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Combination of air-source heat pumps with liquid desiccant dehumidification of air

Li Zhang [a,*], Eiji Hihara [b], Michiyuki Saikawa [a]

[a] Central Research Institute of Electric Power Industry, 2-6-1 Nagasaka, Yokosuka-shi, Kanagawa 240-0196, Japan
[b] Department of Human and Engineered Environmental Studies, Graduate School of Frontier Sciences, University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa-Shi, Chiba 277-8563, Japan

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ABSTRACT

This paper proposes a frost-free air source heat pump system with integrated liquid desiccant dehumidification, in which frosting can be retarded by dehumidifying air before entering an outdoor heat exchanger. And the water removed from the air is used to humidify a room. Simulation is carried out at a dry-bulb temperature of −7 to 5.5 °C and a relative humidity of 80% depending on the frosting conditions. The results show that the coefficient of performance (COP) is in the range of 2.6–2.9, which is 30–40% higher than that of heat pump heating integrated with an electric heater humidifying system. And it is found that the optimum value of the concentration of lithium chloride aqueous solution is 37% for the frost-free operation mode. Experiments are conducted for liquid desiccant system under low air temperature and high relative humidity conditions. Experimental results show that the dew point of the dehumidified air is decreased by 8 °C and the humidity ratio of the humidified air is kept at 8.1 g kg^{-1}, which ensures the frost-free operation of the heat pump evaporator and the comfortable level of room humidity simultaneously. The heating load of solution is 3–4.5 times larger than cooling load of solution, which agrees with the assumption given at the part of the simulation. Furthermore, the deviations between the calculated COP_{LHRU} and the experimental results are within 33%.

1. Introduction

An air-source heat pump that uses air as a heat source offers an economic form of heating. Depending on the climate, air-source heat pumps are about 1.5–3 times more efficient than electric resistance heating alone. However, one of the problems is evaporator frosting, and the subsequent need for defrosting, which occurs when an air-source heat pump is operating at low ambient temperature and high relative humidity. Frost normally accumulates when air temperature is between −7 °C and 5 °C and relative humidity is over 60% [1].

Frost accumulation on an evaporator has several consequences. First, the accumulation of large amounts of frost will reduce the air flow rate by blocking air passages and increasing resistance to heat transfer [2,3]. This causes the heating capacity and COP to be reduced [4–6]. Other problems caused by frosting include increased equipment cost due to the addition of auxiliary heating elements, reduced equipment reliability, and increased loss of the operational load during the defrosting process. Therefore, preventing or delaying the frosting process is an important concern in designing an air-source heat pump. There are many factors that influence the frost formation and deposition process; these may include the temperature and characteristics of a cold surface and humidity, temperature, and velocity of air. Many efforts have been made to find various functional surfaces that can reduce frost deposition or from which it is easy to remove the frost layer, such as hydrophilic polymeric coatings [7,8] and hydrophobic and hydrophilic surfaces [9].

When frost accumulated on the evaporator coil exceeds a certain level, the performance of the unit degrades to such a level that frost must be removed from the evaporator surface on either a continuous or intermittent basis. Defrosting can be achieved by supplying heat to an outdoor heat exchanger by various methods, including reversing the cycle [6,10], defrosting with warm air using an electric resistance heater [1], and hot-gas refrigerant bypass [11–13].

As for the reverse-cycle defrosting method, by using a 4-way valve, the normal heating operation and the refrigerant flow are reversed. During the defrosting process, hot gas is pumped into an outdoor coil so as to melt the frost. However, reversing the cycle has a disadvantage that heat is often extracted from the conditioned space, which makes users feel uncomfortable. Another disadvantage is that some melted water remains on the heat-exchanger surfaces. As the defrost cycle ends and the heat pump changes to its heating mode, this water freezes to form a high-density frost, which is slow to melt during subsequent defrosts [1]. In a warm-air defrosting system, the air before the evaporator is heated in order to melt the frost on the coil surface. Defrosting with warm

* Corresponding author. Tel.: +81 4 6856 2121; fax: +81 4 6856 3346.
E-mail address: zhangli@criepi.denken.or.jp (L. Zhang).

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Nomenclature

A_1–A_{11}	air state points
C_s	concentration (%)
C_p	specific heat capacity (kJ (kg °C)$^{-1}$)
COP	coefficient of performance
d_e	equivalent diameter of air channel (m)
D	diffusivity (m^2 s^{-1})
h	enthalpy (kJ kg^{-1})
K	mass transfer coefficient (kg (m^2 s)$^{-1}$)
m_a, m_s	mass flow rate of air and solution (kg s^{-1})
m_{vap}	mass flow rate of vapor (kg s^{-1})
P	pressure (Pa)
Q	heat load (kW)
r	latent heat of vaporization (kJ kg^{-1})
Re	Reynolds number
RH	relative humidity (%)
S_1–S_6	solution state points
Sc	Schmidt number
T	temperature (°C)
W	electric power (kW)
X	humidity ratio (g (kg dry air)$^{-1}$)

