

Improvement of conventional liquid desiccant dehumidification technology

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Abstract: A new system of liquid desiccant dehumidification, called ultrasound atomization dehumidification system, is proposed. In this system, a packed bed is replaced by ultrasound atomization technology, so high resistance and liquid desiccant consumption caused by the packed bed are avoided. A mathematical model is established to predict the efficiency and the liquid consumption of the dehumidification process under ideal conditions. Through comparing the simulation results with the experimental data of a conventional packed-bed dehumidifier, it is found that the liquid desiccant consumption of the conventional packed-bed dehumidifier is much greater than that under ideal conditions. In the proposed system, the dehumidification process occurs on the surfaces of the micron liquid desiccant droplets produced with the irradiation of ultrasound, so there is a greater contact area created with the same quantity of the liquid desiccant; moreover, the power consumption is lower because there are no nozzles and no solution pump. It can be seen that this new system is closer to ideal conditions when compared with the conventional liquid desiccant dehumidification system.

Key words: packed bed; liquid desiccant dehumidification; atomization dehumidification; ultrasound; simulation

In recent years, liquid desiccant dehumidification has drawn much attention due to its remarkable advantages, such as flexible operation and easily realized regeneration with renewable and cheap fuels^[1].

Packed-bed dehumidifiers, well known for their large effective air-desiccant contact area, sufficient heat and mass transfer, good gas treatment capacity and compact construction, have been research hotspots in the liquid desiccant dehumidification field. Packed bed form, flow patterns, and dehumidification performance have been studied by numerous researchers. Two types of packings are generally used, random packing^[2] and structured packing^[3~4]. The former can provide proper air-liquid contacting area, but the required desiccant flow rates for good wetting and the air pressure drops are generally high. The latter are designed to improve mass transfer effectiveness in the dehumidifier by taking advantage of the fixed orientation of the mass transfer surfaces^[5]. There are two forms of flow configuration for packed-bed dehumidifiers: cross-flow configuration and counter-flow configuration. Many researchers so far have conducted experiments on the counter-flow dehumidification

systems and established mathematical models to predict the dehumidification performance^[6~8]. Later, Liu et al.^[9] and Moona et al.^[10] investigated the performance of the cross-flow liquid desiccant dehumidification system and developed some correlations for the crossflow.

All the above-mentioned researches are intended to make packed-bed dehumidifiers exert better performance. Seldom have scholars paid attention to their inherent demerits. As the air-desiccant contact area is provided by wetting the inner packing area sufficiently, the thickness of liquid film must be seriously considered. Because the thickness will enlarge the required liquid desiccant volume and affect the sufficient utilization of the liquid desiccant if the thickness is too great, whereas the wettened area and the dehumidification performance will be reduced if the thickness is too small. Actually, a large amount of liquid desiccant is always chosen to ensure enough air-desiccant contacting area, which results in regeneration energy, transportation energy and the system cost to become greater.

Furthermore, the reacting time cannot be long enough, because the packed-bed height must be maintained at a moderate level to ensure that the energy consumption of the fan can be accepted.

In order to further study the factors affecting the utilization of the liquid desiccant in a packed-bed dehumidifier, we compare the dehumidification performance between the packed-bed dehumidifier and an ideal condition. Through analyzing the differences between these two conditions, we try to solve the problems about low utilization, high consumption and short reaction time in the packed-bed dehumidifier.

1 Mathematical Model for Liquid Desiccant Dehumidifying under Ideal Conditions

The following assumptions are made for the analysis of the liquid desiccant dehumidification process under ideal conditions.

- 1) It is an adiabatic process, and there is no heat and mass transfer to the surroundings.
- 2) The specific heat of the fluids with respect to the temperature is constant.
- 3) The desiccant inlet temperature and concentration are constant.
- 4) The reaction is sufficient, and the reacting time is long enough.
- 5) The outlet liquid desiccant and the outlet air have the same temperature and water vapor pressure.

