Experimental and Theoretical Study on a Low-Temperature Heat Pump Sludge Drying System

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Introduction

Low-temperature heat pump sludge drying technology, which is energy-saving, environmental protection, operational safety, has been studied and popularized with the development of heat pump[1].

Hossain et al.[2] established the theoretical model of the heat pump sludge drying system based on the balance equation of mass and heat transfer, energy efficiency equation, and theoretical and empirical equation. The simulated results are shown that the average coefficient of performance system is 5.45,the rate of dehumidification is 140.03kg/h, the power consumption ratio of dehumidification is 0.038kg/kWh, and the drying efficiency is 78.23%.

This study designed and constructed a low-temperature heat pump sludge drying system, and carried out experimental research. The theoretical models of refrigerant circulation and circulation of moist air, which based on heat and mass transfer, energy balance equation and theoretical and empirical Equation, are established. Based on the validated model, the effects of evaporating temperature, condensing temperature and mass flow rate on the drying rate are analyzed. Finally, it is further conducted to suggest the optimal operation.

Fig.1 shows the system design. The refrigerant circulation consists of evaporator, compressor, condenser, expansion valve and the connecting pipes. The moist air circulation is composed of evaporator, condenser, centrifugal fan, drying closet and vent tubes.

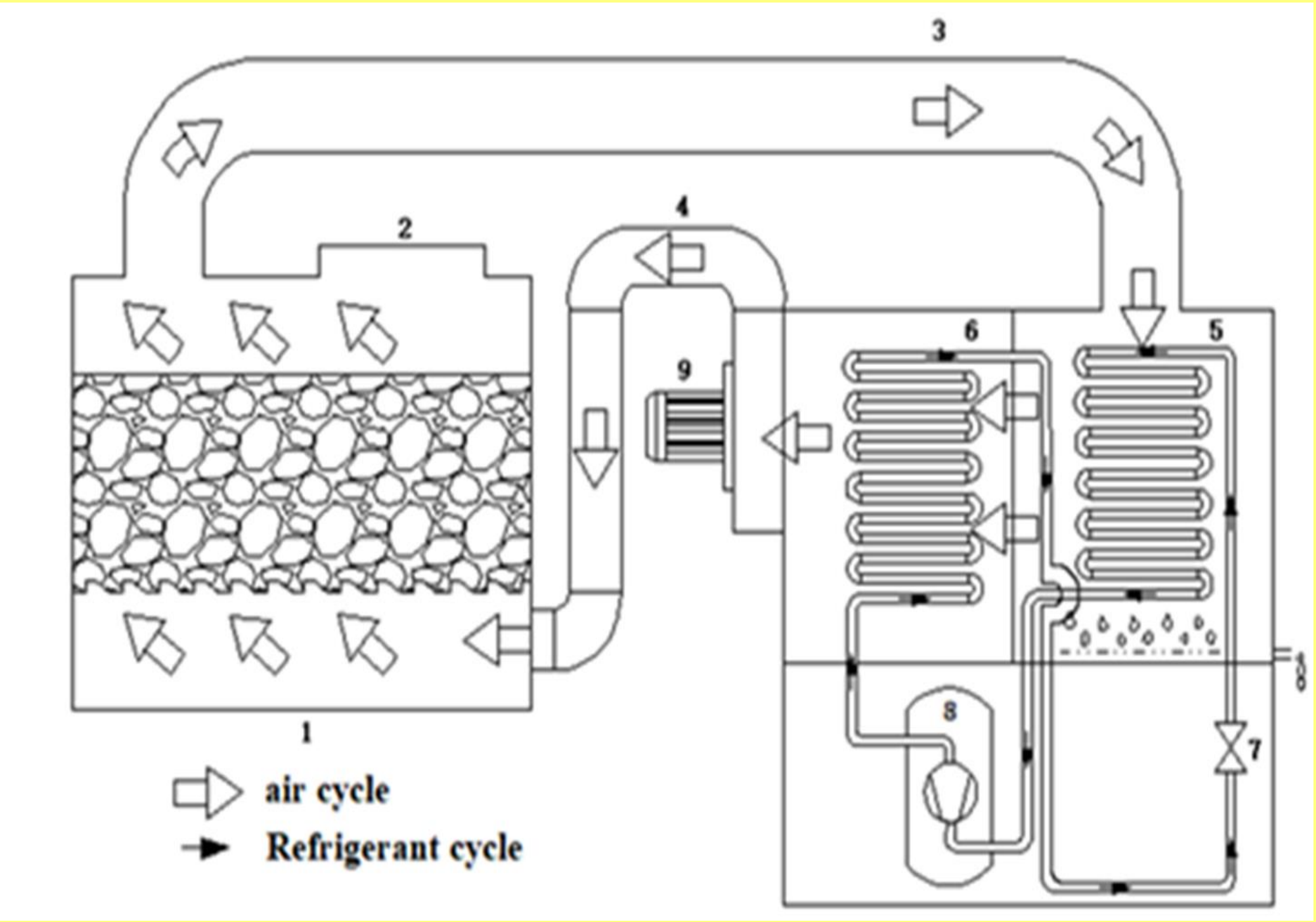


Fig.1. The operational principle of heat pump sludge

Model establishment

