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Research Paper

Numerical analysis on the performance of mechanical vapor recompression system for strong sodium chloride solution enrichment

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HIGHLIGHTS

- MVR system is used to evaporate a type of anti-frozen solution in HVAC fields.
- Regeneration performance of anti-frozen solution of heat-source tower is studied.
- Influence factors on evaporating performance of input parameters are modelled.
- An experimental plant of is established to validate the mathematical model.

ARTICLE INFO

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Solution regeneration of anti-frozen solution
Heat pump
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ABSTRACT

Mechanical Vapor Recompression (MVR) system is an efficient system for evaporation, which has been employed in extensive fields. Solution regeneration in HVAC fields is significant. In this paper, MVR system is used to regenerate a type of anti-frozen solution of heat-source tower heat pump, the sodium chloride solution with high concentration. A system model has been built to analyze the stable operating performance of regeneration. Meanwhile, an experiment plant of MVR system has been established to monitor the actual operating performance of the system to validate the model.

Operating parameters of the system are calculated based on the system model. Performance indicators are analyzed according to the parameters calculated above. The influence of the input parameters on the evaporating performance of the system is studied, including the frequency of compressor, temperature of inlet weak solution, concentration of inlet weak solution. With the increase of frequency of compressor or the increase of inlet solution temperature, evaporation rate, quantity of heat transfer and power consumption of compressor increase accordingly. Power consumption of the compressor to evaporate per ton of water reaches 16.8 kWh, when the suction pressure is 25 kPa, the concentration of the inlet weak solution is 18%, and the frequency of compressor is 100 Hz. Concentration of solution has a great effect on the boiling point elevation of the solution. Therefore, when the concentration of solution is high, power consumption of compressor increases significantly, and COP decreases sharply. When the inlet concentration increases 1%, the power consumption of the compressor to evaporate per ton of water increases 8.2%, and COP decreases 2.7%.

1. Introduction

Evaporation of solution usually refers to a process of which a part of solvent evaporates from the heated solution to concentrate the non-volatile component of the solution. And it is one of the most common processes for industrial manufacture, such as chemical fields [1], food industries [2,3], sea water desalination fields [4,5], and treatment of industrial waste water [6]. The existing techniques of solution evaporation, includes single-effect evaporation, multi-effect evaporation, thermal vapor recompression, and mechanical vapor recompression, etc. As one of the most energy-intensive manufacture processes, the quantity of energy consumption of evaporation is considerable. Based on the investigation conducted in UK, the average energy consumption for the evaporation facilities is 4.87 GJ to evaporate per ton of water [7]. In China, energy consumption of evaporation accounts for 12% of the total energy consumption of national economy according to the statistics [8]. Therefore, application of energy-saving equipment on evaporation fields is necessary.

Mechanical Vapor Recompression (MVR) system is an efficient system for evaporation. The weak solution is heated in a heat exchanger. The vapor is evaporated from the weak solution and the solution is concentrated. The vapor is sucked and compressed by the

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Nomenclature

c_p	specific heat capacity (kJ/(kg·K))
d	inner diameter of evaporating pipe (m)
F	heat transfer area (m^2)
g	acceleration due to gravity (m/hr^2)
h	specific enthalpy (kJ/kg)
h_{in}	heat transfer coefficient for inside annular liquid (kcal/m^2·h·°C)
h_{out}	heat transfer coefficient for heating steam (kcal/m^2·h·°C)
k	thermal conductivity (kcal/m·h·°C)
K_{total}	total heat transfer coefficient (W/(m^2·K))
m	mass flow rate (kg/s)
P	pressure (kPa)
Q	quantity of heat transfer (kW)
r	latent heat of vaporization (kJ/kg)
T	temperature (°C)
V	suction volume rate (m^3/s)
V_m	rate of evaporated vapor flow (kg/h)
W	power consumption (kW)
x	mass concentration (kg/kg)
Δ	variation
ρ	density (kg/m^3)
η	efficient
μ	viscosity (kg/m·h)
Γ	liquid flow rate per wetted periphery (kg/m·h)