The overall energy balance for the dehumidification process can be written as

$$G_a h_{a,0} + G_l h_{l,0} = G_a h_a + [G_l + G_a(d_0 - d)] h_l \quad (1)$$

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where G_a and G_l are the superficial air (gas) flow rate and the liquid desiccant mass flux ($\text{kg}/(\text{m} \cdot \text{s})$), respectively; $h_{a,0}$, $h_{l,0}$, h_a and h_l are the enthalpy of the inlet air, the inlet liquid desiccant, the outlet air and the outlet liquid desiccant (kJ/kg), respectively; d_0 and d are the humidity of the inlet air and the outlet air (kg/kg), respectively.

And the enthalpy value of dry air can be written as

$$h_{a,0} = 1.01t_{a,0} + (2501 + 1.85t_{a,0})d_0 \quad (2)$$

$$h_a = 1.01t + (2501 + 1.85t)d \quad (3)$$

where $t_{a,0}$ is the inlet air temperature ($^{\circ}\text{C}$); t is the final temperature of both the desiccant and the treated air under ideal conditions ($^{\circ}\text{C}$).

If the chosen liquid desiccant is lithium chloride, we need to write the relationship formula^[11] as follows among its enthalpy value, concentration and temperature.

$$t_{l,0} = -0.0003\varepsilon_0 h_{l,0}^2 + (0.29418\varepsilon_0 + 0.2577)h_{l,0} + 3.1883\varepsilon_0 - 0.9082 \quad (4)$$

$$t = -0.0003\varepsilon h_l^2 + (0.29418\varepsilon + 0.2577)h_l + 3.1883\varepsilon - 0.9082 \quad (5)$$

where $t_{l,0}$ is the temperature of inlet liquid desiccant ($^{\circ}\text{C}$); ε_0 and ε are the concentrations of inlet liquid desiccant droplets and outlet liquid desiccant droplets (kg/kg), respectively.

The overall mass balance for the dehumidification process can be written as

$$G_a(d_0 - d) = [G_l + G_a(d_0 - d)](1 - \varepsilon) - G_l(1 - \varepsilon_0) \quad (6)$$

As the outlet liquid desiccant and the outlet air have the same water vapor pressure, the following equation is obtained:

$$P_l(\varepsilon, t) = \frac{101325d}{0.662 + d} \quad (7)$$

where $P_l(\varepsilon, t)$ is the vapour pressure of outlet liquid desiccant droplets (Pa).

Conde^[12] provided formulae to calculate the water vapour pressure of lithium chloride, when liquid temperature and consistency are given.

Solving Eqs. (1) to (7) by computer, we can obtain the humidity ratio of outlet air d , the concentration of outlet liquid desiccant ε and the outlet temperature t with determined $t_{a,0}$, d_0 , G_a , G_l , $t_{l,0}$, ε_0 .

2 Results and Discussion

Nelson and Goswami^[13] obtained reliable sets of experimental data for packed-bed dehumidification using lithium chloride (LiCl) as the liquid desiccant. A comparison of these data with the results obtained from the simulation of the dehumidification process under ideal conditions is given in the following.

Figs. 1 to 6 show the experimental results together with the theoretical modelling results under ideal conditions with the same inlet parameters. In Figs. 1 to 6, m_{cond} is the water condensation rate, and $G_{l,0}$ is the inlet liquid desiccant mass flux. Fig. 1 shows that the experimental consumption of liq-

uid desiccant is five times higher than the calculated results with the same dehumidification capacity. It means that the liquid desiccant consumption under ideal conditions is far less than that in the packed-bed dehumidifier. It is coincident with the actual situation in which the liquid amount is always much greater than the treated air. In fact, in order to obtain enough air-desiccant contact area, excessive liquid desiccant quantity is always chosen to sufficiently wet the inner packing area. That is why the liquid that leaves the dehumidifier still has strong dehumidification capacity. Fig. 2 further shows the differences in desiccant consumption between the packed bed and the ideal dehumidification process. When liquid desiccant quantity reaches about $5 \text{ kg}/(\text{m}^2 \cdot \text{s})$, the dehumidification effect, which just reaches 0.3 to 0.4 g/s under the experimental conditions, can achieve about 0.49 g/s under ideal conditions. This can be explained by the simulation results of the ideal conditions shown in Fig. 2. As Fig. 2 shows, first, dehumidification capacity increases sharply with the quantity of liquid desiccant; then, it turns to increase slowly after the quantity reaches an inflection point. Obviously, it is economical to maintain the quantity of liquid desiccant below the inflection point. Since the quantity of $5 \text{ kg}/(\text{m}^2 \cdot \text{s})$ is over the inflection point, the dehumidification capacity can hardly increase again with the increasing quantity of liquid desiccant under the experimental conditions. In a word, on the premise of wetting the inner part of the packed area adequately, the liquid desiccant is always overused in packed-bed dehumidification.

