapor pressure so it can attract more moisture. The relationship of inlet temperature to performance is when all other variables are constant, lower inlet temperatures enhance performance and higher temperature reduce performance.

For a system designer, this relationship has several implications, including:

- If high temperatures are expected, the engineer needs to confirm capacity at the highest expected process air temperature, perhaps selecting a desiccant which may be less temperature sensitive. Or the designer can pre-cool the air to assure the desired outlet moisture.
- Cooler than expected process air conditions do not degrade performance. This is one reason why desiccant units rather than cooling based dehumidifiers are often use in cold storage areas and spaces which are not heated in wintertime.
- The beneficial effect of lower process inlet temperature is smaller at very low inlet moisture contents.

The slower the air moves through the desiccant bed, the drier the outlet moisture will be (for rotary honeycombe dehumidifier case). Dehumidifiers are generally selected at the highest velocity that will accomplish the moisture removal because high velocities mean smaller, less costly equipment.

For a designer some implications of changes in process air velocity include:

- If the outlet moisture must be very low, the process air is quite critical, and the designer may want to install an airflow monitoring device and control system to avoid unplanned velocity changes.
- At high inlet moisture levels, the performance difference between low velocities and high velocities is rather small, so larger equipment may provide only small improvements in performance.
- If moisture removal rate is more important than delivered air dewepoint, then high velocities will result in smaller, more economical equipment.

In a rotary dehumidifier, the desiccant is heated by air entering reactivation. The hotter the desiccant, the more easily it gives up moisture, so the reactivation air temperature has a strong effect on performance. Essentially, the drier the desiccant can be made in reactivation, the more moisture it can absorb when it rotates into the process air stream. For the system designer, the effect of reactivation temperature suggests:

- If very dry outlet conditions are necessary, plan to use high reactivation temperatures
- Desiccant dehumidifiers can make use of even very low temperature reactivation heat sources. When available, the designer should consider using economical energy sources like hot water from cogeneration, or steam condensate. However, the dehumidifier will need to be larger than one which uses a high temperature reactivation energy source to produce the same outlet condition in the process air.
- Dehumidifiers are often selected at peak summer design conditions, when air entering the reactivation heaters is quite warm even before it is heated. During the winter, spring and fall, the air is much cooler. Since the reactivation air temperature affects dehumidifier performance, the designer should check unit capacity at the lower entering air temperature.

The mechanical concern is air leakage between the moist air entering reactivation and dry air leaving the process side of the unit. Any air leakage from reactivation to process will raise the moisture level in the process air considerably. For system designer, this suggests that when using rotary bed, multiple vertical bed or rotary honeycombe desiccant units:

- The manufacturer of dehumidifier should be consulted concerning the effect of any air leakage between reactivation and process in a given set of circumstances.
- When extremely dry outlet conditions are necessary, it may be advisable to mount the process air fan before rather than after the dehumidifier so that any leaks would move dry process air to reactivation rather than reverse.

The performance of some other desiccants, notably molecular sieves and activated alumina, is considerably more sensitive to moisture in reactivation air. These desiccants are very useful for adsorbing moisture from warm airstreams. This means they do not lose performance on the process side when that air is warm, but conversely, such desiccants can still adsorb moisture even from warm reactivation air.

In rotary dehumidifier, the reactivation air carries heat to the desiccant as well as carrying away moisture once it is releases by the desiccant. More air (higher velocity) is necessary for heating than for carrying away moisture. It is important to keep the reactivation airflow and temperature in proportion to the moisture load being absorbed by desiccant on the process air side. If the moisture loading of the desiccant increases, more energy must be applied to the desiccant to insure complete reactivation and to keep the system in equilibrium.

The effect of less reactivation air is similar to having a lower reactivation temperature, because the net heat available to the desiccant is a function of airflow multiplied by the temperature difference between the air and the desiccant. In other words, high temperature and high reactivation airflows deliver more heat to the desiccant, which means it can absorb more moisture in process because the material has been more completely dried in reactivation.

However, if the temperature entering reactivation stays constant and airflows is increased beyond the minimum necessary to carry the heat to the desiccant, the energy will simply be wasted. Unless there is an increase in the moisture to be removed from the desiccant, the reactivation air leaves the dehumidifier warmer than necessary, carrying heat off to the weather.

Implications for the system designer include:

- Rough filtration of reactivation air is always necessary. The designer should insure that changing or cleaning these filters is an easy and obvious task for maintenance personal to accomplish. Otherwise, the filters will eventually clog, reducing airflow, which reduces performance.
- Reactivation airflow should be properly controlled to avoid higher than expected air velocities through the desiccant.
- Mechanical considerations limit the practical number of choices for fans and heaters. However, the operational range necessary in reactivation may be very broad because of wide seasonal variations in process air moisture load.

There are other implications for the designer that depend on the type of desiccant used in the unit, for instance:

- When liquid is used, the desiccant has capacity to absorb hundreds of times its own weight in water vapor, which has many advantages. However, when dry desiccant is used in a rotating dehumidifier, it must be well reactivated

- Granular desiccants like molecular sieves and silica gel are often used in packed tower, rotating tray or multiple vertical bed dehumidifiers. Higher than expected air velocities in either process or reactivation in these units can `fluidize` the desiccant, the air lifts it, and the desiccant bounces, which leads to air leakage through the bed and desiccant powdering. Both problems affect performance, so airflow should be controlled to avoid them.
- In liquid desiccant dehumidifiers, excessive air velocities can pull droplets of desiccant into the air. In reactivation, this can lead to corrosion of ductwork, and on the process side, the desiccant may not be useful to have in the conditioned space.

The amount of moisture removed from the air depends on how much desiccant the air contacts as it moves through the dehumidifier, more desiccant means more moisture removed. In a rotary honeycomb dehumidifier, there are two ways to present more desiccants to the air, make the wheel deeper or turn it faster. Either strategy will remove more moisture from the air, but both have an additional energy cost.

Increasing the depth of the wheel increases the resistance to air flowing through the unit. More surface area in contact with the air means more air friction. In the case of rotary tray, packed towers or multiple vertical beds, the desiccant is granular, so the flow is turbulent. This means the resistance to airflow essentially increases as the square of the air velocity. In the case of honeycomb dehumidifiers, the effect is somewhat less. Airflow through the straight passages is laminar rather than turbulent, but resistance still increases in proportion to wheel depth. So in all cases, increasing bed depth also increases fan energy cost.

2.5 The Source of Regeneration Energy

The energy cost of the process is due to desiccant reactivation, obtained by heating, which requires low grade heat, obtainable either by a waste heat source, such as the heat recovery from an internal combustion engine, or by solar collectors, heat produced by a conventional burner. The commonly employed energies include electric, gas, and solar energy. Commonly used solid desiccant, which are all concluded from experiment have high regeneration temperature (2-7), (2-8), (2-11) – (2-13). Hence the regenerating energy for the saturated adsorbents is huge consumption of the dehumidification system.

2.5.1 Electric energy

Using electric energy as a source of energy for regeneration is the mostly popular energy used due to its convenience as shown in Fig. 2-10. However, using electric power will improve the energy consumption and reduce the COP of the whole system. For systems utilizing electrical energy for regeneration, the COP can only be improved at a small degree than the traditional air dehumidification/cooling system (2-13), (2-14).

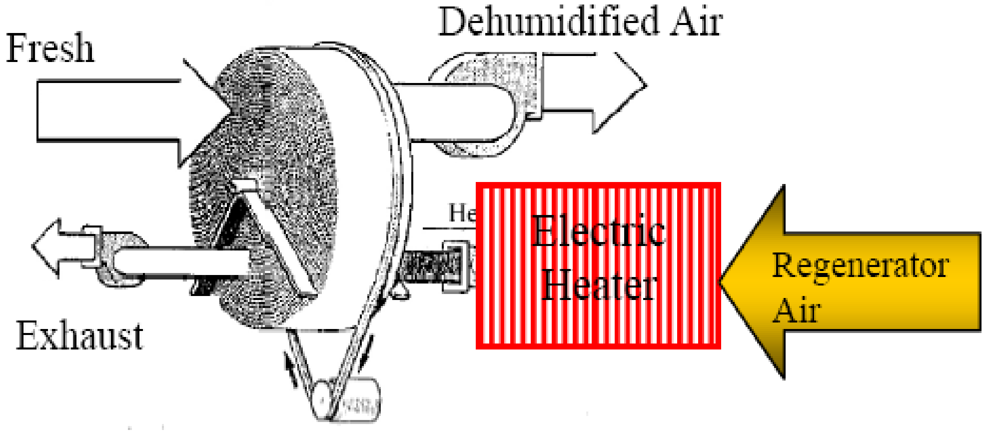


Fig.2-10 Rotating desiccant wheel(2-13)

2.5.2 Gas energy

Another source of energy that is used for regeneration is gas because of its convenience, as shown in Fig.2-11. The burned hot air at a low humidity is supplied to the bottom of the desiccant wheel and carries moisture out. In this case, the burned air temperature will heat up the desiccant wheel and then induce the supply air temperature rising. Hence, to obtain a desired cooling air, this system has to cooperate with a traditional HVAC system and only part of the supply air is dehumidified. But the COP can not be improved greatly, similar to the electrically driven system.

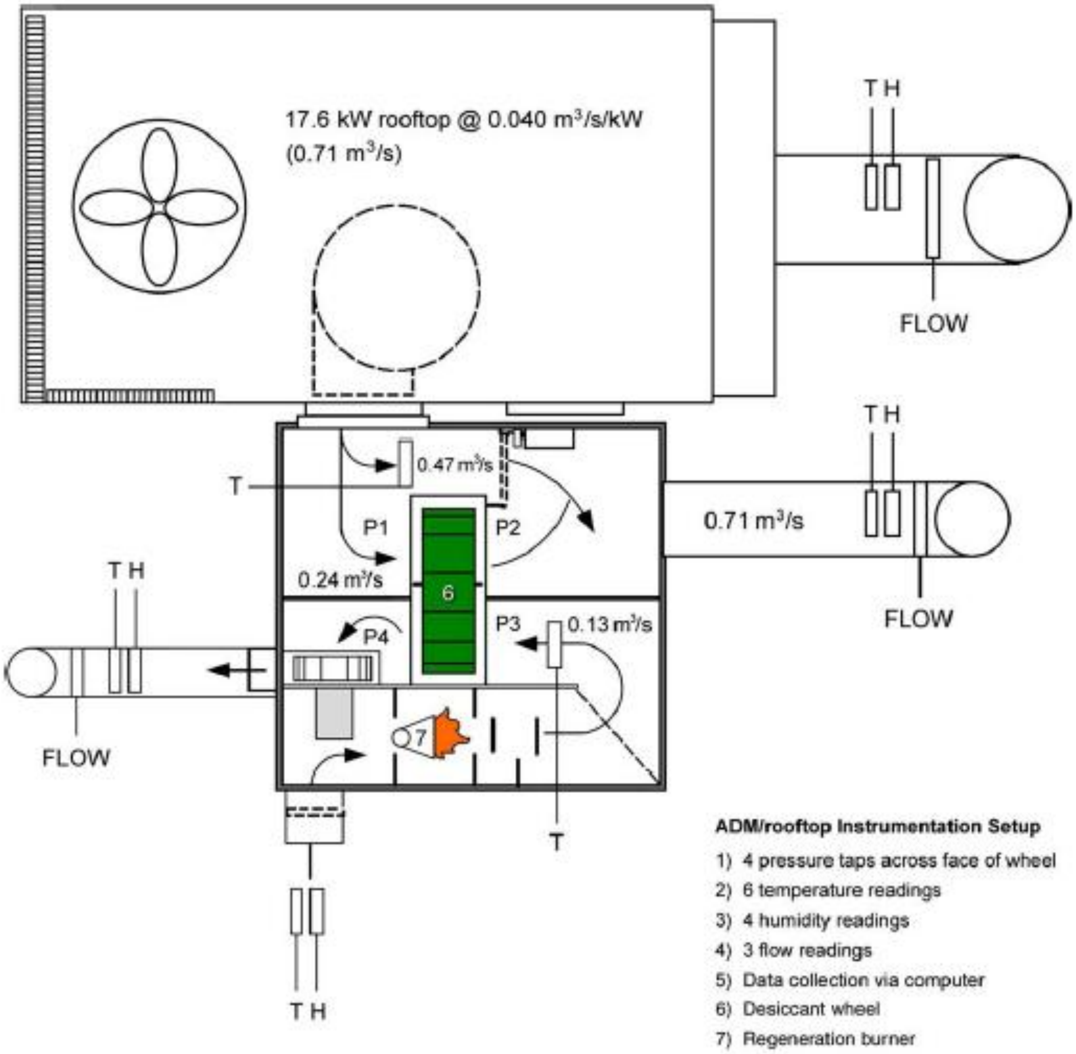


Fig.2-11 Rooftop cooling system(2-14)

2.5.3 Solar energy

The using of solar energy for regenerating desiccants is popular because it free energy source, renewable and clean energy. It also can recover/store the weak desiccant during the day time and service the strong desiccant to the dehumidifier in both day and night time. For a big system, when the sun energy is plentiful, the desiccant regeneration and store system even produce and save strong desiccants for a few days running requirement, which is a great help for continuously cloudy/rainy days (2-15). Method to utilize solar energy as desiccant regeneration source is classified into three kinds: solar desiccant, solar air and solar water. A solar desiccant collector employs the saturated desiccant as an adsorbent to absorb solar energy directly and evaporate out the moisture. As shown in Fig. 2-12, the solar collector bed recovers the weak solid desiccant during the day time and supplies a strong desiccant to dehumidify humid air at night time.

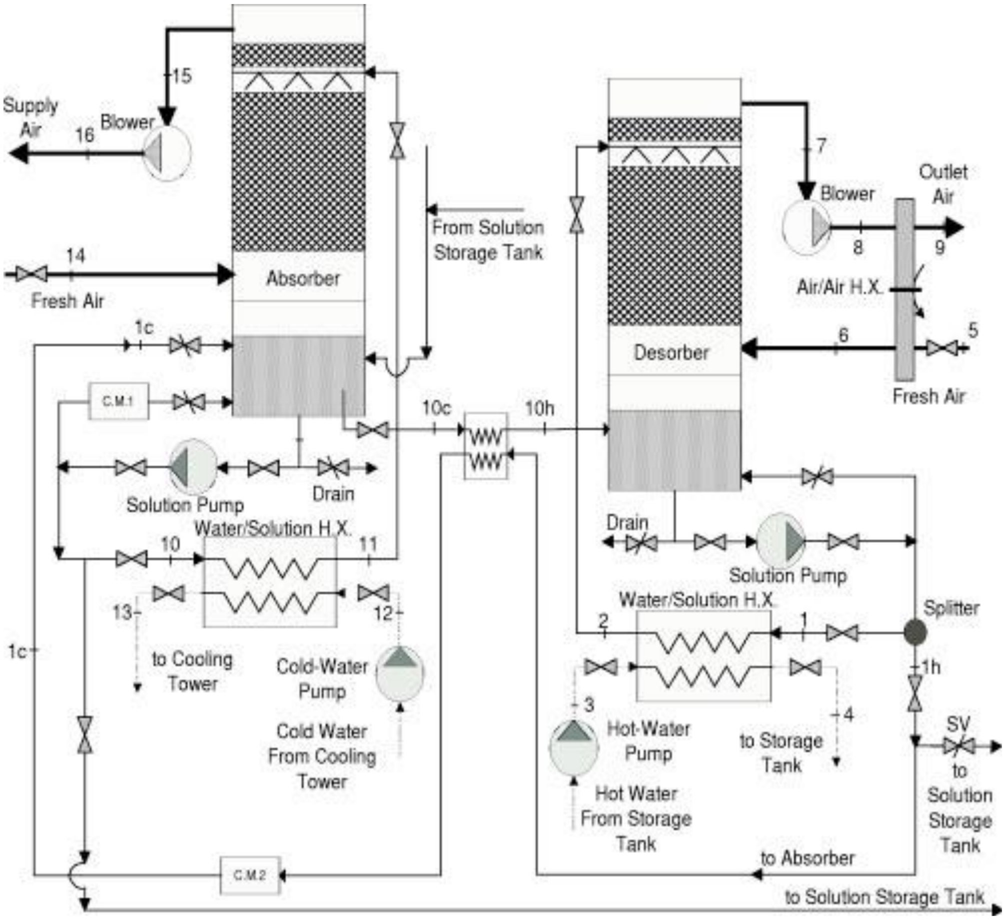


Fig.2-12 Silica gel bed(2-15)

Environment or room air flows through the solar panel, is heated by the solar energy directly and is then supplied to the regenerator as shown in Fig. 2-13. In This system, the regenerator air can reach a high temperature and the regenerator has a high efficiency, but a long air transfer route from collector to regenerator needs more channel space and insulation protection. So in a practical project, a solar water collector is preferred way to collect and store energy (2-16).

A solar water collector supplying the hot water to heat up the regenerator air is the most acceptable method to utilize and storage solar energy. As shown in Fig.2-13, when the solar energy is plentiful, hot water carries heat exchange with the regenerator air and surplus energy is stored in the tank preparing for shortage of solar energy(2-17).

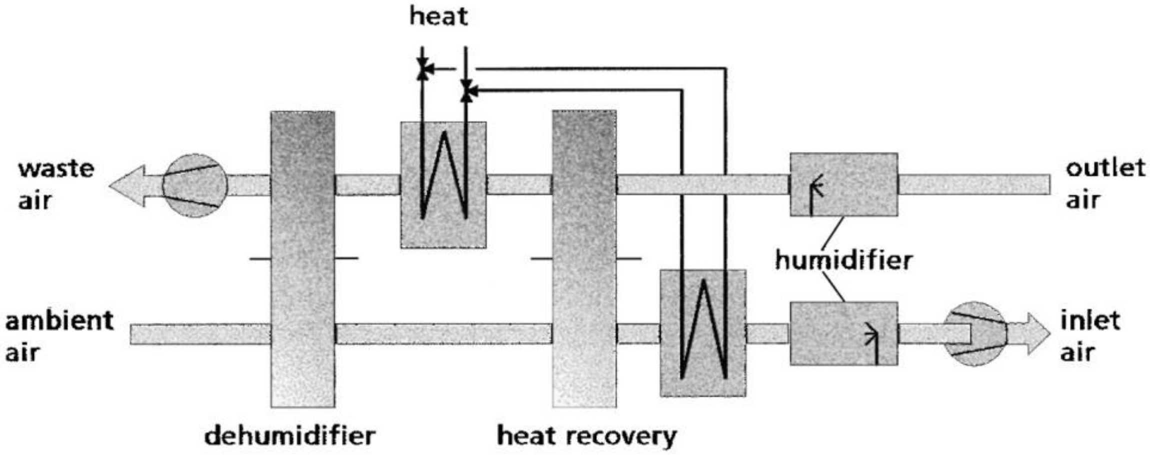


Fig.2-13 Rotating desiccant wheel(2-17)

Advantages and disadvantages of utilizing solar energy compared with three other kinds of energies are expressed as the following(2-18), (2-19).

- Solar energy is one type of renewable energy, free energy and it does not emit any green house gases
- Solar energy is widely available in the regions with a hot and humid climate
- Solar water can service and store the solar energy more conveniently than solar desiccant and solar air
- The capital cost for installing solar energy is high but running cost is less than electric and gas energies
- Less convenient than electric and gas heaters
- Can not be used for a long time without solar radiation
- Relatively inefficient compared with electrical and gas heaters

2.5.4 Waste heat energy

The use of waste heat energy in desiccant integrated air conditioning system proposed by Elsayed(2-20), whose employed waste heat from an air cycle refrigerator to regenerate desiccant that is saturated of water vapor as depicted in Figure 2-14. The results showed that the coefficient of performance on the air conditioning system was higher than the conventional vapor compression system.

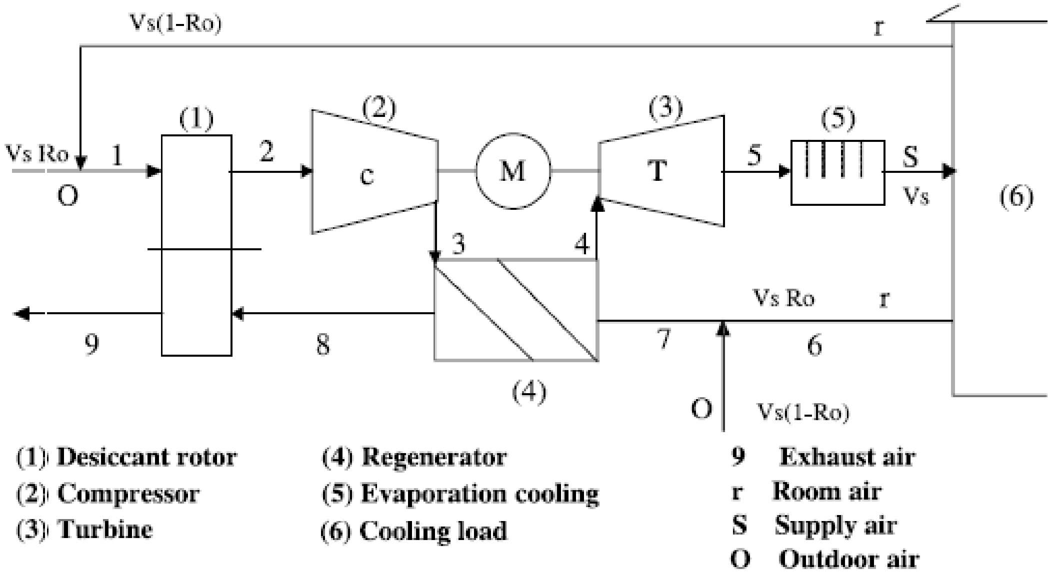


Fig. 2-14 Desiccant integrated air conditioning system(2-20)

2.6 Fluidization Applied to Sorption Material

One of the primary works in fluidized bed system for continuous adsorption and desorption process belongs to Reichhold and Hofbauer(2-21). They proposed a design procedure for internally circulating fluidized bed for continuous adsorption and desorption as depicted in Fig. 2-15 This system can be used more generally for many other reaction/regeneration operations. It helps to separate and to recover gaseous pollutants and reusable compounds. Two fluidized bed are arranged next to each other. The partition wall in the upper and the lower part of the fluidized beds has horizontal openings to let solid matter pass through. As the two beds are fluidized at different rates, the bed material starts to circulate between the two beds. The bed material doubles as an adsorbent. In the adsorption zone, polluted gas is used for fluidization, in desorption zone, heated air or steam is used. The main difference from the conventional fixed bed adsorbers are that plants can be built in a more compact manner, higher flow rates can be achieved, and separate optimization of the two zones is possible.

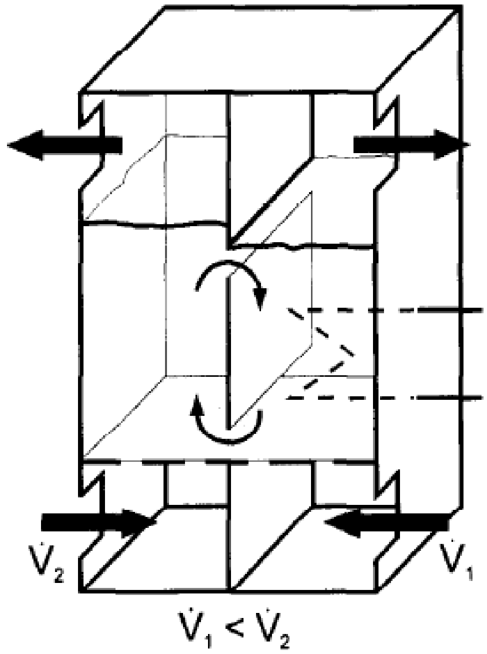


Fig.2-15 Internally circulating fluidized bed acting as a reaction and regeneration system (adsorption/desorption system)(2-21)

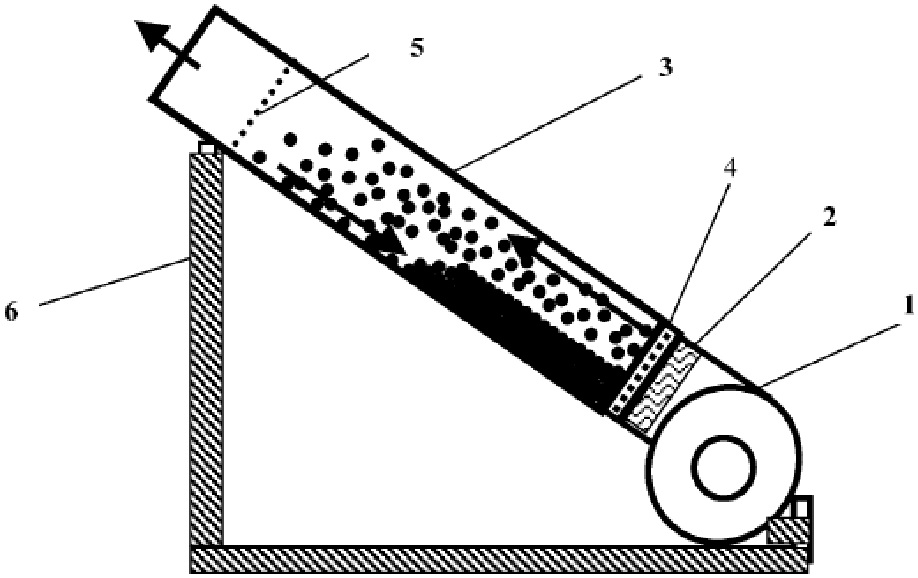
Aly and Fathalah(2-22) used a three phase model of simultaneous heat and mass transfer of a batch operation for fluidized bed. The model employs an elaborate five equations porosity model. Various correlations for the minimum fluidization parameters are surveyed and compared with the adequate one is being adopted in the model. The governing equations together with the boundary and initial conditions are presented for a cyclic operation of the bed. These are numerically solved for a test case where the bed is charged with silica gel particles to dehumidify a process air stream. The results indicate the ability of the developed model to provide the required data for the concerned batch operated fluidized bed.

Inaba et al.(2-23) performed an experimental and theoretical analysis of adsorption characteristics of the organic powder adsorbent in a fluidized bed. The organic powder type adsorbent was made from the bridge complex of sodium polyacrylate and its diameter ranged from 30 μm to 48 μm. The measured result of adsorption isotherm equilibrium revealed that the mass ratio of the present organic adsorbent adsorbed water vapor to the adsorbent dried were 1.3 to 2.3 times larger than that of silica gel adsorbent in the air relative humidity range from 3 to 80%. The humid air was used as working fluid for transient experiment. The test organic powder type adsorbent was fluidized in a rectangular vessel by flowing the air from its bottom. The adsorption rate of water vapor and the variation of the air temperature in the adsorbent bed with time were measured under various inlet air temperature and humidity and air flow rates. The completion time for the adsorption process increased with decreasing air temperature and increasing the air relative humidity and the air flow rate.

Horibe et al.(2-24) experimentally examined the sorption characteristics of organic powder sorption material in fluidized bed with a cooling pipe. The measured results revealed that the sorption process was accelerated and the water uptake ability was improved by the cooling effect of water flowing through pipe. Furthermore, the data of non-dimensional time of the sorption process, modified Sherwood number and Nusselt number were correlated by means of Reynolds number, quantity of modified Stefan number and non-dimensional temperature ratio which is used for concerned cooling temperature.

Horibe et al.(2-25) studied on a fluidized bed with multiple cooling pipes. They investigated adsorption characteristics of a new organic sorbent desiccant material (HU300P) for a new air conditioning system. The sorption rate of the water vapor in the sorbent bed was measured under various conditions. It was found that the sorption rate is highly dependent on the affect of cooling pipes. The sorption ratio increases and the completion time for the sorption process decreases by using multiple cooling pipes.

Syahrul(2-26) performed an experimental and theoretical analysis of desorption characteristics of organic powder sorption material in fluidized bed with a heating pipe. The completion time for desorption process decreases by increasing inlet air velocity and increasing inlet air temperature. However, the completion time for desorption process will increase by increasing relative humidity of the inlet air, initial relative humidity of the material and initial height of the bed. The effect of inlet air parameters (velocity, temperature, and humidity) and initial material sorbent (HU300P) parameters (temperature, humidity, and height of the bed) were clarified quantitatively. Moreover the non-dimensional correlation equations the variation of non-dimensional completion time *Fo,* non-dimensional mass transfer factor $Sh^*/Sc^{1/3}$ and Nusselt number with Reynolds number, the quantity Ste^* of modified Stefan number and dimensionless height of the bed (h/d_p) respectively were presented.



1. Air blower, 2. Air heater, 3. glass tube, 4 and 5. Inlet and outlet screen,
6. Stand to support the inclined bed.

Fig 2-16 Solid desiccant in inclined fluidized bed System(2-27)

Hamed(2-27) investigated the adsorption and desorption operation in an inclined fluidized bed using silica gel as the working desiccant, as can be seen in Fig. 2-16. The experimental involves a circular glass tube containing the particles of silica gel, which is tested at an inclination angel of 45°. The moisture capacity of the bed is measured using a gravimetric technique. Process air at nearly constant ambient parameters (humidity and temperature) and different values of flow rate are used during adsorption. Moisture concentration in the bed is analyzed through visual observation of the color of silica gel particles. Experimental measurements indicate that the regeneration and adsorption rates are highly dependent on the air stream velocity. A satisfactory regeneration rate is confirmed at regeneration temperature as low as 90 °C when inclined fluidized bed is applied.

Horibe(2-28) investigated the dehumidification performance of organic powder sorbent in a fluidized bed during batch cycle operation. The experiments were carried out under the various conditions such as cycle time, inlet air velocity, temperature of the heat exchanger, and the amount of sorbent. As a result, the cycle time which maximizes the amount of dehumidification became clear. The most suitable cycle time was decided by balance of the speed of sorption reaction and the effect of heating and cooling, which were controlled by heat exchanger temperature. Decreasing the desorption temperature suitable cycle time became shorter and increase the amount of dehumidification. On the other hand, increasing the sorption temperature will decrease the amount of dehumidification.

Palancz(2-29) proposed a mathematical model for continuous fluidized bed drying by employing a Kunii-Lavenspiel type, three-phase model inside the bed. The bubble phase was assumed to be in plug flow while the interstitial gas, as well as the solid particles was considered to be perfectly mixed. He assumed a simplified lumped model for solid particles and studied the effects of the process parameters on the moisture content of solids. However, he mentioned that the lumped model for solid particles was not realistic and recommended to improve the lumped particle model by taking into account the internal resistance to the heat and mass transfer inside the moisture solid.

Garnavi(2-30) proposed numerical simulation of continuous fluidized bed dryer based on the two phase theory. In the model, bubble size variations along the bed height are taken into consideration. This condition is that differentiate it from model which are proposed by Palanez(2-29) and Lai and Chen(2-31).

Desorption and sorption processes are essentially a process of simultaneous heat and mass transfer Heat is necessary for evaporation, is supplied to the particles of the material and moisture vapor is removed from the material into the medium. Heat is transported by convection from the surroundings to the particle surfaces, and by conduction into the particle. Moisture is transported in the opposite direction as a liquid or vapor; on the surface it evaporates and passes on by convection to the surroundings.

2.7 Summary

The brief overview with respect to the fluidized bed and desiccant dehumidification system was introduced in this chapter. Fluidized bed and dehumidification system are very broad area and there have been many researchers and publication paper appeared in the literature regarding those subjects. Fluidization is the operation by gas or liquid which solids are transformed into a fluid like state through contact with a gas or liquid when a gas or liquid is passed upward through a layer of solid particles. The behavior of solids fluidized by gases falls into four clearly recognizable groups, which are: Group A, B, C, and Group D which characterized by density difference and mean particle size. Each of the fluidization regimes has characteristic solids concentration profiles. The main characteristics of the pertinent gas solid flow regimes are: Fixed bed, minimum fluidization, smooth fluidization, bubbling fluidization, slugging fluidization, and lean phase fluidization.

The operation of circulating fluidized bed systems requires that both the gas flow and the solids circulation rate are controlled, in contrast to the gas flow rate only in a dense phase fluidized bed system. The solids circulation is established by a high gas flow. The integral parts of a Continuous Fluidized Bed (CFB) loop are the riser, gas solid separator, down comer and solid flow control device. The CFB is thus a fluidized bed system in which solid particles circulates between the riser and the down comer. The riser is the main component of the system. The riser can not be considered as an isolated entity in the CFB loop because the pressure drop over the riser must be balanced by that imposed by the flow through its accompanying component such as the downcomer and the circulation device.

Desiccant cooling technology provides a tool for controlling humidity (moisture) levels for conditioned air spaces. Desiccant systems work in conjunction with conventional air conditioning systems to dehumidify the air. Desiccant can be in the form of a solid or a liquid. People have identified types of desiccant that are appropriates as a component of commercial heating, ventilation and air conditioning (HVAC) systems. These desiccants have been selected base on their ability to hold large quantities of water vapor, their ability to be reactivated, and cost.

Air conditioning loads can be divided into two components, namely sensible and latent loads. In order to remove the latent heat, the traditional refrigerant vapor compression system, cools the process air down below its dew point in order to condense out water vapor contained therein. One of the ways to remove moisture from air is by passing the air over a desiccant, which pulls moisture from the air through differences in vapor pressure. In order to be effective, the desiccant must be capable of addressing the latent cooling load in a continuous process. Desiccant material attract moisture through the process either adsorption or absorption and sorption. Sorption behavior of both absorption and adsorption occur simultaneously. Commercially available desiccant systems are based on five configuration or technologies that are: liquid spray towers, solid packed tower, rotating horizontal bed, multiple vertical bed, and rotating desiccant wheel.

There are eight key parameters which affect the performance of desiccant dehumidifiers and the exact effect of each parameter depends on the type of dehumidifier. These include: process air moisture, process air temperature, process air velocity through the desiccant, reactivation air temperature, reactivation air moisture, reactivation air velocity through the desiccant, amount of desiccant presented to the reactivation and process airstreams, and desiccant sorption-desorption characteristics.

Commonly used solid desiccant, which are all concluded from experiment have high regeneration temperature. Hence the regenerating energy for the saturated adsorbents is huge consumption of the dehumidification system. The commonly employed energies include electric, gas, and solar energy. Advantages and disadvantages of utilizing solar energy compared with three other kinds of energies are expressed as the following: Solar energy is one type of renewable energy, saving energy and reducing air pollution; Solar energy is plentiful in the regions with a hot and humid climate; Solar water can service and store the solar energy more conveniently than solar desiccant and solar air; The capital cost of utilizing solar energy is high but running cost is less than electric and gas energies; Less convenient than electric and gas heaters; Can not be used for a long time without solar radiation; and Less regenerator efficiency compared with electrical and gas heaters.

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Chapter 3
Materials

3.1 Desiccant

The desiccants are natural or synthetic substances capable of absorbing or adsorbing water vapor due to the difference of water vapor pressure between the surrounding air and the desiccant surface$^{(3-1)}$. They are encountered in both liquid and solid states. Each of liquid and solid desiccant system has its own advantages and shortcomings. In addition of having lower regeneration temperature and flexibility in utilisation, liquid desiccant have lower pressure drop on air side. Solid desiccant are compact, less subject to corrosion and carryover. There are literally hundreds of desiccants, each designed and manufactured for a specific task. They can be categorized by their ability to attract and hold water vapor at specific temperatures and relative humidities$^{(3-2)}$. Commonly used desiccant materials include lithium chloride, tryethylene glycol, silica gel, aluminium oxides, lithium bromide solution and lithium chloride solution with water, etc.

The essential characteristic of desiccants is their low surface vapor pressure. If the desiccant is cool and dry, its surface vapor pressure is low, and it can attract moisture from the air, which has a high vapor pressure when it is moist. After the desiccant becomes wet and hot, its surface vapor pressure is high, and it will give off water vapor to the surrounding air. Vapor moves from the air to the desiccant and back again depending on vapor pressure differences.

Most solid materials can attract moisture. For instance, plastics like nylon can absorb up to 6% of their dry weight in water vapor. Gypsum building board can also store a great deal of water vapor, and the oxide layer on metals attracts and holds a small amount of water vapor under the right conditions. The difference between this materials and commercial desiccants is capacity. Desiccant designed for water vapor collection attract and hold from 10 to over 10000 percent (100 times) of their dry weight in water vapor, however this material are designed for irreversible process, where other materials have lower capacity(3-3).

One subtle distinction between desiccants is their reaction to moisture. Some simply collect it like sponge collects water, the water is held on the surface of the material and in the narrow passages through the sponge. These desiccants are called adsorbents, and are mostly solid materials. Silica gel is an example of a solid adsorbent. Other desiccants undergo a chemical or physical change as they collect moisture. These are called absorbents, and are usually liquids or solids which become liquid as they absorb moisture. Lithium chloride is a hygroscopic salt which collects water vapor by absorption.

Most adsorbents and absorbents are used to dry humid air for some specially required places as paper factory, spinning mill, food factory and storage, and beverage factory(3-4). However, recently, they have become more popularly used to treat environment air to create desired living conditions for residential buildings(3-5) .

Solid desiccant dehumidification employs the porous and strong hydrophilic materials to adsorb moisture from the air stream. The generally used solid desiccants include silica gel, natural and synthetic zeolites, activated alumina, titanium silicate, synthetic polymers, lithium chloride, etc (3-4) , (3-6) .

Experiment had been carried out by Dai(3-4), who proved that the regeneration temperature of carbon methanol was in the range of 80-100°C; DH-5 and DH-7 (kind of adsorbents which were manufactured by Nanjing Inorganic Chemical Plant) were about 100°C; and 13x, alumina and silica gel need higher regeneration temperature in the range of 200-300.

Base on the dehumidifying capability, Cui(3-7) preferred DH-5 and DH-7 as the adsorbents rather than silica gel and molecular sieves, which reaches 0.7 kg/kg. The wide regeneration temperature and higher cooling capacity of DH-5/DH-7 were found to be superior to silica gel and molecular sieve.

By the comparison of investigations, regarding the performance of activated alumina, silica gel,13X, a kind of zeolite, were carried out by K Daou(3-1). It was concluded that the activated alumina and silica gel were ageing severely after a large number of adsorption/desorption processes, but need a regeneration temperature as high as 200°C, which was very difficult to obtain from solar energy or other kinds of low degree waste heat. 13X molecular sieves served dehumidification more stably but at a lower capacity. LCIX had the longest durability for a large number of adsorption/desorption cycles but had the highest regenerator temperature at 250°C.

Experiment and simulation of lithium chloride assisted air cooling system with refrigerant R-22 was conducted by Jia(3-6). Results indicated that COP of the lithium chloride assisted cooling system was 37.5% higher than conventional vapor compression system. However the regeneration temperature of lithium chloride was lower than 100°C.

The main four factors to be considered in selection a solid desiccant are absorption capacity, durability, stability and regenerator temperature. Table 1.1 list the parameters of several commonly used solid desiccant, which are all concluded from experiment(3-1), (3-4),(3-6),(3-7). DH-5 and DH-7 is preferred choice of adsorbent owing to its high dehumidification capacity and low regeneration temperature. Silica gel is the second material to service high absorption capacity with lower regenerating temperature. Charcoal takes the following position owing to its higher absorption capacity as well as high regeneration temperature. Activated alumina is the fourth with a lower adsorption capacity than charcoal. Although 13X and 5A have high adsorption capacity, their high regeneration temperatures hold back their application.

Liquid desiccant dehumidification systems can be operating continuously at a regeneration temperature below 80°C (3-1). Lithium chloride, Lithium bromide, calcium chloride and Triethylene glycol are usually used as a liquid desiccant owing to their highr absorption capacity, for instance, Lithium Chloride can hold 130% of water of its mass under the same air flow condition (21°C and 20%) (3-5), (3-8). Liquid desiccant can remove the extra moisture from the air flow but cause the air temperature to increase due to the condensation of water vapor, which release heat to the air. Therefore, a pre-cooled liquid desiccant is needed to achieve both cooling and dehumidification of the passing air.