1. The model of heat pump

In the present study, finned-tube type heat exchanger is employed in the evaporator and condenser.

The heat transfer coefficient at the refrigerant side is given as:

single-phase region[3]:

$$h_c = \frac{\lambda_c}{d_i} 0.023 Re^{0.8} Pr^n \qquad (1)$$

where n is the index, 0.4 is taken in the evaporator and 0.3 is taken in the condenser.

double-phase region[4]:

$$h_c = h_{cl}\left[(1-x)^{0.8} + \frac{3.8x^{0.76}(1-x)^{0.04}}{Pr^{0.38}}\right] \qquad (2)$$

where h_{cl} is heat transfer coefficient of liquid phase, W/(m²·K);

The heat transfer coefficient at the air side is given as[5]:

$$h_a = 0.982 \frac{\lambda_a}{de} {Re_a}^{0.424} \left(\frac{s_f}{d_b}\right)^{-0.0887} \left(\frac{Ns_2}{d_b}\right)^{-0.159} \qquad (3)$$

where d_b is diameter of finned tube, m; N is the number of tube rows; s_2 is tube pitch, m.

The heat transfer coefficient of moist air in the evaporator is different from that in the drying working condition due to the dehumidification phase transition, so it needs to be corrected, which can be expressed as[6]:

$$h_{a,eva} = \xi h_a (A_f \cdot \eta_f + A_b)/A_{tot} \qquad (4)$$

where ξ is dehumidification coefficient; η_f is efficiency of fin.

2. The model of drying closet

$h_{t,dry}$ is the heat transfer coefficient between the moist air and sludge, which can be expressed as[7]:

$$h_{t,dry} = \frac{\lambda_a}{L_m}(2 + 0.65 Re^{0.5} Pr^{1/3}) \qquad (5)$$

$h_{m,dry}$ is the mass transfer coefficient, which is given as[8]:

$$h_{m,dry} = \frac{h_{t,dry}}{\rho_{a,dry} Cp_{a,dry}} \left(\frac{\alpha_{a,dry}}{D}\right)^{-2/3} \qquad (6)$$

where $\alpha_{a,dry}$ is thermal diffusivity, m²/s; D is diffusion coefficient, m²/s.