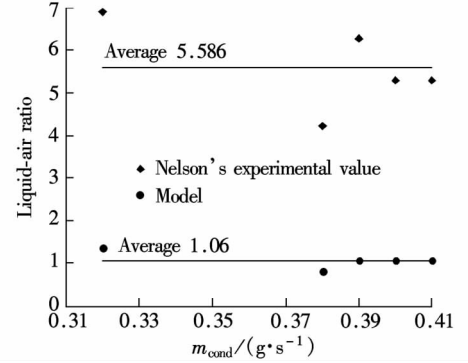


Fig. 1 Comparison of liquid-air ratio

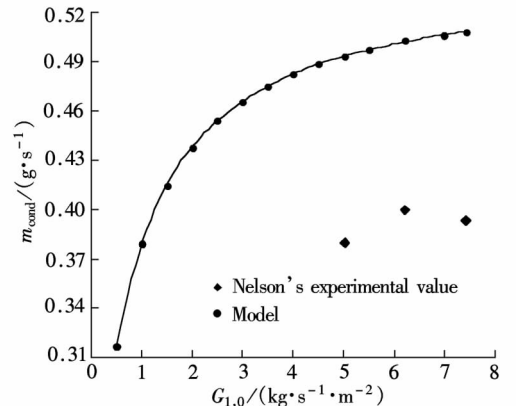


Fig. 2 Comparison of desiccant consumption

Fig. 3 shows that the dehumidification capacity increases with the concentration of liquid desiccant in both the ideal and the experimental conditions. Obviously, this is explained

by the fact that the higher the concentration, the better the mass transfer property.