Table 3-1 Comparison of adsorbent-adsorbate(3-9)

Adsorbent-adsorbate	**Max. adsorption capacity (kg/kg)**	**Regenerator temperature (°C) (approximate value)**
4A-water	0.22	350
13X-water	0.30	350
5A-water	0.33	350
Clinoptilolite(natural zeolite)-water	0.12	240
Mordenite-water	0.11	250
Chabazite-water	0.17	250
Charcoal-water	0.40	250
Activated alumina-water	0.19	250
Silica gel-water	0.37	150

Compare with solid desiccant, the liquid desiccants are competitive with solid desiccants due to their advantages such as: more flexibility, capability of absorbing pollutants and bacteria, relative lower regeneration temperature and lower air side pressure drop, etc (3-1), (3-10). Commonly used desiccants involve LiCl, LiBr, $CaCl_2$, and KCOOH, LiCl+LiBr solution, etc (3-11) - (3-13). In 1937, hygroscopic salt solution such as LiCl+H_2O, LiBr+H_2O, KCOOH+H_2O etc, were used as absorbents replacing the commonly solid desiccants to deal with large latent loads. With the technological development of utilizing waste and renewable energy such as solar energy, more liquid desiccant systems constituted of a dehumidifier core and regeneration unit have been researched and employed with conventional HVAC system to service the desire air at a high COP (3-12).

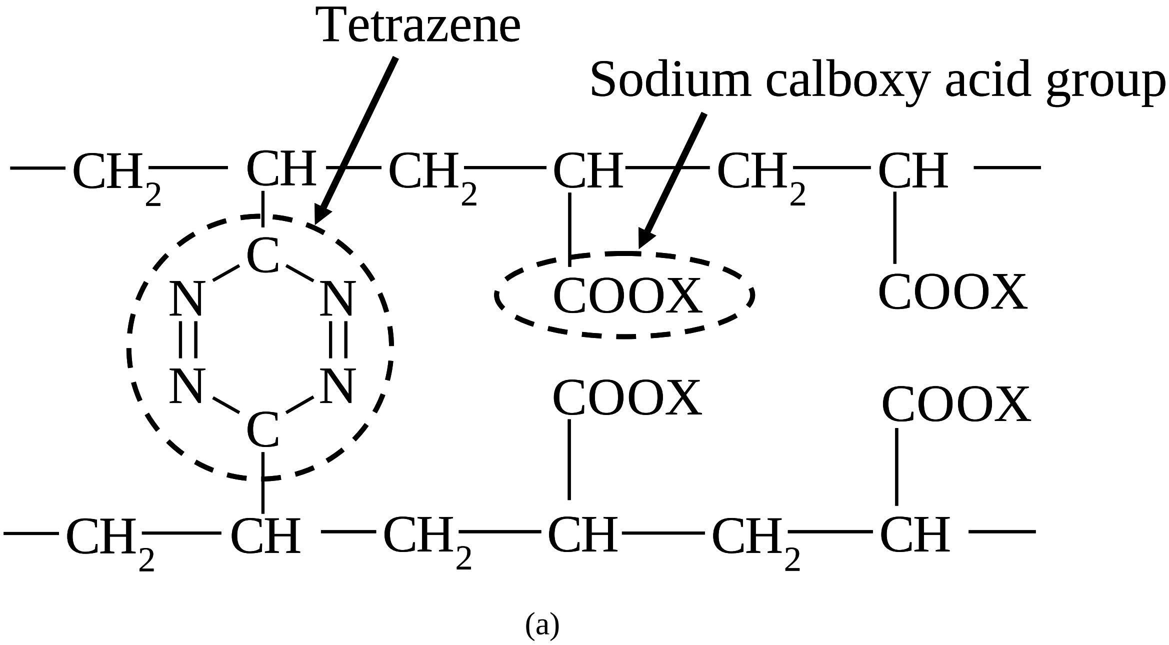
Experiment and theoretical analysis of heat and mass transfer in a packed column dehumidifier/regenerator with salt solution of LiCl+H_2O, LiBr+H_2O and KCOOH+H_2O was conducted by Longo and Gasparella (3-11). Theoretical analysis indicated that a transition concentration between regeneration and dehumidification around 25%, 42% and 57% of LiCl, KCOOH and LiBr solution respectively. The LiCl and LiBr solutions presented a better dehumidification performance than KCOOH solution, which performed better regeneration. Although KCOOH+H_2O was less corrective and more compatible with environment, its high price obstructed its application.

When the mass concentrations of LiBr and $CaCl_2$ solutions had a similar crystallization temperature (11-12°C), Lazzarin(3-13) deducted that $CaCl_2$ performed less dehumidification than LiBr solution. In the experimental and modeling researches carried out by Pietruschka (3-5), it was proved that calcium chloride solution offered significantly lower dehumidification potential than LiCl solution, although it had a cheaper price and no causticity to metal.

3.2 Characteristics of the present polymer sorbent

Figure 3-1(a) and (b) show the chemical structure and powder of organic sorbent of the present polymer of sodium acrylate with a cross linking structure consisting of tetrazene, which has 4 nitrogen atoms. Water vapor molecules are sorbed into the sodium acrylate site on a side chain of the polymer with increasing volume. Thus, this phenomenon, in which the sodium acrylate site sorbs water vapor molecules by a weak force with deformation of its shape, and it able to desorp the water vapor from the sorption sites under the low temperature condition. The sorption heat is almost same as the condensation heat of water vapor. The temperature level for desorbing water vapor from the sorption site ranges from 45 to 80°C.

The sorption characteristics of the water vapor from the moist air is influenced by the external diffusion based on the concentration boundary layer growing near the surface of the sorbent particles and the internal diffusion based on the pore of the sorbent particles. In particular, the pore morphology of the sorbent particles exert a significant influence on the internal diffusion in relation to the sorption characteristics. The pore size distribution of the sorbent particles was measured by the mercury press-injection and nitrogen permutation method. The measured pore size was distributed from 4×10^{-3} nm to 60 nm, which was ranged from the molecular diffusion area to Knudsen diffusion area. While, the pore size of the commercial silica gel ranged from 10 nm to 8×10^{4} nm, which belonged to the molecular diffusion are.



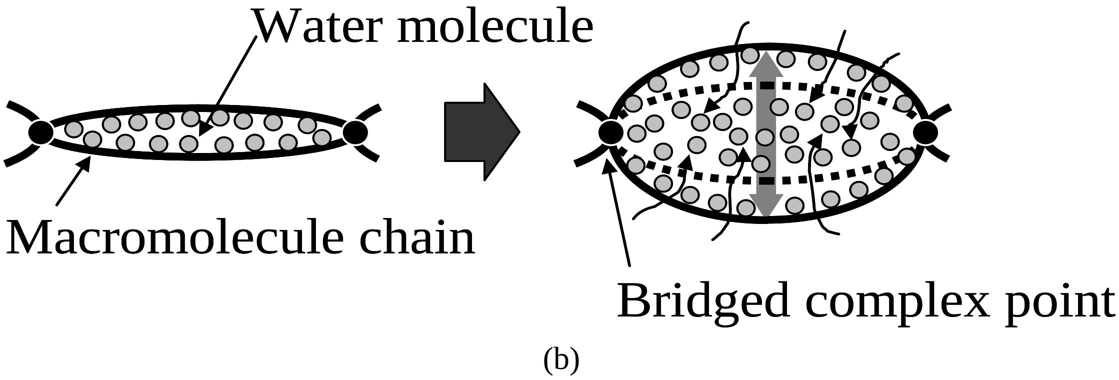


Fig. 3.1 (a) Chemical structure of sorbent particle; (b) Construction of swelling

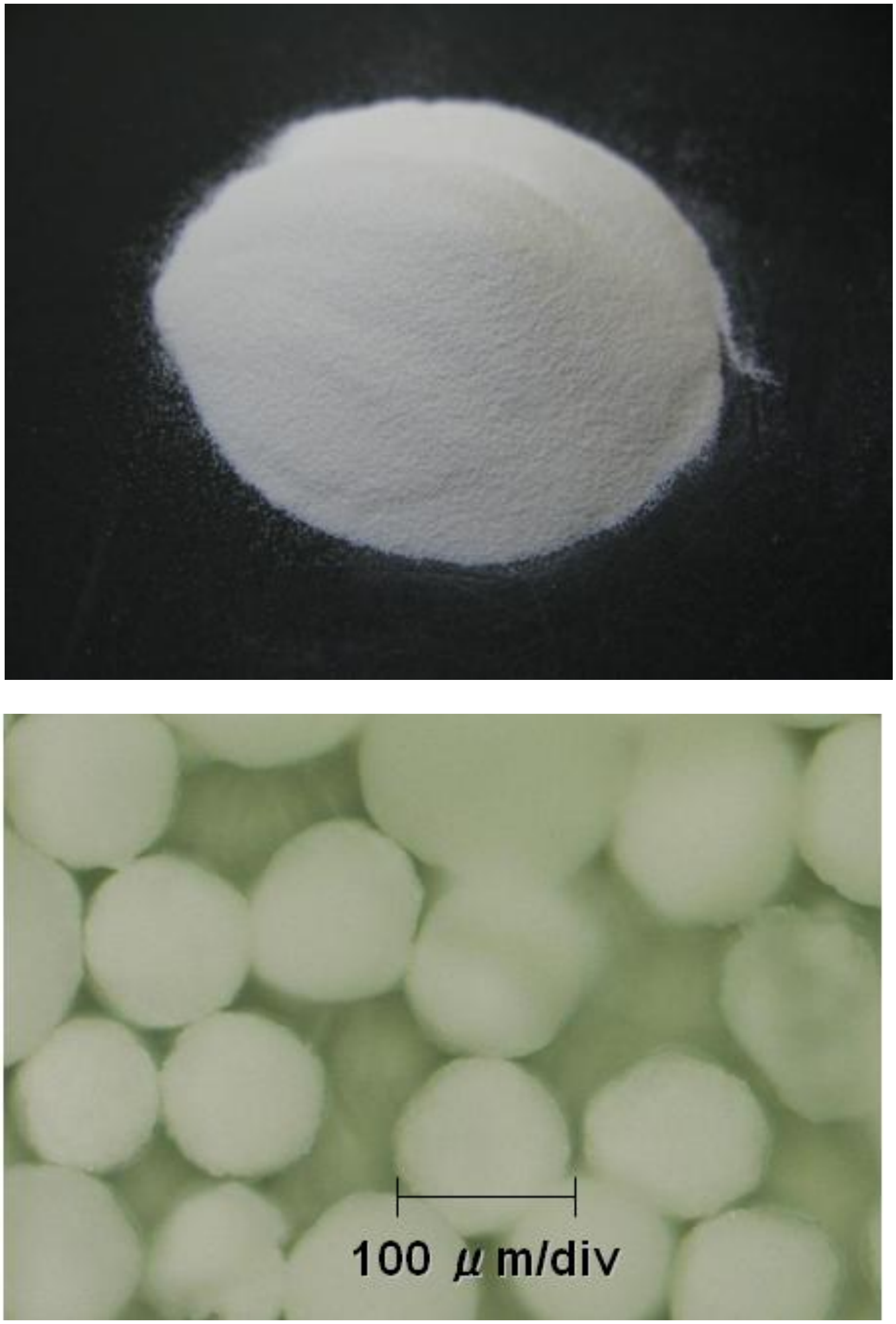


Fig. 3.2 Organic sorbent powder type

The inorganic adsorbent such as silica gel and zeolite etc. have been used generally in desiccant system, but this adsorption heat cycle has been pervaded to a lesser extent due to degradation phenomenon of powdering the inorganic adsorbent caused by expansion and shrinkage under the adsorption and desorption processes. One of the method for solving this problem is to use an organic sorbent like adsorption polymers. In this study, sorption polymers as an organic sorbent (HU720PR) are used as a desiccant material. The polymer has larger sorption capacity than silica gel (3-15) – (3-17).

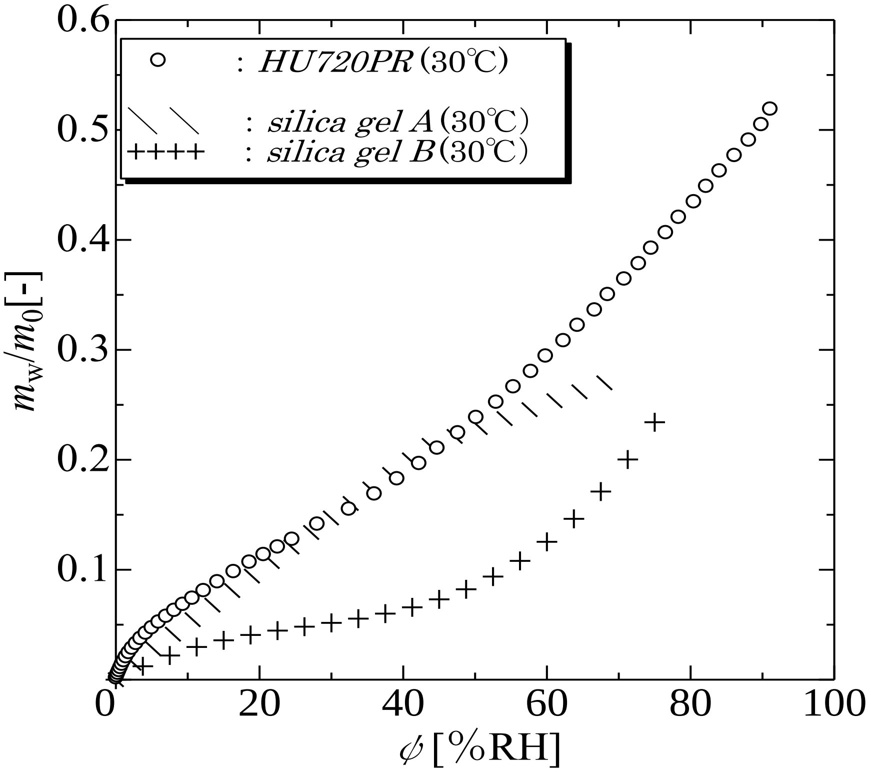


Fig 3.3 Adsorption isotherm of HU720PR and silica gel

The organic sorbent is a bridge complex of sodium polyacrylate. This bridge complex containing the carboxyl group as water vapor adsorption site has a larger adsorption abilities as compared with silica gel. When the organic sorbent uptakes water vapor, the heat of sorption is about the same as that the latent heat of water vapor of condensation is released. It is estimated that the expansion phenomenon is a result of expanding bridge complex by the increasing of pressure. Sorption material used in this research is HU720PR, powder type organic sorbent. Mean diameter of the sorbent is 113 μm with density 931 kg/m^3. Each desiccant has unique sorption characteristics which affect the performance of the dehumidifier. These characteristics can be shown graphically as a capacity isotherm. Figure 3.3 shows the sorption isotherm diagram of HU720PR and silica gel (type A and type B). Ratio m_w/m_0 means the mass ratio of sorbed water vapor, m_w to the dried organic sorbent, $m_{0,}$ and it was named non-dimensional sorption ratio. The data of m_w/m_0 for the organic sorbent is greater than that of silica gel over the whole relative humidity range; shows that this material can sorbs more water vapor by the expansion phenomena. It could be concluded that this organic sorbent is the suitable material for high relative humidity range because it can uptake water vapor more than silica gel with running condition 80%RH.

Table 3-2. Comparison between Organic sorbent and Silica gel

	Sorbent	Silica gel
Adsorption capability [g/g] (30℃,80%RH)	0.60	Type A：0.40 Type B：0.25
Desorptions Temperature [℃]	～80	Type A：150～200 Type B：100～150
Form [mm]	Spherical, Particle diameter 0.1～0.15	Spherical, Particle diameter 0.05～0.2
Adhesion nature to basis material	Adhesion become possible with a binder	Adhesion is impossible
Other characteristics	Expanding is possible until 20% Hard to form powder Low desorption temperature Little degradation in performance due to reproduction	Easy to fine powder by heat stress High desorption temperature Performance degradation by desorption is large

Dou(3-1), Dai(3-4), and Grossman(3-9) clarified that solid desiccant need higher regeneration temperature than liquid desiccant , above 80°C, so that it is difficult to utilize the solar energy and other low grade energy as regeneration temperature. Base on Table 3-2, the highest regeneration temperature of organic sorbent used in this research is 80°C.

Table 3-3 Properties of organic sorbent powder, silica gel A and silica gel B

	Organic sorbent	Silica gel A	Silica gel B
Density (kg/m^3)	913	754	511
Thermal conductivity (W/mK)	0.076	0.15	0.04
Specific Heat (kJ/kgK)	1.4	0.96	0.96

The dynamic sorption characteristics of the organic sorbent have been previously investigated in our laboratory for single process either sorption or desorption process in one chamber (3-15) – (3-17). The pressure drop ΔP is about 200 Pa when organic sorbent particles are fluidized with initial bed height 0.01 m and relative humidity of air 60%. This value is lower than that for fixed bed (3-15).

3.3 Summary

The study of desiccant material was introduced and reviewed. Desiccant materials are very broad area and there have been many theoretical and experimental investigations appeared in the literature. The desiccants are natural or synthetic substances capable of absorbing or adsorbing water vapor. They are encountered in both liquid and solid states, Solid desiccant are compact, less subject to corrosion and carryover. Most solid materials can attract moisture. For instance, plastics like nylon can absorb up to 6% of their dry weight in water vapor. Gypsum building board can also store a great deal of water vapor, and the oxide layer on metals attracts and holds a small amount of water vapor under the right conditions. The difference between this materials and commercial desiccants is capacity.

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Solid desiccant dehumidification employs the porous and strong hydrophilic materials to adsorb moisture from the air stream. The generally used solid desiccants include silica gel, natural and synthetic zeolites, activated alumina, titanium silicate, synthetic polymers, lithium chloride, etc. Absorption capacity, durability, stability and regenerator temperature are the main four factors to be considered in selection a solid desiccant. The sorption characteristics of the water vapor from the moist air is influenced by the external diffusion based on the concentration boundary layer growing near the surface of the sorbent particles and the internal diffusion based on the pore of the sorbent particles.

The inorganic adsorbent such as silica gel and zeolite etc. have been used generally in desiccant system, but this adsorption heat cycle has been pervaded to a lesser extent due to degradation phenomenon of powdering the inorganic adsorbent caused by expansion and shrinkage under the adsorption and desorption processes. One of the method for solving this problem is to use an organic sorbent like adsorption polymers. The organic sorbent is a bridge complex of sodium polyacrylate. This bridge complex containing the carboxyl group as water vapor adsorption site has a larger adsorption abilities as compared with silica gel. In this study, sorption polymers powder type as an organic sorbent (HU720PR) are used as a desiccant material. Mean diameter of the sorbent is 113 μm with density 931 kg/m^3. The sorption polymer has larger sorption capacity than silica gel. Each desiccant has unique sorption characteristics which affect the performance of the dehumidifier.

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Chapter 4

Sorption-desorption operations on two connected fluidized beds using organic sorbent powder

4.1. Introduction

Desiccant air conditioning system has been continuously growing during the past several years. This system is considered as a good supplement for air conditioning because it can be a system to overcome the disadvantages of traditional vapor compression air conditioning system. Desiccant air conditioning system can be reduce the use of CFCs that known as ozone destroyer. Desiccant can be regenerated (reactivated) by application of heat to release the moisture where the heat can be from abundant waste heat energy that classified as new energy source which is free and harmless to the environment. Decreasing the cost of desiccant dehumidification system and improving their performance can be providing more opportunities for this technology.

There are some types of equipment configuration that have been investigated for desiccant dehumidifier system. They are solid packed bed(4-1)-(4-3), rotating honeycomb(4-4), horizontal bed(4-5),(4-6), and fluidized bed(4-1), (4-7)-(4-10). The process air flows through the desiccant bed giving up its moisture to the bed particles. After the desiccant bed has saturated with the moisture, the bed is heated and purged of its moisture for regeneration. For the system working continually, water vapor adsorbed/absorbed must be driven out of the desiccant material (regeneration) so that it can be dried enough to adsorb water vapor in the next cycle. This is done by heating the desiccant material which is dependent upon the nature of the desiccant used.

The efficiency of the process improves when the desiccant has a high moisture capacity and the ideal desiccant dehumidifier would have a large surface area(4-11). One of the advantages of fluidized bed is that the rate of heat and mass transfer between gas and particles is high compared with other modes of contacting because interaction contact between particles and gas is high(4-12). This can be very useful in increasing the characteristic of adsorption and desorption of adsorption material in a desiccant chamber.

The inorganic adsorbent such as silica gel and zeolite etc. have been used generally in desiccant system, but this adsorption heat cycle has been pervaded to a lesser extent due to degradation phenomenon of powdering the inorganic adsorbent caused by expansion and shrinkage under the adsorption and desorption processes. One of the method for solving this problem is to use an organic sorbent like adsorption polymers. In this study, sorption polymers as an organic sorbent (HU720PR) are used as a desiccant material. The polymer has larger sorption capacity than silica gel(4-1),(4-4),(4-7). The dynamic sorption characteristics of the organic sorbent have been previously investigated in our laboratory for single process either sorption or desorption process in one chamber (4-1),(4-4),(4-7)-(4-9). The pressure drop ΔP is about 200 Pa when organic sorbent particles are fluidized with initial bed height 0.01 m and relative humidity of air 60%. This value is lower than that for fixed bed(4-13). It is understood that desorption process needs high temperature while sorption process needs low temperature. In order to reduce the influence of heat capacity of the vessel when the processes switch from sorption to desorption and for stable amount of dehumidification and strict humidity control, we proposed fluidized bed with two chambers. One chamber for sorption and the other for desorption which are working continuously because sorbent powder is transferred by spiral tubes that connected the two chambers. The difference from Reichhold and Hofbauer(4-14) work are the kind of sorbent and sorbent circulating process, where the adsorbent circulating by the difference of air velocity between the two chambers. In this work, used sorbent is organic sorbent powder and sorbent circulated by the spiral tubes that connects the two chambers.

The objective of this study is to investigate the operation of continuous sorption and desorption process in two connected fluidized beds. In this study heat and mass transfer were considered to evaluate the effect of spiral revolution speed, air velocity, desorption inlet air temperature, and initial bed height in the chamber to sorption and desorption rates.

4.2. Experimental Set Up

The set-up of the experimental apparatus for sorption and desorption operation is depicted in Figure 4-1. The experimental apparatus mainly consists of

1. an air compressor type PSP200A, a regular output power of 3.7 kW, a maximum output pressure of 0.87 MPa, a maximum output air flow rate of 67m^3/s,

2. an after cooler model AC with maximum pressure 9.9 kgf, cooling brine is used for antifreeze, to produce air with low temperature and low humidity,

3. a filter Orion type QR035, maximum temperature 50°C and maximum pressure 16 bar, capable to eliminating the dust over 0.3 μm in diameter and micro-mist-filter having the capacity to eliminate the dust over 0.01 μm in diameter,

4. a membrane dryer model DM-XB5,

5. the humidifier in the air moisture control unit is made up of a cylinder stainless steel vessel equipped with an air bubble distributor consisted of the spherical fine balls layer. The air humidity is controlled by the air bubbling operation through the air bubble distributor and the air temperature is also adjusted by the input control of electric heater in the humidifier. In the case of low humidity experiments, a film dehumidifier composed of a molecular filter is used to control the air humidity. While the air humidity control for high humidity experiment is performed by using together the humidifier and the film dehumidifier. After passing the humidifier, and before enter the test section, there is another heater that the temperature could be controlled by adjusting output electric power with a PID control unit.

6. air temperature control unit consists of a cylinder stainless steel vessel covered with the thermal insulation material and an electric heater, the maximum electric power of 1.5 kW,

7. heaters, flow meters, sorption and desorption chambers and spiral tubes with geared motors that connects the two chambers.

8. dew point hygrometer, GE sensing type D2R with accuracy measurement ±0.2℃.

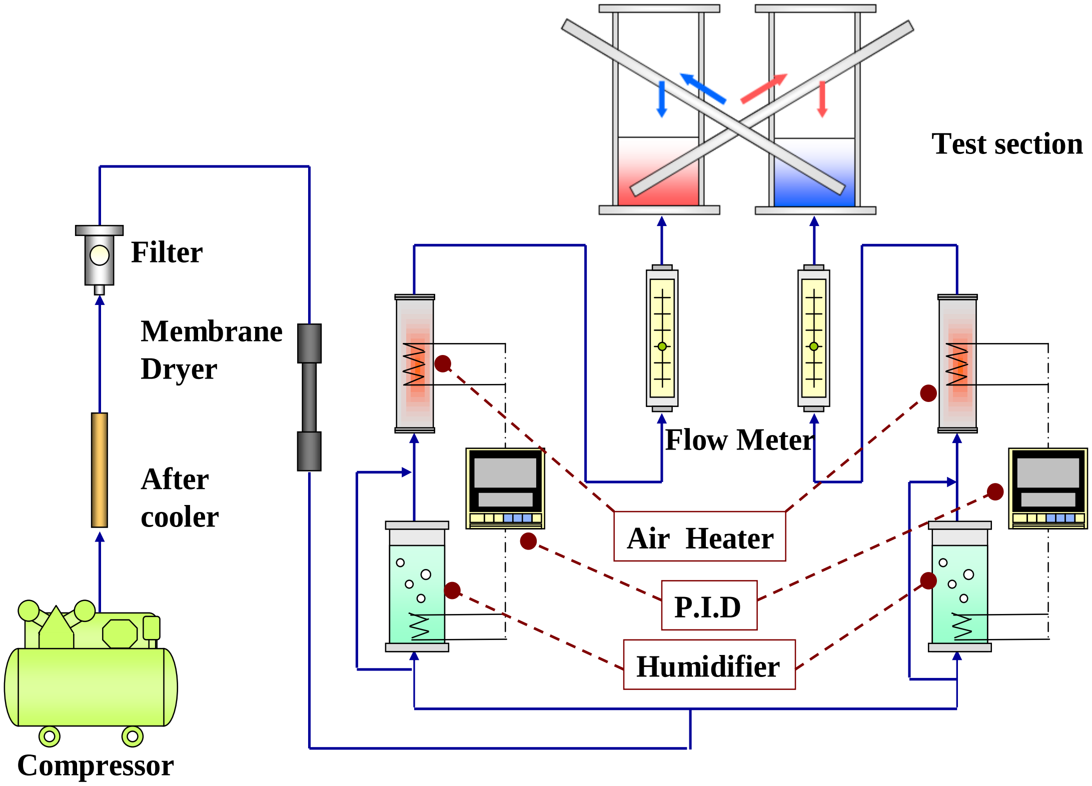


Fig. 4-1 Experimental device

Figures 4-2 – 4-4 show the test section in detailed. Sorption and desorption chambers as test section units are made of transparent acrylic plate which allows viewing the process in the chambers. They are rectangular chambers with cross section area 100 mm x 100 mm and 300 mm height.

The polytetrafluoro ethylene filter # 2 μm as shown in Figure 4-5 and wire mesh are set up in both inlet and outlet of the chambers to distribute air flow uniformly and prevent the leakage of sorbent particles. Figure 4-6 shows the spiral which is made from stainless steel and inserted into the transparent acrylic pipe with inner diameter 16 mm. These spiral tubes transferred the sorbent powder from sorption chamber to desorption chamber or vise versa continuously.

The humidity of air is controlled by the operation of air bubble distributor in the moisture control unit of the humidifier. The temperature of the hot water in the humidifier could be controlled by adjusting output electric power of an electric heater. After passing the humidifier, and before enter the test section, there is another heater that the temperature could be controlled by adjusting output electric power with a PID control unit.

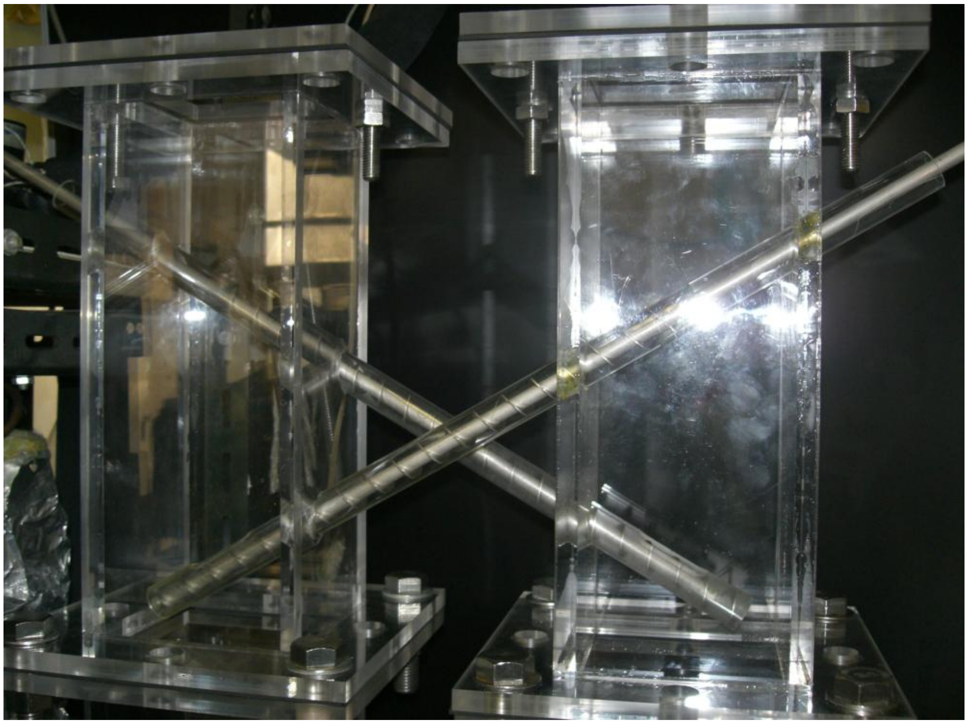


Fig. 4-2 Test Section

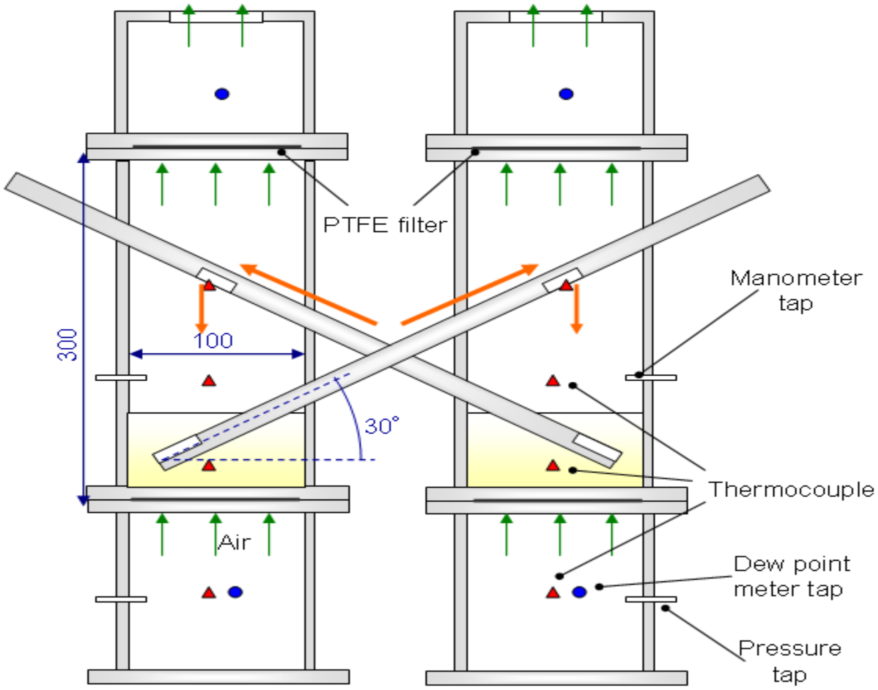


Fig. 4-3 Detail of Test Section

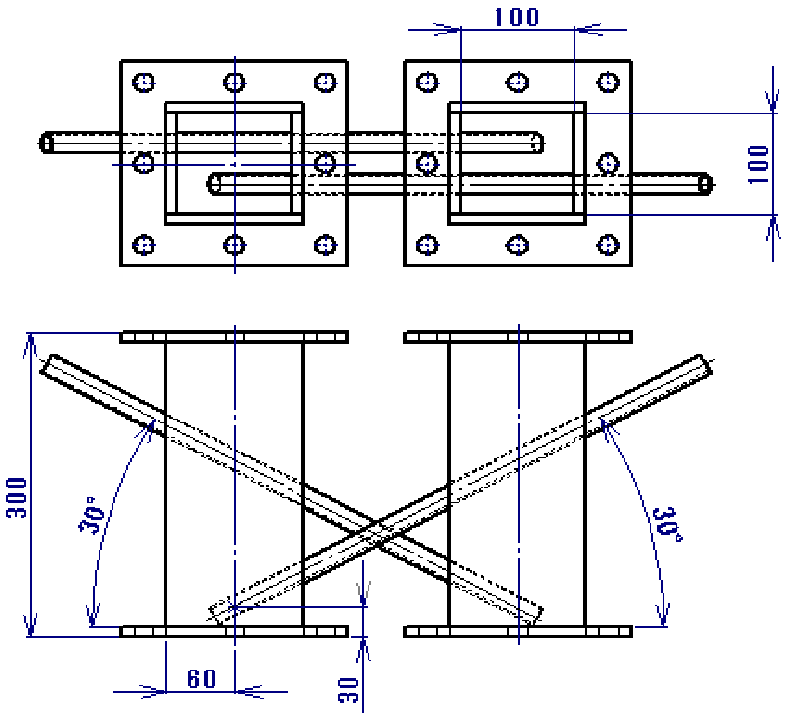


Fig. 4-4 Dimension of Test Section

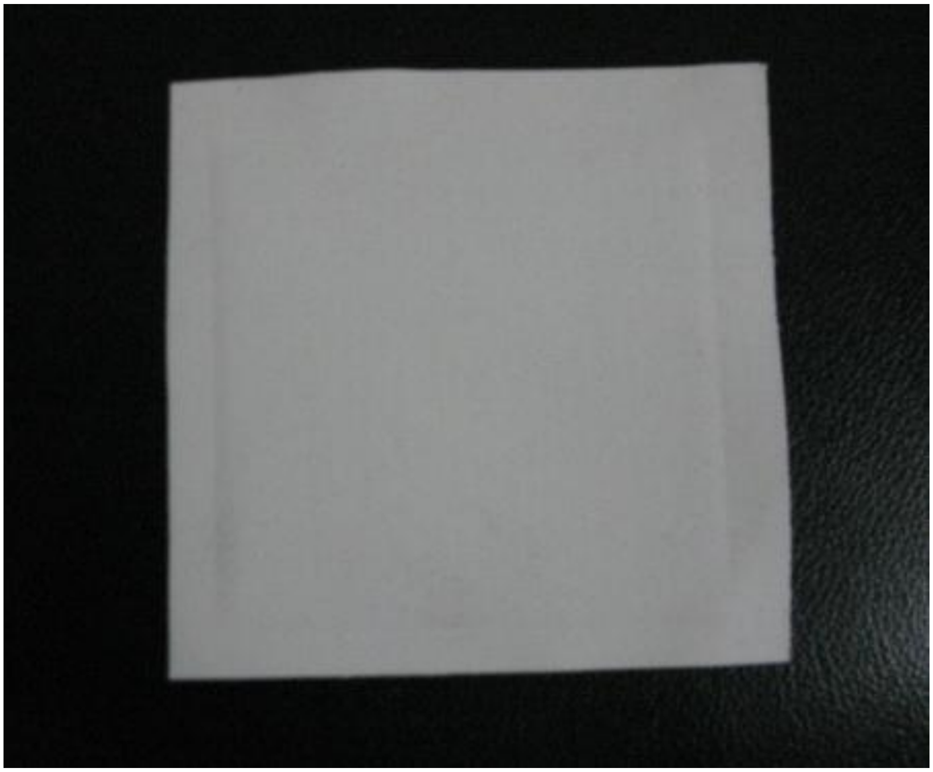


Fig. 4-5 The polytetrafluoro ethylene filter

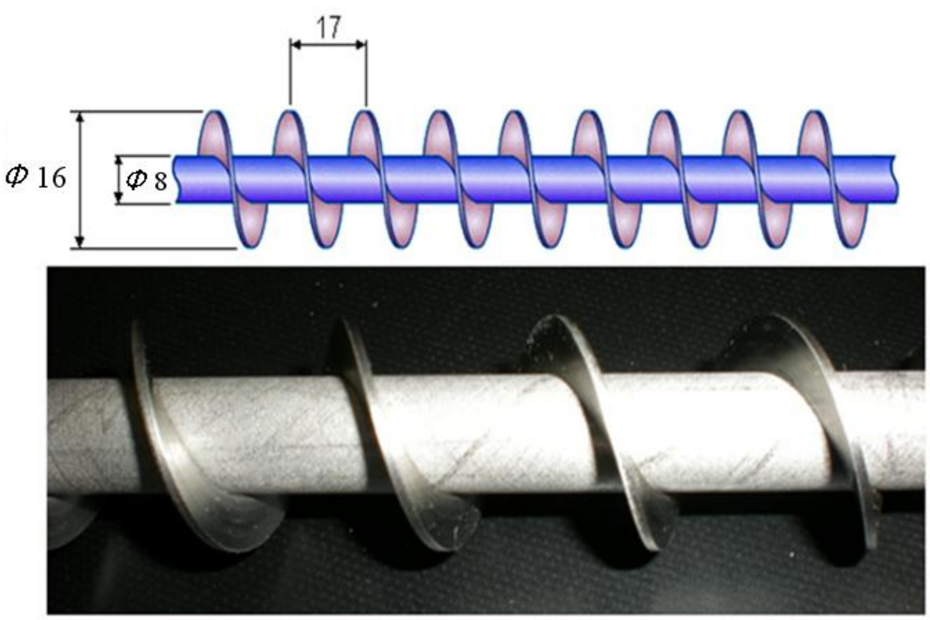


Fig. 4-6 Detail of Spiral Tubes

Flow rate control valve and flow rate meter functioned to control the air flow velocity at the desired value. The measuring accuracy of air amount is 2.5 % in the range of 0.00033 m^3/s – 0.00167 m^3/s. Pressure gauges is used to measure the air pressure at the inlet of the test section.

K type of thermocouples, with diameter 0.32 mm and measuring accuracy of ± 0.1 °C, were used to discover the test powder sorbent temperature profile, inlet and outlet air temperature. One of them was set at the inlet of test section, at the center of the sorbent powder chamber and the other one was set at the exit point of the sorbent at the screw.

The experiment procedure is as follows. First of all, sorption material is dried in a dry oven with temperature 105 °C until water vapor completely removed. Then the sorption powder with specified mass is filled into the test section. After that air with certain temperature, humidity and velocity is exhaled into the desiccant chambers. After the condition reached, spiral switch on with the desired speed. Temperature, humidity and dew point temperature at the chambers and outlet were recorded every 30 seconds. Experimental data were taken until the sorption and desorption reaction reaches equilibrium level. Amount of dehumidification (m_d) was calculated from absolute humidity differences multiplied by air mass flow rate.

Table 4-1 shows the basic condition of this experiment. In this study, it is assumed that the air from a room flows into the system with absolute humidity between 0.015 – 0.017 kg/kg. We choose inlet air absolute humidity 0.016 kg/kg. The inlet air flow is divided into two, one flows to desorption chamber and the other to sorption chamber. At desorption chamber, inlet air is heated and temperature of air is high with low relative humidity. While at sorption chamber, it is not, so that the relative humidity of air remains high. Desorption inlet air temperature is set 50 and 70 ℃ for air velocity effect and spiral revolution speed effect experiment. For desorption inlet air temperature variation, air velocity and spiral speed are set 0.033 m/s and 5 rpm respectively.

Table 4-1 Experimental Condition:

<table>
<tr><td colspan="4">Desorption inlet air condition</td></tr>
<tr><td>Temperature:
50, 60 and 70°C</td><td>Absolute humidity:
0.016 kg/kg</td><td>Relative humidity:
30% (50°C)
15% (60°C) and
10 % (70°C)</td><td>Air velocity:
0.033, 0.04 and 0.48 m/s</td></tr>
<tr><td colspan="4">Sorption inlet air condition</td></tr>
<tr><td>Temperature:
30°C and 35°C</td><td>Absolute humidity:
0.016 kg/kg</td><td>Relative humidity:
60 % (30°C)</td><td>Air velocity:
0.033, 0.04 and 0.48 m/s</td></tr>
<tr><td colspan="4">Other Conditions</td></tr>
<tr><td colspan="2">Dry sorbent mass: 150, 200 and 300 g for each chamber, which are equal with initial sorbent height 0.016 m, 0.021 m and 0.032 m respectively</td><td colspan="2">Spiral speed:
0.7, 1.5, 2, 2.5, 5, 10, 15, 20, 30, 50, and 100 rpm</td></tr>
</table>

4.3 Preliminary experiment

Figure 4-7 present the difference between batch and circulate system. Desorption process needs high temperature while sorption process needs low temperature. Commonly batch system is used for the fluidized bed, where one process occurs in one chamber, and the system must be switch to change the process. For dehumidification process using batch system, desorption process occur after sorption process is finish and vise versa. Two connected fluidized bed is proposed to reduce the influence of heat capacity of the vessel when the processes switch from sorption to desorption and to stabilize the amount of dehumidification and strict humidity control. One chamber for sorption and the other for desorption which are working continuously because sorbent powder is transferred by spiral tubes with geared motors that connected the two chambers.