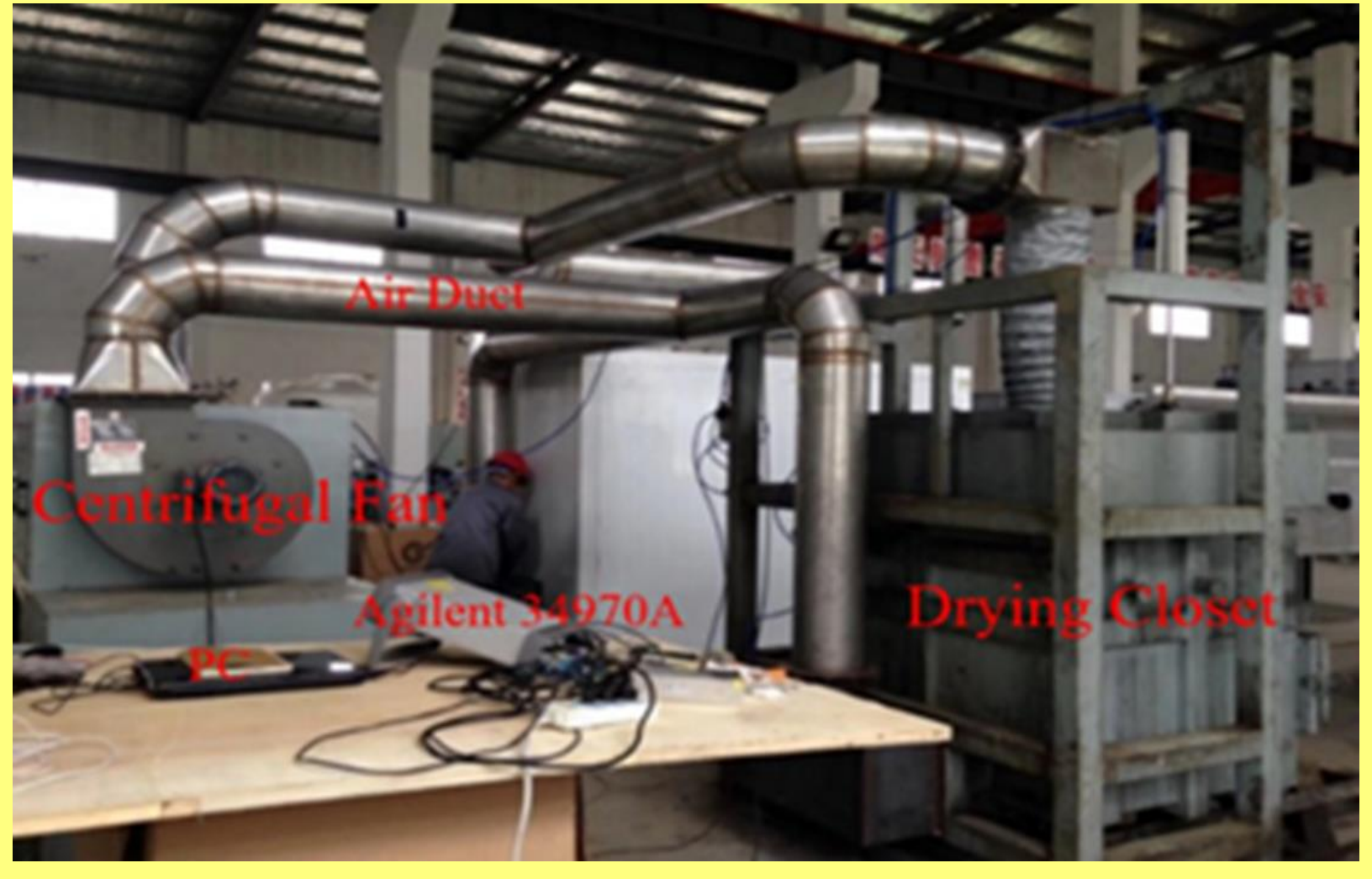
