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New concept of desiccant-enhanced heat pump

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ABSTRACT

Comfortable, efficient and affordable heating, ventilation and air conditioning (HVAC) systems in buildings are highly desirable to achieve zero energy building effort. Traditional vapor compression air-conditioners hold a lower COP (coefficient-of-performance) (typically 3.2–3.8) because it often operates at a lower evaporation temperature (5–7 °C) and a higher condensing temperature (50–55 °C) caused by cooling-based dehumidification that handles both sensible and latent load together. Room temperature and humidity independent control or desiccant systems have been proposed to overcome these challenges, however, the *COP* of current desiccant systems is quite small and additional heat sources are usually used. In this paper, a desiccant-enhanced direct expansion heat pump (DDX HP) based on water-sorbing heat exchangers was reported, with an ultrahigh COP value of more than 6 without sacrificing any comfort and compactness. The efficiency is double in comparison with today normal room air conditioners, which is a breath-taking and revolutionary progress in HVAC industry. This new approach opens up the possibility of designing a zero energy building with DDX HP powered by solar PV, and the simulation results show that one PV model (265Wp) can effectively handle about 10 m^2 cooling load in Shanghai in summer.

1. Introduction

There is a growing concern that the increasing demand for heating, cooling, and refrigeration services world-wide may consequently lead to global warming and environmental unfriendliness [1–3]. To alleviate this trend, major efforts are being directed at improving thermal performance of building envelopes and enhancing the energy efficiency of building services within them to address the critical needs of the zero energy building effort [4]. However, it is impractical and far too costly to design a zero energy building with standard HVAC systems by attempting to generate all the required energy through on-site renewable energy. As noted in [4], the approach for a zero energy building is to greatly reduce the energy needs through efficiency gains, and only then make up the remaining energy needs through on-site renewable generation. Although there have been significant breakthroughs in the past decade on alternate efficient cooling technologies such as magnetic [5], thermoelectric [6], elastocaloric [7] and thermoacoustic [5] cooling, most of these ideas have not been translated into viable technologies due to multiple reasons. For example, the maximum cooling demonstrated for magnetic refrigeration has been less than 1 kW. Considering that more than 90% of the cooling systems today are based on vapor compression, it is valuable to dramatically improving the energy efficiency of vapor compression based systems while reducing greenhouse gas emissions and the cost to the consumers.

Air-conditioning systems utilizing vapor compression heat pump cycle have seen energy efficiency improvements through reductions in required compressor operation; mainly by decreasing the difference between high and low pressures. Efficiency improvement in this manner requires dispersing temperature rise, which greatly decreases the latent capacity as shown in [8]. In air-conditioning systems there is generally a compromise between efficiency and latent capacity. This is because current air conditioners remove the water vapor from the moisture air by cooling it below the dew point. So it is quite normal that HVAC systems do not provide sufficient humidity control under certain conditions (e.g. when sensible cooling loads are low) and do not offer adequate fresh air ventilation which is necessary to ensure indoor air quality in tight homes but can significantly improve the latent load.

To solve this problem, innovative system designs such as temperature and humidity independent control (THIC) had been proposed [9]. A THIC system usually consists of a thermal driven dehumidification unit (for example liquid or solid desiccant system) and a vapor compression air-conditioner specializing for the sensible heat load. It was reported that THIC systems might save 25–50% [10] electrical consumption by adopting a higher evaporation temperature (e.g. 15–20 °C) and the corresponding COP increases by about 40–60% [10] under different operating conditions compared to conventional HVAC systems. However, the *COP* (= Latent load/primary thermal energy input) of current solid desiccant systems is quite small, typically ranging from

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0.5 to 1.0 [11] due to the required high regeneration temperature (usually in the range of 60–120 °C [11,12]). Even though sometimes solar heat or industry waste heat can be used, a large volume and high utility cost limits their large-scale application in residential buildings [10].

In recent years, to attenuate these influences, an inner-cooling desiccant heat exchanger has attracted more and more attention [13–18]. Freni et al. [13] developed a dip-coating technique and prepared a SAPO-34 coated fin-tube heat exchanger for adsorption refrigeration. Experimental results show that the coated adsorber clearly offered faster adsorption rate, higher mass specific cooling power. Bongs et al. [14] presented a silica gel-coated indirect evaporating heat exchanger for dehumidification driven by solar heating air. This work confirms that the internal evaporative cooling lead to a promising advance in cooling performance compared to indirect evaporating cooling or adiabatic desiccant cooling. Ge et al. [16,17] investigated the effects of two kinds of desiccant on the cooling performance of desiccant-coated heat exchanger under different conditions and obtained the similar results. Zhang et al. [15] furtherly studied its airside heat and mass transfer characteristics in details. In fact, one thing in common is all these studies focus on air cooling or water cooling desiccant heat exchanger. By this way, the heat released in adsorption process can be carried away quickly by the inner heat transfer media, which is very useful to reduce the regeneration temperature. However, this kind of desiccant heat exchangers still work as a dehumidifier, and need additional cooling and heating sources. All these make the whole HVAC systems complex and expensive.