Figure 4-8 shows the position of the hole in the tube so that sorbent can filled fully the tube as can be seen in the Figure 4-9.

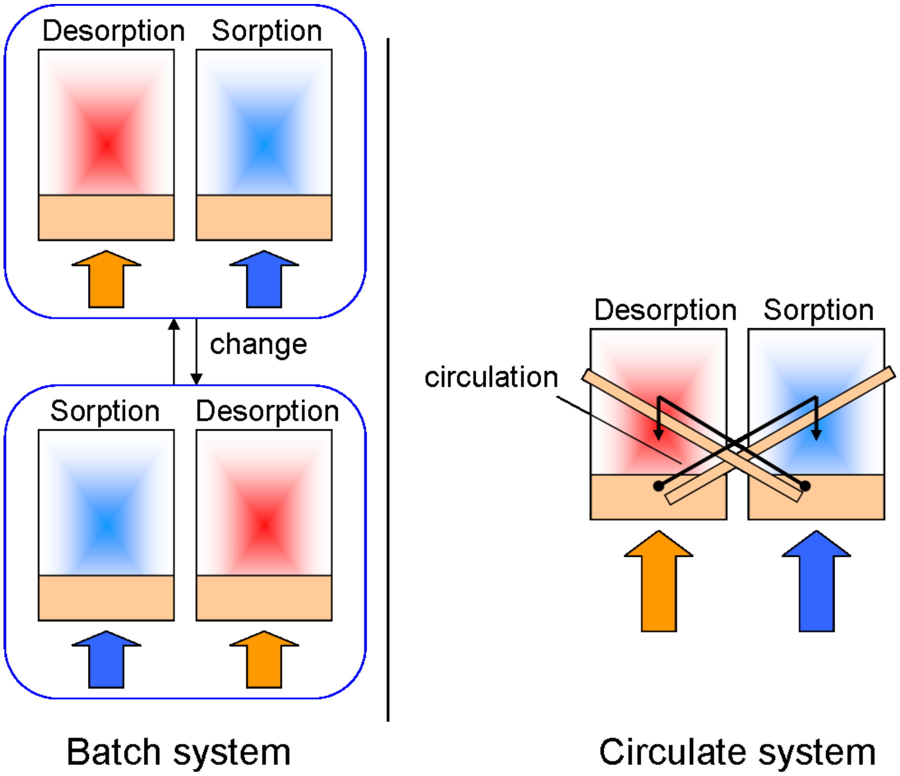


Fig.4-7 Difference of batch system and circulate system

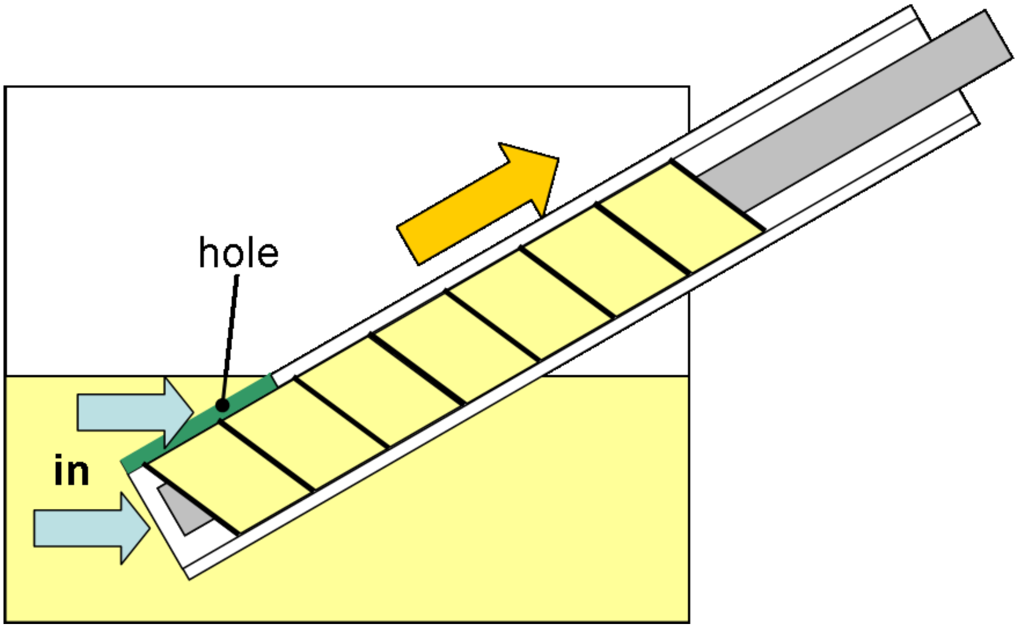


Fig. 4-8 Hole in the spiral tube

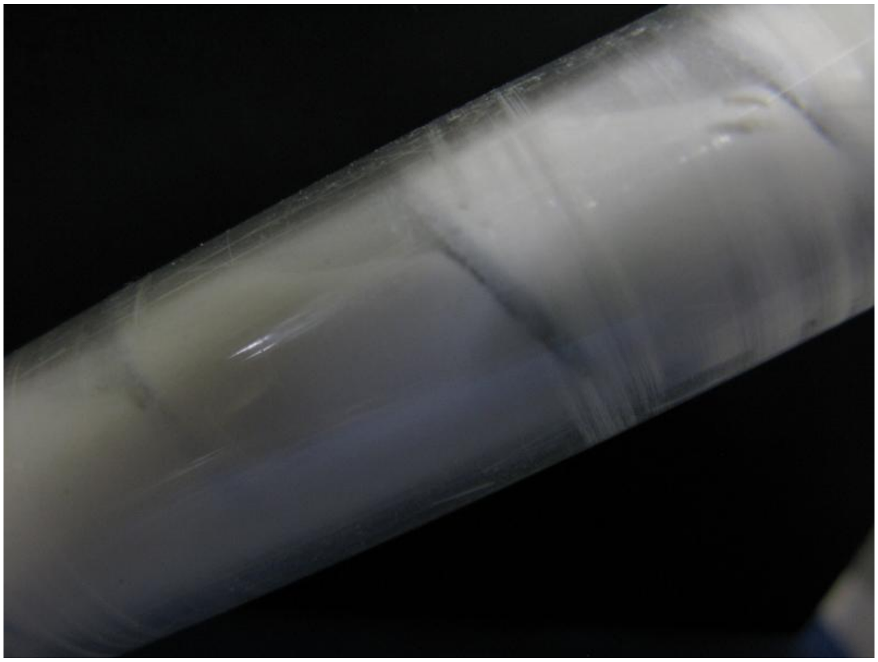


Fig. 4-9 Spiral tube filled with sorbent

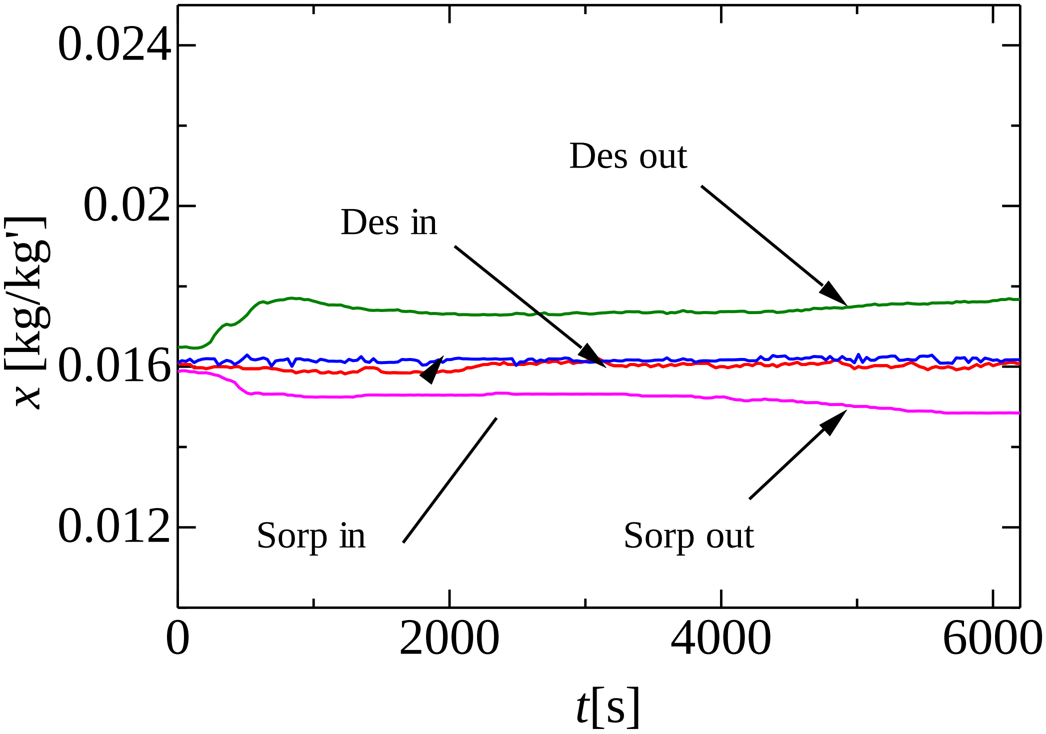


Fig. 4-10 Time history of absolute humidity

The experiments have been carried out to investigate the heat and mass transfer behavior in the sorption and desorption process. Figure 4-10 shows one of the time history of absolute humidity inlet and outlet of sorption and desorption at the chambers. Experimental conditions are desorption inlet air temperature T_D is 50°C, dew point temperature 21.4 °C and absolute humidity x_{in} = 0.016 kg/kg, sorption inlet air temperature T_S is 30 °C, dew point temperature 21.4 °C and x_{in} = 0.016 kg/kg. Air velocity u_0 which flow into the two chambers is 0.033 m/s. Spiral speed is 10 rpm that can carry about 6 g/min sorbent from desorption to sorption chamber or vise versa. Initial bed height of sorbent that used is 0.016 m. When it is fluidized with the air velocity 0.033 m/s, the height of sorbent is extending to 0.026 m. Base on the time, it can be confirmed that the experiment condition is balance. Pressure in the both chamber is set to be balanced so that the air is not move from one chamber to the others through the spiral tubes. Base on the result of observation of movements of the sorbent particles, it is assumed that the sorbent in the chamber and the sorbent added are well mix, so that the amount of absolute humidity sorbed at sorption chamber and released at desorption is almost equal. The figure clarifies that at desorption chamber, air is humidified, because absolute humidity of air out from the chamber increases. At the other hand, at sorption chamber, air is dehumidified by the sorbent. Amount of water vapor releases in desorption chamber is about same with that sorbs in sorption chamber, thus the experiment condition is equilibrium. Furthermore, the constant value of air at outlet is referred to as homogenous and steady state, which means the composition of the reaction rate are identical at all times and at every spot for all components. The continuously added sorbent is well mixed with the sorbent in the chamber and sorbent is continuously being removed.

4.4 Spiral revolution speed effect

Figure 4-11 through Figure 4-14 are the graphs for investigating the effect of spiral revolution speed in circulating fluidized bed for continuous desorption and sorption process. Figure 4-11 presents the effect of spiral revolution speed to the absolute humidity of air at outlet for desorption and sorption process. It is confirm that for desorption process, absolute humidity out increases by decreasing the spiral revolution speed. While, the opposite condition occurs on sorption process, absolute humidity decreases by decreasing the spiral revolution speed. Because dry sorbent is transferred from desorption chamber, the water vapor that is sorbed by the sorbent would increase at sorption chamber. In contras, when the spiral revolution speed is 0.7 rpm, absolute humidity out from the sorption chamber increases and from desorption chamber decreases. Amount of water vapor released or sorbed from sorbent is too small because of the small sorbent transferred.

Different from the other experiment about circulating particle in fluidized bed where circulating particle is depend only on the different air velocity(4-14). In this experiment, particle circulation rate can be easily set up by using spiral tubes with geared motor. The air velocity at desorption and sorption chamber is same. The sorption and desorption process were in balance condition because the amount of water vapor releases in desorption chamber is about the same with that sorbed in sorption chamber as shown in Figure 4-11. This condition is coinciding with the aim of this experiment, finding stable amount of dehumidification, absolute humidity outlet for sorption and desorption process. Decreasing the spiral revolution speed makes stay time of sorbent in desorption chamber increase that causes the more water vapor can discharge from the sorbent as can be seen in Figure 4-12. F_0 is defined as amount of sorbent transferred per unit time. The time that sorbent powder remains inside the chamber influences the amount of dehumidification m_d. But when the circulation rate of sorbent powder is too small, water vapor released or sorbed at desorption chamber and sorption chamber decreases.

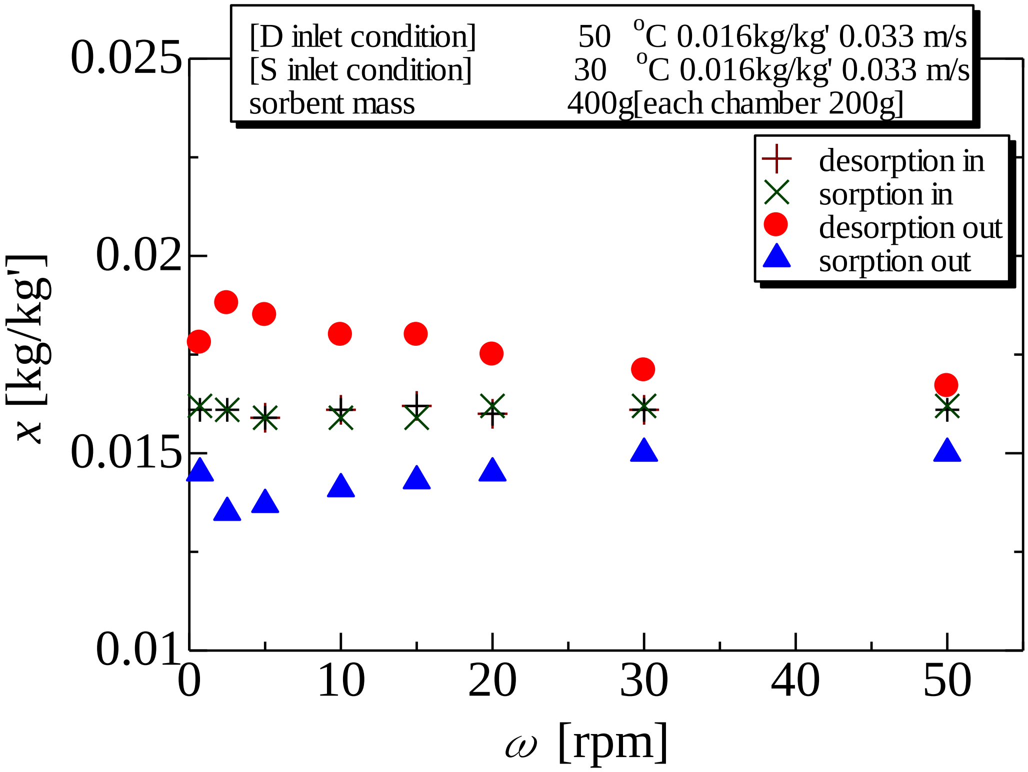


Fig.4-11 Absolute humidity difference with difference spiral revolution speed

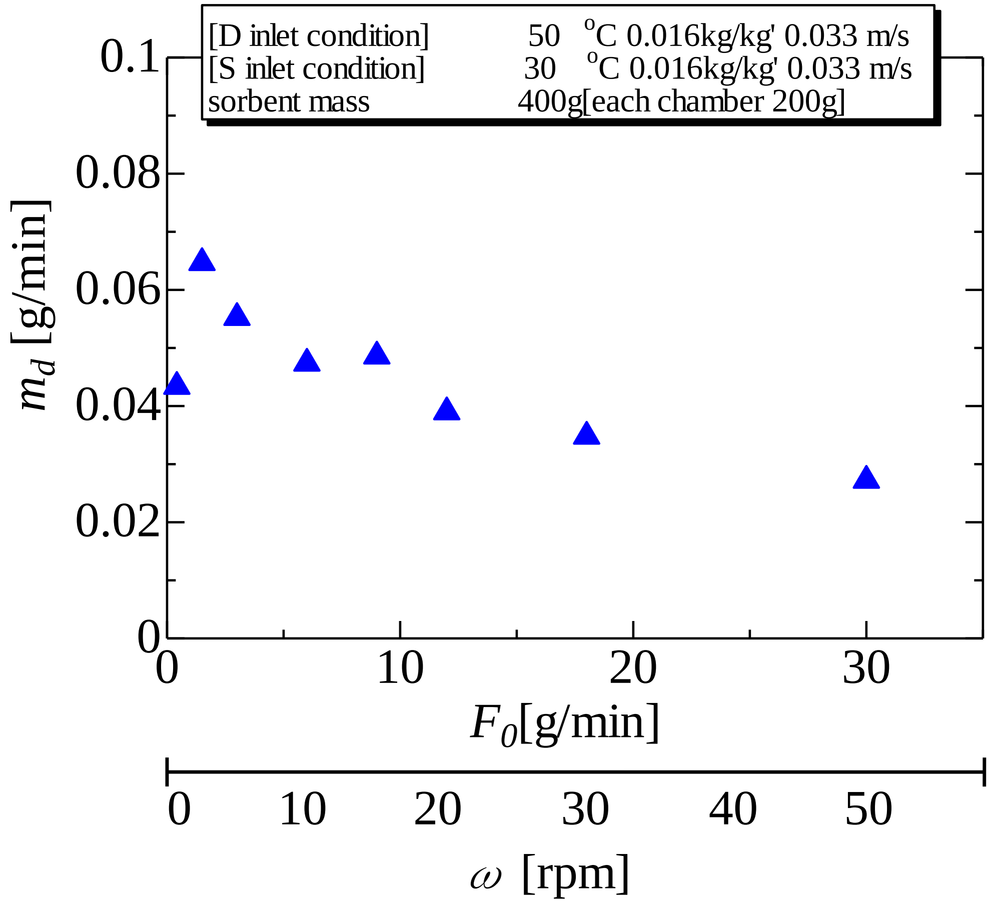


Fig.4-12 Amounts of dehumidification with sorbent circulation rate

Figure 4-13 shows the amount of dehumidification with the difference in inlet absolute humidity. Tables 4-2 – 4-4 present the difference between the conditions is on their inlet absolute humidity. Absolute humidity for sorption and desorption chamber at condition 1 is same 0.016 kg/kg. Condition one is approaching the real condition. Absolute humidity for condition 2 is 0.0105 and 0.016 kg/kg for desorption and sorption process respectively. For condition 3, absolute humidity for desorption is 0.003 kg/kg and 0.012 for sorption. In condition one, the amount of dehumidification at first is increasing from 0.7 rpm to 2.5 rpm. By continuing to increase the spiral revolution speed, the amount of dehumidification decreases. The experiment is continued base on this condition.

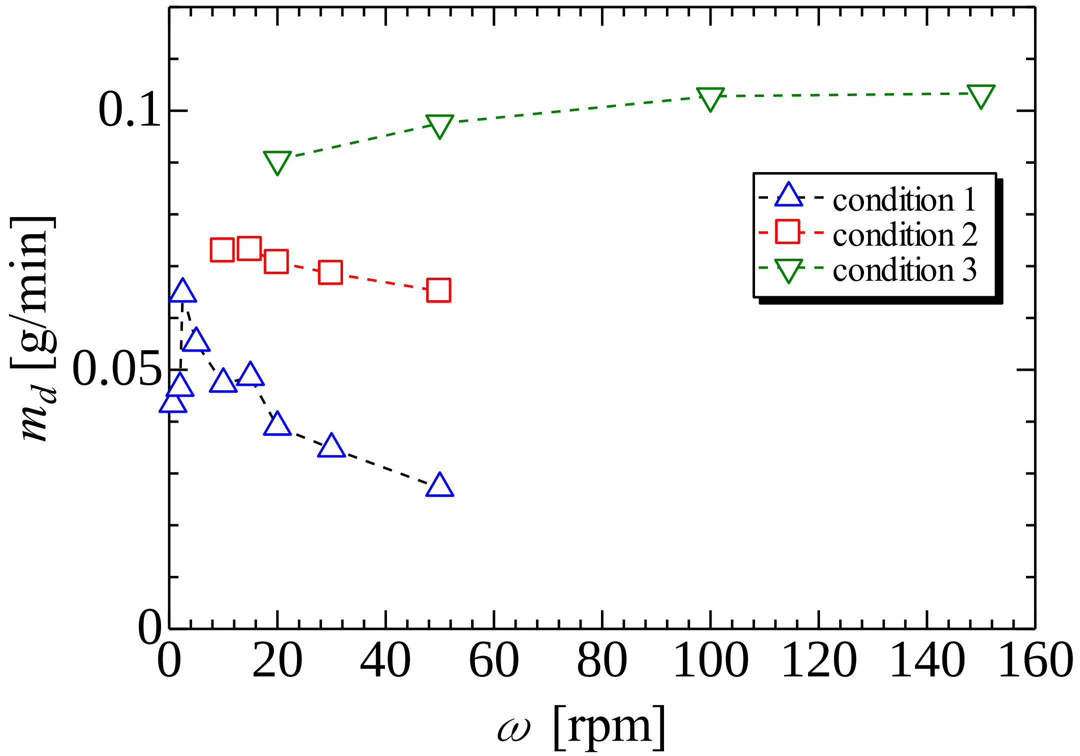


Fig. 4.13 Spiral tube filled with sorbent

Table 4-2 Real simulated experiment condition (condition 1)

Desorption inlet air condition		
Temperature : 50°C	Absolute humidity : 0.016 kg/kg	Air velocity : 0.033 m/s
Sorption inlet air condition		
Temperature : 30°C	Absolute humidity 0.016 kg/kg	Air velocity : 0.033 m/s
Other condition		
Sorbent mass : 400 g (each chamber 200 g)	Spiral speed : 10, 20, 30, 50, and 100 rpm	

Table 4-3 Real simulated experiment condition (condition 2)

Desorption inlet air condition		
Temperature : 50°C	Absolute humidity : 0.0105 kg/kg	Air velocity : 0.033 m/s
Sorption inlet air condition		
Temperature : 30°C	Absolute humidity 0.016 kg/kg	Air velocity : 0.033 m/s
Other condition		
Sorbent mass : 400 g (each chamber 200 g)	Spiral speed : 10, 15, 20, 25, and 50 rpm	

Table 4-4 Preparation experiment condition (condition 3)

Desorption inlet air condition		
Temperature : 50°C	Absolute humidity : 0.003 kg/kg	Air velocity : 0.033 m/s
Sorption inlet air condition		
Temperature : 30°C	Absolute humidity 0.012 kg/kg	Air velocity : 0.033 m/s
Other condition		
Sorbent mass : 400 g (each chamber 200 g)	Spiral speed : 20, 50, 100, and 150 rpm	

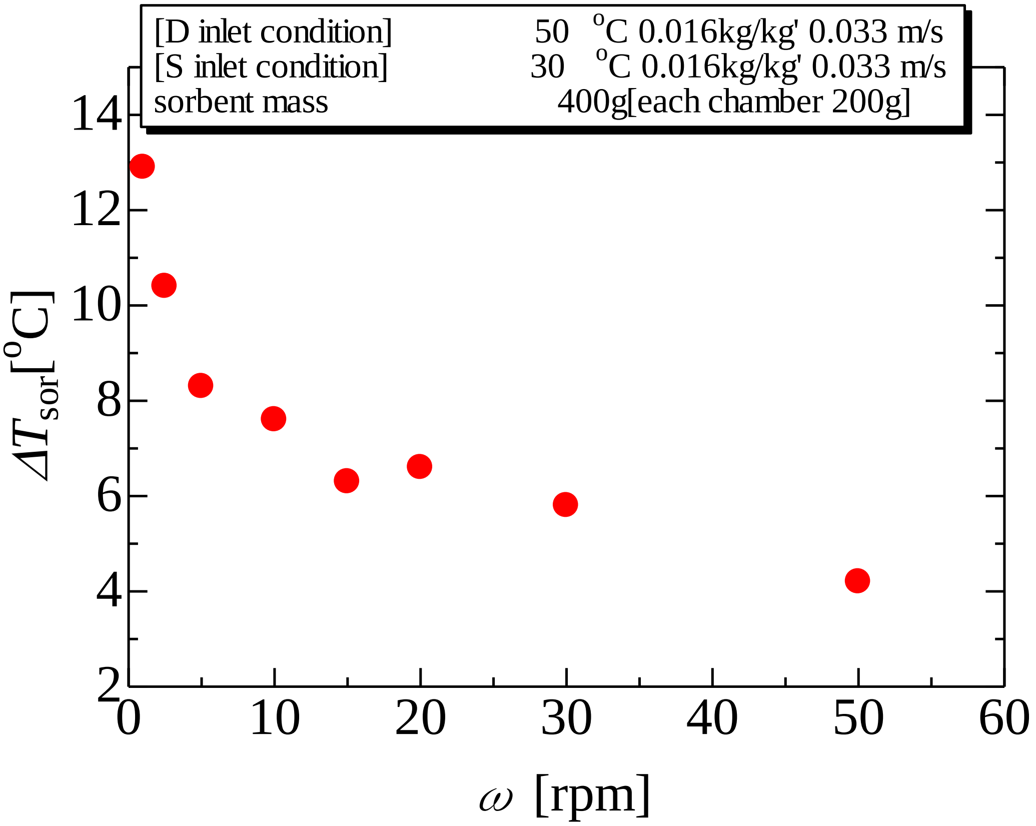


Fig.4-14 Temperature difference with difference spiral revolution speed

Figure 4-14 shows the effects on the spiral revolution speed to sorbent temperature difference. Sorbent temperature difference, ΔT_{sor} represents the temperature difference between sorbent in desorption chamber and sorbent in sorption chamber. Regarding the difference spiral revolution speed, it is found that the difference temperature of the sorbent ΔT_{sor} is higher in the case of lower spiral revolution speed. Since the desorption process is an endothermic process, sorbent needs energy from the air in the form of heat. In the other hand, the sorption process is an exothermic process, sorbent releases energy in the form of heat to the air. Increasing the spiral revolution speed decreases the residence time distribution of particle. This condition affects the ability of sorbent to release or to sorbs water vapor. As the amount of the circulating sorbent increases by increasing the spiral revolution speed, the transferred heat by heat capacity of sorbent from the chamber to another one increases, so ΔT_{sor} decreases. For desorption process, high sorbent temperature is needed, but low temperature is better for sorption temperature. So the better performance of the process will_be in the high temperature difference of the sorbent. On the contrary, ΔT_{sor} for spiral revolution speed 0.7 rpm is the highest, but not followed by amount of dehumidification as can be seen in Figure 4-12, because the amount of sorbent that circulating can not influence the sorbent temperature balance in the chamber.

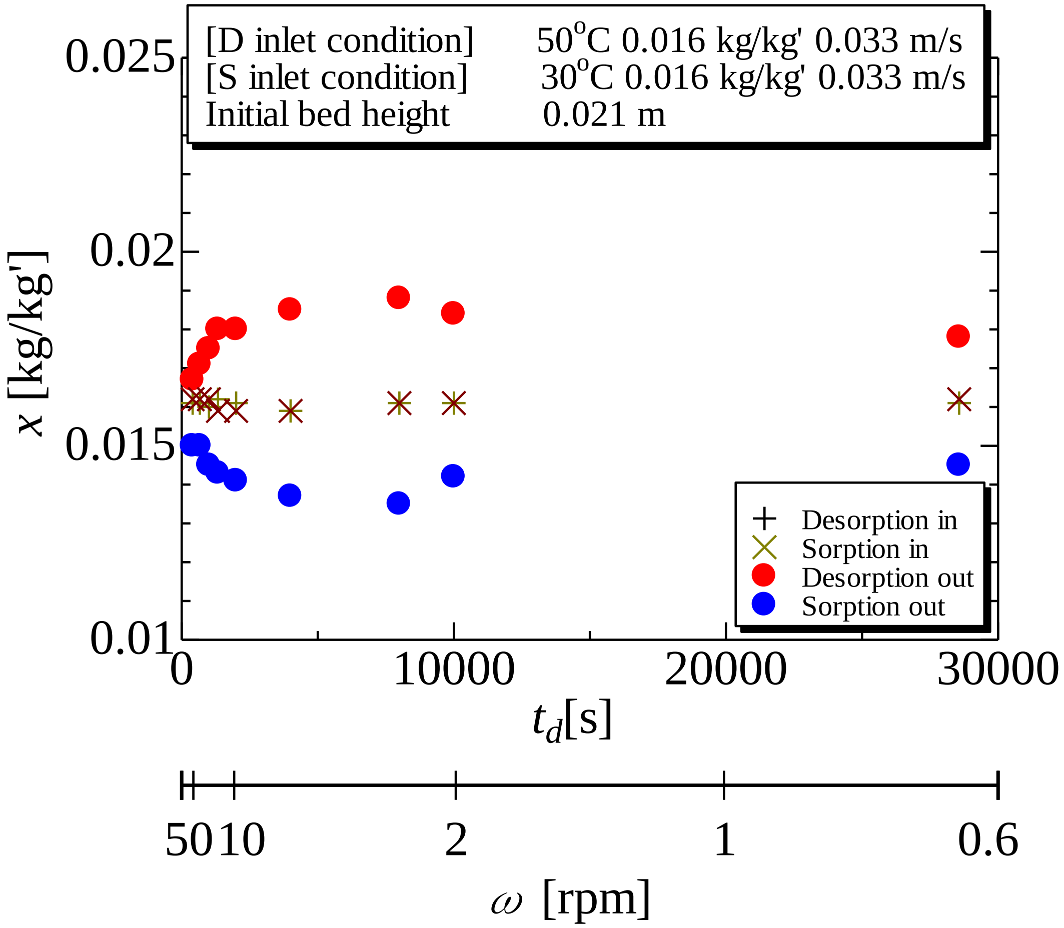


Fig. 4-15 Absolute humidity differences with the difference of residence time distribution

In this experiment, the air velocity at desorption and sorption chamber is same and sorbent circulation rate can be easily set up by using spiral tubes with geared motors. Residence time distribution t_d (s) that is the average amount of time that a sorbent particle spends in a particular system is an important tool in the study of continuous flow systems to characterizing the flow and mixing in the chamber$^{(4\text{-}12)}$. Therefore, the residence time distribution is used for analyzing the data. t_d is defined with Equation (1),

$$t_d = \frac{m_0}{F_0} \tag{1}$$

Where, m_0 (m) is sorbent mass in the chamber. F_0 (kg/s) is sorbent circulation rate, amount of sorbent that is transferred per unit time. For this system, the value of F_0 is arranged by regulating the spiral revolution speed ω (rpm) with correlation:

$$F_0 = 0.6\,\omega \tag{2}$$

As shown in the Equation (1), residence time distribution measurement varies directly with the amount of sorbent that is present in the system. Moreover, increasing the circulation rate means the decrease in the residence time distribution of sorbent in the chamber. For circulation rate effect, amount of sorbent used in two chambers is 400 g and equal with initial bed height 0.021 m. Figure 4-15 presents the effect of the residence time distribution to the absolute humidity of air at outlet for desorption and sorption process. It is confirm that for desorption process, absolute humidity out increases by increasing the residence time until the highest value, at residence time distribution t_d = 8000 s, that is ω = 2.5 rpm. And then, absolute humidity out decreases by increasing the residence time distribution. And the opposite condition occurs on sorption process. Increasing residence time causes more water vapor can be released by sorbent at desorption chamber. While at sorption chamber, the more water vapor can be sorbed by the sorbent with the increasing in residence time distribution. Further decreasing in spiral revolution speed to 2 and 0.7 rpm, absolute humidity out from desorption chamber decreases and from sorption chamber increases. The decreasing amount of water vapor sorbed or released from the sorbent is caused by the small amount of sorbent is transferred and because of the residence time of sorbent in one chamber is too long and sorbent at sorption chamber become saturated by water vapor, sorbent at desorption chamber is too dry so that the ability of sorbent to sorb or to release water vapor decreases.

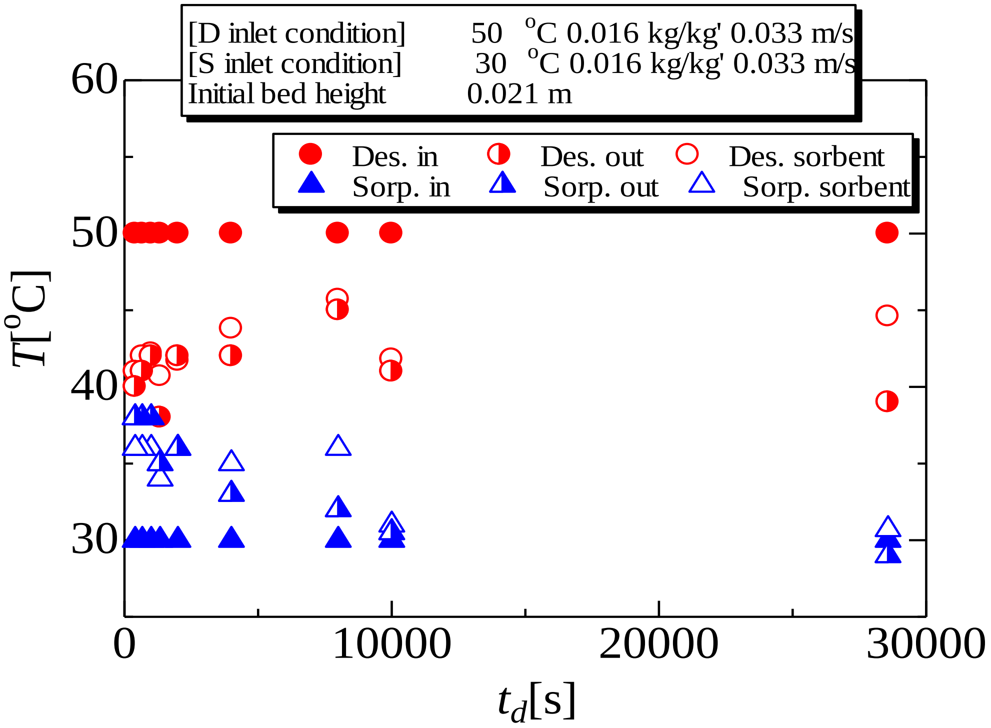


Fig.4-16 Temperature profiles with the difference of residence time distribution

Figure 4-16 shows the effects on the residence time distribution to temperature profiles in the chamber. As indicated in the figure, for desorption chamber, sorbent temperature and outlet air temperature tend to increase by increasing the residence time distribution while at sorption chamber they tend to decrease. Temperature of air at inlet for desorption chamber is 50°C. As mention before, sorbent temperature in desorption chamber is affected by endothermic reaction, heat capacity of sorbent that is transferred from sorption chamber, and heat and mass transfer between sorbent and air. In this experimental condition, heat and mass transfer between air and sorbent may remain constant because of the same air velocity. Increasing the residence time distribution means the decrease in amount of sorbent that is transferred by spiral tube and furthermore the decrease in exothermic reaction and its influence to the temperature of sorbent in the chamber. So that sorbent temperature increases and it approaches inlet air temperature by increasing the residence time. Temperature of air at outlet is coinciding with the sorbent temperature. The opposite condition occurs in the sorption chamber.

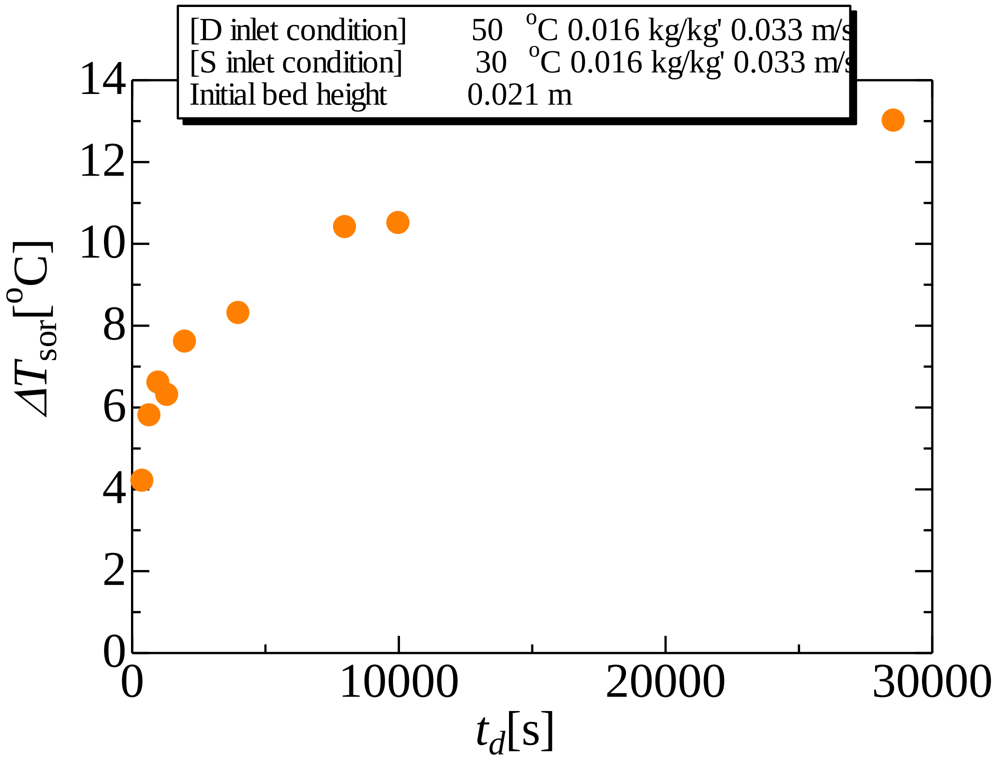


Fig. 4-17 Sorbent temperature differences with the difference of residence time distribution

Figure 4-17 shows sorbent temperature difference with the difference in residence time distribution. Regarding the difference of the residence time, it is found that the difference temperature of the sorbent ΔT_{sor} is higher in the case of higher residence time. For desorption process, high sorbent temperature is needed, but low temperature is better for sorption process. The better performance of the process will be in the high temperature difference of the sorbent. But the highest performance is at residence time distribution 8000 s. As shown in Figure 4-17, this phenomenon can be explained that the amount of sorbent transferred decreases and length of time of sorbent stay in the chamber increases with an increase in residence time distribution.