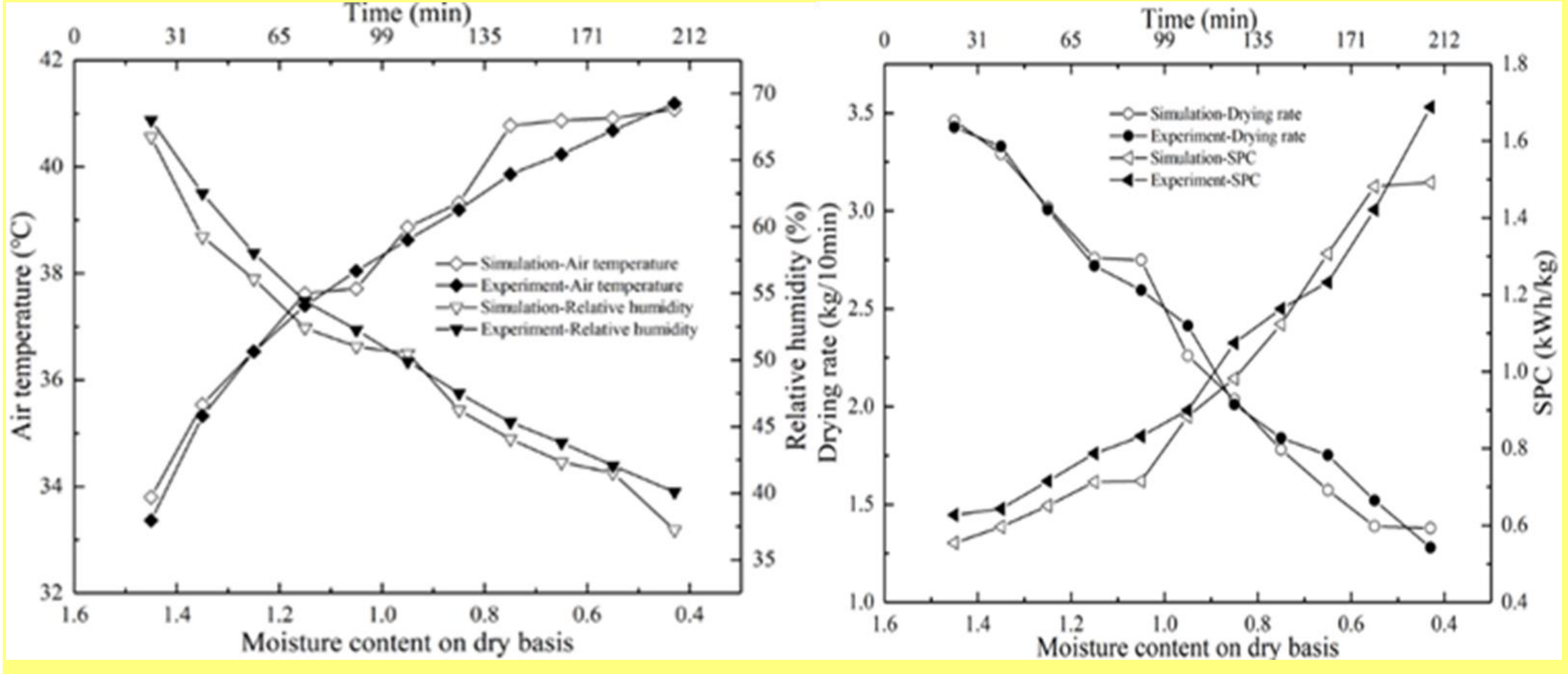


