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Sensitivity and stability analysis on the performance of ultrasonic atomization liquid desiccant dehumidification system

Zili Yang, Kaisheng Zhang, Zhiwei Lian, Huibo Zhang*

State Key Laboratory of Ocean Engineering, Shanghai Jiao Tong University, Shanghai, 200240, PR China

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ABSTRACT

Liquid desiccant dehumidification systems have drawn a great deal of attention in the HVAC industry due to its great energy saving potentials. Numerous studies have been conducted to investigate the relationships between the operating conditions and the system performance. However, it seems that the existing relationships were built improperly since almost all of them were established through the incomplete single-factor tests, rather than the full-factorial tests. This makes the existing work unable to clarify the overall significance of the various operating conditions on affecting the system performance. To address this unexplored issue, an L18 × L8 cross-product orthogonal array together with the statistical analysis method (ANOVA) was adopted in this work to investigate the significance of operating conditions in promoting the system performance (i.e. sensitivity analysis) and stability (i.e. stability analysis). 144 experimental and simulation runs were conducted within the ultrasonic atomization liquid desiccant dehumidification system (UADS) as the example to demonstrate the analysis. It was found that though direct influence on the system can be exerted by all the operating conditions, their significance differed markedly. Based on the analysis, the operating conditions can be classified into four types while the optimal conditions for the UADS were also figured out and validated.

1. Introduction

Liquid desiccant dehumidification systems have attracted a great deal of attention in recent years for the great energy saving potential in the HVAC industry [1–3]. Instead of over-cooling the airflow below the dew point in the traditional vapor compression system, moisture in the humid air is absorbed directly and effectively by the desiccant solution in the liquid desiccant dehumidification systems. This contributes a lot to reducing the latent load of air conditioning system and no extra energy is required any longer to reheat the subcooled air before being supplied to the conditioned space. In addition, the desiccant solution can be regenerated efficiently by utilizing the renewable energy, such as the solar energy or the industrial waste heat. These advantages offer great economic benefits and make the liquid desiccant dehumidification systems one the most appealing research topics [4–7].

In view of this, researchers have devoted great efforts to investigate the performance of various liquid desiccant dehumidification systems [8–11]. It has been revealed that the system performance is influenced directly by their operating conditions, such as the flow rates of humid air and desiccant solution, the temperatures of airstream and desiccant solution, the desiccant mass fraction and the air humidity ratio, etc. To clarify the impacts of these operating conditions on the system performance, studies have been conducted extensively in a variety of systems with different types. For example, Longo and Gasparella [12], Fumo and Goswami [13] etc. studied the effects of airstream and desiccant solution on the performance of dehumidification systems equipped with counter-flow packed beds while performance characteristic of cross-flow configured systems were studied by Liu et al. [14], Moon et al. [15] and Gao et al. [16], etc. Furthermore, a series of parametric investigations on performance of the dehumidification systems integrated with the ultrasonic atomization technology (UADS) was conducted by Wang et al. [17], Bian et al. [18] and Yang et al. [19], etc.

However, it seems that these relationships were not properly built since almost all of them were established by means of the

* Corresponding author.
E-mail address: zhanghuibo@sjtu.edu.cn (H. Zhang).

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Nomenclature

UADS	ultrasonic atomization liquid desiccant dehumidification system
G	mass flow rate, [kg s^{-1}]
t	temperature, °C
n	desiccant mass fraction (otherwise noted), [%]
d	humidity ratio, [g $kg^{-1}_{dry\ air}$]
DE	dehumidification effectiveness, [%]
MRR	moisture removal rate, [g s^{-1}]
h	enthalpy [kJ kg^{-1}]
P	pressure [Pa]
Mol	molar mass [g mol^{-1}]
POC	percentage of contribution, [%]
k	Thermal conductivity, [W m^{-1} K^{-1}]