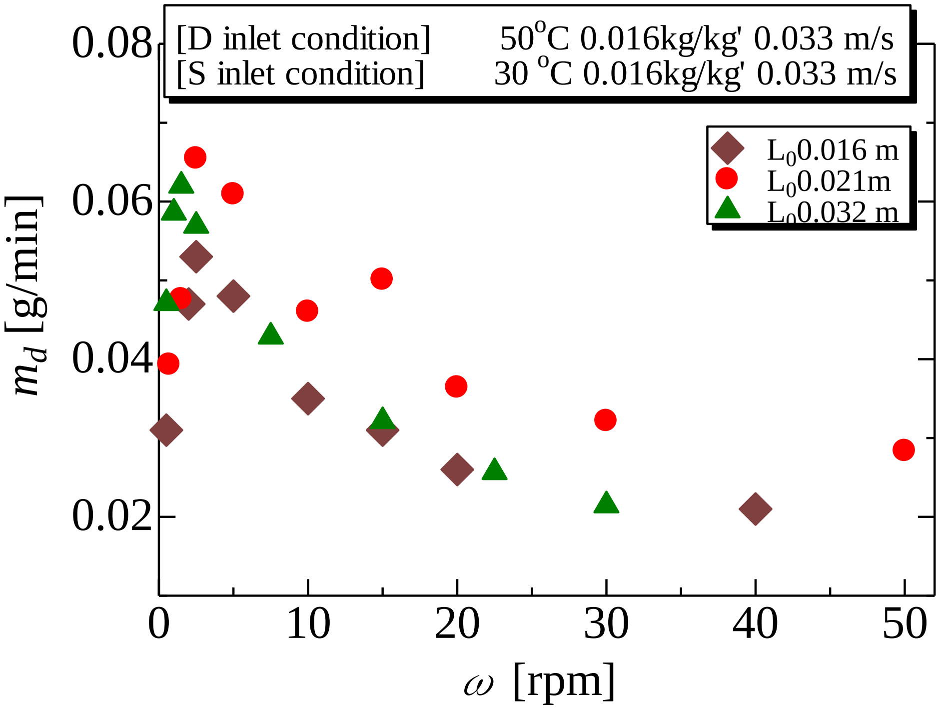


Fig. 4-18 Amount of dehumidification with the difference of spiral speed revolution

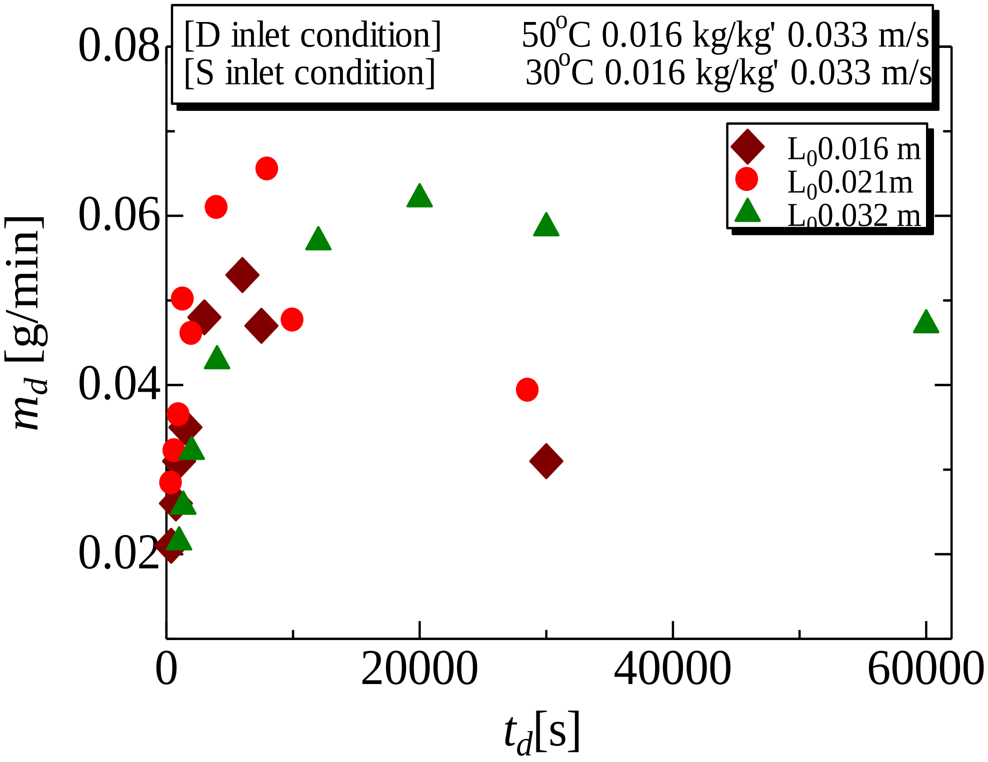


Fig. 4-19 Amount of dehumidification with the difference of residence time distribution

Figure 4-18 and Figure 4-19 show the amount of dehumidification with the differences in spiral revolution speed ω and residence time distribution t_d respectively. Increasing the spiral revolution speed ω will increase the amount of dehumidification sharply until it reaches maximum value and then slowly down. This pattern is same for different initial bed height. Increasing t_d of sorbent in desorption chamber will increase the amount of dehumidification and then further increasing of t_d, the amount of dehumidification is decreasing. Residence time distribution represents the perfection of mixing between the sorbent in the chamber with the sorbent added. Increasing t_d makes longer time for the sorbent which is added into the camber and the sorbent in the chamber to form a perfect mixing. As a result, increasing t_d increases the amount of dehumidification until it reaches maximum value. While the other parameters are maintained same, different initial bed height will causing different residence time distribution for them to reach their highest value of amount of dehumidification. Residence time distribution t_d at the highest value of amount of dehumidification increases with an increase in initial bed height. Since residence time distribution is figuring the perfection of mixing between the sorbent transferred and sorbent in the chamber, increasing the initial bed height will increase the time for the sorbent to form a perfect mixing. This condition affects the changing of residence time distribution for the highest value of amount of dehumidification as increasing the initial bed height.

4.5 Air Velocity Effect

In Fluidized bed system, the velocity of air that flow into the chamber plays important role. In this experiment, the range of air velocity is between its minimum fluidization velocity and its terminal velocity which are 0.004 m/s and 0.056 m/s respectively. To investigate the effect of inlet air velocity, desorption and sorption experiments were conducted for air velocity 0.033, 0.042 and 0.048 m/s.

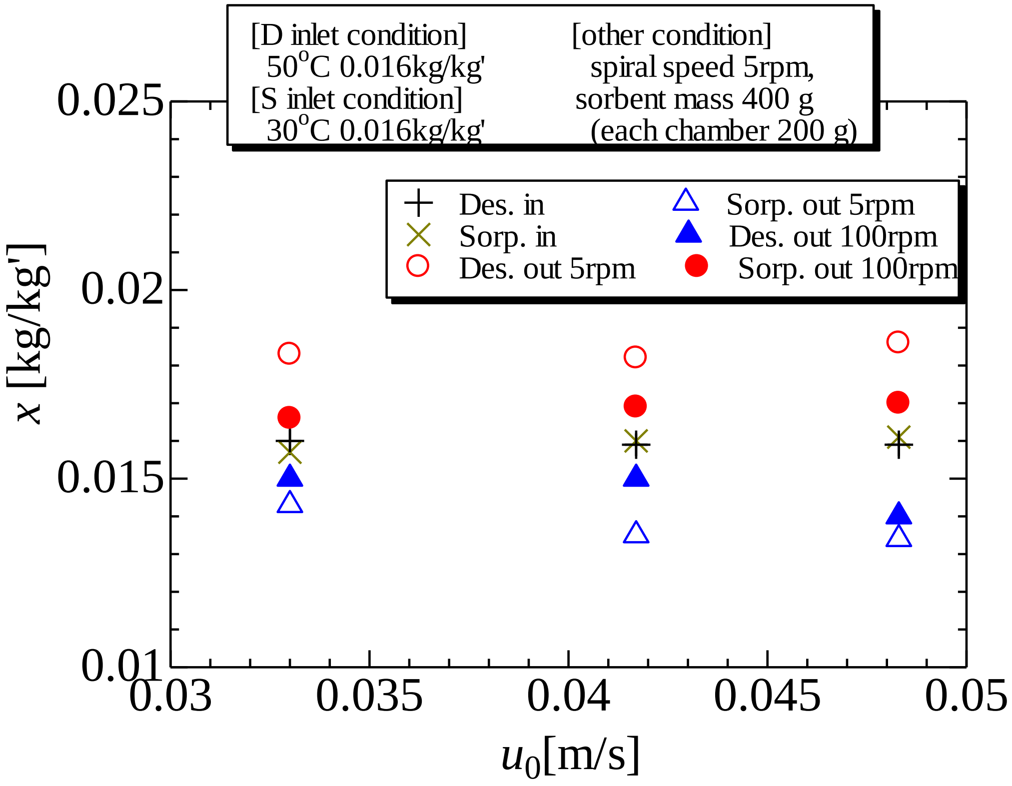


Fig.4-20 Absolute humidity out with difference air velocity

Figure 4-20 shows the effect of air velocity on absolute humidity at outlet. Absolute humidity at outlet increases by increasing air velocity at desorption chamber, while it decreases by increasing the air velocity at sorption chamber. And absolute humidity out is different by the difference of spiral revolution speed in same air velocity. Increasing the air velocity indicates a larger amount of air passing through the fluidized bed per unit time, this causes the amount of bubble to increase, so the contact surface area between air and sorbent increases which might increase the performance of the sorbent. Increasing air velocity also effects the decreasing of boundary layer concentration between air and sorbent which might increase the amount of dehumidification. So that the amount of water vapor which can be sorbed increases for sorption chamber, and for desorption chamber amount of water vapor released from sorbent particle increases.

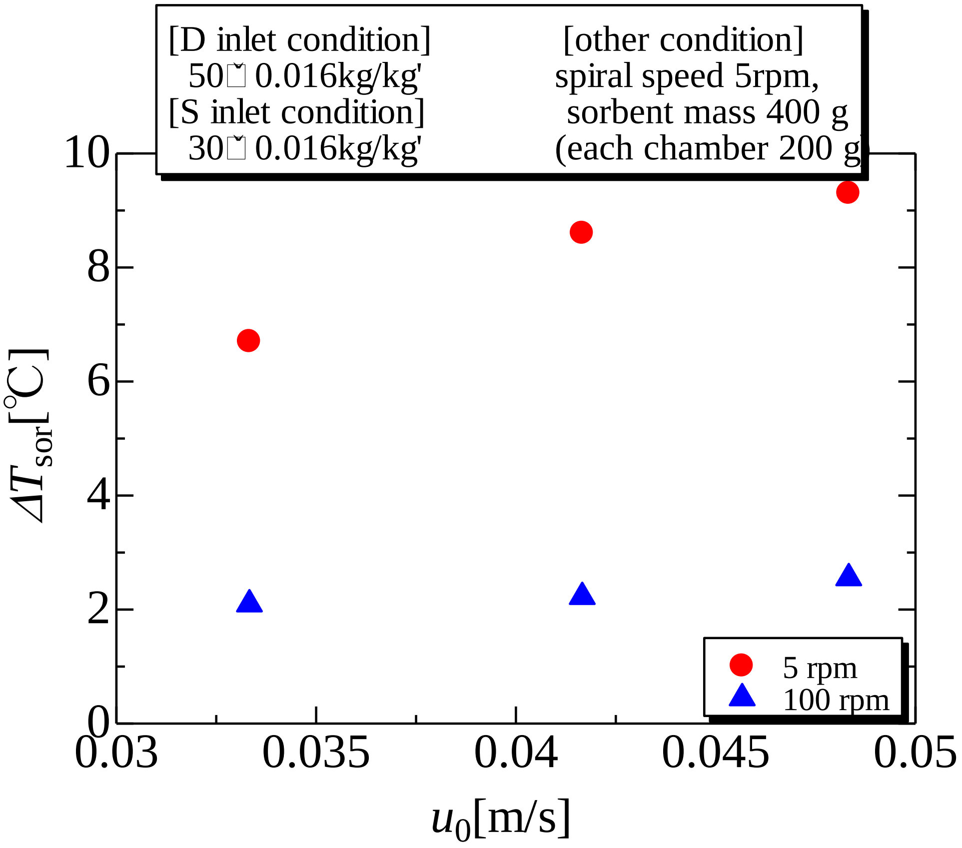


Fig.4-21 Sorbent temperature difference with difference air velocity

The increasing absolute humidity of air at outlet by increasing the air velocity coincides with the temperature difference between the sorbent as shows in Figure 4-21. Increasing the air velocity increases the temperature difference between the chambers. Heat and mass transfer between sorbent and air increases by increasing the air velocity. At desorption chamber, sorbent temperature increases and approaching the inlet air temperature, 50 °C. And at sorption chamber, sorbent temperature decreased until it reaches 30 °C. This has led to the increasing of sorbent temperature difference along with increasing the air velocity. In addition, at desorption chamber, endothermic reaction occurs. The amount of water vapor released increases is followed by the decreasing of sorbent temperature. And contrary reaction occurs at sorption chamber as exothermic reaction, water vapor sorbed increasing is followed by the increasing sorbent temperature. This result coincides with Horibe(4-7) that the increase of sorbent temperature by increasing air velocity could be explained by the fact that an increase of heat generation in the sorption process is brought by increasing water vapor supply to the sorbent and mass transfer coefficient.

The effects of process air velocity on desorption and sorption performance can be seen in Figure 4-22. It also shows the comparison amount of dehumidification between spiral speed 5 rpm and 100 rpm. The pattern of the graph between 5 rpm and 100 rpm is same, amount of dehumidification increases by increasing the air velocity. Sorbent mass rate is about 3 g/min and 60 g/min for spiral revolution speed 5 rpm and 100 rpm respectively. The amount of dehumidification m_d is coinciding with the previous result, which increasing the air velocity increases the amount of dehumidification. Spiral revolution speed affects the amount of dehumidification as also shows in the figure. Figure 4-23 can be strengthening the explanation of the air velocity effect. As can be seen in the figure, the amount of bubble in Fig.4-23 (a) is lesser than that of Fig.4-23 (b).

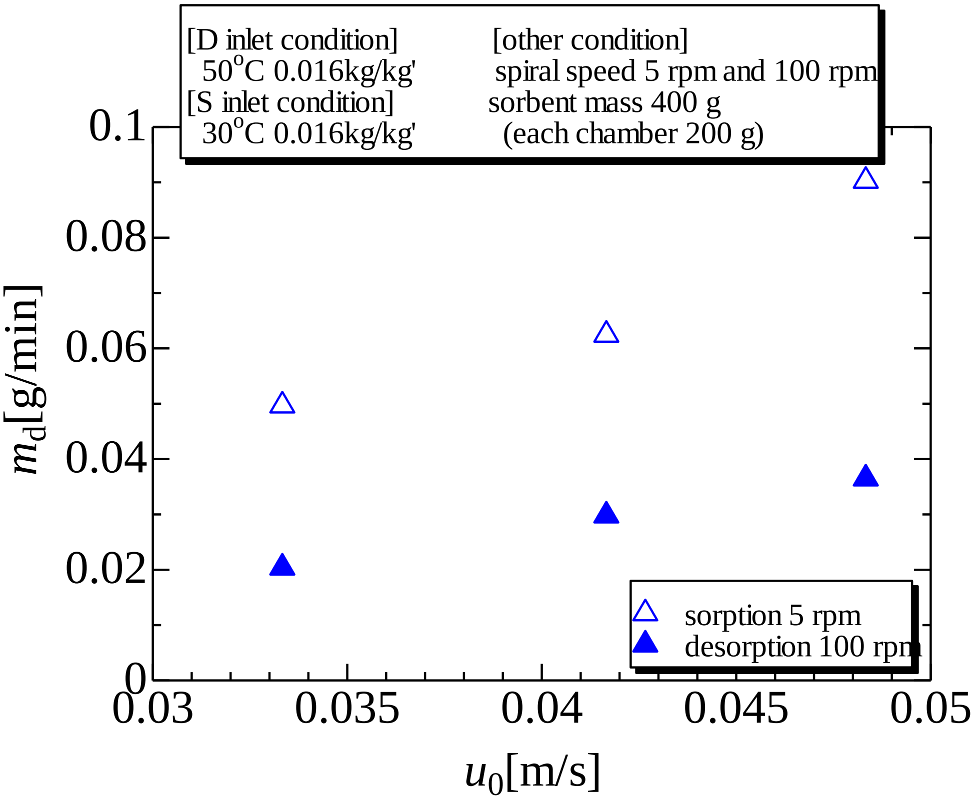
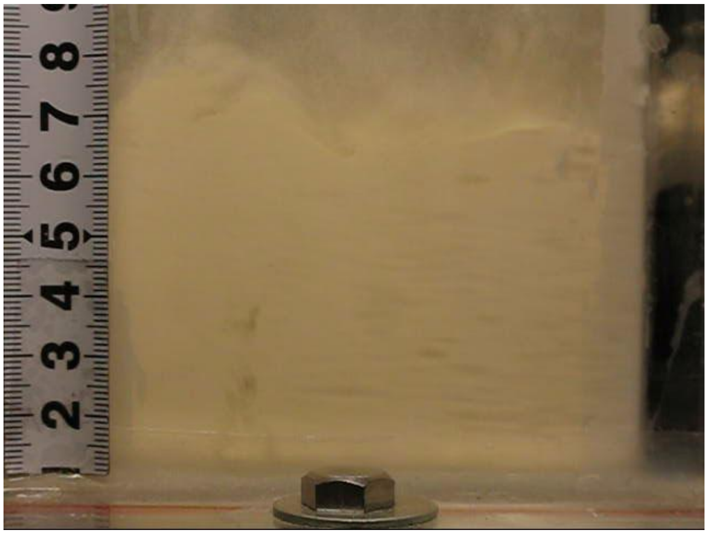


Fig.4-22 Amount of dehumidification with difference air velocity

(a) u_0 = 0.033 m/s



(b) u_0 = 0.048 m/s

Fig.4-23 Profile sorbent in the chamber with the difference of air velocity

4.6 Sorbent initial bed height effect

In this experiment, the initial bed height L_0 is 0.016 m, 0.021 m and 0.032 m for the sorbent mass 150 g, 200 g and 300 g for each chamber, respectively. Figure 4-24 shows the relationship between absolute humidity x and the initial bed height L_0 with spiral revolution speed ω = 2.5 rpm and sorbent mass rate is about 1.5 g/min. Absolute humidity of air at outlet for L_0 = 0.021 m is higher compared with 0.016 m and 0.032 m. Figure 4-25 contributes to the understanding of the behavior of the fluidization as the initial bed height condition change. Decreasing initial bed height of sorbent at the same air velocity will increase the size of bubble in the chamber. The growing size of bubble decreases the contact surface area per volume between sorbent and air, so the absolute humidity of air at outlet also decreases for desorption chamber and increases for sorption chamber. This condition clearly shows in the Figure 4-25a and 4-25d, where initial bed height of sorbent L_0 is 0.016 m, bubble size is bigger than that of Figure 4-25 and 4-25c with L_0 = 0.021 m and 0.032 m respectively. Figure 4-26 shows the amount of dehumidification with the difference of initial bed height. Amount of dehumidification of L_0 = 0.021 m is higher compare with that of 0.016 m and 0.032 m. This phenomena occurs because of the time of air to passing through the sorbent is lower, for L_0 = 0.016 m and because of the size of bubble is bigger, so that contact time and contact surface area between sorbent and air is lower. For L_0 = 0.032 m, contact time between sorbent and air is the longest because of the highest initial bed height, but it is not followed by the amount of water vapor sorbed or released. This condition can be explained as follows. Increasing the initial bed height will diminish the swirling effect of the sorbent. Swirling effect is effected by the air velocity and initial bed height of the sorbent. Binod and Vijay(4-15) explained that reduced the bed height would trigger the swirl motion. The reduction of swirling effect of sorbent will reduce the heat and mass transfer process, and as a result reduces the amount of water vapor sorbed at sorption chamber and released at desorption chamber.

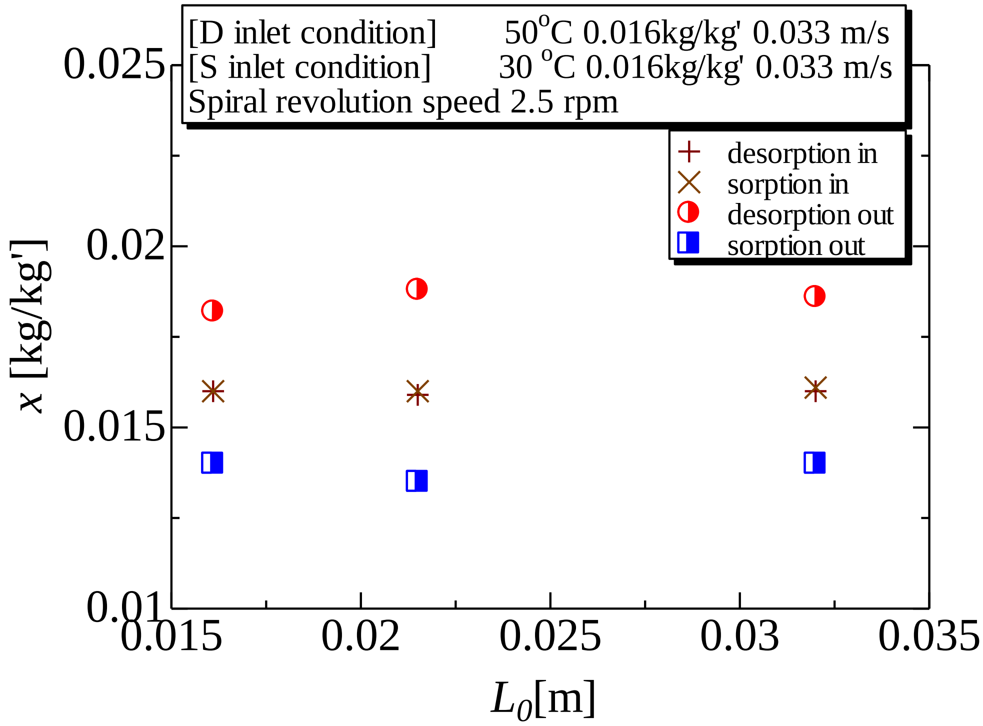
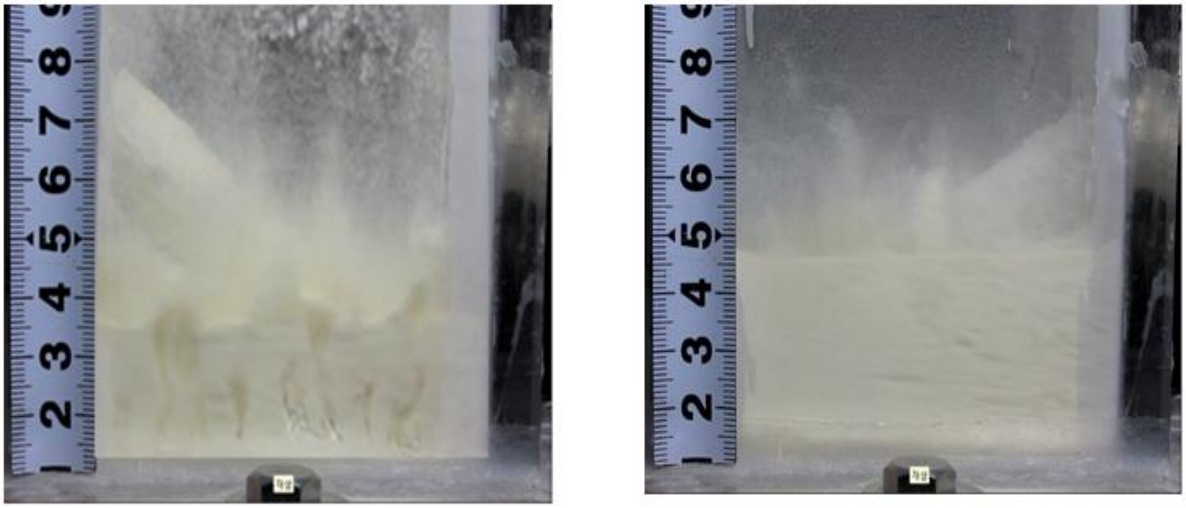
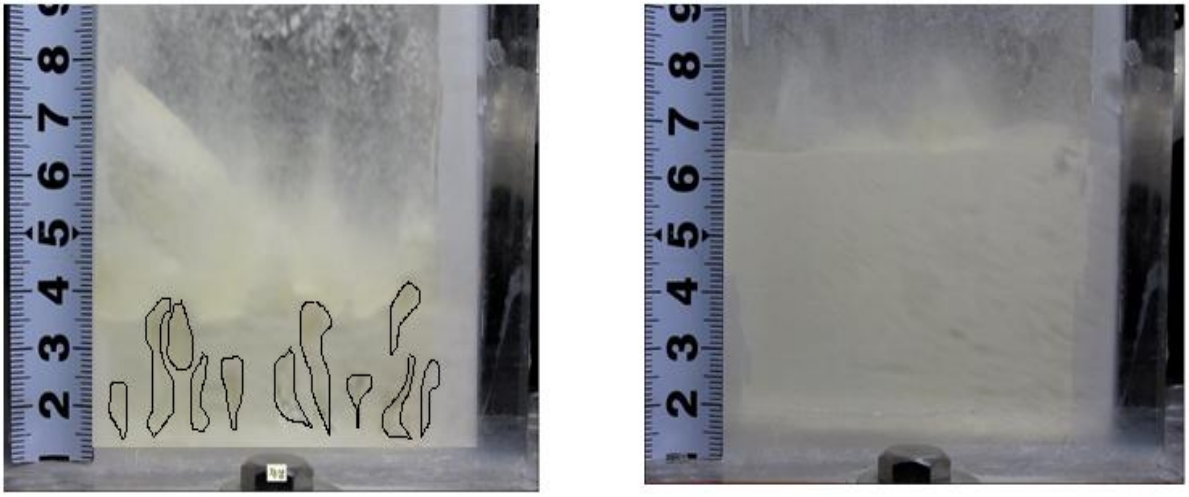


Fig. 4-24 Absolute humidity differences with the difference of initial bed height



(a) $L_0 = 0.016$ m (b) $L_0 = 0.021$ m



(d) *Bubbles at* $L_0 = 0.016$ m (c) $L_0 = 0.032$ m

Fig. 4-25 Profile sorbent in the chamber with the difference of initial bed height

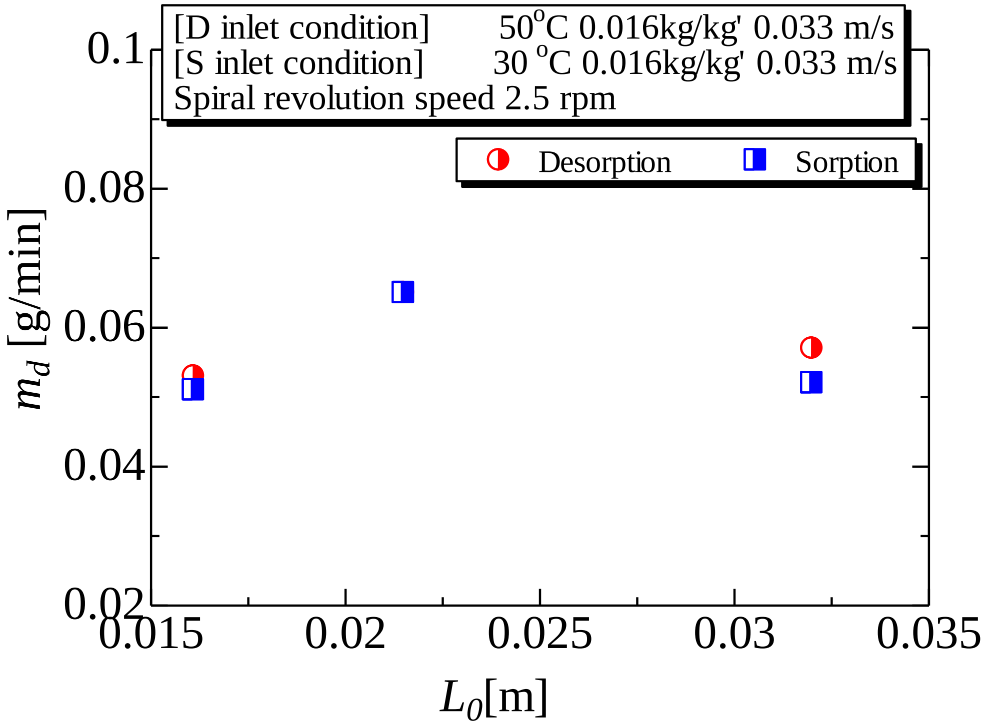


Fig. 4-26 Amount of dehumidification with the difference of initial bed height

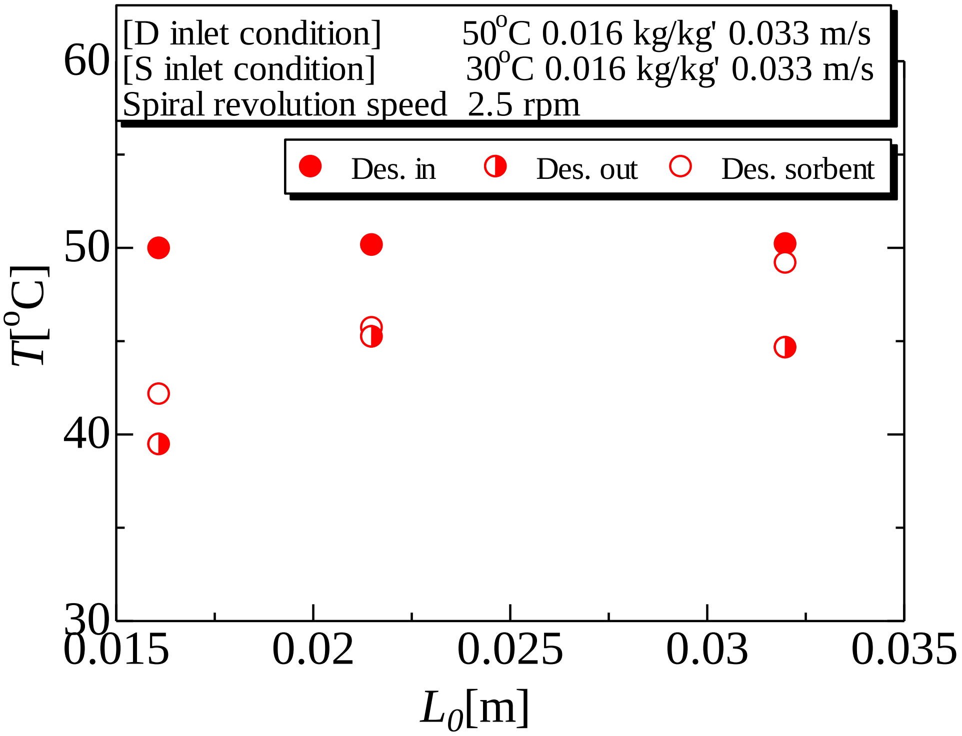


Fig. 4-27 Sorbent temperature profiles with the difference of initial bed height

Figure 4-27 shows temperature profile on the differences of initial bed height L_0, at spiral revolution speed ω = 2.5 rpm. The figure shows inlet air temperature, sorbent temperature and outlet air temperature for desorption chamber. Desorption process needs high temperature to release its moisture content. Inlet air temperature of desorption chamber for these data is 50°C. Temperature of air at desorption chamber tends to decrease because of the reaction of sorbent in the chamber. The figure shows that sorbent temperature in the chamber varies base on the initial bed height. The temperature of sorbent at desorption chamber is influenced by three factors, they are: 1. endothermic reaction that is occurring at desorption process, 2. heat capacity of sorbent that is transferred from the sorption chamber, and 3. heat and mass transfer between sorbent and air. Rate of the influence of those factors is varying base on the initial bed height. As a result, the tendency of sorbent temperature is increasing by increasing the initial bed height. For initial bed height 0.016 m, heat and mass transfer between sorbent and air is poor because contact surface area between sorbent particle and air decreases by the bigger size of bubble formed in the chamber and the time of air to flow through the chamber is shorter. First and second factors tend to decrease the sorbent temperature. As the initial bed height increases to 0.032 m, the influence of the first and second factors is decreasing compare with the third factor. Otherwise, the time of air to passing through the sorbent is longer, so that sorbent temperature in this condition is higher compare with initial bed height 0.016 m and 0.021 m. Outlet air temperature is affected by the sorbent temperature. On the other hand, increasing initial bed height from 0.016 m to 0.021 m will increase the sorbent temperature and this condition is in line with the increasing of amount of dehumidification. But when initial bed increase to 0.032 m, the increasing sorbent temperature is not followed by the increasing amount of dehumidification as can be seen in Figure 4-26. Sorption process needs low temperature to sorb water vapor from air. In dry and cool condition with low relative humidity, sorbent surface vapor pressure is low and it can attract moisture from the air which has high relative humidity(4-11).

4.7 Effect of desorption inlet temperature

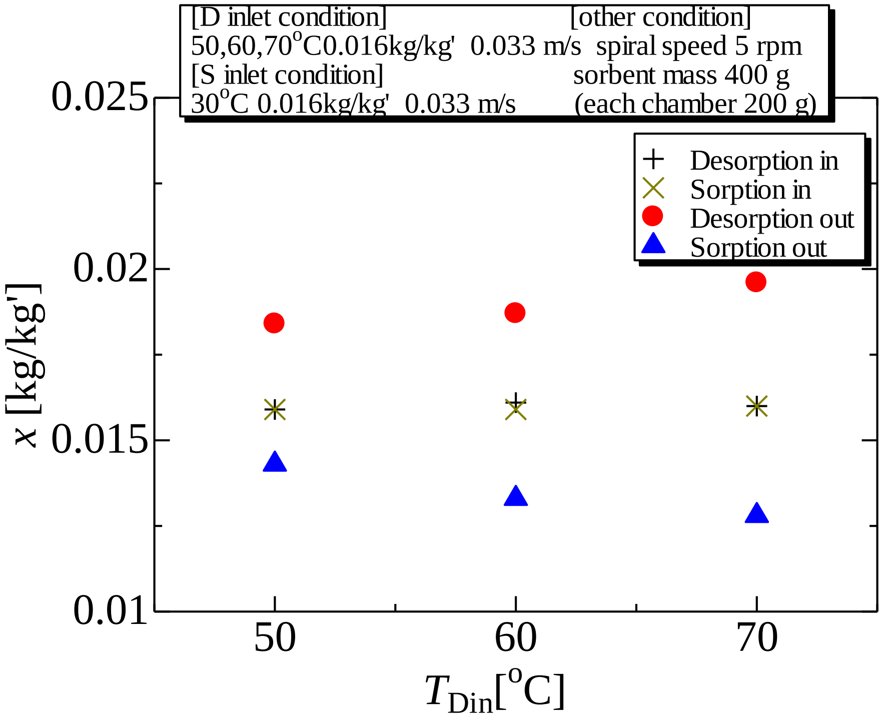


Fig. 4-28 Absolute humidity with the difference of desorption inlet temperature

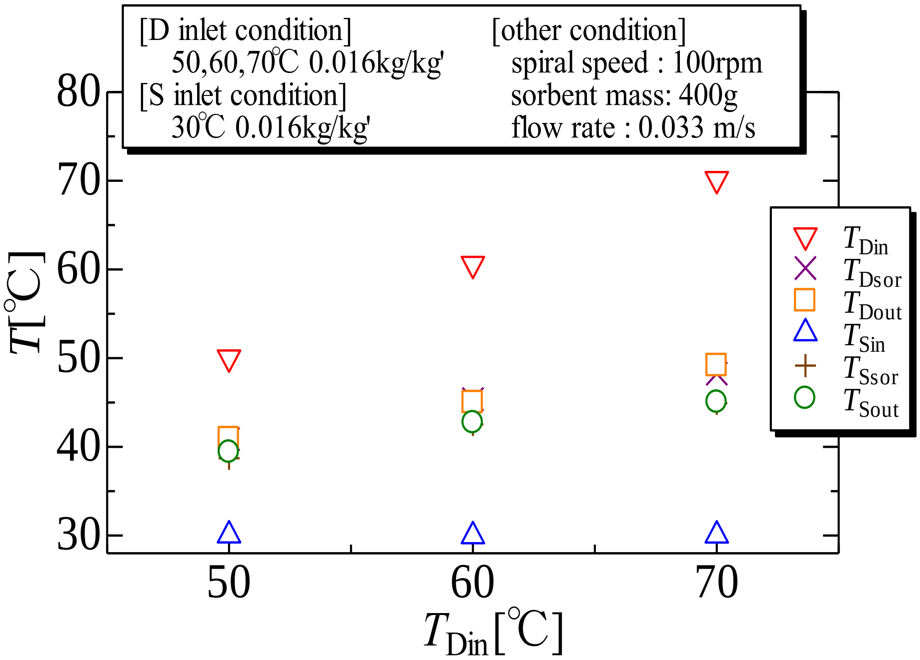


Fig.4-29 Temperature profile with difference desorption inlet temperature

In order to compare and analyze the effect of desorption inlet temperature, the experiment were performed with changing desorption inlet temperature T_{Din} and keeping sorption inlet temperature constant 30℃. Figure 4-28 shows the relationship between absolute humidity at outlet and desorption inlet temperature. It is can be confirmed that absolute humidity out affected by desorption inlet temperature T_{Din}. Increasing desorption inlet temperature as regeneration temperature will increase the average temperature of sorbent. Thus, the sorbent more dry due to the enhancing rate of water vapor released. This, in turn, results in an increase in the absolute humidity at outlet. At sorption chamber, the amount of water vapor, which can be sorbed by sorbent, increases because of the sorbent more dry. Desorption inlet temperature is the driving force of sorbent for releasing moisture content so that the amount of absolute humidity out at outlet increases by increasing desorption inlet temperature. This condition strengthened by Figure 4-29 which presents temperature profile in the chamber, and Figure 4-30, in which temperature difference between the two chambers increases by increasing desorption inlet temperature.

The target of absolute humidity of air at outlet of sorption chamber is 0.010 kg/kg. The lowest absolute humidity of outlet air for experimental condition at desorption inlet temperature T_D = 70°C is 0.013 kg/kg. Therefore, we should propose to improve the ability of sorbent to sorbed water vapor for reaching the target by some methods such as adding the stage of sorption and desorption process.

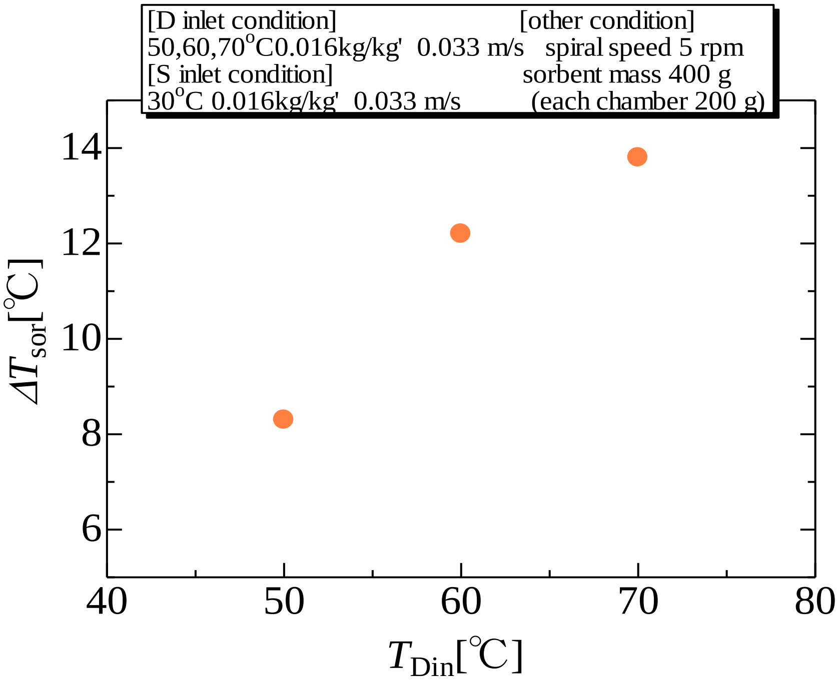


Fig.4-30 Sorbent temperature difference with the difference of desorption inlet air temperature

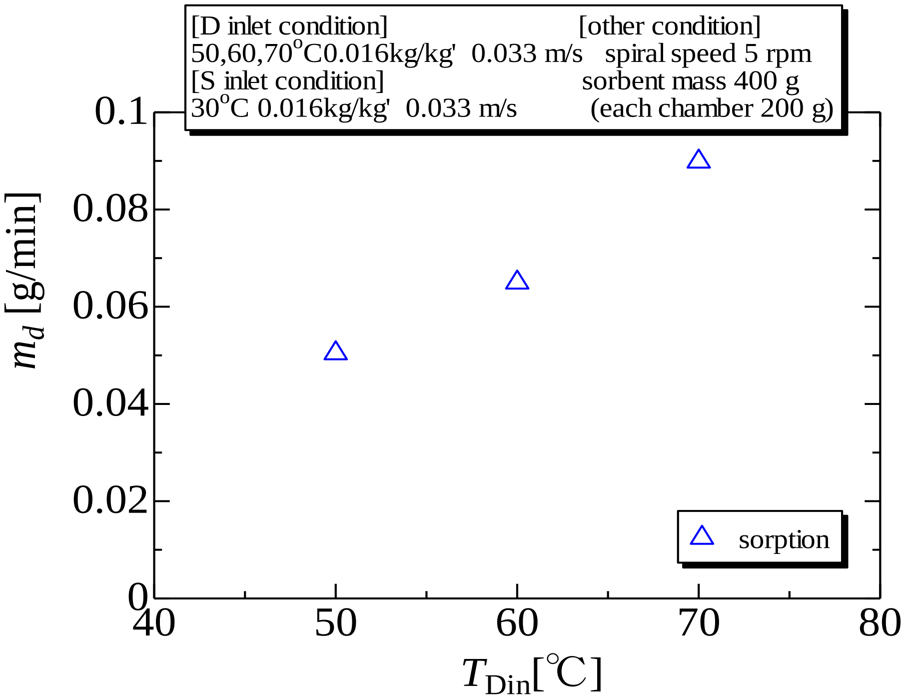


Fig. 4-31 Amount of dehumidification with difference of desorption inlet temperature

Figure 4-31 shows the effect of desorption inlet temperature on the amount of dehumidification. Increasing desorption inlet temperature will increase sorbent temperature in both chambers. Increasing desorption inlet temperature causes the mass transfer to increase. As the results, the amount of water vapor release from sorbent powder increases at desorption chamber. Decreasing the moisture content of the sorbent which is transferred from desorption chamber will improve the ability of sorption materials at sorption chamber to sorb the water vapor of the air. Rong-Luan(4-16) explained that the amount of adsorption in an adsorbent is affected by the degree of adsorbent regeneration temperature. Ramzy(4-5) also explained that lower humidity of air at bed could be attained with increasing in regeneration temperature where the regeneration temperatures range of this experiment of 323-343 K.