Fig. 2. View of the experimental platform.

Experiment

The experimental setup of the heat pump sludge drying system is shown in Fig.2. The main parameters, which were collected during the experimental test, are the temperature and relative humidity of moist air, the ambient temperature, the power consumption of the heat pump system, the speed of wind, and the pressure drop of the circulation of moist air. The above data was collected by agilent data acquisition instrument every 30 seconds. Dehumidification amount was collected every 10 minutes.



A **B**

Fig.3. Comparisons between simulated and experimental results

Comparisons between the simulated results and experimental results of the temperature and relative humidity of outlet moist air of the drying closet are shown in Fig. 3-A. The corresponding average errors are 0.79% and 3.28%, respectively.

Comparisons between simulated results and experimental results of drying rate and SPC are shown in Fig. 3-B. The corresponding mean deviations are 0.85% and 5%, respectively.

Results

EVAPORATING TEMPERATURE

Influence of the evaporating temperature to the drying rate is shown in Fig. 4, where the drying rate decreases with increasing evaporating temperature. Therefore, low evaporating temperature can ensure better drying effect.

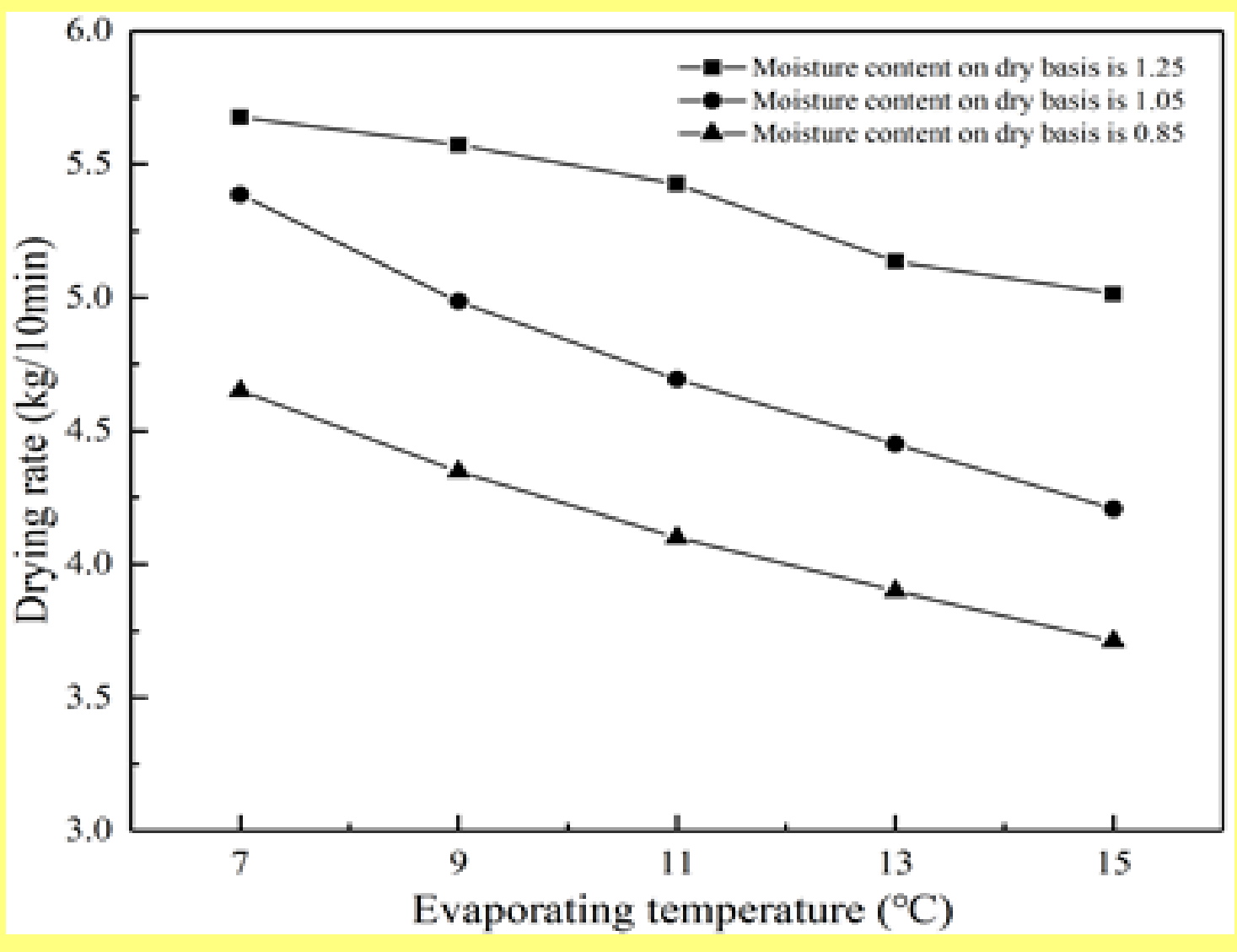


Fig. 4. Influence of the evaporating temperature to the drying rate.

CONDENSING TEMPERATURE

Influence of the condensing temperature to the drying rate is shown in Fig.5, where the drying rate increases with increasing condensing temperature. Obviously, high condensing temperature can improve the drying effect of the system.