Subscript

b	boiling point
cp	certain pressure
cw	condensed water
dis	discharge
ele	electric heater
f	film
in	inlet
isen	isentropic compression
np	normal pressure
out	outlet
s	solution
suc	suction
V	vapor
w	water

Abbreviation

COP	coefficient of performance (kW/kW)
SMER	specific moisture extraction rate (kWh/ton)

compressor. Afterwards, the compressed vapor with high temperature is conducted back to the heat exchanger, where the condensing heat of vapor is used to heat the weak solution. In the system, the grade of the vapor is lifted by the compressor, turning to the heating source of the weak solution. And the power consumption of the compressor depends on the temperature difference of heat transfer and the boiling point elevation of solution. Therefore, the MVR system could concentrate solution with a small amount of energy consumption from the compressor and water pumps under normal operation. As an energy-saving system, MVR system is mainly studied and widely applied recently.

Study on operating performance of MVR system is necessary for its application and system optimization. And some researchers have conducted some research on the performance of MVR system. Working medium is different based on different application fields, and different working medium would show different operating performance. Aybar [9] has studied the influence of evaporating pressure and condensing pressure on the energy consumption of compressor with water as working medium. Mounir et al. [10], Zhao [11,12], Liu [13] and Gu et al. [14,15] have also utilized water as working medium to study the performance of MVR system. The working performance under different compression ratio is analyzed. Faisal et al. [16], Hisham et al. [17,18] and Wu et al. [19] have designed the MVR system with sea water as working medium. The influence of heat transfer temperature difference and heat transfer area on the system is studied in their paper. Performance of MVR systems with water injection compressor and without water injection is compared in Yang's [20] research by experiments. They concluded that under the same energy consumption, the evaporation rate with water injection of compressor is larger than that without water injection. Liang [21] has proposed a two stage MVR system to deal with the industrial ammonium sulfate waste water. Temperature of outlet solution and energy consumption of compressor is measured by experiments to validate the model. T. G. Walmsley [22–24] has applied pinch analysis to optimize the heat exchanger network integrated with MVR system, which could decrease the energy consumption by 67%.

However, regeneration of brine solution with high concentration is of vital importance in HVAC fields [25,26], such as liquid desiccant air-conditioning system and heat-source tower heat pump system. Desiccant solution in the independent temperature-humidity control air conditioning system is used to dehumidify the air, which is usually the brine solution with high concentration. To guarantee the dehumidification performance of the solution, regeneration of desiccant solution is necessary [27,28].

Solution regeneration is also important in heat-source tower heat pump system in HVAC fields. Heat and mass transfer between air and solution exists in the heat-source tower, vapor from the air will condensate in the solution, resulting in the decrease of solution concentration, which could bring the risk of solution frozen [29]. Therefore, solution regeneration of heat-source tower heat pump system is necessary and of vital importance to guarantee the normal operation of system.

And strong sodium chloride solution is a type of anti-freezing solution applied in heat-source tower. Application study of MVR system to regenerate this type of working medium and in HVAC area is insufficient in previous research. Study of influence of boiling point elevation of solution on the operation performance of MVR system is rare in previous research. As the boiling point elevation of strong solution is much higher than that of the weak solution, which would have great influence on the energy consumption of compressor in MVR system. Therefore, study of influence of boiling point elevation on operation performance is significant to extend application in HVAC area of MVR system.

In this paper, strong sodium chloride solution is selected as the working medium of the MVR system. A stable model of the MVR system is established to analyze the performance of MVR system. Influence of input parameters on the system is discussed, including frequency of compressor, inlet solution temperature and inlet solution concentration. And an experiment plant is also built to validate the model. Influence of the system parameters on energy consumption performance and evaporation performance of the system is studied.

2. Modeling

The schematic diagram of the MVR system is shown in Fig. 1. The system is mainly composed of a shell and tube heat exchanger, a compressor, a solution pump, a water pump, valves and some connecting pipes. The weak solution flows in the tube side. Vapor evaporated from the solution is compressed by the compressor, and the