4.8 Effect of Sorption Inlet Air Temperature

Figure 4-32 shows the effect of the sorption inlet air temperature on the absolute humidity out of sorption and desorption process. The experiment were performed for 5 rpm, air velocity 0.033m/s, desorption inlet temperature 50°C and the variation on sorption inlet air temperature 25, 30 and 35°C. The figure presents the decrease of absolute humidity out with the increase of sorption inlet air temperature. Increasing sorption inlet air temperature decreases the ability of sorbent to sorb water vapor. As the result, the absolute humidity out for desorption process decreases by increasing the sorption inlet air temperature, while for sorption process, absolute humidity out increases. This condition is enhanced by Figure 4-33, where increases the sorption inlet temperature decreases the sorbent temperature different in the both chamber.

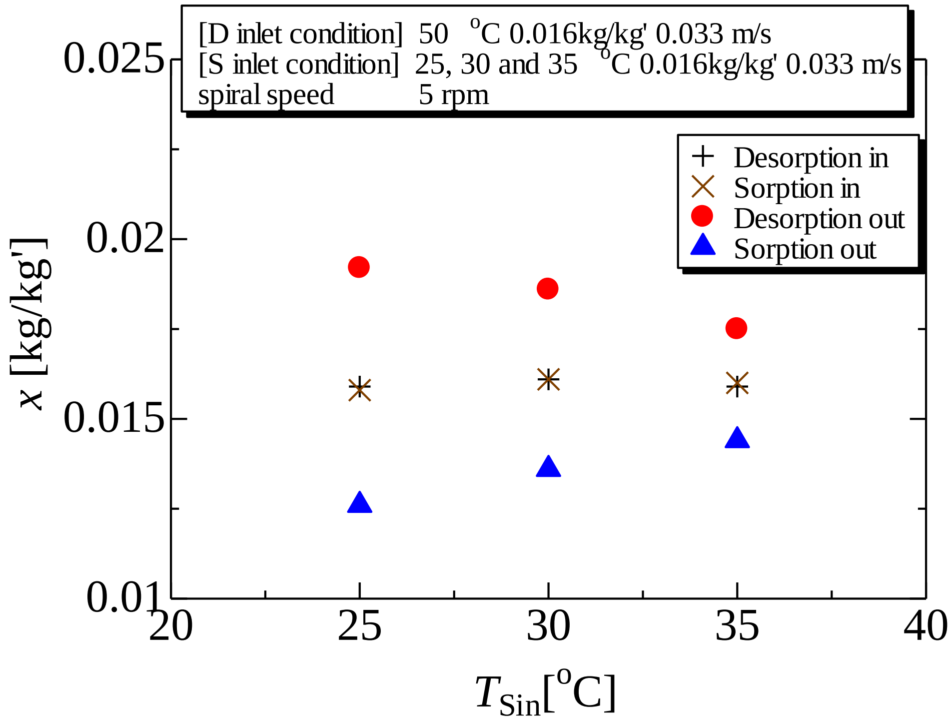


Fig. 4-32 Absolute humidity with the difference of sorption inlet air temperature

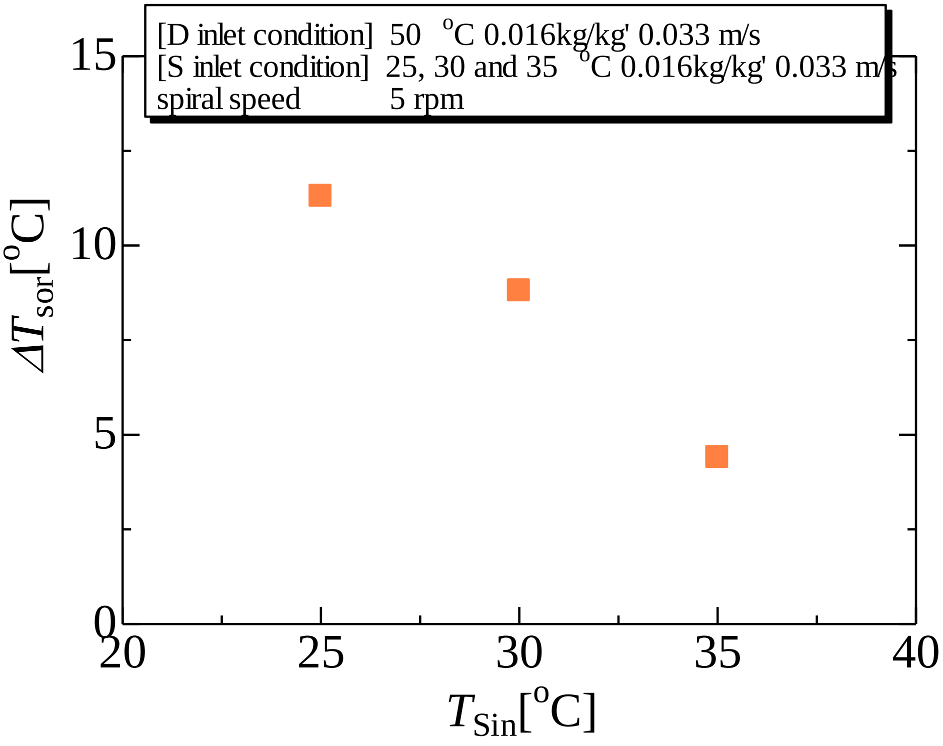


Fig.4-33 Sorbent temperature difference with the difference of sorption inlet air temperature

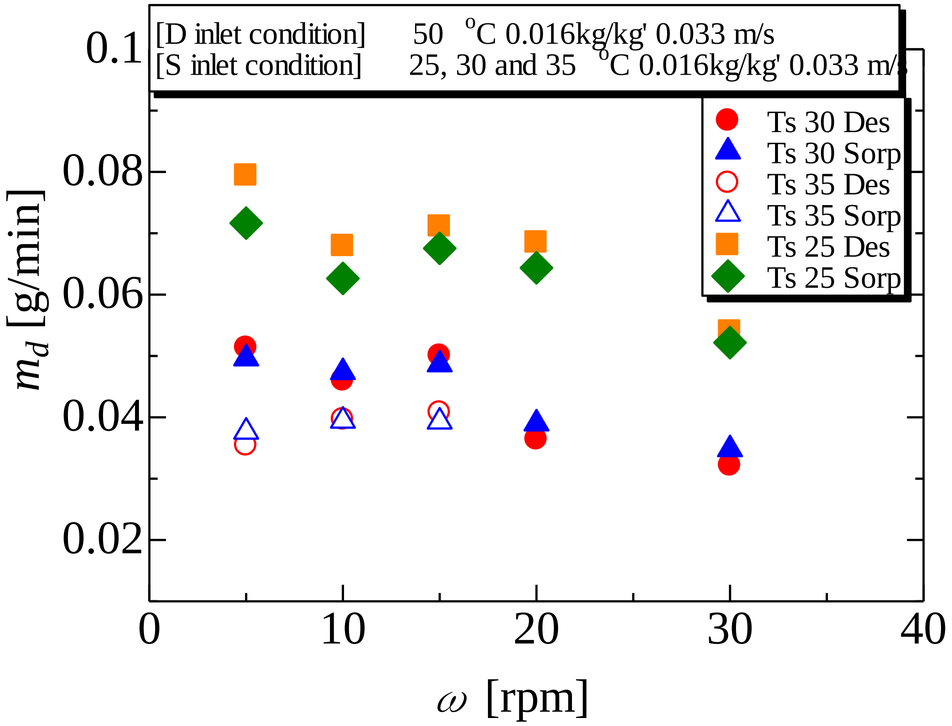


Fig. 4-34 Amount of dehumidification with difference desorption inlet temperature

Figure 4-34 shows the relationship between temperatures of sorption inlet and the amount of dehumidification. The figure indicates that decreases the sorption inlet temperature, amount of dehumidification increases. These phenomena can be explained as follows. Desiccant surface vapor pressure depends on the temperature of the material as well as on its water content. Desiccant performance is affected by the temperature of the incoming air(4-11). By decreasing the sorption inlet temperature, the ability of sorbent to attract water vapor increases, so that amount of dehumidification increases as can be seen in the figure.

4.9 Data reduction for amount of dehumidification

The non dimensional parameters that exert an influence on the Sherwood number were derived by using the dimension analysis method and considering the various factors. The dimensionless number which displays the experimental conditions regarding inlet air velocity, u_0 (m/s) is Reynolds number *Re* which is defined as Equation (3), where ρ_a

(kg/m^3) is air density, d_p (m) is the average sorbent particle diameter in dry condition, and μ (Pa.s) is kinematic viscosity of air.

$$Re = \frac{\rho_a u_0 d_p}{\mu} \tag{3}$$

Equation (4) is dimensionless number which displays the residence time distribution of sorbent; where D (m^2/s) is molecular diffusion of water vapor to air, and t_d (s) is represent the time needed for circulating the sorbent one cycle.

$$t_d^{\ *} = \frac{D\, t_d}{d_p^{\ 2}} \tag{4}$$

Equation (5) with the dimensionless temperature ratio T^* is used for concerned desorption inlet temperature, represent the effect of desorption inlet temperature. T_{dew} is dew point and in this research 21.4 ℃ is used as dew point temperature because absolute humidity is 0.016 kg/kg for inlet air in both chambers.

$$T_d^{\ *} = \frac{T_{D\,in} - T_{dew}}{T_{S\,in} - T_{dew}} \tag{5}$$

Equation (6) is dimensionless number L_0^* which is used for concerned initial bed height of sorbent L_0 (m) in the chamber.

$$L_0^* = \frac{L_0}{d_p} \tag{6}$$

Equation (7) is defined as Sherwood number where h_d (m/s) is coefficient mass transfer. Sherwood number is a non-dimensional number of effective mass transfers coefficient h_d which is a function of amount of dehumidification, A is mass transfer area effective, and ρ_a is air density. Mass transfer area effective of sorbent calculated by Equation (9), where A_s (m^2) is surface area and V_s (m^3) is volume of one particle of sorbent and V (m^3) is sorbent volume in one chamber.

$$Sh = \frac{h_d\ d_p}{D} \tag{7}$$

$$h_d = \frac{m_d}{A\,\Delta\rho} \tag{8}$$

$$A = V\frac{A_s}{V_s} = \frac{m_0}{\rho}\frac{4\pi\, r^2}{(4/3)\,\pi\, r^3} = \frac{m_0}{\rho}\frac{1}{(1/3)\,r} \tag{9}$$

The relationship between Sherwood number *Sh* and Reynolds number *Re* is shown in Fig. 4-35. The Sherwood number *Sh* increases with an increase in Reynolds number. It is understood that the decreasing in boundary layer thickness according to the increasing in air velocity.

Figure 4-36 shows the relationship between Sherwood number and non dimensional residence time distribution. Increasing the residence time distribution of sorbent in the chamber will increase the mass transfer coefficient of sorbent, so that Sherwood number also increases.

Figure 4-37 shows the effect of non dimensional temperature to the Sherwood number. The figure indicates that mass transfer coefficient of sorbent increases by increasing desorption inlet temperature. The more dry the sorbent, the more the amount of mass transfer will be.

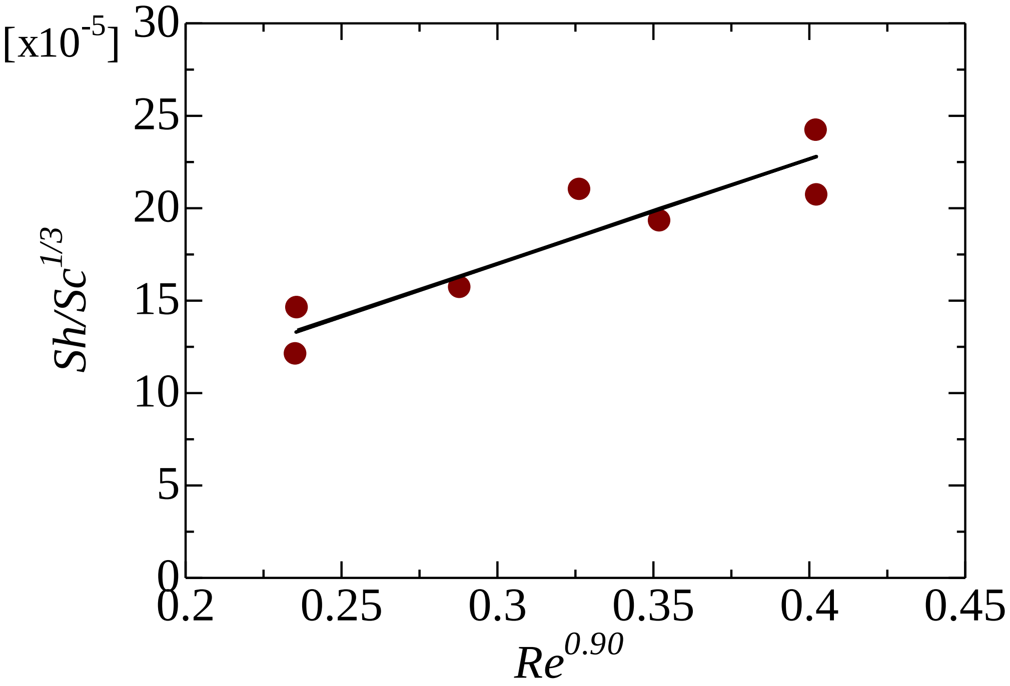


Fig. 4-35 Relationship between Reynolds number and Sherwood number

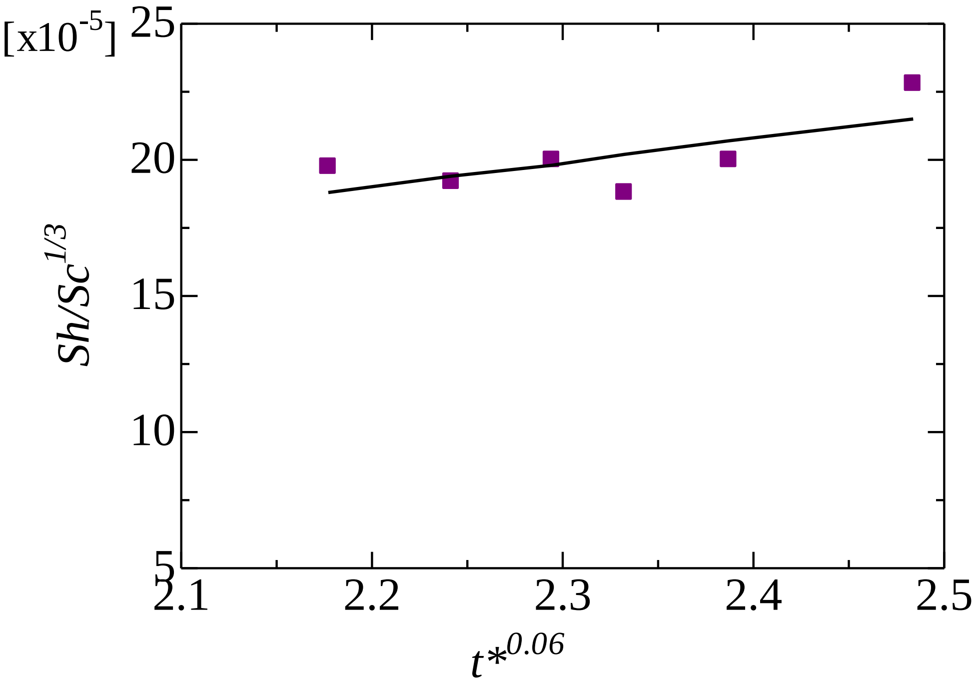


Fig. 4-36 Relationship between residence time distribution and Sherwood number

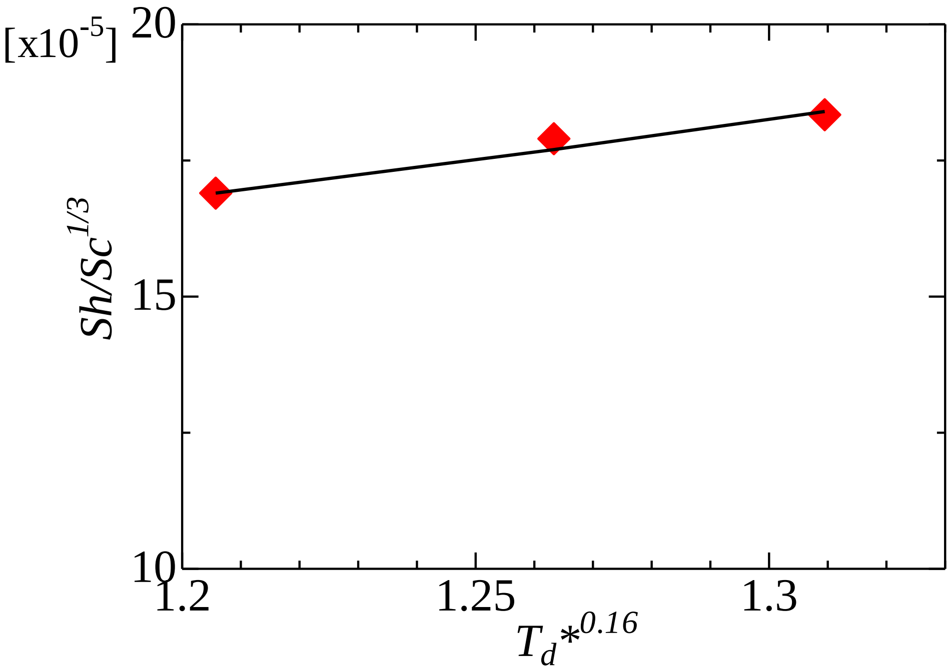


Fig. 4-37 Relationship between non-dimensional temperature and Sherwood number

Figure 4-38 presents the variation of non-dimensional parameters and Sherwood number. The following formula is shown in the solid line in the figure. The data of non-dimensional parameters were correlated by means of the equations (11) with standard deviation of 7% by using least squares method. The Applicable ranges Re = 0.201 ~ 0.364, L_0^* = 190 ~ 285, t_d^* = 4x10^5 ~ 8x10^6, and $T_d{}^*$ = 3.3 ~ 5.6 with spiral revolution speed from 0.7 to 100 rpm and sorbent circulation rate 0.42 to 30 g/min. As previous report proposed$^{(4-1)}$, the dependence of Sc on Sh was dealt as a proportion of $Sc^{1/3}$. It is seen that the data of Sh increases with an increasing in Re because the increasing mass transfer coefficient in relation with mass boundary layer thickness. Sherwood number Sh decreases with increasing circulation rate of the sorbent.

$$Sh/Sc^{1/3} = 0.14Re^{0.90}{t_d^*}^{0.06}{L_0^*}^{-1.10}{T_d^*}^{0.16} \tag{10}$$

It is seen that Sherwood number Sh increases with the increasing residence time since sorbent releases larger water vapor along with longer time spend in the chamber. Since Sherwood number represents the mass transfer by convection and mass transfer by diffusion, Sh decreases with the increasing in sorbent initial bed height confirms that in this condition diffusive mass transfer gives larger effect than that of convective mass transfer.

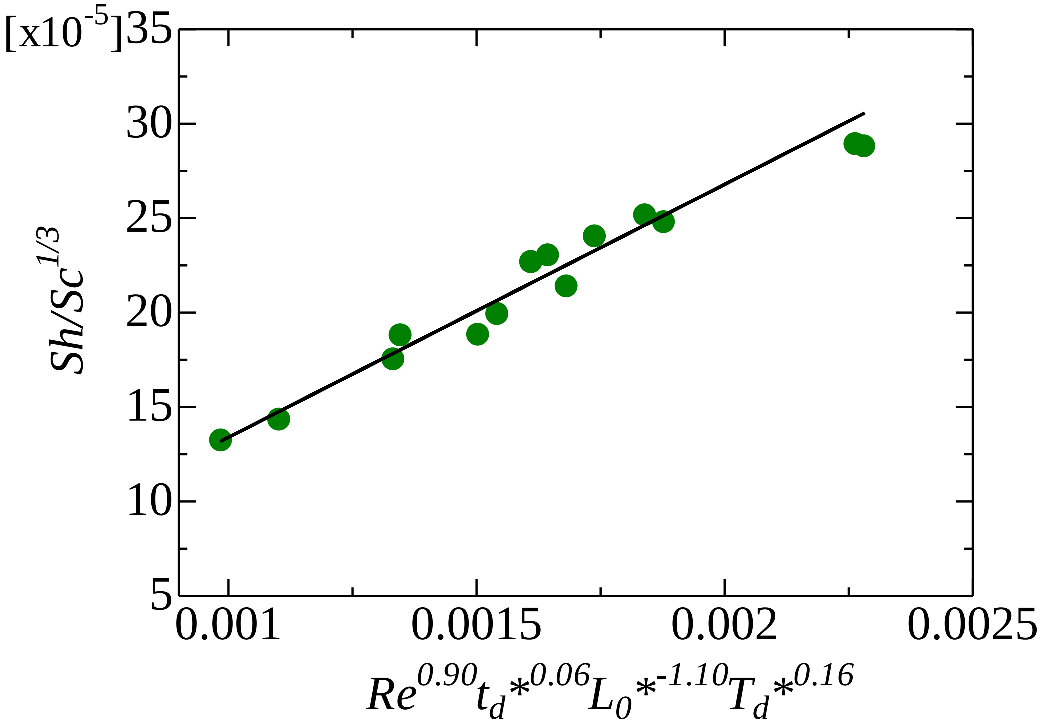


Fig.4-38 Relationship between non dimensional parameters and Sherwood number

4.10 Summary

The experiments have been carried out to investigate the heat and mass transfer behavior in the sorption and desorption process in two connected fluidized beds. In this study heat and mass transfer parameters were considered to evaluate the effect of spiral revolution speed, air velocity, initial bed height, desorption inlet air temperature, and sorption inlet air temperature in the chamber to sorption and desorption rates. At desorption chamber, air is humidified, At the other hand, at sorption chamber; air is dehumidified by the sorbent. Amount of water vapor releases in desorption chamber is about same with that sorbs in sorption chamber, thus the experiment condition is equilibrium.

It is confirm that for desorption process, absolute humidity out increases by decreasing the spiral revolution speed. While, the opposite condition occurs on sorption process, absolute humidity decreases by decreasing the spiral revolution speed. The time that sorbent powder remains inside the chamber influences the amount of dehumidification m_d. But when the circulation rate of sorbent powder is too small, water vapor released or sorbed at desorption chamber and sorption chamber decreases.

Regarding the difference spiral revolution speed, it is found that the difference temperature of the sorbent ΔT_{sor} is higher in the case of lower spiral revolution speed. Increasing the spiral revolution speed decreases the residence time distribution of particle. This condition affects the ability of sorbent to release or to sorbs water vapor. Increasing the circulation rate means the decrease in the residence time distribution of sorbent in the chamber. For desorption process, absolute humidity out increases by increasing the residence time until the highest value, at residence time distribution t_d = 8000 s, that is ω = 2.5 rpm. And then, absolute humidity out decreases by increasing the residence time distribution. And the opposite condition occurs on sorption process. For desorption chamber, sorbent temperature and outlet air temperature tend to increase by increasing the residence time distribution while at sorption chamber they tend to decrease. So that sorbent temperature increases and it approaches inlet air temperature by increasing the residence time.

Increasing the spiral revolution speed ω will increase the amount of dehumidification sharply until it reaches maximum value and then slowly down. This pattern is same for different initial bed height. Increasing t_d increases the amount of dehumidification until it reaches maximum value. While the other parameters are maintained same, different initial bed height will causing different residence time distribution for them to reach their highest value of amount of dehumidification. Residence time distribution t_d at the highest value of amount of dehumidification increases with an increase in initial bed height.

Increasing the air velocity indicates a larger amount of air passing through the fluidized bed per unit time. So that the amount of water vapor which can be sorbed increases for sorption chamber, and for desorption chamber amount of water vapor released from sorbent particle increases. At desorption chamber, sorbent temperature increases and approaching the inlet air temperature. And at sorption chamber, sorbent temperature decreased. This has led to the increasing of sorbent temperature difference along with increasing the air velocity.

It also shows the comparison amount of dehumidification between spiral speed 5 rpm and 100 rpm. The pattern of the graph between 5 rpm and 100 rpm is same, the amount of dehumidification increases by increasing the air velocity. Sorbent mass rate is about 3 g/min and 60 g/min for spiral revolution speed 5 rpm and 100 rpm respectively. Decreasing initial bed height of sorbent at the same air velocity will increase the size of bubble in the chamber. The growing size of bubble decreases the contact surface area per volume between sorbent and air, so the absolute humidity of air at outlet also decreases for desorption chamber and increases for sorption chamber.

The sorbent temperature in the chamber varies base on the initial bed height. The tendency of sorbent temperature is increasing by increasing the initial bed height. The sorbent more dry due to the enhancing rate of water vapor released. This, in turn, results in an increase in the absolute humidity at outlet. Increasing desorption inlet temperature will increase sorbent temperature in both chambers. Increasing desorption inlet temperature causes the mass transfer to increase. As the results, the amount of water vapor release from sorbent powder increases.

Increasing sorption inlet air temperature decreases the ability of sorbent to sorb water vapor. As the result, the absolute humidity out for desorption process decreases by increasing the sorption inlet air temperature; while for sorption process, absolute humidity out increases. Increases the sorption inlet temperature decreases the sorbent temperature different in the both chamber. The decrease the sorption inlet temperature, amount of dehumidification increases.

The non dimensional parameters that exert an influence on the Sherwood number were derived by using the dimension analysis method and considering the various factors. The data of non-dimensional parameters were correlated by means of the following equations with standard deviation of 7% by using least squares method.

$$Sh / Sc^{1/3} = 0.14 Re^{0.90} {t_d^*}^{0.06} {L_0^*}^{-1.10} {T_d^*}^{0.16}$$

The Applicable ranges Re = 0.201 ~ 0.364, L_0^* = 190 ~ 285, t_d^* = 4x10^5 ~ 8x10^6, and $T_d{}^*$ = 3.3 ~ 5.6 with spiral revolution speed from 0.7 to 100 rpm and sorbent circulation rate 0.42 to 30 g/min.

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Nomenclature

A : mass transfer area effective, m^2

A_s : surface area of one particle of sorbent, m^2

D : mass diffusivity, m^2/s

d_p : sorbent diameter, m

F_0 : sorbent flow rate, kg/s

h_d : mass transfer coefficient, m/s

m_d : amount of dehumidification, g/min

m_0 : sorbent mass, kg

m_w/m_0 : dimensionless sorption ratio

Re : Reynolds number

r : sorbent radius, m

Sh : Sherwood number

Sc : Schmidt number

T : temperature, ℃

t : time, s

u_o : inlet air velocity, m/s

V : sorbent volume in one chamber, m^3

V_s : volume of one particle of sorbent, m^3

Greek symbols

ρ : density, kg/m^3

ψ : relative humidity, %

ω : spiral revolution speed, rpm

x : absolute humidity, kg/kg'

μ : viscosity, Pa･s

Subscripts

dew : dew point

Din : desorption inlet

g : gas

Sin	: sorption inlet
p	: sorbent

Chapter 5

Dehumidification Characteristics of Organic Powder Sorption Material in Continuous Fluidized Bed with Cooling and Heating Pipe

The dehumidification characteristics of organic powder sorption materials have been studied by using continuous fluidized bed with cooling and heating pipe. In this chapter will explained more the previous experimental results in our lab regarding the dynamic sorption characteristics of organic sorbent materials by using fluidized bed with cooling or heating in batch system. The Following experimental is investigation of sorption material in continuous fluidized bed with cooling and heating pipe. Sorption rate of water vapor and the variation of temperature in the sorbent bed with time were measured under various conditions.

5.1 Introduction

Dehumidification and regeneration are the mutually contrary processes of the moisture condensation or evaporation out/into the air stream. Hence, the dehumidifier and regenerator are similar to each other. A desiccant system removes moisture from the process air stream, but for every Btu of latent heat (moisture) removed, it adds more than one Btu of sensible heat. That is, air leaving the process side of the system is dry (at low dew point) but hot. Therefore, most applications include a cooling coil downstream of the system to recool the process air(5-1).

Desiccant cooling consists of dehumidifying the incoming air stream by forcing it through a desiccant material and then drying the air to the desired indoor temperature. To make the system working continually, water vapor adsorbed/absorbed must be driven out of the desiccant material (regeneration) so that it can be dried enough to adsorb/absorb water vapor in the next cycle(5-2). Comfort air conditioning requires efficient control of both temperature and humidity. Various solid desiccant systems employing rotary desiccant wheels$^{(5\text{-}1),\ (5\text{-}3)\ -\ (5\text{-}5)}$, fluidized bed$^{(5\text{-}6)\ -\ (5\text{-}8)}$ have been proposed and studied.

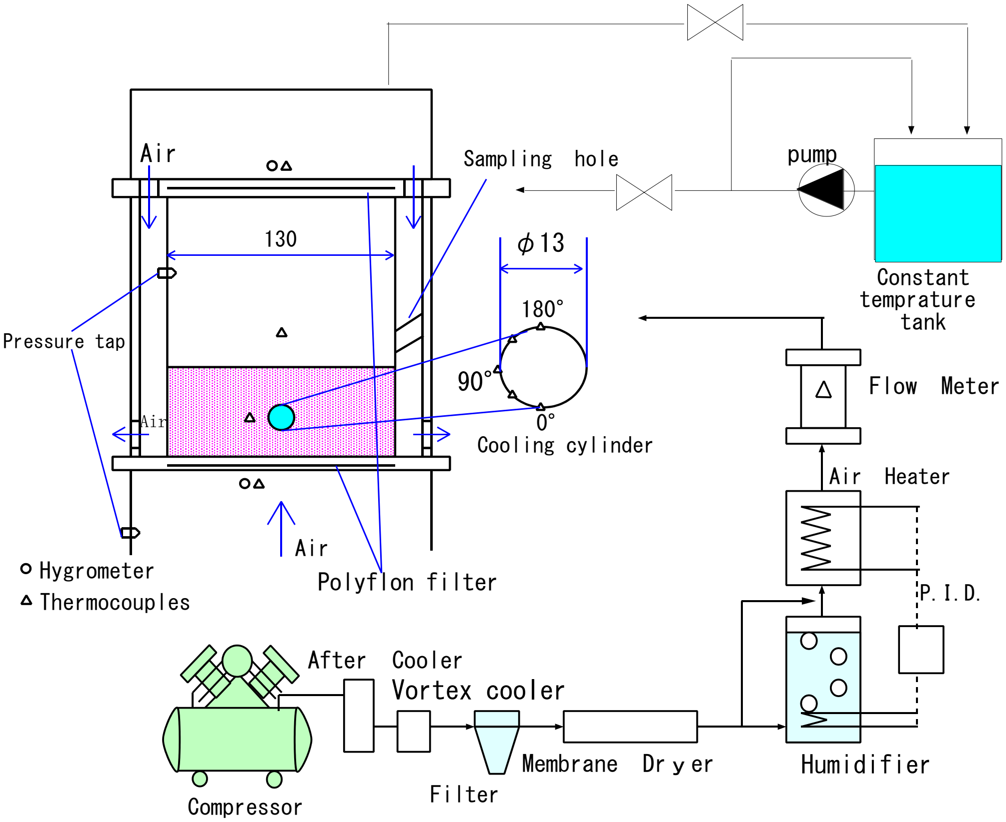

Fig. 5-1 Schematic of experimental apparatus of a cooling pipe$^{(5\text{-}7)}$

In order to improve the performance of desiccant in fluidized bed, a new bed configuration should be investigated. Horibe$^{(5\text{-}7)}$ have been studied sorption characteristics of organic powder sorption material in fluidized bed with a cooling pipe as can be seen in Figure 5-1. A pipe as heat exchanger is inserted in the fluidized bed chamber. The dynamic sorption characteristics of organic sorbent materials have been studied by using fluidized bed with a cooling pipe. The organic powder type sorbent made from a bridged complex of sodium polyacrylate which is one of the sorption polymers is adopted in this study. Sorption rate of water vapor and the variation of temperature in the sorbent bed with time were measured under various conditions. As can be seen in Fig. 5-2 and 5-3, the completion time for the sorption process decreases by using a cooling pipe. Fig. 5-4 shows the sorption ratio increases by installing the cooling pipe inside the batch column in order to increase heat and mass transfer between the sorbent material and the moist air.

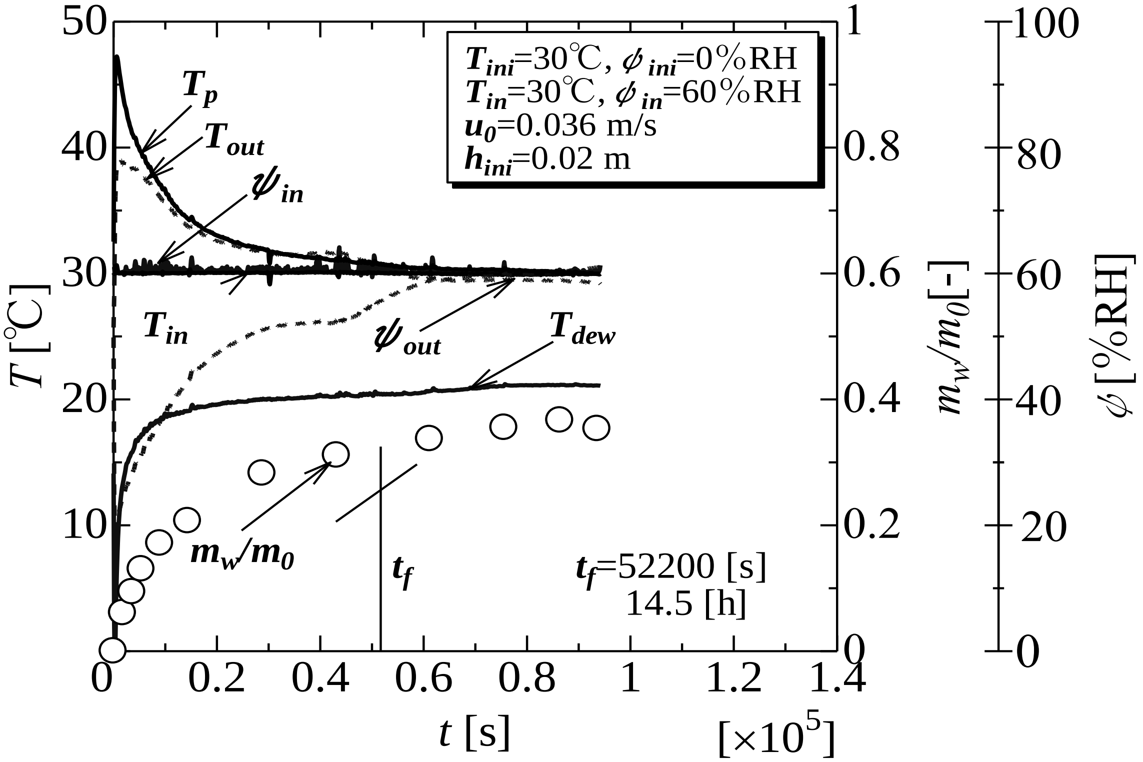

Fig. 5-2 Time histories without cooling pipe(5-7)

Since relative humidity (RH) is a function of vapor pressure, the direction of moisture transfer can be characterized by the difference between the relative humidity of the process and regeneration air streams. The desiccant can retain little moisture when the regeneration air RH is low, so water vapor will migrate from the desiccant to the regeneration air. When the RH of the process air is high, the desiccant can adsorb more moisture from that air stream. Maintaining an adequate difference between the relatives humidity of the process air and regeneration air streams is essential to dehumidify effectively using a desiccant system. Lowering the relative humidity allows the desiccant to reject more water vapor to the regeneration air, thus enabling it to sorb more water vapor from the process air. In many cases, the modest amount of heat added by the preheat coil can be recovered from the condensing process of the refrigeration equipment.

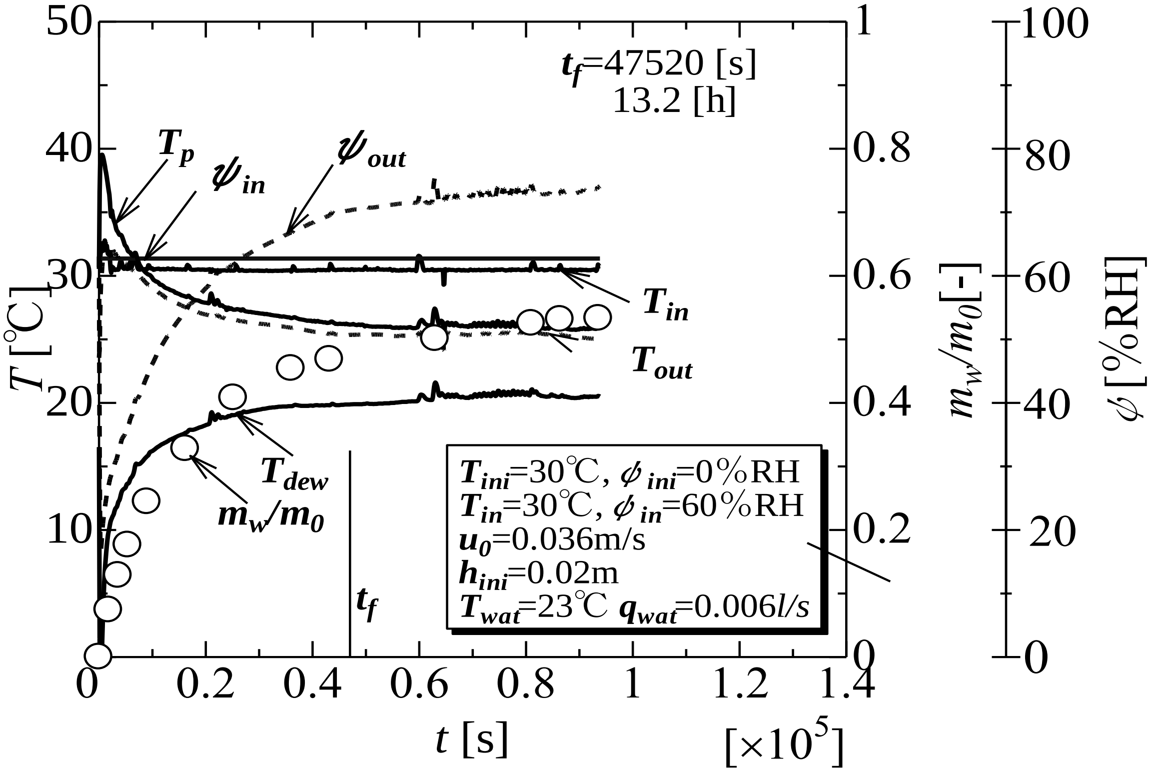

Fig.5-3 Time histories with a cooling pipe(5-7)

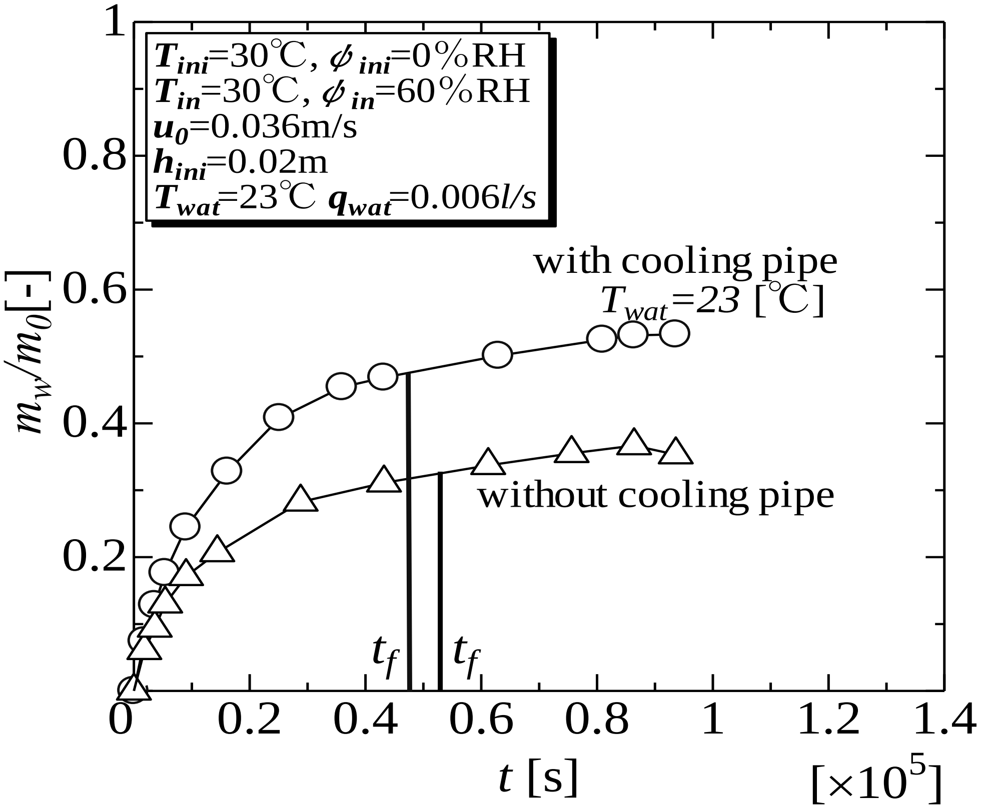

Fig. 5-4 Dimensionless sorption ratio and experimental completion time(5-7)

Horibe(5-8) also investigated sorption process in fluidized bed with multiple cooling pipes to study adsorption characteristics of a new organic sorbent desiccant material (HU300P) for a new air conditioning system. The mass ratio of the present sorbent desiccant powder type is from 1.3 to 2.3 times greater than that of silica gel. The sorption rate of the water vapor in the sorbent bed was measured under various conditions. It was found that the sorption rate is highly dependent on the effect of cooling pipes. The sorption ratio increase and the completion time for the sorption process decreases by using multiple cooling pipes.