Subscripts

equ	equilibrium
l	liquid desiccant
a	air
max	maximum
min	minimum
i	inlet
o	outlet
d	dry
q	moisture
AT	atmospheric
ideal	ideal condition

incomplete single-factor experiment rather than the full-factorial test. That is to say, instead of all the factors being varied within their operating range, only the level of one factor was changed within the range while the conditions of the other factors were fixed at one specific level (the nominal level) in the existing studies. Since the effects of these operating conditions on the system performance could be non-linear, their significance or even the effects trend may change significantly when different conditions were chosen as the nominal level. For example, it has been well documented in many studies, where the single-factor experiments were employed, that the system dehumidification effectiveness (DE) would increase with the rise of the desiccant mass fraction [16,18,19]. This was true when the system was running under certain circumstances. However, the impact from desiccant mass fraction on the system DE could change considerably when different levels of other factors such as the desiccant temperature were chosen as the nominal conditions. For instance, Yang et al. [19] investigated the effects of the desiccant mass fraction on the DE of the UADS with the desiccant temperature $t_{l,i} = 25$ °C as the nominal level. In this case, it was noticed that the system DE was growing significantly with the increase of the desiccant mass fraction [19]. However, when altered the nominal conditions of the desiccant inlet temperature from 25 °C to 29 °C, 31 °C, 33 °C or 35 °C, which were still within the study range of the dehumidification condition, the significance and even the effects trend of the desiccant mass fraction on the DE have changed markedly, as shown in Fig. 1. This is because dehumidification process is composed of heat and mass transfer where sensible heat transfer may occur when the inlet desiccant temperature is higher than the temperature of humid air (33 °C in present case). In this situation, the desiccant solution can be cooled by the air, which will potentially raise the practical dehumidification ability of the desiccant solution. As the consequence, the practical air outlet humidity ratio, $d_{a,o}$, would be lower than expected and closer to the equilibrium value of the desiccant solution, d_{equ}, as shown in Fig. 2. Hence, higher dehumidification effectiveness, which is defined as Eq. (1) shows in Section 2.1.1, was achieved at the beginning. With the increase of the desiccant inlet mass fraction, the dehumidification ability of the desiccant solution would be predominantly affected by the desiccant mass fraction. Thus, though both of the $d_{a,o}$ and d_{equ} decreased significantly (Fig. 2), the decreasing rate of the d_{equ} would be faster than the rate of $d_{a,o}$ since the latter was already at a lower level due to the effect of the aforementioned sensible heat transfer. Therefore, decreasing trends of DE were observed in Fig. 1 when $t_{l,i} > t_{a,i}$. When further increasing the desiccant mass fraction, which means much stronger desiccant solution was adopted, the humid air would be dehumidified much more effectively. This would lead to a rapid drop of the air outlet humidity ratio, $d_{a,o}$, which can be even faster than the decreasing rate of the d_{equ}, and result in the rise of DE. Hence, the DE was decreasing at the beginning and then increasing with growth of the desiccant mass fraction when $t_{l,i} > t_{a,i}$. By contrast, when the desiccant temperature is lower than the air temperature ($t_{l,i} < t_{a,i}$), the practical dehumidification ability of the desiccant could be hindered since it can become warmer than its inlet condition due to the sensible heat transferred from the air to the desiccant solution. Thus, the DE would start at a low level as displayed in Fig. 1. With the rise of desiccant mass fraction, the humid air can be dehumidified effectively, leading to the significant drop of $d_{a,o}$ whose dropping rate could be more rapid than the decreasing rate of d_{equ}. As the result, the DE tended to increase continuously with the growth of the desiccant mass fraction when $t_{l,i} < t_{a,i}$. This phenomenon indicates that conclusions of the previous investigations may not be firm enough when the whole range of operating conditions are taken into consideration during the study. Besides, it also makes the existing work unable to clarify the overall significance of the operating conditions in promoting the performance and the stability of the liquid desiccant dehumidification systems. To address this unexplored topic, the following issues are to be concerned in this work:

1. How to evaluate the overall significance of the operating conditions on the performance of liquid desiccant dehumidification systems with rigid mathematical analysis?
2. As to the ultrasonic atomization liquid desiccant dehumidification system (UADS), which operating conditions are most sensitive in improving the system performance?
3. What are the effects of the operating conditions' fluctuation on the UADS performance? How to minimize the undesirable interference and enhance the system stability?

2. Methods

2.1. Taguchi Method

Taguchi method is believed to be one of the best methods to figure out the operational conditions that are significant in approaching the system's optimal performance (i.e. sensitivity analysis) and reducing the fluctuation of the performance output