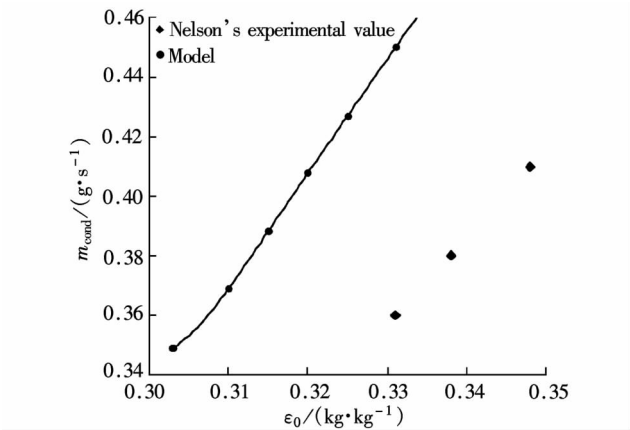


Fig. 3 Comparison of desiccant concentration

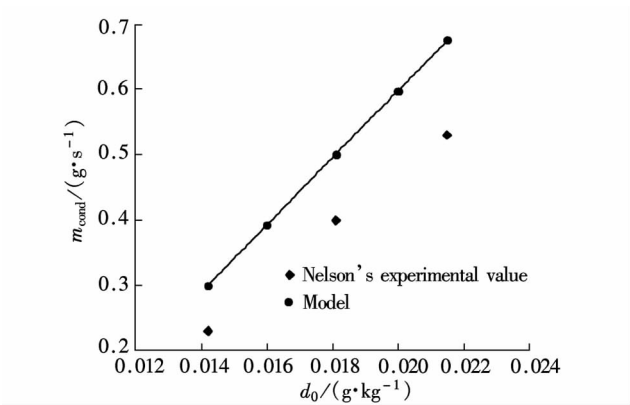


Fig. 4 Comparison of inlet air humidity

Figs. 4 to 6 show that the changing trend under ideal conditions and the experimental conditions are almost the same. Fig. 4 shows that humidifying capacity increases with the humidity of the inlet air under both the ideal and the experimental conditions, but the dehumidification capacity under ideal conditions is higher than that under the experimental conditions with the same inlet air humidity. Fig. 5 shows that the humidification capacity decreases with the inlet air temperature under both the ideal and the experimental conditions, but the dehumidification capacity under ideal conditions is higher than that under the experimental conditions with the same inlet air temperature. Fig. 6 shows that the humidification capacity decreases with the inlet liquid desiccant temperature under both the ideal and the experimental conditions, but the dehumidification capacity under ideal conditions is higher than that under the experimental conditions with the same inlet liquid desiccant temperature.

All these can be explained that, under ideal conditions, the liquid desiccant is supposed to be fully used, whereas, in the packed-bed dehumidification the utilization of liquid desiccant is always inadequate.

3 Improvement of Packed-Bed Dehumidification

Through the above mentioned comparative analyses, there is a contradiction here; i. e., the contacting area which is beneficial to the dehumidification process and the resistance which will cost a greater energy consumption both increase with the height of the packed bed. Therefore, the height of

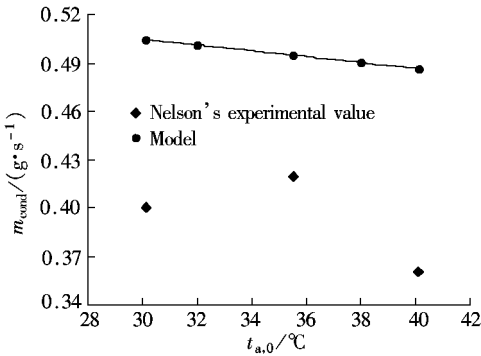


Fig. 5 Comparison of inlet air temperature

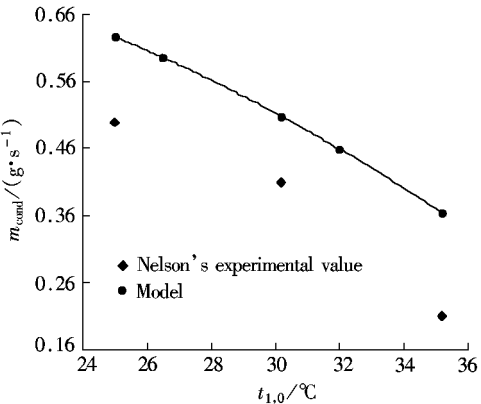


Fig. 6 Comparison of inlet desiccant temperature

the packed bed must stay in a moderate level, which limits the increments of the air-liquid contacting area and time, and this is another reason for the inadequate utilization of liquid desiccant.

A new concept of liquid desiccant dehumidification called atomization dehumidification combining the advantage of the spray tower and the technology of ultrasound atomization is discussed here to overcome the disadvantages of the packed-bed dehumidification. And the preliminary concepts of the structure chart are shown in Fig. 7. As Fig. 7 shows, first, liquid desiccant mist is produced by irradiation of ultrasound. Then, the mist carried by the inlet air enters the air-liquid mixing pipeline during the carrying process, and the dehumidification process occurs on the surfaces of the micron liquid desiccant droplets. Finally, the mist is removed by a gas-liquid separator, and the dehumidified air goes out of the system. The dehumidification process is finished. After being captured by the mist eliminator, the micron drop-