The previous experimental result about continuous sorption and desorption process in connected fluidized bed is not reaching yet the target of absolute humidity (*x*) value which is about 0.01 kg/kg(5-9). For increasing the results of sorption and desorption, new configuration is proposed to approach the absolute humidity target. Differently from the previous work, the present research deals with powder type organic sorbent in continuous fluidized bed with a cooling and a heating as a heat exchanger pipes which were inserted in the chambers. The installing heating or cooling pipe in the chamber is subjected to increase the heat and mass transfer between sorbent and the moist air and to increase the sorbent temperature at desorption chamber while at sorption chamber, to decrease the sorbent temperature.

5.2 Experimental Set Up

The set-up of the experimental apparatus for sorption and desorption operation is depicted in Figure 5-5. The experimental apparatus mainly consists of an air compressor, an after cooler, a filter, a membrane dryer, humidifiers and a temperature controller, heaters, flow meters, sorption and desorption chambers and spiral tubes with geared motors that connects the two chambers, constant temperature tanks.

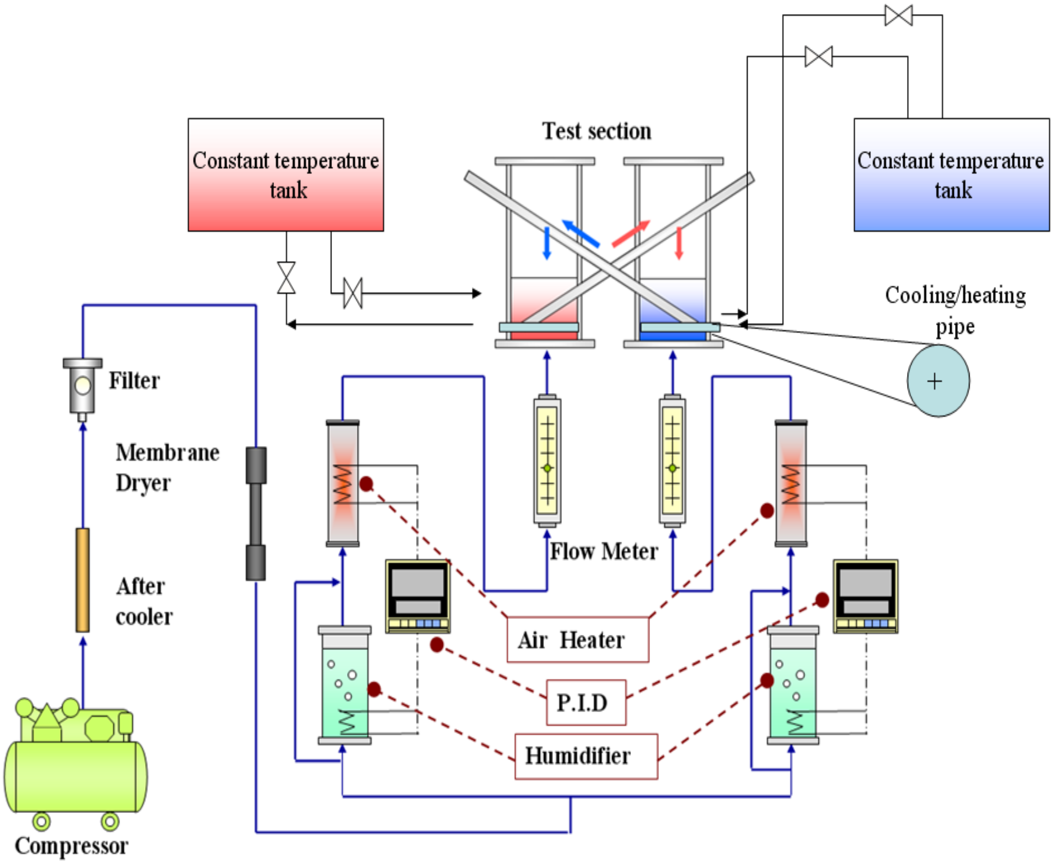

Fig. 5-5 Experiment devices with a cooling pipe (CP) and a heating pipe (HP)

Figure 5-6 shows the test section with a cooling and a heating pipe inserted in the chamber. Sorption and desorption chambers as test section units are made of transparent acrylic plate which allows viewing the process in the chambers. They are rectangular chambers with cross section area 100 mm x 100 mm and 300 mm height. The polytetrafluoro ethylene filter # 2 μm and wire mesh are set up in both inlet and outlet of the chambers to distribute air flow uniformly and prevent the leakage of sorbent particles. The spiral is made from stainless steel and inserted into the transparent acrylic pipe with inner diameter 16 mm. These spiral tubes transferred the sorbent powder from sorption chamber to desorption chamber or vise versa continuously.

The humidity of air is controlled by the operation of air bubble distributor in the moisture control unit of the humidifier. The temperature of the hot water in the humidifier could be controlled by adjusting output electric power of an electric heater. After passing the humidifier, and before enter the test section, there is another heater that the temperature could be controlled by adjusting output electric power with a PID control unit.

Flow rate control valve and flow rate meter functioned to control the air flow velocity at the desired value. The measuring accuracy of air amount is 2.5 % in the range of 0.00033 m^3/s – 0.00167 m^3/s. Pressure gauges is used to measure the air pressure at the inlet of the test section.

K type of thermocouples, with diameter 0.32 mm and measuring accuracy of ± 0.1 °C, were used to discover the test powder sorbent temperature profile, inlet and outlet air temperature. One of them was set at the inlet of test section, at the center of the sorbent powder chamber and the other one was set at the exit point of the sorbent at the screw. The humidity of inlet and outlet air was measured with dew-point hygrometer with measuring accuracy of ± 0.2 °C.

The cooling or heating water that exists in the preset temperature in the water bath (setting precision 0.1 °C) is supplied to the heating or cooling pipe by passing over the cooling or heating water with a magnetic type of pump. The cooling or heating water flows to the pipe in the test section then returns to the water bath again. Mass flow is adjusted with the valve installed on the exit side of examination part. Figure 5-7 shows a cooling or a heating pipe made of copper. Heating or cooling pipe is double pipe with outer pipe diameter is 13 mm. K type of thermocouples are embedded in the surface of the pipe. They are in the top, center and the bottom of the pipe, so that the surface temperature of the pipe can be measured at each position. Pipe is inserted 5 mm above the bottom of the chamber.

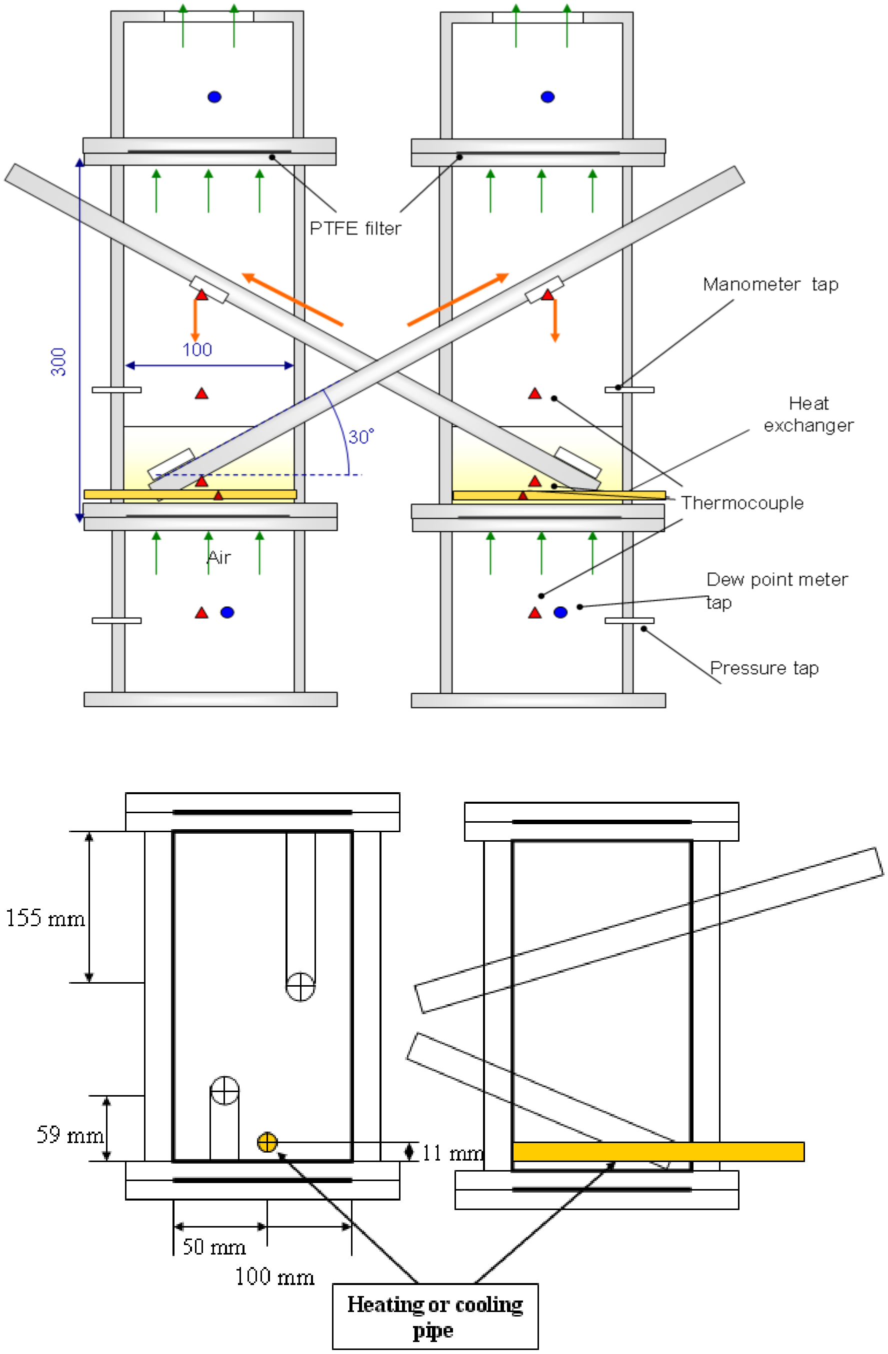

Fig. 5-6 Detail of test section with heating or cooling pipe

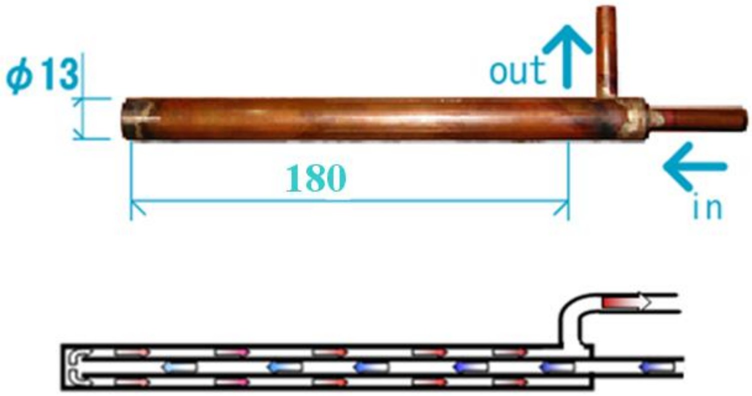

Fig. 5-7 Heating or cooling pipe

The experiment procedure is as follows. First of all, sorption material is dried in a dry oven with temperature 105 °C until water vapor completely removed. Then the sorption powder with specified mass is filled into the test section. After that air with certain temperature, humidity and velocity is exhaled into the desiccant chambers. After the condition reached, spiral switch on with the desired speed. Temperature, humidity and dew point temperature at the chambers and outlet were recorded every 30 seconds. Experimental data were taken until the sorption and desorption reaction reaches equilibrium level. Amount of dehumidification (m_d) was calculated from absolute humidity differences multiplied by air mass flow rate.

Table 5-1 shows the basic condition of this experiment. In this study, it is assumed that the air from a room flows into the system with absolute humidity between 0.015 – 0.017 kg/kg. We choose inlet air absolute humidity 0.016 kg/kg. The inlet air flow is divided into two, one flows to desorption chamber and the other to sorption chamber. At desorption chamber, inlet air is heated and temperature of air is high with low relative humidity. While at sorption chamber, it is not, so that the relative humidity of air remains high. Desorption inlet air temperature is set 50 ℃ for air velocity effect and spiral revolution speed effect experiment. For sorption and desorption inlet air temperature variation, air velocity and spiral speed are set 0.033 m/s and 2.5 rpm respectively.

Heating pipe is inserted in desorption chamber. For air velocity effect and spiral revolution speed experiment, the pipe temperature is set 60°C. On the other hand, cooling pipe is inserted in sorption chamber, and is set 25°C for air velocity and spiral revolution speed experiments.

Table 5-1 Experimental Condition:

<table>
<tr><td colspan="4">Desorption inlet air condition</td></tr>
<tr><td>Temperature (T_{Din}):
50°C</td><td>Absolute humidity(x_{in}):
0.016 kg/kg</td><td>Relative humidity (ψ_{in}):
30% (50°C)</td><td>Air velocity (u_0):
0.033, 0.04 and 0.48 m/s</td></tr>
<tr><td colspan="4">Sorption inlet air condition</td></tr>
<tr><td>Temperature(T_{Sin}):
30°C</td><td>Absolute humidity (x_{in}):
0.016 kg/kg</td><td>Relative humidity (ψ_{in}):
60 % (30°C)</td><td>Air velocity (u_0):
0.033, 0.04 and 0.48 m/s</td></tr>
<tr><td colspan="4">Other Conditions</td></tr>
<tr><td colspan="2">Dry sorbent mass (m_0): 200 g for each chamber, which are equal with initial sorbent height 0.021 m</td><td colspan="2">Spiral speed (ω):
0.7, 1.5, 2, 2.5, 5, 10, 15, 20, 30, 50 rpm</td></tr>
<tr><td colspan="2">Desorption pipe temperature (T_{HP})
50, 55, 60, and 65 °C</td><td colspan="2">Sorption pipe temperature (T_{CP})
15, 20, 25, and 30 °C</td></tr>
</table>

5.3 Preliminary Experiment

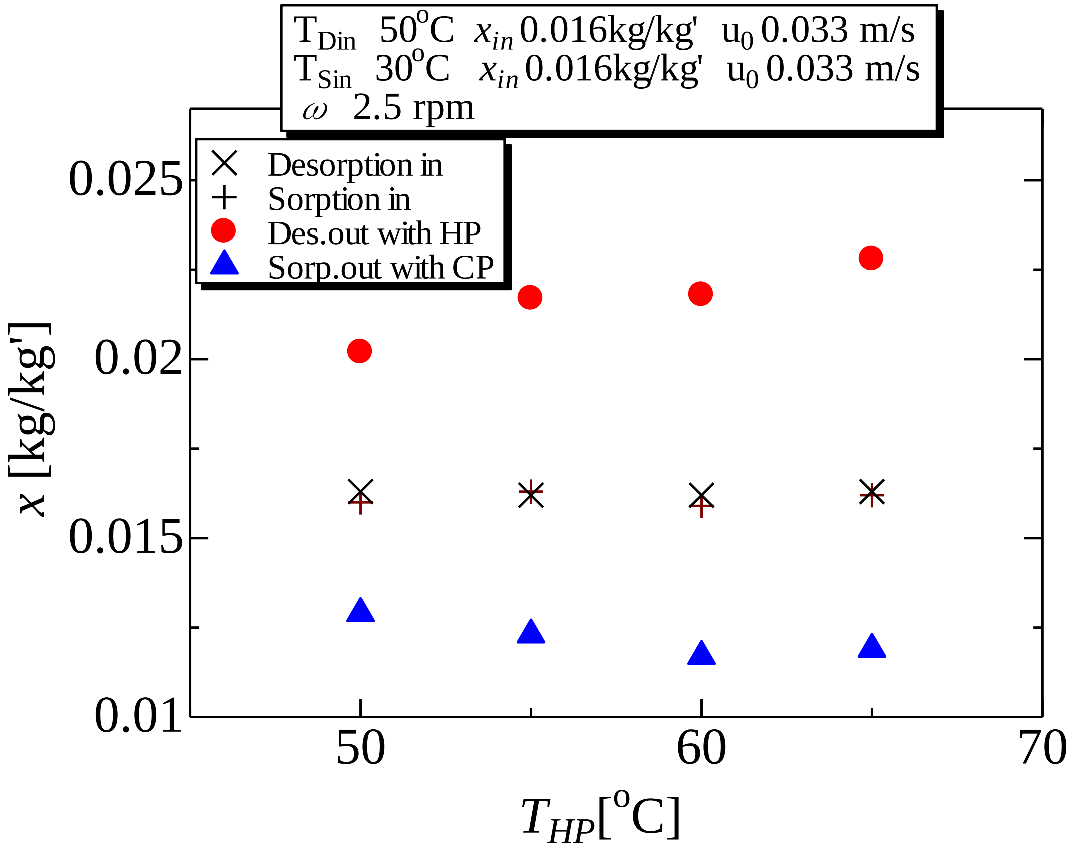

Fig. 5-8 Desorption heating pipe temperature effect on absolute humidity

Figure 5-8 shows the effect of desorption heating pipe temperature on absolute humidity out of sorption and desorption process for spiral revolution speed 2.5 rpm, desorption inlet air temperature 50°C, sorption inlet air temperature 30°C, and air velocity 0.03 m/s. Temperature of sorption cooling pipe is constant 25 °C. It can be seen that increasing desorption heating pipe temperature increases absolute humidity out at desorption chamber, and decreases absolute humidity out at sorption chamber. The explanation of this phenomenon is as follows. Increasing desorption heating pipe temperature will affecting desorption sorbent temperature to increase which is present in Figure 5-9. This increasing desorption sorbent temperature causes the amount of water vapor that can be released by sorbent increases so that the sorbent is drier.

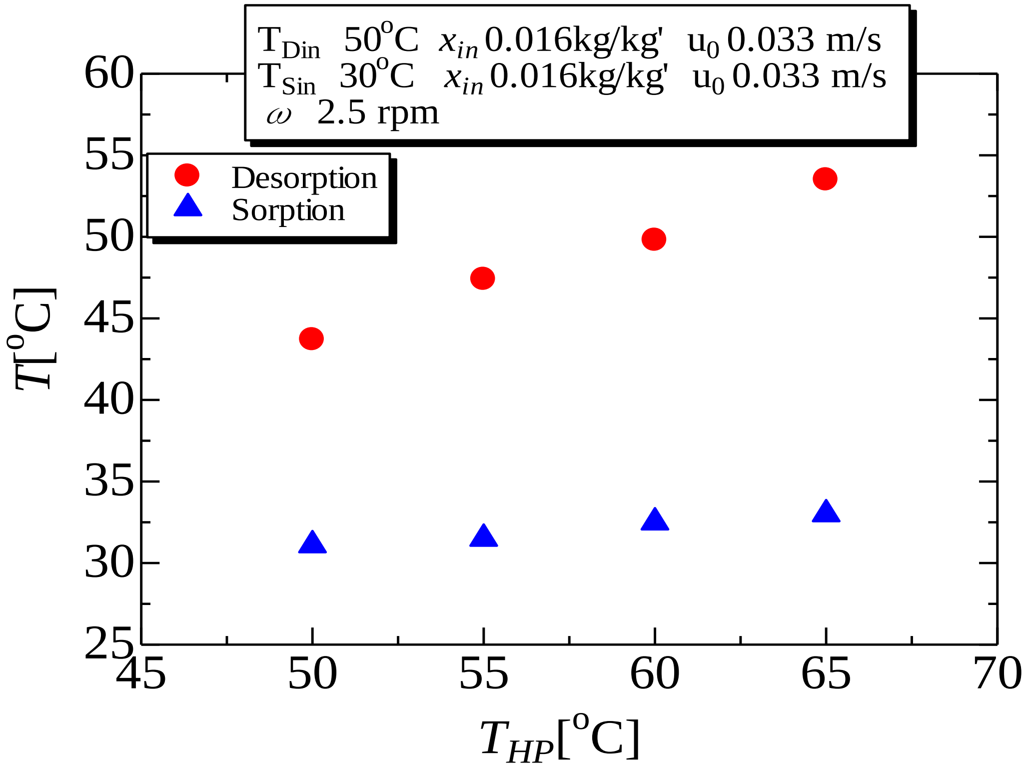

Fig. 5-9 Desorption pipe temperature effect on sorbent temperature

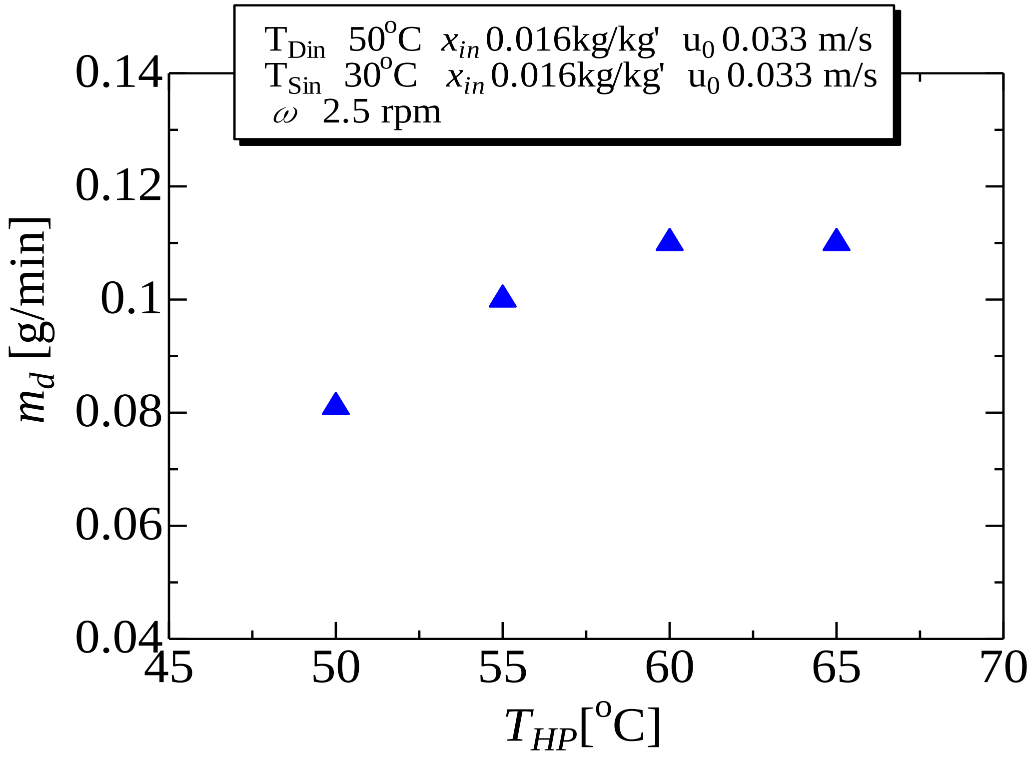

Fig. 5-10 Desorption pipe temperature effect on amount of dehumidification

Figure 5-10 depicts the effect of desorption pipe temperature on the amount of dehumidification. The increase in desorption heating pipe to 60°C increases the amount of dehumidification. Increasing desorption heating pipe temperature to 65 °C doesn't give effect to the amount of dehumidification. The increase of desorption sorbent temperature causes the more water vapor can be released from the sorbent which will increase the ability of sorbent to sorb water vapor at sorption chamber. From Figure 5-9 can be seen that the temperature of sorbent at sorption chamber almost constant which is also affect the ability of sorbent to sorb water vapor. The drier the sorbent is not followed by the increasing ability of sorbent to sorb water vapor; because when the sorbent is drier, it is followed by the increasing of sorbent temperature which it is can reduce the performance of sorption process.

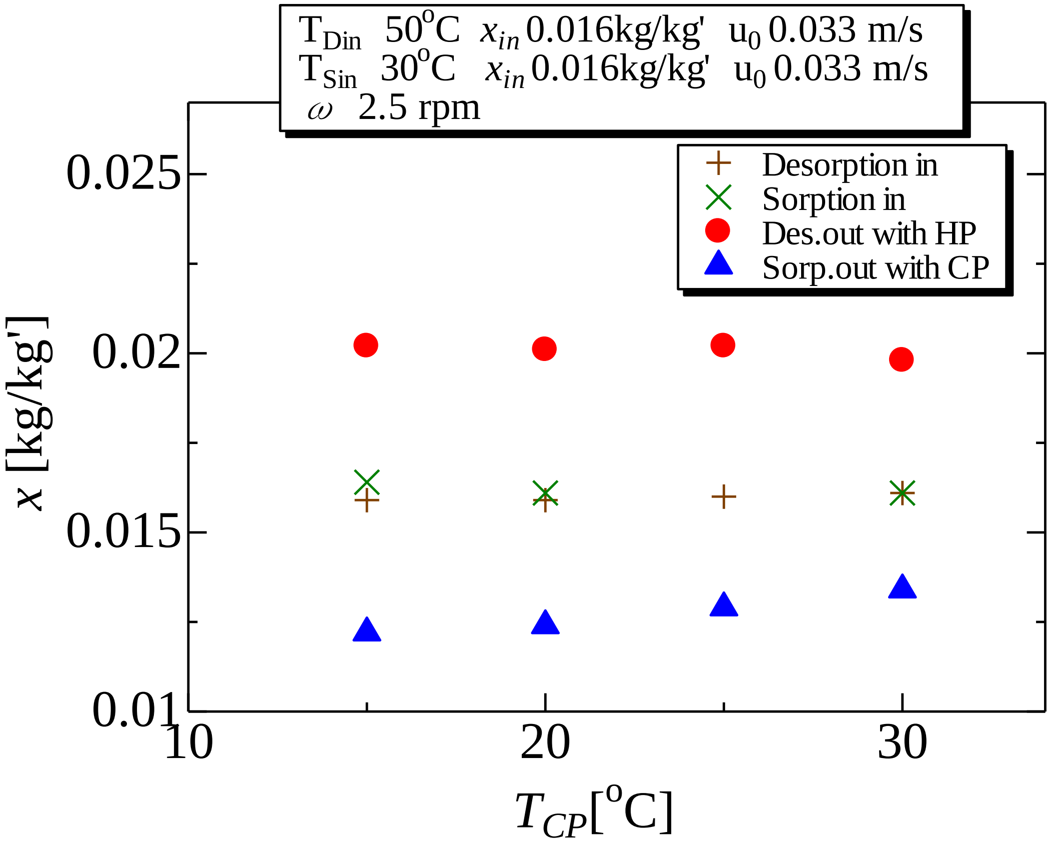

Fig. 5-11 Sorption cooling pipe temperature effect on absolute humidity

Figure 5-11 presents the effect of sorption cooling pipe temperature on absolute humidity for spiral revolution speed 2.5 rpm, air velocity 0.03 m/s, desorption and sorption inlet air temperature is 50°C and 30°C respectively. Temperature of desorption heating pipe is remained constant 60°C. Fig.5-11 shows the decrease of desorption absolute humidity out and the increase of sorption absolute humidity out with the increase of sorption cooling pipe temperature. This condition occurs because sorption process needs low temperature, so that by increasing its temperature will decrease the amount of absolute humidity which is sorbed by the sorbent and then will decrease the amount of absolute humidity out at desorption chamber. Figure 5-12 shows the increasing sorbent temperature at sorption chamber by increasing the sorption cooling pipe temperature while sorbent temperature at desorption chamber constant. The increasing sorbent temperature decreases the ability of sorbent to sorb water vapor. This condition is accordance with Horibe(5-7) who found that sorption ratio increases by installing the cooling pipe inside the batch column.

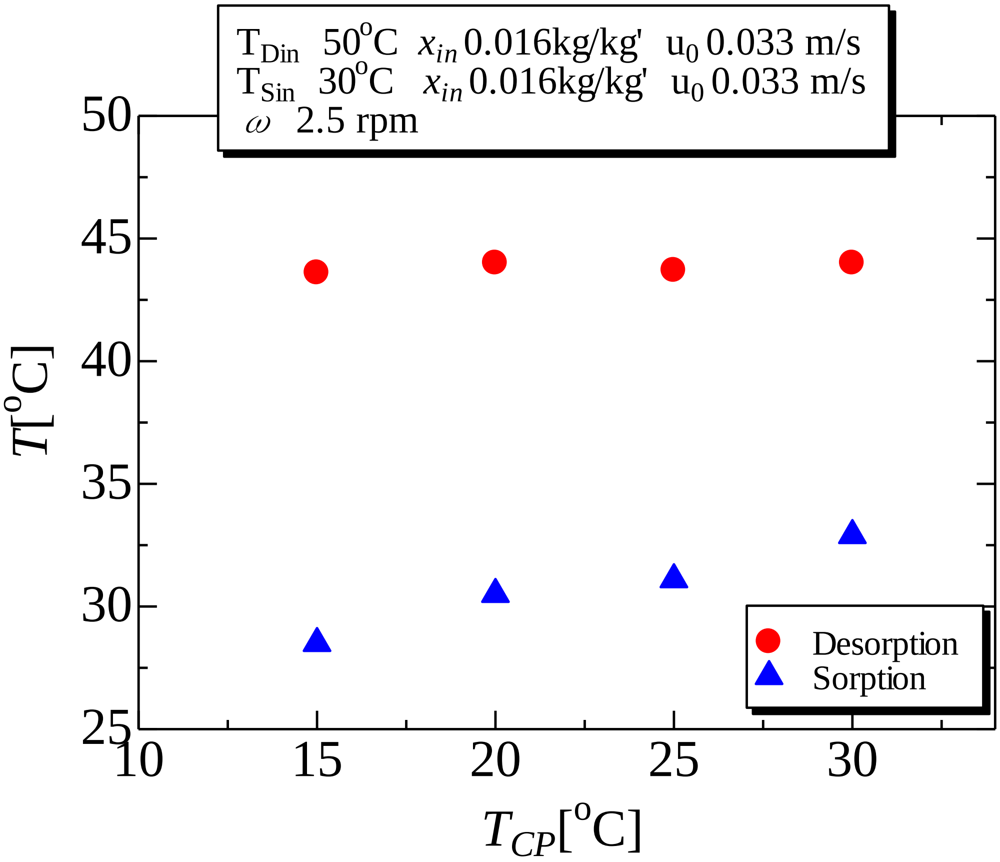

Fig. 5-12 Sorption cooling pipe temperature effect on sorbent temperature

Figure 5-13 shows the effect of sorption cooling pipe temperature on the amount of dehumidification. The figure presents the decrease of amount of dehumidification with the increase of the sorption cooling pipe temperature. The difference value of the amount of dehumidification is getting bigger by the increasing of sorption cooling pipe temperature. As explained before, the ability of sorbent to sorbed water vapor decreases by increasing its temperature.

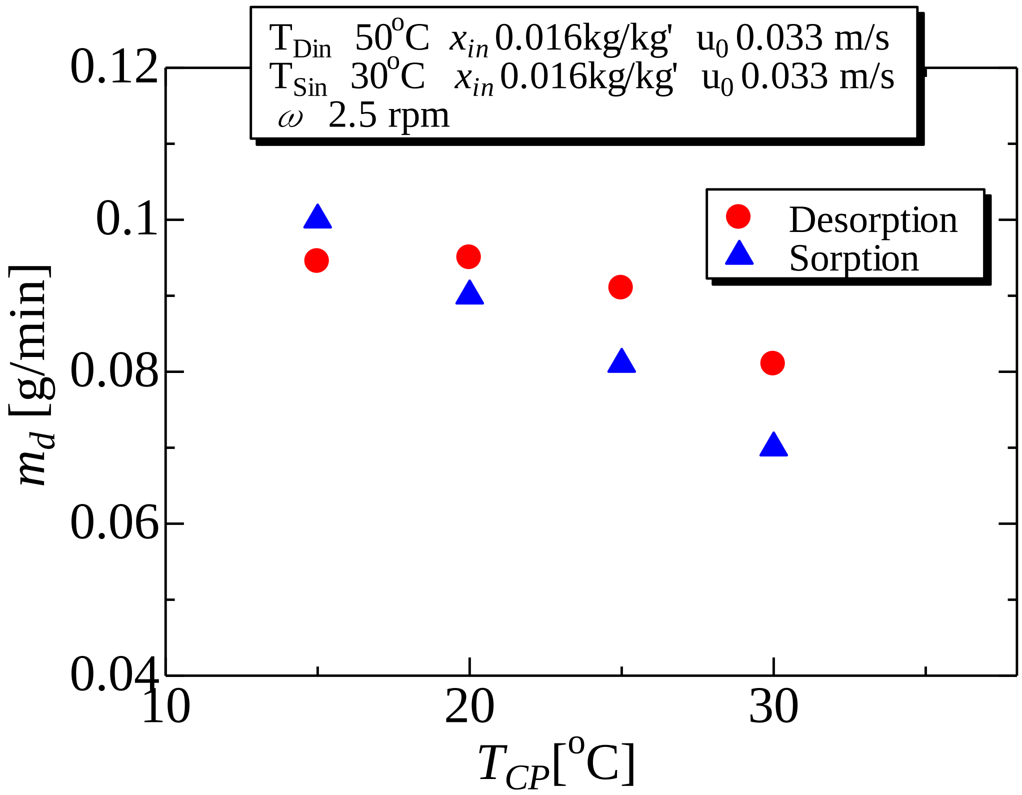

Fig. 5-13 Sorption cooling pipe temperature effect on amount of dehumidification

5.4 Air Velocity Effect

Figure 5-14 to Figure 5-17 are the graphs showing the air velocity effect for continuous sorption and desorption process. Air velocity is one of the operating parameters in fluidized bed system and has dominant effect on removing surface moisture. Figure 5-14 presents the effect of air velocity on absolute humidity for sorption and desorption process with spiral revolution speed 5 rpm, desorption and sorption inlet air temperature is 50°C and 30°C respectively, desorption heating pipe temperature 60°C and sorption cooling pipe temperature 25°C, and air velocity 0.03, 0.04 and 0.048 m/s.

This figure also presents the comparison of absolute humidity out between desorption and sorption process without heat exchanger and with heat exchanger. A small increasing of absolute humidity at desorption chamber and decreasing at sorption chamber were found by increasing the air velocity process without heat exchanger. Increasing the air velocity indicates a larger amount of air passing through the fluidized bed per unit time and increasing air velocity also effects the decreasing of boundary layer concentration between air and sorbent, these cause the amount of water vapor which can be sorbed increases for sorption chamber, and for desorption chamber amount of water vapor released from sorbent particle increases. By inserting heating or cooling pipe in the chamber, increasing the velocity, absolute humidity out from desorption and sorption chambers are not increasing. This condition is coincide with the explanation of Law and Mujumdar(5-10) who explained that when heat transfer coefficient reaches maximum value, increasing gas velocity will hinder heat transfer between the solid and the heating surface. This is because of increasing preponderance of bubble (not solid particles) and the heating surface, which decreases particle-to-surface of internal immersed tubes.

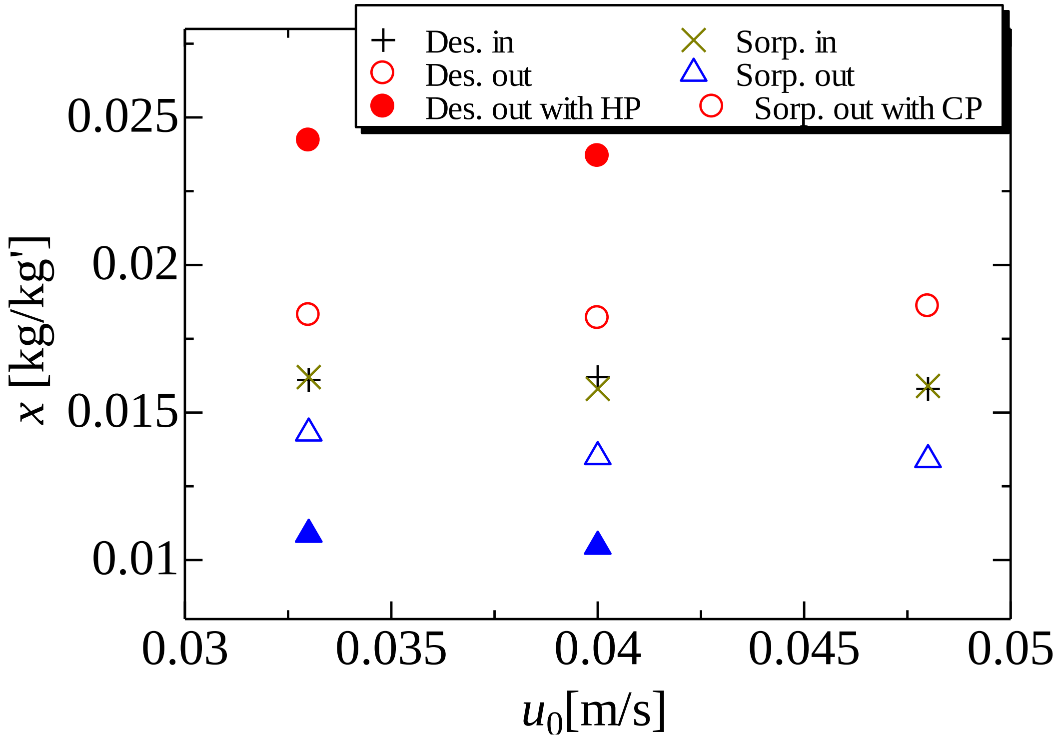

Fig. 5-14 Velocity effect on absolute humidity

Inserting heating or cooling pipe in the chamber, increasing the velocity, a small decreasing of absolute humidity out occurs at desorption and sorption chamber. This small change in the absolute humidity out causes the amount of dehumidification balance is getting well for amount of dehumidification by inserting heating or cooling pipe in the chamber as depicted in Figure 5-15. Figure 5-16 also present the amount of dehumidification with heating or cooling pipe with spiral revolution speed 2.5 rpm. By increasing the velocity, contact surface area between sorbent particle and air increases and more uniform, so that the amount of dehumidification in the two chambers becomes uniform.