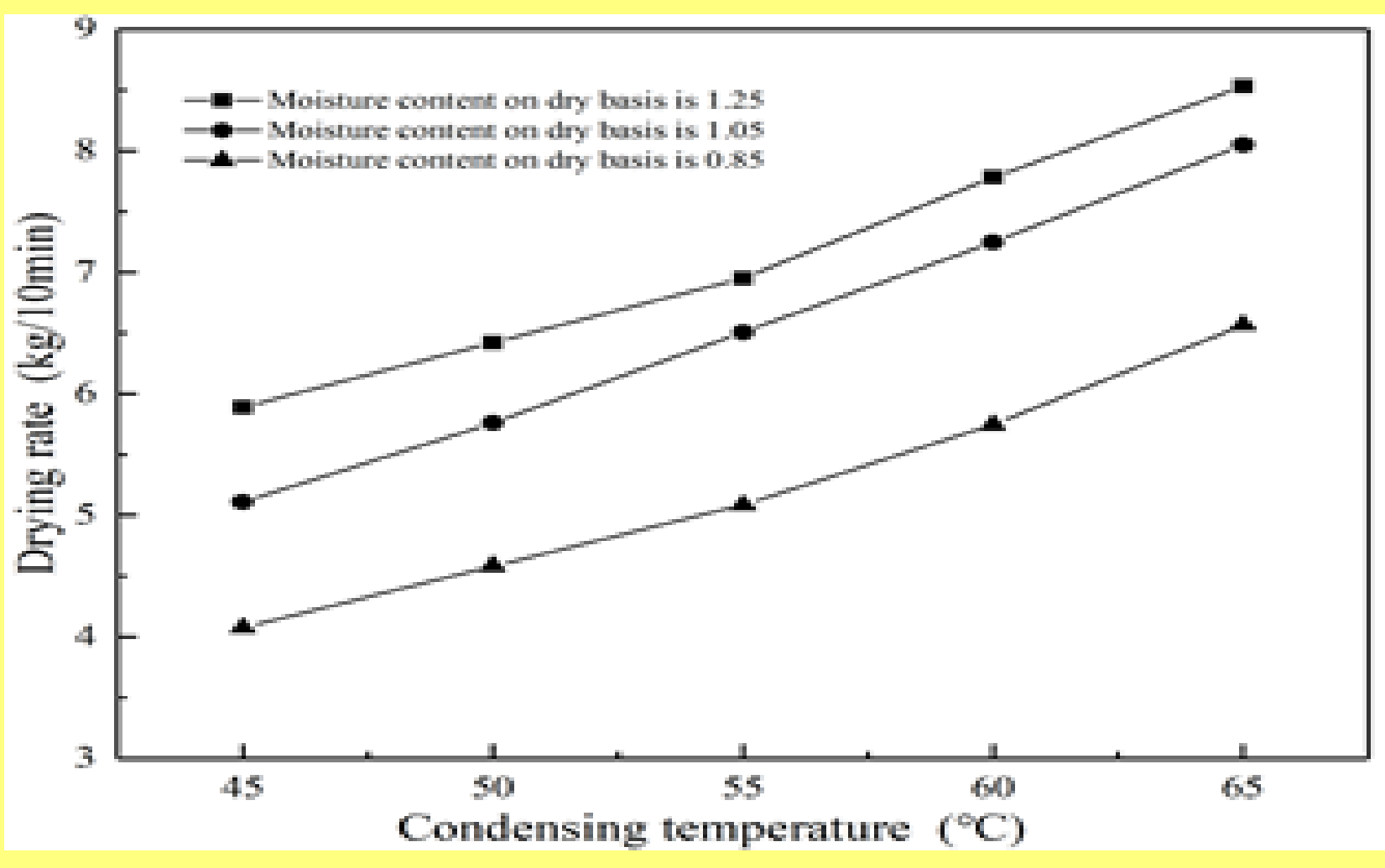


Fig. 5. Influence of the condensing temperature to the drying rate.

AIR MASS FLOW RATE

Influence of the air mass flow rate to drying rate is shown in Fig. 6. The result shows that the drying rate increases first and then decreases with increasing the air mass flow rate.

A similar trend can also be found in [9]. It is because that the relative humidity of the evaporator inlet air increases first and then decreases in the simulation. Moreover, it is assumed that the relative humidity of moist air at the outlet of evaporator is saturated. Therefore, the moisture content difference of moist air between the inlet and outlet of evaporator increases first and then decreases. While the air mass flow rate continues to increase, the former plays a more important role. Finally, the interaction causes the drying rate to increase first and then decrease.