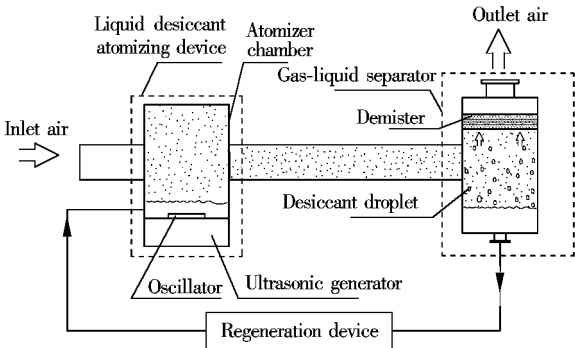


Fig. 7 A simplified structure chart of atomization dehumidification

lets merge into bigger droplets falling into the bottom of the gas-liquid separator, and then the gathered liquid desiccant is transported by the pump into the regeneration device to recover its dehumidification capacity and begin another dehumidification process. The dehumidification process starts at the beginning of air-liquid contact, and ends at air-liquid separation. In this process, the water vapour pressure near the surface of the liquid desiccant droplets is lower than that of the treating air, so the water vapour can diffuse continuously into the liquid desiccant. If the contact time is long enough, finally the water vapour pressure near the surface of the droplets will be the same as that of the treated air. In the actual situation, the reaction time can be adjusted by the length of the air-liquid mixing pipeline.

In this new form, the dehumidification process occurs on the surface of the micron liquid desiccant droplets produced with the irradiation of ultrasound, and the packed bed is not needed anymore. Although this dehumidification process is similar to the process occurring in the spray tower, it has some significant differences: 1) The liquid droplets produced by ultrasound have much small diameters and nearly zero initial velocities, so they are finer than those produced by the spray tower. 2) There are no spray nozzles and pressure pump (transporting liquid desiccant to the spray nozzles) in atomization dehumidification, which avoids the problem of high backpressure which limits the smaller droplets' diameters in the spray tower. 3) The energy consumption of the ultrasound atomizing apparatus is much smaller than that of the pressure pumps. So, comparing with the spray tower dehumidification process, the atomization dehumidification costs less energy and provides a greater liquid-air contact area.

It can be seen that this new system is closer to ideal conditions. First, no packing bed exists in this system, and all the contact area is provided by the atomized liquid desiccant without any other auxiliary facility, so there is more contacting area created with the same quantity of the liquid desiccant, which is beneficial to use the liquid desiccant sufficiently. Secondly, for the sufficient utilization, the consumption of the liquid desiccant becomes lower, and the regeneration energy decreases correspondingly. Thirdly, the air-liquid contact time can be easily adjusted by changing the length of the air-liquid mixing pipeline. Finally, in this system, nozzles are not needed anymore; the solution pump is also removed, so the power consumption is lower.

4 Conclusion

Through simulating the dehumidification performance under ideal conditions and comparing it with the packed-bed dehumidifier, it is found that the dehumidification capacity increases sharply with the quantity of the liquid desiccant, and then, the increment rate becomes much lower after the quantity reaches an inflection point. So, it is economical to maintain the quantity of liquid desiccant below an inflection point. Ultrasound atomization dehumidification is proposed to improve the conventional liquid desiccant dehumidification technology. The dehumidification process of this new type is closer to ideal conditions due to the following reasons:

1) No packed bed exists in this system, and all the contact area is provided by the atomized liquid desiccant, which is beneficial to use the liquid desiccant sufficiently.

2) For sufficient utilization, the consumption of the liquid desiccant becomes lower, and the regeneration energy decreases correspondingly.

3) Nozzles are not needed anymore; the solution pump is also removed, so the power consumption is lower.

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传统液体除湿技术的改进

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摘要:提出一种新型的液体除湿系统——超声雾化液体除湿系统,该系统用超声雾化技术取代了传统塔式除湿过程中的填料,避免了由填料带来的溶液耗量大和阻力大的缺点.建立了数学模型来预测在理想条件下液体除湿过程的效率及耗液量.通过对比计算结果和传统塔式除湿的实验数据,发现后者的溶液耗量远大于理想情况下的耗量.另外,在提出的系统中除湿过程发生在通过超声作用产生的微小除湿剂液滴表面,等量的除湿剂能够产生更大的反应表面积;整个新系统中没有喷嘴和溶液泵,系统阻力和能耗相应降低.因此,该方法比塔式除湿方式更接近于理想情况.

关键词:填料塔;液体除湿;雾化除湿;超声;模拟

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