Comparing the result of absolute humidity out the process without heating or cooling pipe and with heating or cooling pipe, the figure clearly shows that absolute humidity out for desorption process with heating pipe is higher than without heating pipe. For sorption process, absolute humidity out is lower for process with cooling pipe than that of without cooling pipe. This condition is supported by Fig.5-17 which shows sorbent temperature in the both chambers for sorption and desorption, process without heating or cooling pipe and with heating or cooling pipe. Heating pipe is inserted in desorption chamber for increasing the sorbent temperature, while cooling pipe is inserted in sorption chamber for decreasing its temperature. And the result shows that heating pipe is able to increase desorption sorbent temperature to around 49°C, thus enhances the rate of evaporation and decreases the moisture content of sorbent. While cooling pipe is able to maintain sorbent temperature in the chamber around 31°C. Fujita(5-11) found that water temperature of cooling pipe affected the sorption ratio of sorbent, sorption ratio increases by decreasing the water temperature of cooling pipe.

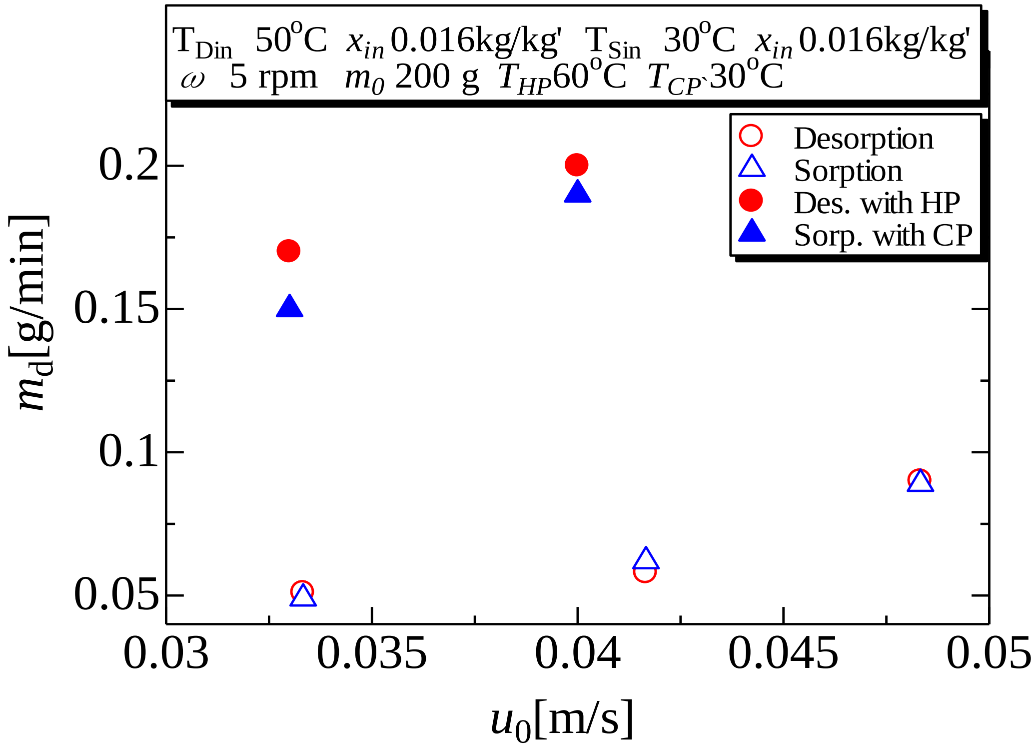

Fig. 5-15 Velocity effect on amount of dehumidification (5 rpm)

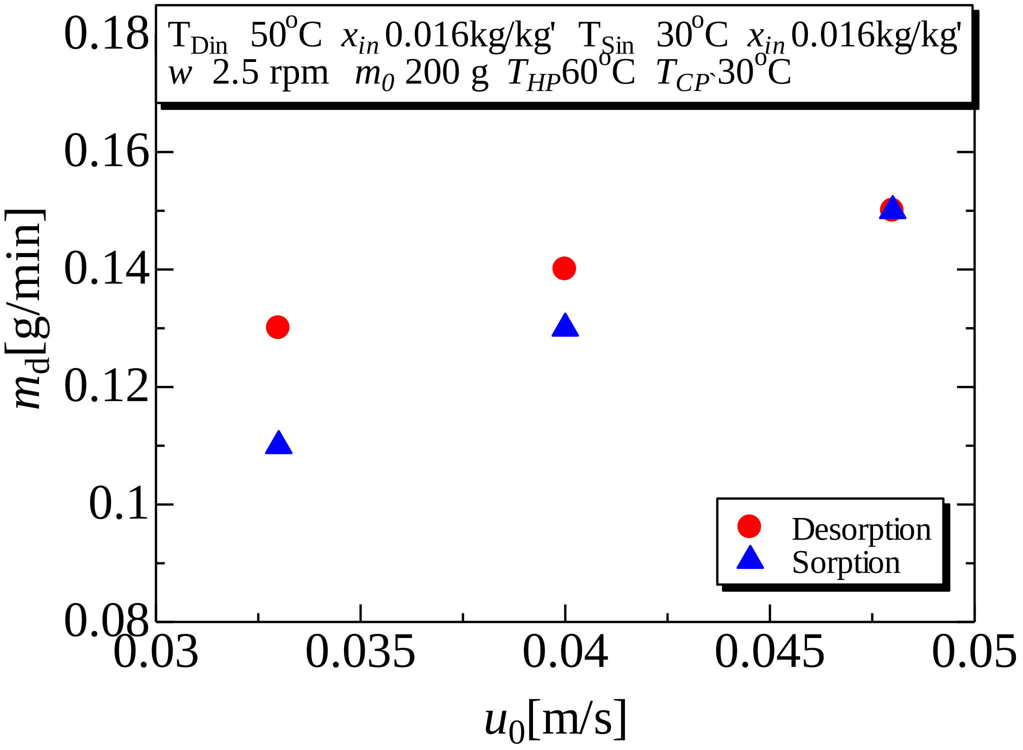

Fig. 5-16 Velocity effect on amount of dehumidification (2.5 rpm)

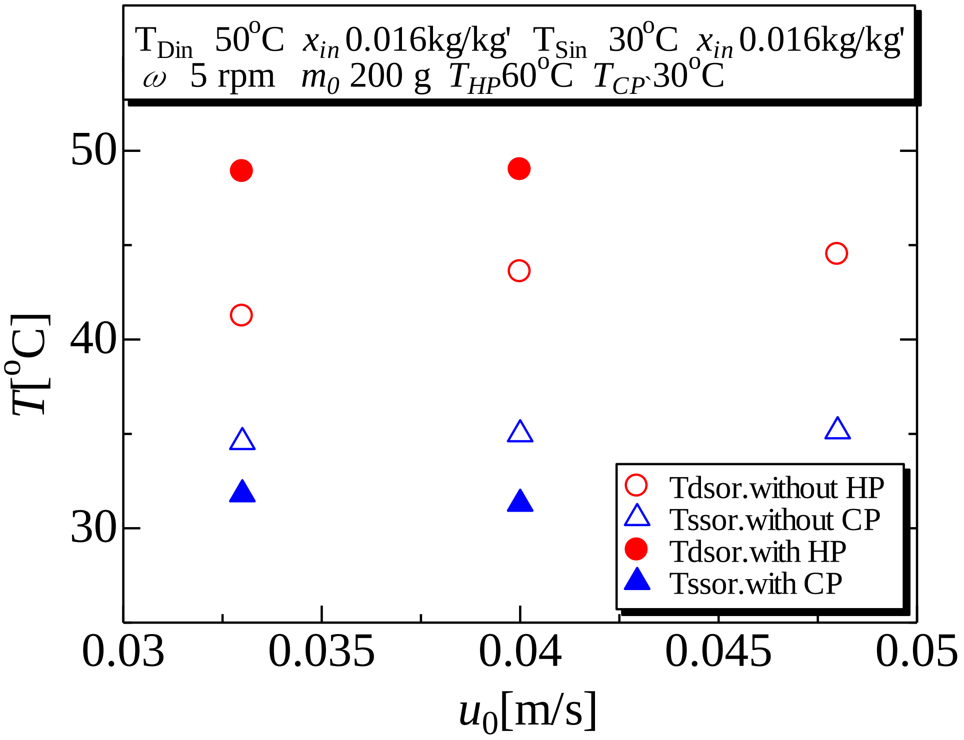

Fig. 5-17 Velocity effect on sorbent temperature

5.5 Spiral Revolution Speed Effect

Figure 5-18 shows the effect of spiral revolution speed to the absolute humidity of air at outlet for sorption and desorption process. This figure also shows the comparison between sorption and desorption process without heating (HP) or cooling pipe (CP) and with heating or cooling pipe. Absolute humidity out of desorption process without heating pipe is lower than that of with heating pipe. As known, desorption process at desorption chamber needs high temperature to release its water content, while sorption process at sorption chamber needs low temperature to sorb water vapor from the air. Heating pipe which is inserted to desorption chamber can improve the sorbent temperature so that the sorbent ability to release its water content increases. By inserting cooling pipe at sorption chamber, sorbent temperature at sorption chamber is not increase by the sorption process as it was occurring without cooling pipe, so that sorbent temperature at sorption chamber is below 33°C, while as previous experiment result, 30°C is the good temperature of this organic sorbent for sorption process(5-9). And as can be seen in Figure 5-19, sorbent temperature different between desorption and sorption chambers have the same tendency with sorbent temperature different without heating or cooling pipe.

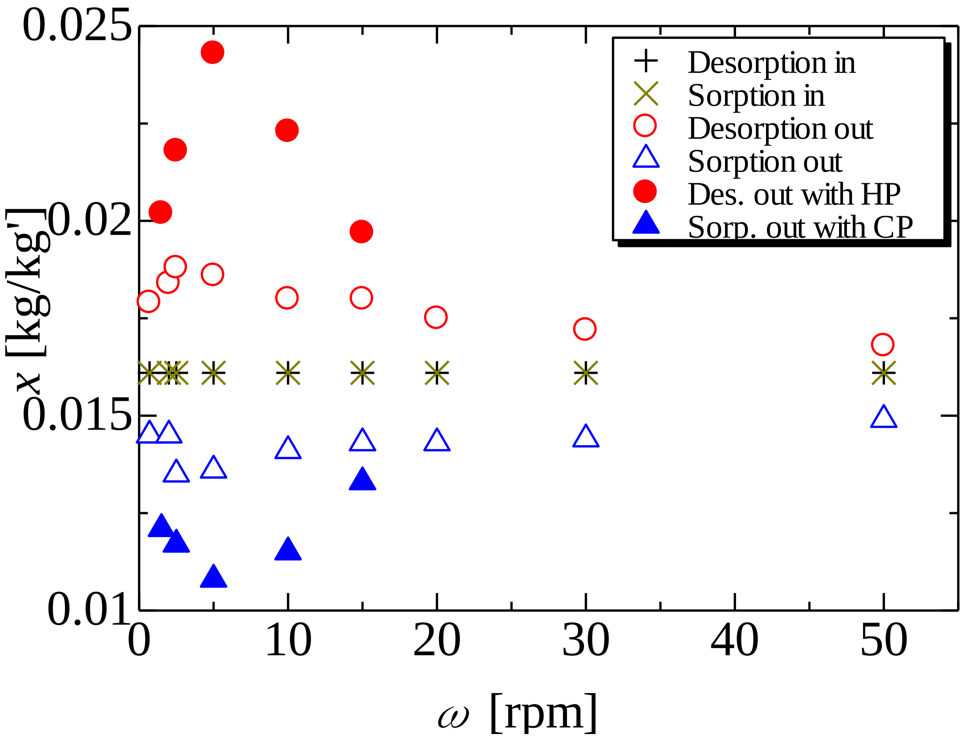

Fig. 5-18 Spiral revolution speed effect on absolute humidity

On desorption process, firstly absolute humidity out increases by increasing spiral speed revolution, until the peak is reach at 5 rpm. Then, absolute humidity decreases by increasing the spiral revolution speed. For sorption chamber, the increasing spiral revolution speed decreases the absolute humidity out. And the lowest value of absolute humidity out from sorption chamber is at 5 rpm and the value increases with the increasing spiral revolution speed. This pattern can be seen also for the amount of dehumidification in Figure 5-20. Comparing the absolute humidity out of desorption and sorption process without HP or CP and with HP or CP, the peak of absolute humidity out is different. The highest absolute humidity of desorption process without HP is at 2.5 rpm while desorption process with HP is at 5 rpm. The lowest absolute humidity of sorption process without CP is at 2.5 rpm and 5 rpm for sorption process with CP. By inserting HP pipe in desorption chamber, sorbent temperature in the chamber increases. Increasing the sorbent temperature in desorption chamber also increases the ability of sorbent to release its water content and furthermore increases the amount of sorbent that can be releasing its water content. On the other hand, inserting CP pipe at sorption chamber, sorbent temperature decreases, so that the ability of sorbent to sorb water vapor from air increases and the amount of sorbent that can sorb water vapor increases. Amount of sorbent which is transferred by spiral revolution speed 2.5 and 5 rpm is 1.5 and 3 g/min respectively. This condition also enhanced by Figure 5-21 and 5-22.

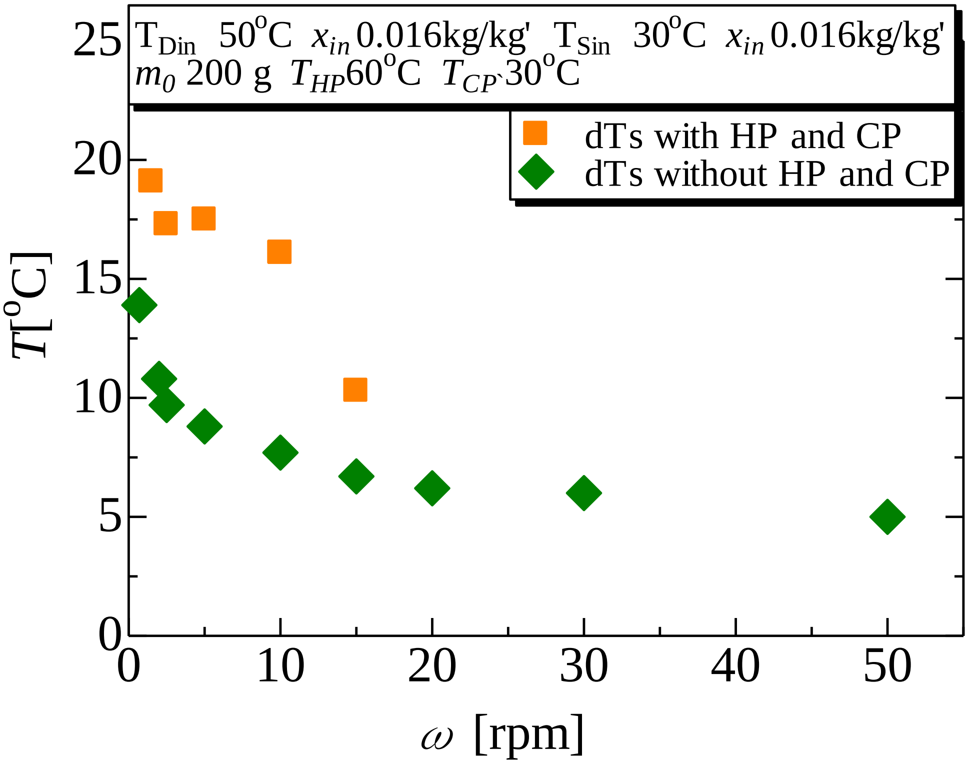

Fig. 5-19 Sorbent temperature different between the chambers

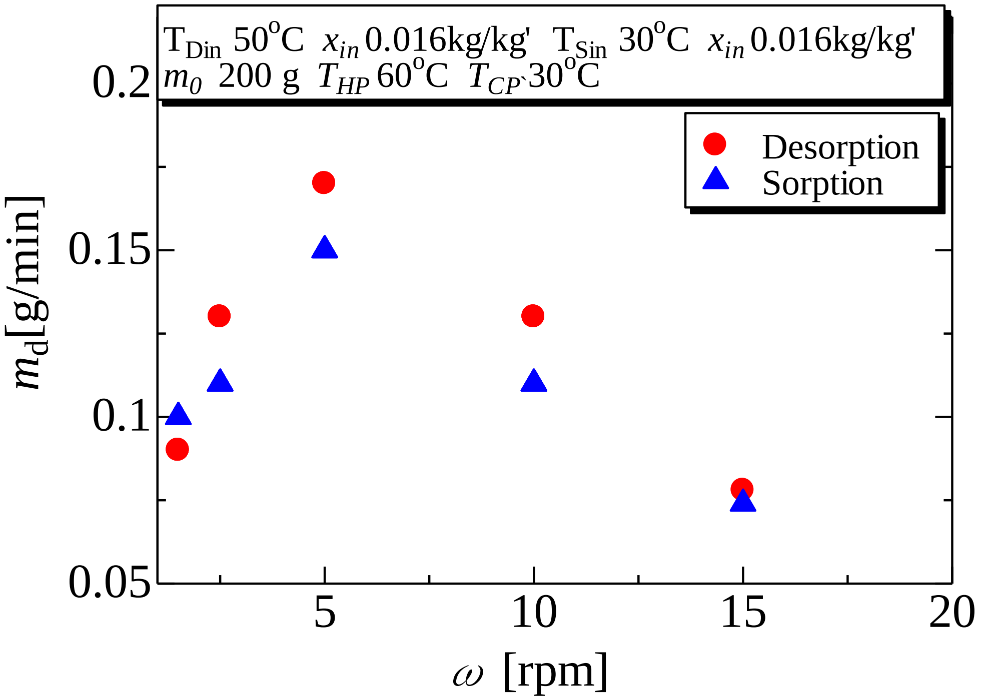

Fig. 5-20 Spiral revolution speed effect on amount of dehumidification

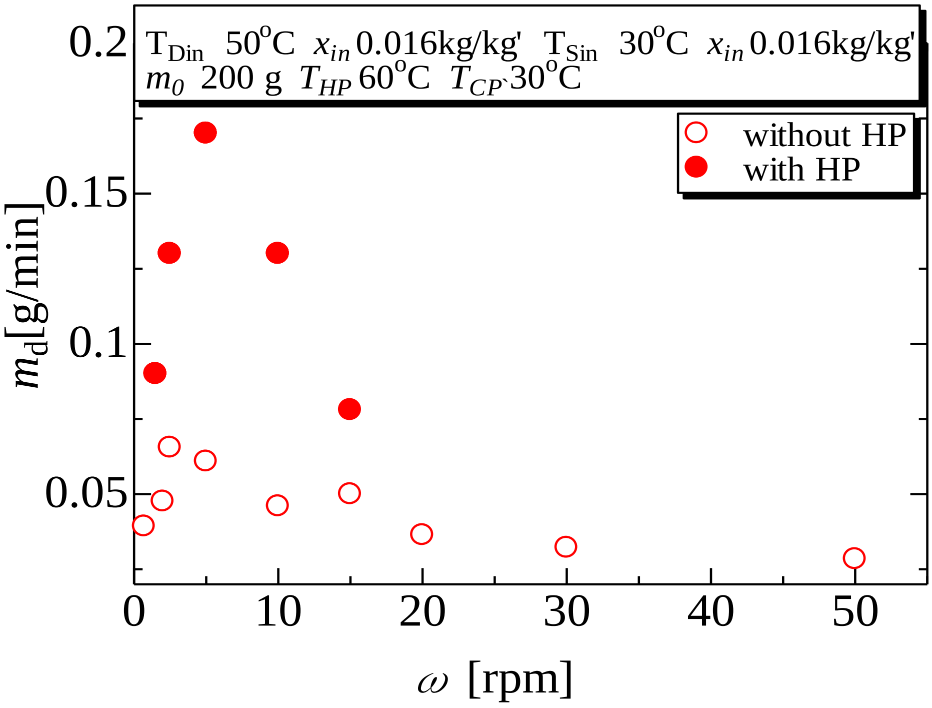

Fig. 5-21 Spiral revolution speed effect on amount of dehumidification

(Desorption with and without heating pipe)

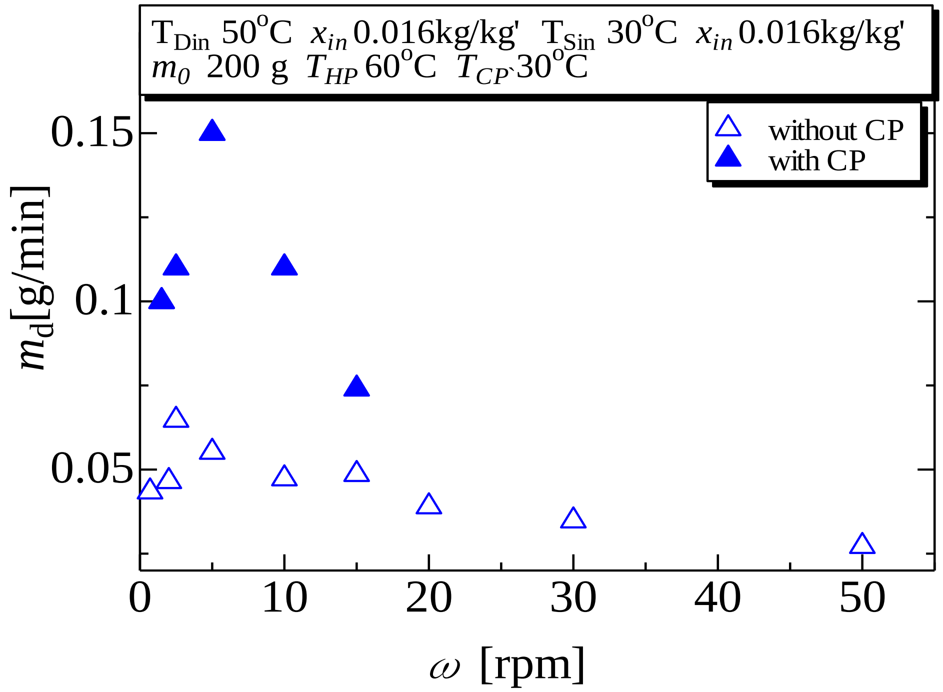

Fig. 5-22 Spiral revolution speed effect on amount of dehumidification

(Sorption with and without cooling pipe)

5.6 Summary

The dehumidification characteristics of organic powder sorption materials have been studied by using continuous fluidized bed with a heating pipe (HP) and a cooling pipe (CP). Differently from the previous chapter, the present chapter deals with powder type organic sorbent in continuous fluidized bed with HP or CP pipes which were inserted in the chambers. Sorption rate of water vapor and the variation of temperature in the sorbent bed with time were measured under various conditions.

Increasing desorption heating pipe temperature increases absolute humidity out at desorption chamber, and decreases absolute humidity out at sorption chamber. Increasing desorption heating pipe temperature will affecting desorption sorbent temperature to increase. The value of absolute humidity for sorption and desorption process without heating pipe is lower than that of process with heating pipe. The increasing in desorption HP temperature increases the amount of dehumidification.

The decreasing of desorption absolute humidity out and the increasing of sorption absolute humidity out with the increase of sorption cooling pipe temperature. The increasing sorbent temperature at sorption chamber by increasing the sorption CP temperature while sorbent temperature at desorption chamber constant. The increasing sorbent temperature decreases the ability of sorbent to sorb water vapor. The difference value of the amount of dehumidification is getting bigger by the increasing of sorption CP temperature.

A small increasing of absolute humidity at desorption chamber and decreasing at sorption chamber were found by increasing the air velocity process without heat exchanger. By inserting HP or CP in the chamber, increasing the velocity, a small decreasing of absolute humidity out occurs at desorption and sorption chamber. Absolute humidity out for desorption process with HP is higher than without HP. Heating pipe is able to increase desorption sorbent temperature to around 49°C, while cooling pipe is able to maintain sorbent temperature in the chamber around 31°C.

Absolute humidity out of desorption process without HP is lower than that of with HP. On desorption process, firstly absolute humidity out increases by increasing spiral revolution speed, until the peak is reach at 5 rpm. Then, absolute humidity decreases by increasing the spiral revolution speed. For sorption chamber, the increasing spiral revolution speed decreases the absolute humidity out. And the lowest value of absolute humidity out from sorption chamber is at 5 rpm and the value increases with the increasing spiral revolution speed. The peak of absolute humidity out without HP or CP and with HP or CP is different. The highest absolute humidity of desorption process without HP is at 2.5 rpm while desorption process with HP is at 5 rpm. The lowest absolute humidity of sorption process without CP is at 2.5 rpm and 5 rpm for sorption process with CP. Increasing the sorbent temperature in desorption chamber by inserting HP is causing the ability of sorbent to release its water content increases and furthermore increases the amount of sorbent that can be releasing its water content. So that the peak of spiral revolution speed is changing from 2.5 rpm to 5 rpm where the amount of sorbent is transferred changes from 1.5 to 3 g/min.

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Nomenclature

m_d : amount of dehumidification, g/min

m_0 : sorbent mass, kg

m_w/m_0 : dimensionless sorption ratio

T : temperature, ℃

t : time, s

u_o : inlet air velocity, m/s

HP : heating pipe

CP : cooling pipe

Greek symbols

ρ : density, kg/m^3

ω : spiral revolution speed, rpm

x : absolute humidity, kg/kg'

ψ : relative humidity, %

Subscripts

Din : desorption inlet

g : gas

Sin : sorption inlet

p : sorbent

Chapter 6

Mathematical Modeling and Numerical Analysis

6.1 Mathematical Modeling

As a preliminary step in hydrodynamic modeling of fluidized bed, the main features of the bed such as flow-rate through the phases, volume fractions, contacting pattern of materials, and other related parameters must be known. Flow pattern and its behavior is one of the most complicated and unpredictable challenge in fluidization. As a result of the solids movement and the bubbling action, the fluidizing gas passes through the bed in a complex and random manner. In the early days, simple contacting models such as plug flow, mixed flow, dispersion, and tanks in series were tried. The aim of these models was to account for the observed nonhomogenity of fluidized bed, in effect, the bubble and the dense phase.

Hajidavalloo and Hamdullahpur(6-1) explained that in 1960s there were two major advances in the understanding of gas/solid contacting in bubbling fluidized bed, firstly, Davidson’s analysis of the flow of gas within and in the vicinity of rising gas bubbles and, secondly, Rowe’s finding that a rising bubble was accompanied by a wake of solids and that this was the main mechanism causing solid circulation in fluidized bed.

These developments led to a new class of fluidized bed models called the hydrodynamic models, in which the bed behavior was based on the characteristics of these rising bubbles. Over a dozen of these models have been proposed but all to the extreme of very fine particles in which the rising bubbles are surrounded by very thin clouds of circulating gas mainly because it was often of practical importance in the fluidized bed reactors. That is the reason why most work on fluidized bed drying employed the hydrodynamic model suitable for small size particle (group A as can be seen in Figure 6-1) irregardless of the characteristics of particle used for drying. However, with increasing in the use of large particle beds in different applications, researchers have examined them and developed many hydrodynamic models to predict the behavior of bubble and dense phase(6-2).

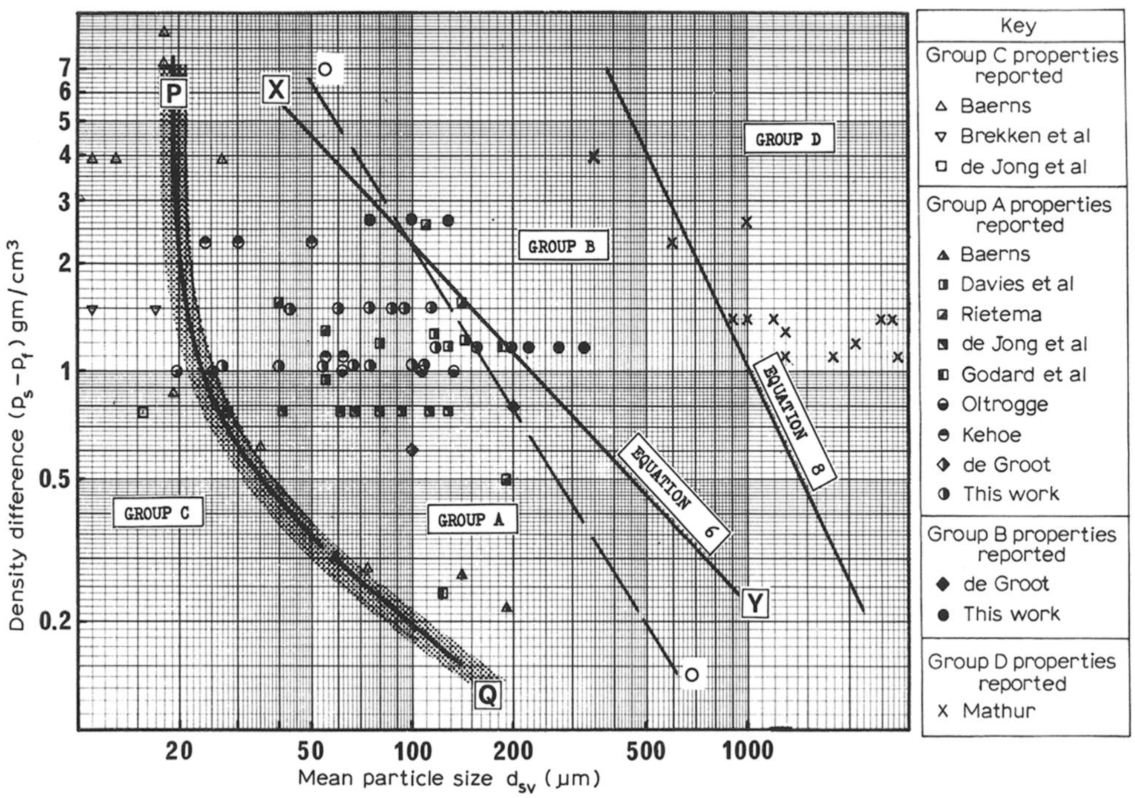

Fig. 6-1 Powder classification diagram for fluidization by air(6-2)

6.1.1 Gas Flow Pattern in Fluidized Bed

Gas flow in fluidized bed is not uniform. This nonuniformity manifests itself as existence of different phases inside the bed. A first attempt to model the bed behavior was two-phase theory which later on was found has some shortcoming to cover all types of fluidization. Discrepancies up to 50% in the value of flow rate was reported(6-2) in using the two-phase theory of fluidization. Different theories were proposed for modeling the fluidization process considering its variation with particle type.

Particles which fall into group A Particles are relatively of small size(6-2). Two-phase theory is fairly an accurate model for this type of material. When these particles are fluidized, the bed expands considerably at velocities between u_{mf} and the velocity at which bubbles appears, u_{mb}. This is as a result of slightly cohesive forces between these particles. Gas bubbles rise more rapidly than the rest of the gas, which percolates through the emulsion. These gas bubbles appear to split and coalesce frequently as they rise through the bed, resulting in a restricted bubble size not far above the distributor, usually less than 10 cm, even in large bed. So the assumption of average bubble size can reasonably be used for this group. Since a constant size of bubble can be assumed for this group, the voidage distribution could be assumed constant along the bed height.

Because the bubble rises much faster than emulsion gas, according to Davidson’s analysis, the rising bubbles are surrounded by thin clouds of re circulating gas. This cloud restricts the heat and mass transfer between bubble gas and interstitial gas. As mentioned earlier, two-phase model is suitable for this type of particles which assumes that all the gas in excess of u_{mf} flows through the bed as bubbles while the emulsion stays at minimum fluidizing conditions. So the following correlation from two-phase model can be used.

The bubble flowrate is evaluated based on the finding of Hilligardt and Werther as proposed in Hajidavalloo(6-1):

$$Q_b = \psi\left(u_0 - u_{mf}\right)A_t \tag{1}$$

where Ψ is constant which proposed by Hilligardt and Werther in Hajidavalloo, and its value is 0.85 for group A particles of Geldart`s classification (6-2). Here Q_b is bubble flow rate (m^3/s), u_0 is superficial gas velocity (m^2/s), u_{mf} is minimum fluidization velocity (m^2/s) and A_t is Cross section area of chamber (m^2).

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For the bubble size, the correlation proposed by Darton et al in Kunii and Lavenspiel(6-3) is used.

$$d_b = 0.54\left(u_0 - u_{mf}\right)^{0.4}\left(H_f + 4\sqrt{A_o}\right)^{0.8} g^{-0.2} \tag{2}$$

where: H_f = expanded bed height, m

A_0 = distributor plate area per orifice, m^2

g = gravity acceleration, m s^{-1}

The bubble rise velocity is predicted using the following correlation,

$$u_b = (u_0 - u_{mf}) + 0.71(gd_b)^{0.5} \tag{3}$$

The bubble voidage is predicted by,

$$\varepsilon_b = \frac{Q_b}{A_t u_b} \tag{4}$$

$$H_f = \frac{m_s}{\rho_s \varepsilon_s A_t} = \frac{H_{mf}}{1-\varepsilon_b} \tag{5}$$

where: m_s = solid moisture content, dry basis, kg water/kg solid

ρ_s = density of solid, kg m^{-3}

ε_s = solid volume fraction in bed

H_{mf}= bed height at minimum fluidization condition, m

For relatively dry particles, the minimum fluidization velocity, u_{mf} is given by Kunii and Levenspiel$^{(6\text{-}3)}$:

$$\frac{1.75}{\varepsilon_{mf}^3 \phi_s} R_{e\,mf}^{\;2} + \frac{150(1-\varepsilon_{mf})}{\varepsilon_{mf}^3 \phi_s^2} R_{e\,mf} = Ar \tag{6}$$

where: ε_{mf} = void fraction at minimum fluidization condition, dimensionless

ϕ_s = sphericity of sorbent particles, dimensionless

Re_{mf} = Reynolds number at minimum fluidization, dimensionless

Ar = Archimedes number, dimensionless

$$Re_{mf} = \frac{d_p u_{mf} \rho_g}{\mu_g} \tag{7}$$

$$Ar = \frac{d_p^3 \rho_g \left(\rho_s - \rho_g\right) g}{\mu_g^2} \tag{8}$$

where: ρ_g = density of gas, kg m^{-3}

μ_g = viscosity of gas, kg m^{-1} s^{-1}

d_p = Particle diameter, m

6.1.2 Mass Balance

The present mathematical model can be considered as an extension of the traditional model being based on the assumption of the equilibrium between the outlet streams. To describe the heat and mass transfer in gas phase, a mathematical model being proposed by Lai and Chen(6-4) type, two phase theory fluidization, is employed. The underlying assumptions of this theory are:

1. The bed is divided into two, gas and solid sorbent.
2. The excess flow of the fluidizing fluid above minimum fluidization conditions.
3. The emulsion gas and sorbent particles are perfectly mixed.
4. Solid sorbent are added and removed at a constant rate.
5. The inlet temperature and moisture content of sorbent particles are assumed to be uniform.
6. The internal resistance of solid sorbent to mass and heat transfer is negligible
7. Solid sorbent are considered to be uniform in size, shape and particle properties
8. Their residence time distribution function is steady state is given by:

$$f\left(t_d\right) = \frac{1}{\bar{t}_d} \exp\left(-\frac{t_d}{\bar{t}_d}\right) \tag{9}$$

where: t_d = residence time distribution, s

$\bar{t}_d$ = mean residence time distribution of sorbent in the chamber, s

9. Viscous dissipation is negligible.
10. The changes in the physical properties of both solid sorbent and the gas due to the change of temperature are negligible.

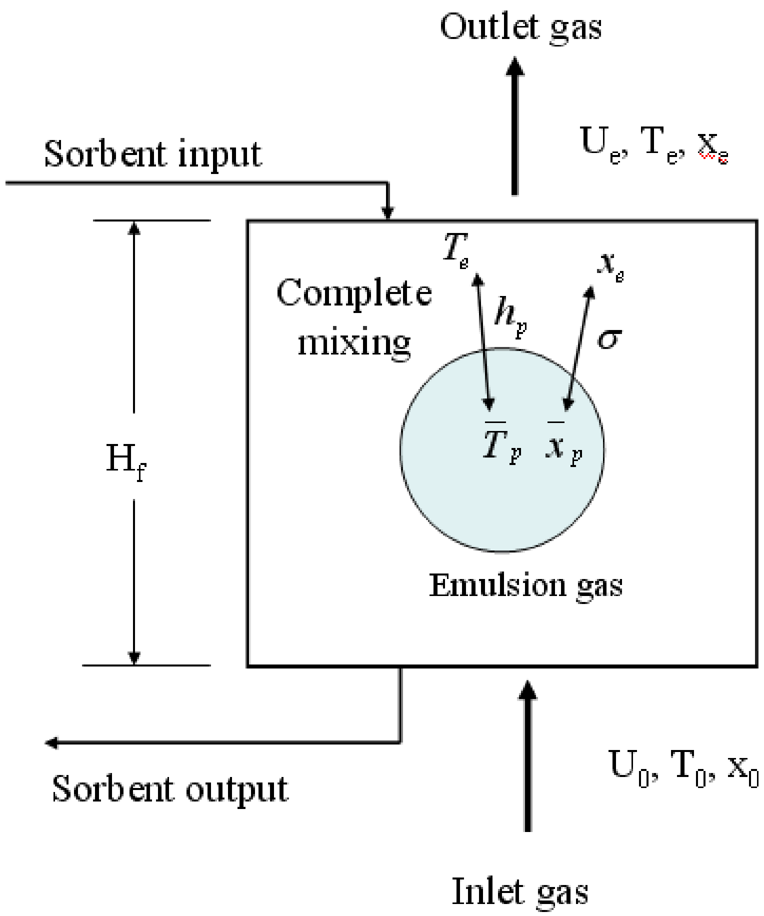

Fig. 6-1 Schematic diagram of continuous desoprtion process in the fluidized bed

Interstitial gas

$$A_t u_{mf} \rho_g (x_e - x_0) = \overline{N}_{wg} S_{\exp} \tag{10}$$

where: x_e = moisture content of emulsion, dimensionless

x_0 = moisture content of air at inlet, dimensionless

$\overline{N}_{wg}$ = average mass flux, kg/m s

S_{exp} = solid feed rate, kg/s

The right hand side of equation 10 is the time average mass flow rate of the releasing moisture and it can be expressed on the basis of the residence time distribution of the sorbent particles.

$$\overline{N}_{wg}=\frac{1}{\bar{t}_d}\int_0^{\infty}f(t_d)N_{wg}(t_d)dt_d \tag{11}$$

or with the evaporation coefficient

$$\overline{N}_{wg}=\frac{1}{\bar{t}_d}\int_0^{\infty}f(t_s)\sigma\left(x_p^{*}-x_e\right)dt_d \tag{12}$$

where: x_p^{*} = moisture content of air at the surface of a particle, dimensionless

$\bar{x}_p^{*}$ is supposed to be time dependent:

$$\overline{N}_{wg}=\sigma\left(\bar{x}_p^{*}-x_e\right) \tag{13}$$

Average moisture content of the gas on the surface of a particle $\bar{x}_p^{*}$:

$$\bar{x}_p^{*}=\int_0^{\infty}\frac{1}{\bar{t}_d}\exp\left(-\frac{t_d}{\bar{t}_d}\right)x_p^{*}dt_d \tag{14}$$

Considering that,

$$\frac{S_{\exp}}{V_b}=\frac{S_{\exp}}{V_s}\left(1-\varepsilon_{mf}\right)\frac{V_e}{V_b}=\frac{6}{d_p}\left(1-\varepsilon_{mf}\right)\frac{1-\delta_b}{\delta_b} \tag{15}$$

where: V_b = volume of bubble, m^3

V_s = volume of solid, m^3

V_e = volume of emulsion, m^3

δ_b = fraction of the fluidized bed consisting bubbles, dimensionless

Moisture balance around the entire gas

$$\left(u_{mf} A_t\right)\rho_g\left(x_e - x_0\right) = \left(H_f A_t\right)\left(1-\delta_b\right)\left(1-\varepsilon_{mf}\right)\left(\frac{6}{d_p}\right)\sigma\left(\bar{x}_p^* - x_e\right) \tag{16}$$

$$\rho_g \frac{u_{mf}}{H_f \delta_b}\left(x_e - x_0\right) = \frac{\left(1-\varepsilon_{mf}\right)\left(1-\delta_b\right)}{\delta_b}\frac{6}{d_p}\sigma\left(\bar{x}_p^* - x_e\right) \tag{17}$$

where: σ = evaporation coefficient which is proposed by Palancz(6-5).