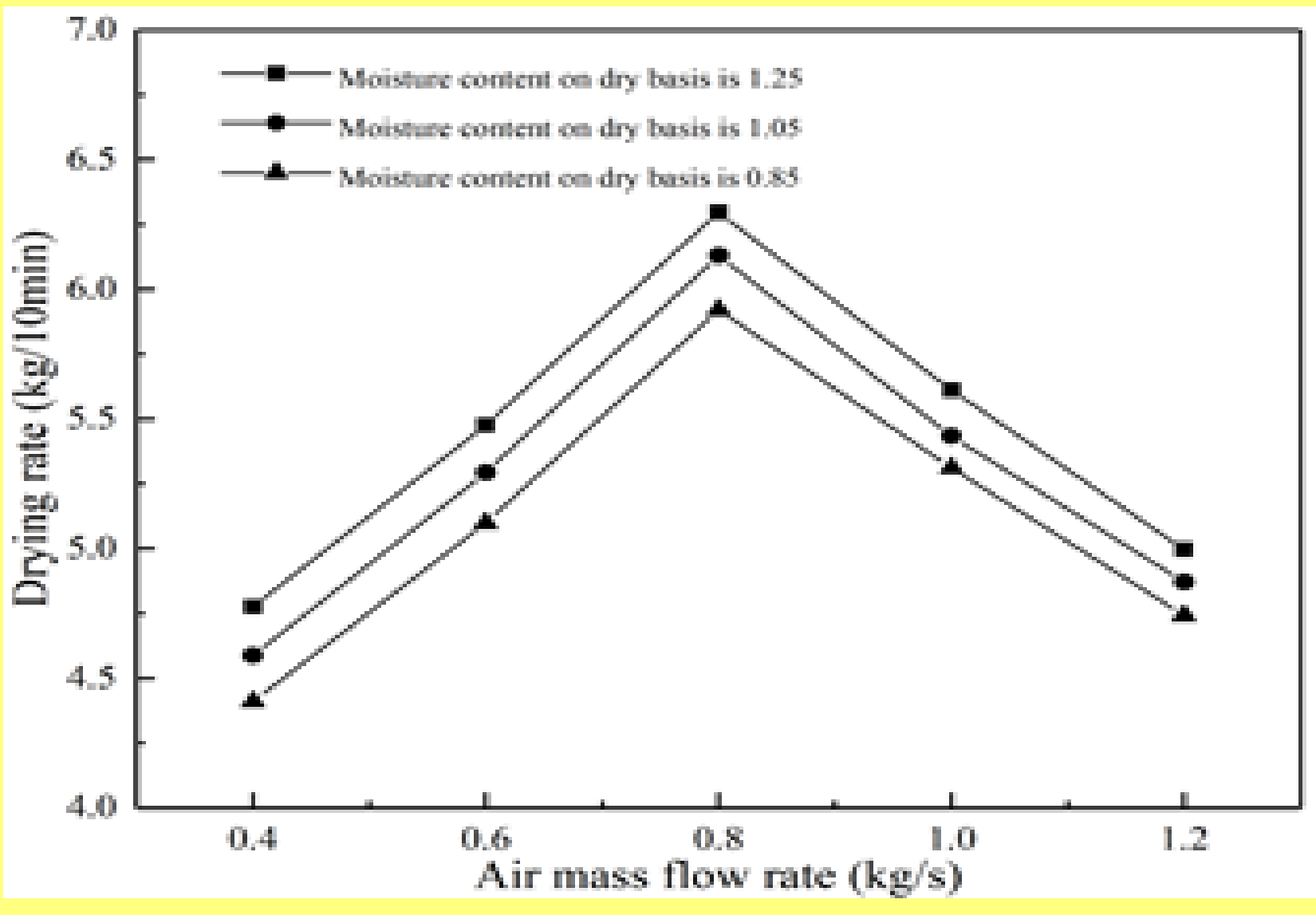


Fig. 6. Influence of the air mass flow rate to the drying rate.

Conclusions

The main conclusions drawn from all these work are:

- The simulation results agree well with the experimental data. The mean deviation is less than 5%;
- Low evaporating temperature can ensure better drying effect;
- High condensing temperature can improve the drying effect of the system;
- An optimal range of 0.8-1 kg/s is suggested..

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