Greek symbols

ρ	density (kg m^{-3})
η_T	temperature effectiveness of dehumidifier/regenerator
η_{ex}	temperature effectiveness of solution heat exchanger
η_{com}	isentropic efficiency of compressor

Subscripts

a	air
con	condenser
deh	dehumidifier
eva	evaporator
in	inlet
LHRU	latent heat removal unit
out	outlet
reg	regenerator
s	solution
SHRU	sensible heat removal unit
w	water

air is not commonly employed in heat-pump operations because heating from electrical resistive heating is inefficient. As for the hot-gas bypass defrosting method, the superheated refrigerant from the compressor directly flows to the evaporator, bypassing the condenser and the expansive device. This method is considered as one of the most effective defrosting methods. The average COP and integrated heating capacity are improved by 8.5% and 5.7%, respectively, as compared to heat pumps where no defrosting method is used [11].

These abovementioned defrosting methods are based on increasing the temperature of the outdoor coil surface in order to melt the frost formed on it. One common problem caused by those defrosting methods is heating shutdown. The sorption dehumidification of air by a liquid desiccant is an interesting method to humidity control [14,15]. In this study, we propose a frost-free air-source heat pump combined with a liquid desiccant system. In this system, frost formation is retarded by dehumidifying air before entering the outdoor coil using liquid desiccants. And the water removed from air is used to humidify room. As a result, the system proposed in our research cannot only provide heating load continuously, but also humidify room without extra water source.

2. System description

Fig. 1 shows the schematic diagram of the frost-free air-source heat pump system, which consists of two major units: a sensible heat removal unit (SHRU) and a latent heat removal unit (LHRU). The SHRU comprises a vapor-compressing heat pump (HP_{SHRU}), which employs R410A as the refrigerant. The task of the SHRU is to handle the sensible heat of return air from the air conditioning room. The LHRU comprises a liquid desiccant system, which uses a lithium chloride aqueous solution as the desiccant and a vapor-compressing heat pump (HP_{LHRU}) to provide cooling and heating load for desiccant solution simultaneously. The tasks of the LHRU are to humidify the fresh air flowing into the air conditioning room and dehumidify air before entering evaporator of HP_{SHRU}.

The operation of the hybrid heat pump system in heating, humidifying and frost-free mode is described as follows. Fresh air (A_1) flows into the regenerator (4), in which it is humidified by contact with hot liquid desiccant (S_1) due to the vapor pressure difference. One part of the humidified air (A_2) mixes with the hot air (A_7) that is heated by the HP_{SHRU} condenser (6') and is supplied to the AC room (10). The surplus part of the humidified air (A_3) is exhausted to the atmosphere after passing through the auxiliary

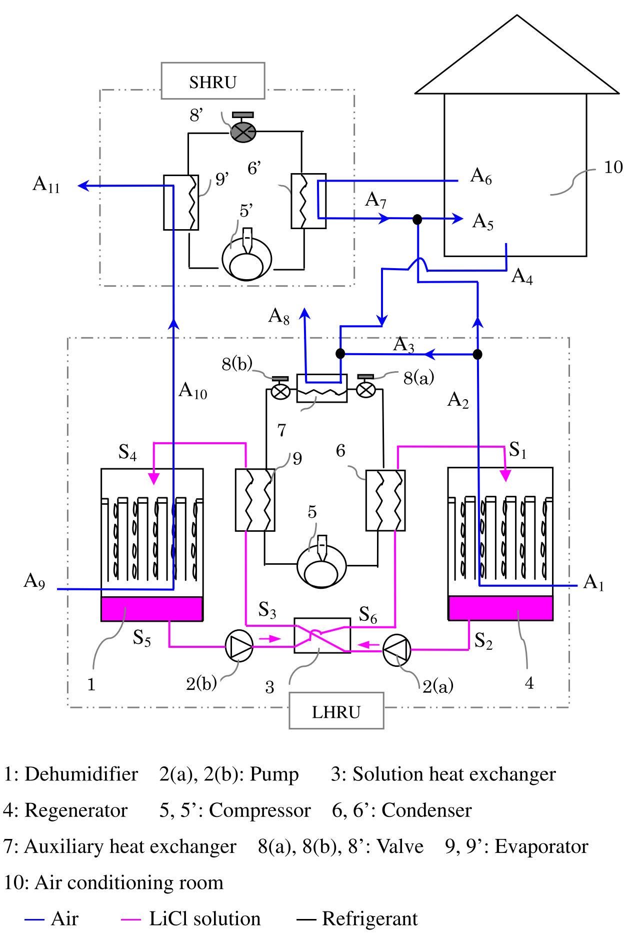

Fig. 1. Schematic diagram of frost-free air-source heat pump system.