Because of the limitations of the flow rate meter that is used in this experiment, so that for the minimum fluidization velocity can be approximated by the following formula(6-3):

$$u_{mf} = \frac{d_p{}^2\left(\rho_s - \rho_g\right)g}{1650\,\mu_g} \qquad Re_p < 20 \tag{18}$$

Bubble growth by the following formula(6-1),

$$d_b = 0.54\left(u - u_{mf}\right)^{0.4}\left(H + 4\sqrt{A_0}\right)^{0.8} g^{-0.2} \tag{19}$$

The rising velocity of a single bubble relative to the emulsion phase is

$$u_{br} = 0.71\left(g\, d_b\right)^{0.5} \tag{20}$$

The bed fraction of bubble phase:

$$\delta_b = \frac{\left(u_0 - u_{mf}\right)}{\left(u_0 - u_{mf}\right) + u_{br}} \tag{21}$$

The voidage of the emulsion can be roughly approximated as proposed by Broadhurst and Becker$^{(6-6)}$:

$$\varepsilon_{mf} = 0.586\phi_s^{-0.72}\left[\frac{\mu_g^2}{\rho_g(\rho_{ws}-\rho_g)gd_p^3}\right]^{0.029}\left(\frac{\rho_g}{\rho_{ws}}\right)^{0.021} \tag{22}$$

where: ρ_{ws} = density of wet solid, kg m^{-3}

The following evaporation coefficient σ is proposed by Palancz$^{(6-5)}$ also used by Aly and Fathalah$^{(6-7)}$ for cyclic operation of the bed using silica gel to dehumidify the air stream. And a good match of the model is found. The coefficient is as follows:

$$\sigma = \frac{h_p \rho_g D_g}{k_g} \tag{23}$$

The heat transfer coefficient between the surface of a sphere of diameter d_p and a fluid through which it is moving with relative velocity u_0 is given by Ranz and Marshall which is proposed by Kunii and Levenspiel$^{(6-3)}$.

$$Nu_p = \frac{h_p d_p}{k_g} = \left(2 + 0.6\,\mathrm{Pr}_g^{1/3}\,\mathrm{Re}_p^{1/2}\right) \tag{24}$$

where: h_p = Heat transfer coefficient between gas and solids, J $s^{-1}m^{-2}$ °C^{-1}

k_g = thermal conductivity of gas, J m^{-1} °C^{-1}

Pr_g = Prandtl number, dimensionless

$$Pr_g = \frac{c_g \mu_g}{k_g} \tag{25}$$

where: c_g = specific heat of gas, $kJkg^{-1}$ °C^{-1}

$$Re_p = \frac{d_p u_0 \rho_g}{\left(1-\varepsilon_{mf}\right)\mu_g} \tag{26}$$

x_p^* expressed by Palancz(6-5):

$$x_p^* = \phi_1\left(T_p\right)\phi_2\left(x_p\right) \tag{27}$$

with

$$\phi_1\left(T_p\right) = 0.622\,\frac{P_w}{760 - P_w} \tag{28}$$

where: P_w = Pressure of saturated water vapor, mm Hg

$$P_w = 10^{\left(0.622 + \frac{7.5T_p}{238 + T_p}\right)} \tag{29}$$

where: T_p = Temperature of particle, ℃

From Palancz(6-5),

$$\phi_2\left(x_p\right) = \frac{x_p^n}{\left(x_p^n + K\right)} \qquad \text{for } x_p \le x_{pc} \tag{30}$$

where: n and K are constant

x_p = moisture content of solid

A moisture balance in a single sorbent:

$$\rho_s \frac{dx_p}{dt_s} = -\left(1 + \frac{\rho_s}{\rho_w} x_{pc}\right) \frac{6}{d_p} \sigma\left(x_p^* - x_e\right) \tag{31}$$

With boundary condition

$x_p = x_{p0}$ at $t_d = 0$

6.1.3 Heat balance

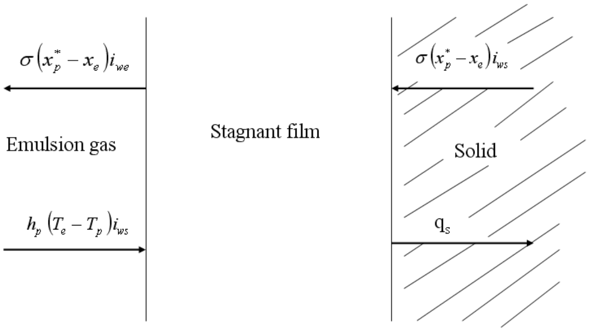

Fig. 6-2 Heat balance around the stagnant film surrounding a solid particle

A steady state heat balance around the entire emulsion gas gives:

$$\begin{aligned}&\left(u_{mf} A_t\right)\rho_g\left(i_0 - i_e\right) + \left(H_f A_t\right)\left(1-\delta_b\right)x\left(1-\varepsilon_{mf}\right)\frac{6}{d_p}\sigma\left(\bar{x}_p^* - x_e\right)\bar{i}_{ws} = \\ &\left(H_t A_t\right)\left(1-\delta_b\right)\left(1-\varepsilon_{mf}\right)\frac{6}{d_p} h_p\left(T_e - \bar{T}_p\right)\end{aligned} \tag{32}$$

Where,

$$\bar{i}_{ws} = c_{wv}\left(\bar{T}_p - T_{ref}\right) + \gamma_0 \tag{33}$$

$$i_0 = c_g\left(T_0 - T_{ref}\right) + x_0\left[c_{wv}\left(T_0 - T_{ref}\right) + \gamma_0\right] \tag{34}$$

$$i_e = c_g\left(T_e - T_{ref}\right) + x_e\left[c_{wv}\left(T_e - T_{ref}\right) + \gamma_0\right] \tag{35}$$

$\overline{T}_p$ is average temperature of particle and time dependent,

$$\overline{T}_p = \int_0^{\infty} \frac{1}{\overline{t}_d} \exp\left(-\frac{t_d}{\overline{t}_d}\right) T_p dt_d \tag{36}$$

$$\frac{\rho_g u_{mf}}{H_f}\left(c_g + c_{wv}x_0\right)\left(T_e - T_0\right) = \left(1-\delta_b\right)\left(1-\varepsilon_{mf}\right)\frac{6}{d_p}\left(\overline{T}_p - T_e\right) x \left[c_{wv}\sigma\left(\overline{x}_p^{*} - x_e\right) + h_p\right] \tag{37}$$

Heat balance in a single sorbent:

$$\rho_s\left(c_p + x_p c_w\right)\frac{dT_p}{dt_d} = \left(1 + \frac{\rho_s}{\rho_w}x_{pc}\right)\frac{6}{d_p}\left[h_p\left(T_e - T_p\right) - \sigma\left(x_p^{*} - x_e\right) x \left(c_{wv}T_e - c_w T_p + \gamma_0\right)\right] \tag{38}$$

with boundary condition

$T_p = T_{p0}$ at $t_d = 0$

where: c_w = Specific heat of water, kJ kg^{-1} °C^{-1}

c_g = Specific heat of gas, kJ kg^{-1} °C^{-1}

c_p = Specific heat of sorbent, kJ kg^{-1} °C^{-1}

c_{wv} = Specific heat of water vapor, kJ kg^{-1} °C^{-1}

The absolute humidity and temperature of the outlet air can be evaluated from the moisture and heat balances as follows:

$$u_0 x_{out} = u_{mf} x_e \tag{39}$$

$$T_{out} = \frac{1}{u_0\left(c_g + x_{out}c_{wv}\right)}\left\{u_{mf}\left[c_g T_e + x_e\left(c_{wv}T_e + \gamma_0\right]\right. - u_0 x_{out}\gamma_0\right\} \tag{40}$$

To obtain the solution of the model equation, a two dimensional trial and error is conducted. For simplification, intermediate variables proposed by Lai and Chen(6-4) is used:

$$X_p^* = \frac{1}{\bar{t}_d}\int_0^{t_d} x_p^* exp\left(-\frac{t_d}{\bar{t}_d}\right) \tag{41}$$

or $$\frac{dX_p}{dt_d} = \frac{x_p^*}{\bar{t}_d} exp\left(-\frac{t_d}{\bar{t}_d}\right) \tag{42}$$

with the boundary condition

$X_p^* = 0$ at $t_d = 0$

$$T_p^* = \frac{1}{\bar{t}_d}\int_0^{t_d} T_p exp\left(\frac{t_d}{\bar{t}_d}\right) dt_d \tag{43}$$

or $$\frac{dT_p^*}{dt_d} = \frac{T_p}{\bar{t}_d} exp\left(-\frac{t_d}{\bar{t}_d}\right) \tag{44}$$

with the boundary condition

$T_p^* = 0$ at $t_d = 0$

$$\bar{x}_p^* = X_p^*\Big|_{t_d = t_d^0} + x_p^*\Big|_{t_d = t_d^0} exp\left(-\frac{t_d^0}{\bar{t}_d}\right) \tag{45}$$

$$\bar{T}_p = T_p^*\Big|_{t_d = t_d^0} + T_p\Big|_{t_d = t_d^0} exp\left(-\frac{t_d^0}{\bar{t}_d}\right) \tag{46}$$

6.2 Computation Procedure

To investigate the effect of the change in the model parameters to the moisture content of the solid outlet, a numerical study was carried out. The following parameters were considered:

- Diameter of the solid particles
- Moisture content, temperature and velocity of inlet air gas
- Diameter of gas bubbles in fluidized bed
- Average residence time distribution of solid particles

Step 1. The following input parameters were selected:

- Temperature of air entering the dryer column, T_0
- Absolute humidity of inlet air, x_0
- Velocity of inlet air, u_0
- Temperature of the initial sorbent in the chamber, T_p
- Initial moisture content of the sorbent x_{p0}
- Critical moisture content of the sorbent x_{pc}
- Sorbent particle diameter, d_p
- Weight of the material, m_0
- Spiral revolution speed, ω

Step 2. The following additional operational input parameters were obtained from experimental data and table, and input in the model:

- Density of air, ρ_a
- Density of sorbent particle, ρ_s
- Viscosity of air, μ_g
- Thermal conductivity of air, k_g
- Specific heat of water, c_w
- Specific heat of water vapor, c_{wv}
- Specific heat of air, c_g
- Specific heat of sorbent, c_p
- Expanded bed height, H_f

- Gas diffusivity, D_g

Step 3. Compute the residence time distribution base on the amount of sorbent in the chamber

$$F_0 = 0.6\omega \tag{47}$$

$$t_d = \frac{m_0}{F_0} \tag{48}$$

Step 4. The following output parameters were calculated:

- Intermediate variable of moisture content, Eq. 41
- Intermediate variable of sorbent particle temperature, Eq. 43
- Moisture content of air at the surface of a particle, Eq. 27
- Pressure of saturated water vapor, Eq. 29
- Moisture content of particle, Eq. 31
- Temperature Particle, 38

The following is flow chart for computational the mathematical model developed.

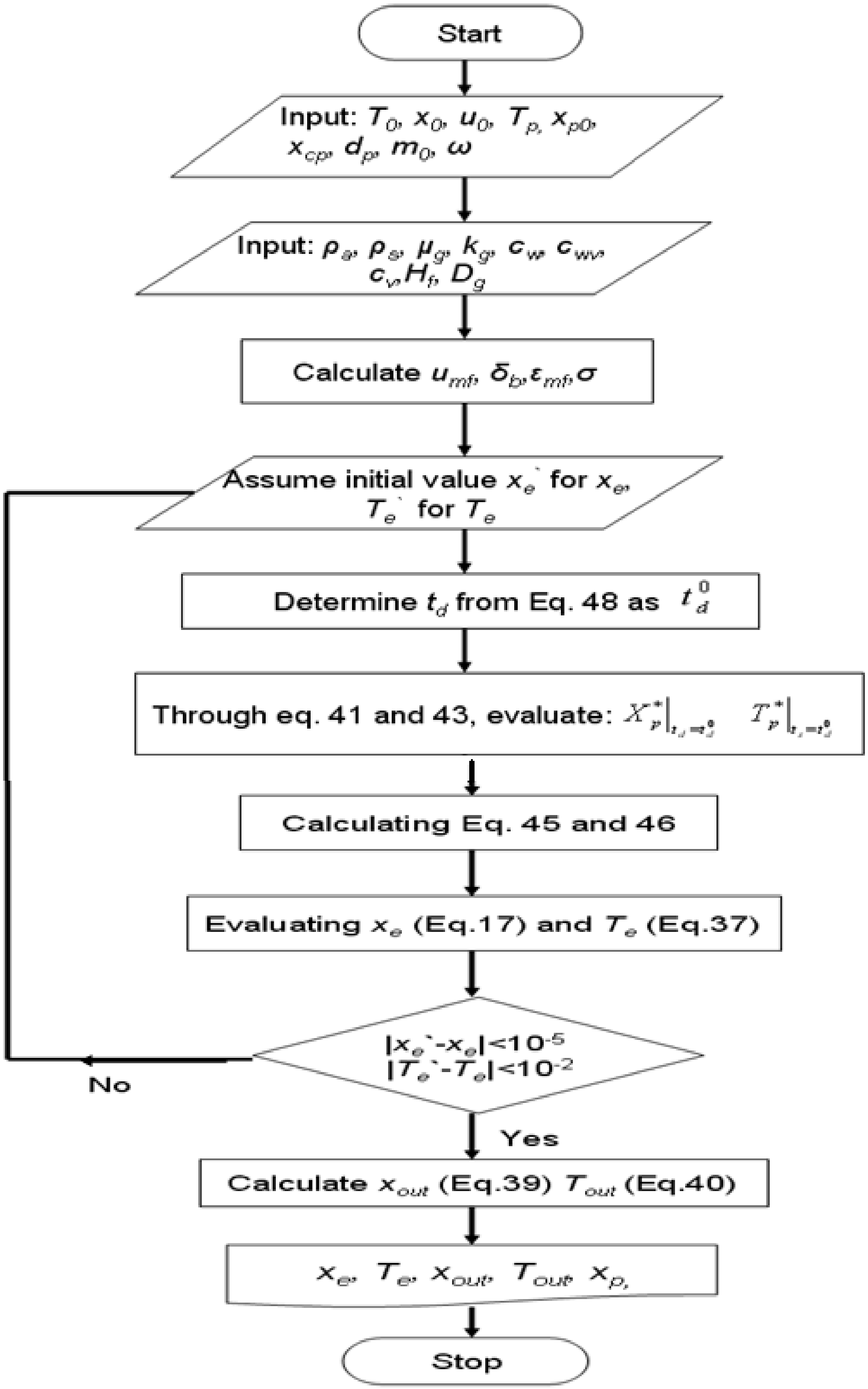

Table 6-1 Input parameters

Input Parameters	**Value**	**Units**
Inlet air temperature (T_0)	50	°C
Inlet air absolute humidity (x_0)	0.016	kg/kg`
Inlet air velocity (u_0)	0.033	$m\ s^{-1}$
Temperature of the initial sorbent (T_p)	47	°C
Initial moisture content of sorbent (x_{p0})	0.35	-
Critical moisture content of sorbent (x_{cp})	0.45	-
Sorbent particle diameter (d_p)	0.000113	m
Sorbent initial weight (m_0)	0.2	kg
Spiral revolution speed (ω)	2.5	rpm

Table 6-2 Additional operational input parameters

Input Parameters	**Value**	**Units**
Density of air (ρ_g)	1.2	$kg\ m^{-3}$
Density of sorbent particle (ρ_s)	913	$kg\ m^{-3}$
Viscosity of air (μ_g)	1.8×10^{-5}	$kg\ m^{-1}s^{-1}$
Thermal conductivity of air (k_g)	0.0293	$J\ m^{-1}\ s^{-1}\ °C^{-1}$
Specific heat of water (c_w)	4.19	$kJ\ kg^{-1}°C^{-1}$
Specific heat of water vapor (c_{wv})	1.93	$kJ\ kg^{-1}°C^{-1}$
Specific heat of sorbent (c_p)	1.4	$kJ\ kg^{-1}°C^{-1}$
Heat of evaporation (γ_0)	2.5×10^3	$kJ\ kg^{-1}$
Expanded bed height (H_f)	0.04	m
Gas diffusivity (D_g)	2×10^{-5}	$m^2\ s^{-1}$

6.3 Results and Discussions

In order to assess the validity of the mathematical model and test its accuracy, the results of numerical solutions are compared with experimental data for continuous desorption process. In developing the mathematical model, attempts have been made to avoid using simplifying assumptions so that the more accurate and general model can be use to analyze configurations. However, in spite of this effort, there are many areas that still need to use simplifying assumptions. Those are mostly because of the lack of experimental data to use for modeling purposes. Some assumptions were made in development of the model and numerical solution as mentioned above.

Dehumidification experiments were carried out on the sorbent to obtain complete and reliable experimental results for comparison with the results of mathematical model. Different types of data are collected during the experiment. These are: temperature of sorbent particle, humidity of outlet air and moisture content of the sorbent particle at different resident time distribution.

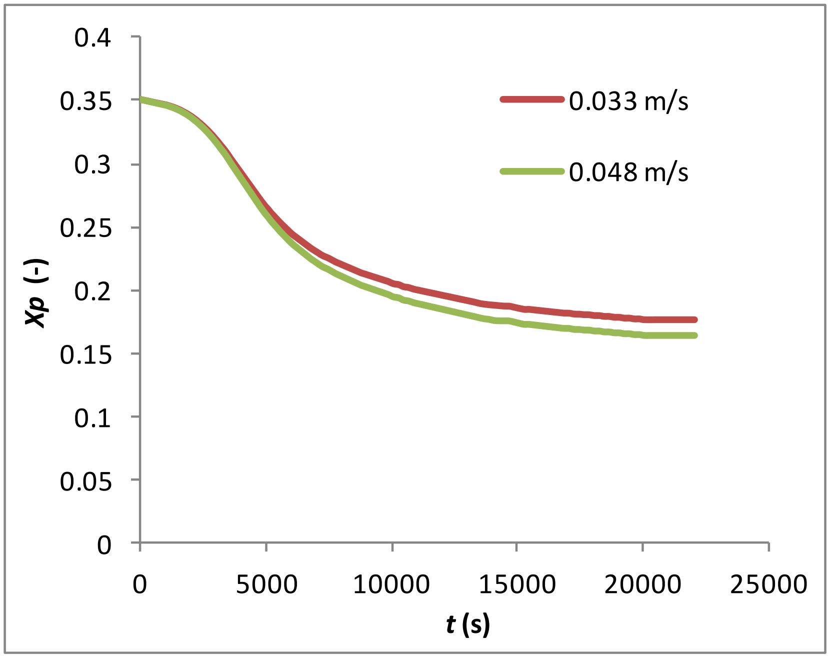

Fig. 6-3 Effect of the gas velocity on sorbent particle moisture content

The influence of the gas velocity u_0 on the performance characteristics of the dehumidification process can be discerned in Figure 6-3. Figure shows the model prediction of average moisture content distribution of sorbent particles in the bed. The increasing inlet air velocity increases the heat and mass transfer between the interstitial gas and sorbent particles. On the other hand, considering that air flow rate in the fluidized bed also grows, the humidity concentration in the interstitial gas may get reduced. These effects can result lower moisture content in the sorbent particle outlet.

Figure 6-4 compares absolute humidity of air at the exit of the bed. As seen in the figure, after the initial stage of process, a difference between experimental and numerical results is obvious. The variation of exit absolute humidity is steep for experimental result, while for numerical result, the exit absolute humidity is slowly up. This may be attributed by the condition of sorbent at the initial stage. Before sorbent is transferred from sorption chamber to desorption chamber, moisture content of the sorbent in desorption chamber is small enough while at sorption chamber is high, so that when sorbent is transferred from sorption chamber, it is quickly to release the water content. As a function of time, absolute humidity exit slowly down and approach gradually their respective equilibrium values. For numerical result, absolute humidity exit slowly increases and after the highest value is reached, it is slowly down and getting equilibrium value. The lower result is for numerical result. The bubble phase is contributed to the result of modeling, while in the modeling for simplification reason, is not including in the model.

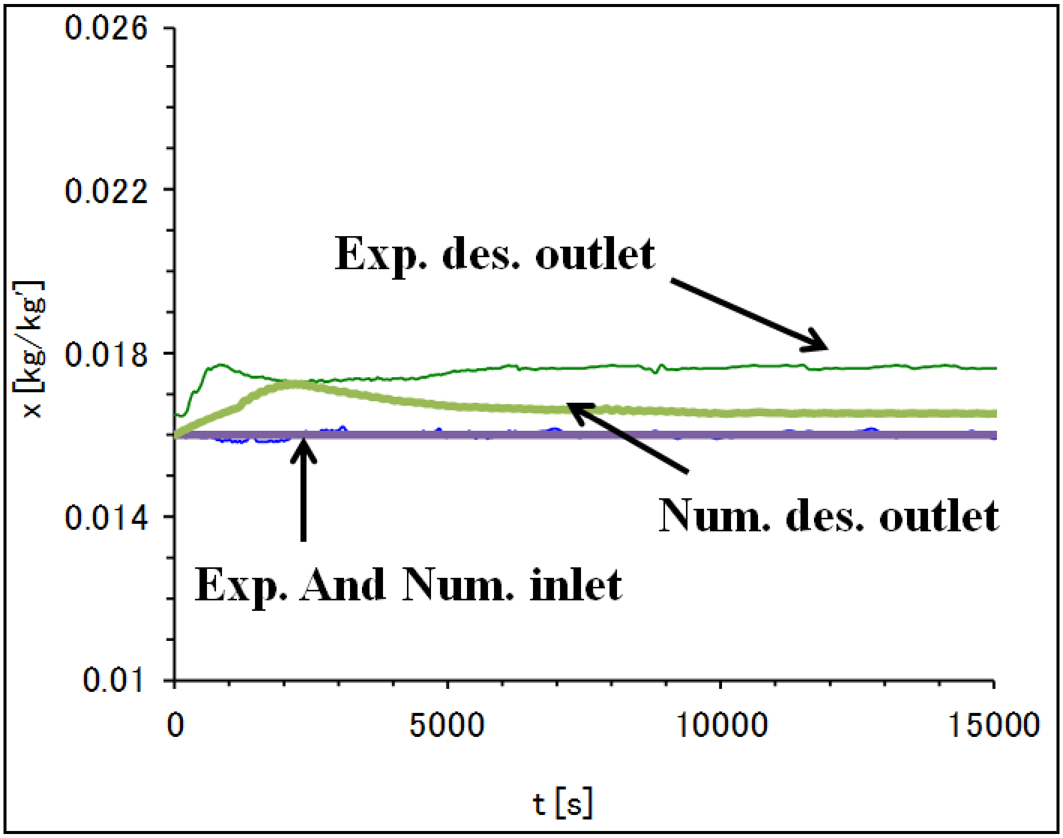

Fig. 6-4 Comparison between experimental data and model prediction for Absolute humidity out

Figure 6-5 present the comparison of temperature of outlet air between experimental result and model prediction. As can be seen in the figure, both results have same tendency. Outlet air temperature decreases sharply at the beginning. A possible explanation can be, that the low temperature of sorbent enter the desorption chamber and desorption process also decreases the sorbent temperature such that decreases the outlet air temperature. Temperature is getting equilibrium with the elapse of time. This condition occur for both experimental data and numerical results.

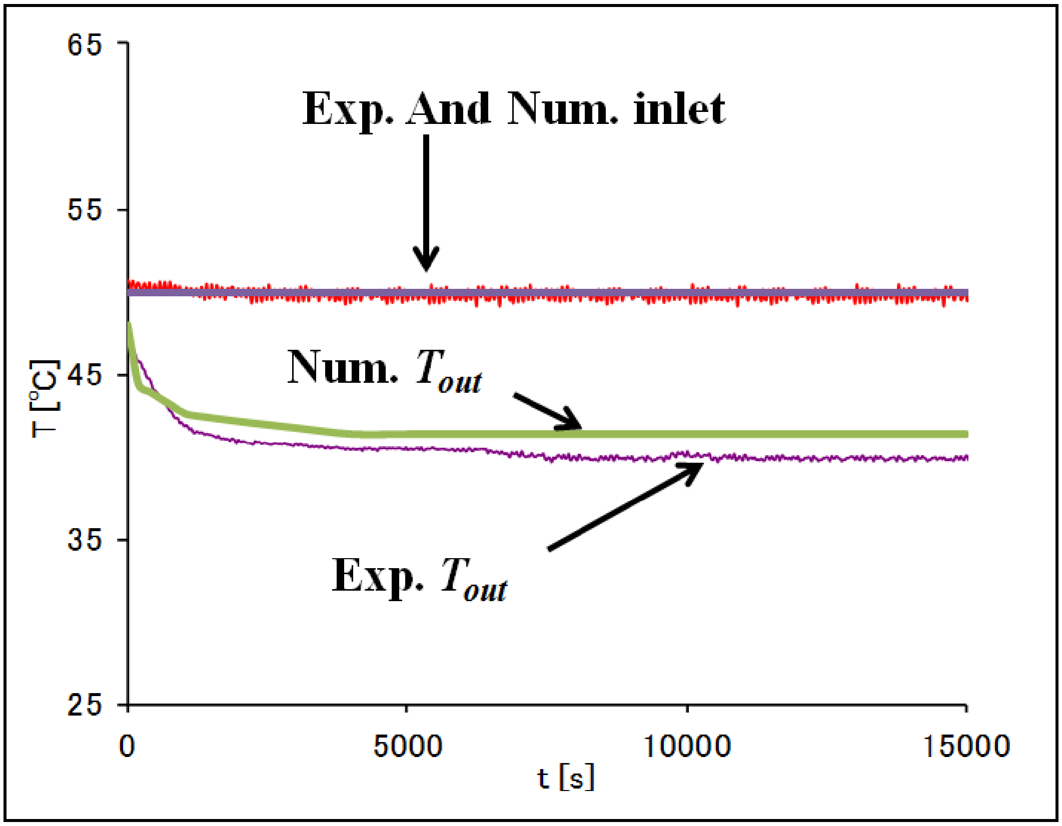

Fig. 6-5 Comparison between experimental data and model prediction for Temperature Sorbent

6.4 Summary

The model is derived by applying mass and heat balances to the chamber for continuous desorption process in the fluidized bed. Dehumidification experiments were carried out on the sorbent to obtain complete and reliable experimental results for comparison with the results of mathematical model. The influence of the gas velocity u_0 on the performance characteristics of the dehumidification process can be evaluated by using the model developed. The increasing inlet air velocity increases the heat and mass transfer between the interstitial gas and sorbent particles. On the other hand, considering that air flow rate in the fluidized bed also grows; the humidity concentration in the interstitial gas may get reduced. These effects can result lower moisture content in the sorbent particle outlet.

The variation of exit absolute humidity is steep for experimental result, while for numerical result, the exit absolute humidity is slowly up. This may be attributed by the condition of sorbent at the initial stage. As a function of time, absolute humidity exit slowly down and approach gradually their respective equilibrium values. For numerical result, absolute humidity exit slowly increases and after the highest value is reached, it is slowly down and getting equilibrium value. The lower result is for numerical result, this result is due to not considering the bubble phase in the model.

Outlet air temperature has same tendency results between experimental result and the model developed. Outlet air temperature decreases sharply at the beginning. Low temperature of sorbent enter the desorption chamber and desorption process also decreases the sorbent temperature such that decreases the outlet air temperature. Temperature is getting equilibrium with the elapse of time. This condition occur for both experimental data and numerical results.

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Nomenclature:

A_t	Cross sectional area of the bed, m^2
A_0	Distributor plate area per orifice, m^2
c_g	Specific heat of gas, kJkg^{-1} °C^{-1}
c_{wv}	Specific heat of water vapor, kJ kg^{-1} °C^{-1}
c_w	Specific heat of water, kJkg^{-1} °C^{-1}
c_p	Specific heat of sorbent particle, kJkg^{-1} °C^{-1}
D_g	Molecular diffusion coefficient of gas, m^{2}s^{-1}
D_{geff}	Effective diffusion coefficient of gas, m^{2}s^{-1}
d_b	Effective bubble diameter, m
d_p	Particle diameter, m
g	Gravity acceleration, m s^{-1}
H_f	Expanded bed height, m
H_{mf}	Bed height at minimum fluidization condition, m
h_p	Heat transfer coefficient between gas and solids, J s^{-1}m^{-2}℃$^{-1}$
i_0	Enthalpy of inlet gas, kJ kg^{-1}
i_e	Enthalpy of emulsion, kJ kg^{-1}
$\bar{i}_{ws}$	Enthalpy of water vapor in the surface of particles, kJ kg^{-1}
k_g	Thermal conductivity of gas, J m^{-1} ℃$^{-1}$
m_p	solid moisture content, dry basis, kg water/kg solid
$\overline{N}_{wg}$	average mass flux, kg/m s
Nu	Nusselt number, dimensionless
Pr	Prandtl number, dimensionless
P_w	Pressure of saturated water vapor, mm Hg
q_s	Conductive heat flux inside a particle, J m^{-1} s^{-2}
Q_b	Bubble flow rate, m^3/s
Re_p	Particle Reynolds number, dimensionless
S_{exp}	Solid feed rate, kg/s
T_0	Temperature of the inlet air, ℃
T_e	Temperature of emulsion, ℃

T_{out}	Temperature of outlet gas, ℃
T_p	Temperature of particle, ℃
$\bar{T}_p$	Average temperature of particle, ℃
T_{p0}	Temperature of inlet particles, ℃
T_{ref}	Reference state temperature, ℃
t_d	Time, s
$\bar{t}_d$	Mean residence time distribution of sorbent in the chamber, s
u_0	Superficial gas velocity, m s^{-1}
u_b	Superficial gas velocity of bubbles, m s^{-1}
u_{br}	Linier gas velocity of single bubble, m s^{-1}
u_{mf}	Superficial gas velocity at minimum fluidization condition, m s^{-1}
V_b	volume of bubble, m^3
V_s	volume of solid, m^3
V_e	volume of emulsion, m^3
x_0	Absolute humidity of air at inlet, dimensionless
x_e	Absolute humidity of emulsion air, dimensionless
x_{out}	Absolute humidity of air at outlet, dimensionless
x_p	Moisture content of solid, dimensionless
$\bar{x}_p$	Average moisture content of solid, dimensionless
x_p^*	Moisture content of air at the surface of a solid particle, dimensionless
$\bar{x}_p^*$	Average moisture content of air at the surface of a solid particle, dimensionless
x_{p0}	Moisture content of inlet solid particles, dimensionless
x_{pc}	Critical moisture content of a solid particle, dimensionless
δ_b	Fraction of the fluidized bed consisting bubbles, dimensionless
ε_s	Solid volume fraction in bed
γ_0	Heat of evaporation, kJ kg^{-1}
ε_{mf}	Void fraction at minimum fluidization condition, dimensionless
μ_g	Viscosity of gas, kg m^{-1} s^{-1}

ρ_g	Density of gas, kg m^{-3}
ρ_s	Density of solid, kg m^{-3}
ρ_w	Density of water, kg m^{-3}
ρ_{ws}	Density of wet solid, kg m^{-3}
σ	Evaporation coefficient, kg m^{-2} s^{-1}
ϕ_s	Sphericity of sorbent particles, dimensionless

Chapter 7

Conclusion

The experiments have been carried out to investigate the heat and mass transfer behavior in the sorption and desorption process in two connected fluidized beds. In this study heat and mass transfer parameters were considered to evaluate the effect of spiral revolution speed, air velocity, desorption inlet air temperature, sorption inlet air temperature, and initial bed height in the chamber to sorption and desorption rates. Experimental conditions are desorption inlet air temperature T_{Din} is 50°C, dew point temperature 21.4 °C and absolute humidity x_{in} = 0.016 kg/kg, sorption inlet air temperature T_{Sin} is 30 °C, dew point temperature 21.4 °C and x_{in} = 0.016 kg/kg. Air velocity u_0 which flow into the two chambers is 0.033 m/s used for spiral evolution speed, initial bed, desorption and sorption inlet temperature effect. Spiral revolution speed used is 2.5 rpm to investigate the effect of air velocity, initial bed height, desorption and sorption inlet air temperature.

At desorption chamber, air is humidified, because absolute humidity of air out from the chamber increases. At the other hand, at sorption chamber, air is dehumidified by the sorbent. Amount of water vapor releases in desorption chamber is about same with that sorbs in sorption chamber, thus the experiment condition is equilibrium. Furthermore, the constant value of air at outlet is referred to as homogenous and steady state. The continuously added sorbent is well mixed with the sorbent in the chamber and sorbent is continuously being removed.

In this experiment, particle circulation rate can be easily set up by using spiral tubes with geared motor. The air velocity at desorption and sorption chamber is same. The sorption and desorption process were in balance condition because the amount of water vapor releases in desorption chamber is about the same with that sorbed in sorption chamber. This condition is coinciding with the aim of this experiment, finding stable amount of dehumidification, absolute humidity outlet for sorption and desorption process.

The following several conclusions can be drawn from experimental results for dehumidification characteristics of organic sorbent desiccant material in continuous fluidized bed

(1) For desorption process, absolute humidity out increases by increasing the spiral revolution speed, and then slowly down. While, the opposite condition occurs on sorption process, absolute humidity decreases by increasing the spiral revolution speed.

(2) Decreasing the spiral revolution speed makes stay time of sorbent in desorption chamber increase that causes the more water vapor can discharge from the sorbent. But when the circulation rate of sorbent powder is too small, water vapor released or sorbed at desorption chamber and sorption chamber decreases.

(3) Regarding the difference spiral revolution speed, it is found that the difference temperature of the sorbent ΔT_{sor} is higher in the case of lower spiral revolution speed. Increasing the spiral revolution speed decreases the residence time distribution of particle. The better performance of the process will_be in the high temperature difference of the sorbent.

(4) It is confirm that for desorption process, absolute humidity out increases by increasing the residence time until the highest value, at residence time distribution t_d = 8000 s, that is ω = 2.5 rpm. And then, absolute humidity out decreases by increasing the residence time distribution. The opposite condition occurs on sorption process.

(5) For desorption chamber, sorbent temperature and outlet air temperature tend to increase by increasing the residence time distribution while at sorption chamber they tend to decrease.

(6) Sorbent temperature increases and it approaches inlet air temperature by increasing the residence time. Temperature of air at outlet is coinciding with the sorbent temperature. The opposite condition occurs in the sorption chamber.

(7) Increasing the spiral revolution speed ω will increase the amount of dehumidification sharply until it reaches maximum value and then slowly down. This pattern is same for different initial bed height.

(8) Increasing t_d increases the amount of dehumidification until it reaches maximum value. Residence time distribution t_d at the highest value of amount of dehumidification increases with an increase in initial bed height.

(9) The amount of water vapor which can be sorbed increases for sorption chamber, and for desorption chamber amount of water vapor released from sorbent particle increases by increasing air velocity.

(10) The heat and mass transfer between sorbent and air increases by increasing the air velocity. At desorption chamber, sorbent temperature increases and approaching the inlet air temperature, 50 °C. And at sorption chamber, sorbent temperature decreased until it reaches 30 °C. Amount of dehumidification increases by increasing the air velocity.

(11) Decreasing initial bed height of sorbent at the same air velocity will increase the size of bubble in the chamber. The growing size of bubble decreases the contact surface area per volume between sorbent and air, so the absolute humidity of air at outlet also decreases for desorption chamber and increases for sorption chamber.

(12) The sorbent temperature in the chamber varies base on the initial bed height. The tendency of sorbent temperature is increasing by increasing the initial bed height.

(13) Increasing desorption inlet temperature as regeneration temperature will increase the average temperature of sorbent. This, in turn, results in an increase in the absolute humidity at outlet. At sorption chamber, the amount of water vapor which can be sorbed by sorbent increases.

(14) The absolute humidity out for desorption process decreases by increasing the sorption inlet air temperature, while for sorption process, absolute humidity out increases. The decrease the sorption inlet temperature, amount of dehumidification increases.

(15) The following non-dimensional correlation were obtained with the Applicable ranges Re = 0.201 ~ 0.364, L_0^* = 190 ~ 285, t_d^* = 4x10^5 ~ 8x10^6, and $T_d^{\ *}$ = 3.3 ~ 5.6, ω = 0.7 ~ 100 rpm and F_0 = 0.42 ~ 30 g/min.

$$Sh/Sc^{1/3} = 0.14Re^{0.90}t_d^{*0.06}L_0^{*-1.10}T_d^{*0.16}.$$

The dehumidification characteristics of organic powder sorption materials have been studied by using continuous fluidized bed with a heating pipe (HP) and a cooling pipe (CP). Differently from the previous chapter, the present chapter deals with powder type organic sorbent in continuous fluidized bed with HP or CP pipes which were inserted in the chambers. Sorption rate of water vapor and the variation of temperature in the sorbent bed with time were measured under various conditions.

Experimental conditions are desorption inlet air temperature T_{Din} is 50°C, dew point temperature 21.4 °C and absolute humidity x_{in} = 0.016 kg/kg, sorption inlet air temperature T_{Sin} is 30 °C, dew point temperature 21.4 °C and x_{in} = 0.016 kg/kg. T_{HP} = 60 °C and T_{CP} = 25 °C. Air velocity u_0 which flow into the two chambers is 0.033 m/s. Spiral speed is 5 rpm that can carry about 6 g/min sorbent from desorption to sorption chamber or vise versa. Amount of sorbent (m_0) used is 200 g.

The following several conclusions can be drawn from experimental results for dehumidification characteristics of organic sorbent desiccant material in continuous fluidized bed with a heating pipe and a cooling pipe immersed in the sorbent

(1) Increasing desorption heating pipe temperature increases absolute humidity out at desorption chamber, and decreases absolute humidity out at sorption chamber.

(2) The value of absolute humidity for sorption and desorption process without heating pipe is lower than that of process with heating pipe. The increase in desorption HP temperature increases the amount of dehumidification.

(3) A small increasing of absolute humidity at desorption chamber and decreasing at sorption chamber were found by increasing the air velocity process without heat exchanger. Absolute humidity out for desorption process with HP is higher than without HP.

(4) Heating pipe is able to increase desorption sorbent temperature to around 49°C, while cooling pipe is able to maintain sorbent temperature in the chamber around 31°C.

(5) The peak of absolute humidity out without HP or CP and with HP or CP is different. The highest absolute humidity of desorption process without HP is at 2.5 rpm while desorption process with HP is at 5 rpm. The lowest absolute humidity of sorption process without CP is at 2.5 rpm and 5 rpm for sorption process with CP.

The following several conclusions can be drawn from mathematical modeling and numerical analysis for dehumidification characteristics of organic sorbent desiccant material in continuous fluidized bed. The model is derived by applying mass and heat balances to the chamber for continuous desorption process in the fluidized bed. Dehumidification experiments were carried out on the sorbent to obtain complete and reliable experimental results for comparison with the results of mathematical model.

(1) The influence of the gas velocity u_0 on the performance characteristics of the dehumidification process can be evaluated by using the model developed. The increasing inlet air velocity increases the heat and mass transfer between the interstitial gas and sorbent particles.

(2) Considering that air flow rate in the fluidized bed also grows, the humidity concentration in the interstitial gas may get reduced. These effects can result lower moisture content in the sorbent particle outlet.

(3) The variation of exit absolute humidity is steep for experimental result, while for numerical result, the exit absolute humidity is slowly up.

(4) For numerical result, absolute humidity exit slowly increases and after the highest value is reached, it is slowly down and getting equilibrium value. The lower result is for numerical result, this result is due to not considering the bubble phase in the model.

(5) Outlet air temperature has same tendency results between experimental result and the model developed. Outlet air temperature decreases sharply at the beginning. Low temperature of sorbent enter the desorption chamber and desorption process also decreases the sorbent temperature such that decreases the outlet air temperature. Temperature is getting equilibrium with the elapse of time. This condition occur for both experimental data and numerical results.

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