Considering the thermal regeneration characteristic, it would be reasonable to use the condensing heat for the regeneration of desiccant dehumidification unit and the refrigerant evaporating to keep low adsorption temperature [10,19]. Then novel desiccant material which has sufficient water adsorption capacity difference at two cycle conditions (such as 15 °C/80%RH and 45 °C/30%RH) can be adopted. It is estimated that, if the HVAC systems have 40–50% latent heat, latent load is removed by desiccant system and sensible load is treated as before, adsorption heat is removed by refrigerant and desiccant is regenerated by condensing heat, evaporation temperature can increase from about 5–7 °C to about 15–17 °C, and condensing temperature can decrease from about 50–55 °C to about 40–45 °C, and then the COP can be nearly doubled.

Here, a novel concept of desiccant-enhanced DX heat pump (DDX HP) was reported, based on the so-called water-sorbing heat exchanger (WSHE) [20] fabricated by coating desiccant on the surfaces of conventional evaporator and condenser. In order to guarantee continuous operation, two same WSHEs will switch from evaporator (condenser) into condenser (evaporator) alternatively. The sensible load is handled in the same way as before by convection but without overcooling, and coated desiccants treat the latent load in a nearly isothermal way. Therefore, the process air leaving the evaporator satisfies the requirement of supply-air. As a result, the evaporation temperature rises while the condensation temperature drops compared to traditional air conditioners because WSHE need not cool the process air below its dew point to condense the moisture and the adsorbed water evaporating strengthens the heat dissipation capacity of condenser. Therefore, DDX HP shows a great potential to achieve much higher energy efficiency.

2. System description

2.1. Working principle

DDX HP can be taken as a combination of traditional vapor compression system and solid desiccant material (Fig. 1), which has a return air inlet (RA) and an outdoor air inlet (OA), a supply air outlet (SA) and an exhausted air outlet (EA). In the system, sensible heat exchangers (including evaporator and condenser) within vapor compression cycle is coated with desiccant materials. Because this novel heat exchanger can adsorb water vapor and retain the removed water, which is totally different traditional heat exchanger, and named as water-sorbing heat exchanger (WSHE). It is the same as conventional vapor compression system, refrigerant in DDX HP operates as following: after absorbing heat in the evaporator, refrigerant vapor is compressed in the compressor, condenses in the condenser and expands through the throttling device, then the cold refrigerant goes to evaporator again. Yet, air flow in DDX HP is more complicated compared with a vapor compression system. When ambient air is pumped into the evaporator, the air flow will be dehumidified by the desiccant coated on the evaporator surface. At the same time, evaporation inside evaporator will cool down the air flow and also takes away the adsorption heat on the desiccant. Processed air then becomes colder and dryer. On the other hand, another group of air is heated by the hot refrigerant inside the condenser. Meanwhile, the coated desiccant at a relatively high temperature desorbs water vapor into the air.

After a time, adsorption ability of coated desiccant in evaporator reaches to saturation, due to abundant moisture inside. Meanwhile condenser is almost completely regenerated by high temperature refrigerant. Then, it is time to switch over the four-way reserving valve, exchanging position between evaporator and condenser. Thus, DDX HP features a process of periodic switchover of the evaporator and condenser. Air duct should also be re-constructed, to persistently guide cooling air into the condenser.

In this case, WSHE can independently handle the sensible and latent loads at the same time without overcooling or reheating (Fig. 2a). Therefore, the process air leaving the evaporator satisfies the requirement of supply-air (Fig. 2b). Specifically, the sensible can be adjusted by changing evaporation temperature and the latent load capacity can be managed by altering the duration of moisture uptake respectively, referred in [21]. Desiccants absorb moisture almost isothermally and can be regenerated by condensation heat. Evaporation temperature can increase from ∼5 °C to ∼15 °C as dew-point condensation is not needed, while condensation temperature could be decreased from ∼55 °C to ∼45 °C owing to the enhancement of heat dissipation due to adsorbed water evaporating. So, DDX HP shows a great potential to achieve much higher energy efficiency (Fig. 2c).

2.2. Experimental setups

To demonstrate the feasibility of this novel concept, a single packaged DDX HP was designed and constructed, illustrated in Fig. 3. The main parts used is detailed shown in Table 1. In this design, the whole system includes two parts: vapor compression loop and air ducts, both are located in a cabinet with two air inlets (OA and RA) and two air outlets (SA and EA). DDX HP has two operation modes for cooling and dehumidification. (1) 4-way valve 5 were power-off, valve 22 and 25 are open and valve 23 and 24 are closed. WSHE 6 is condenser and WSHE 7 is evaporator. Outdoor air (OA) and return air (RA) are sucked into the cabinet by two fans 13 respectively. Part of OA passing through valve 18 and part of RA passing through valve 19 are mixed in chamber 26, formatting the process air; while the rest of OA passing through valve 20 and the rest of RA passing through are mixed in chamber 27, formatting the cooling air. Process air flows through valve 22(up) and then into WSHE 7; after being cooled and dehumidified, it passes valve 25(down) and at last is supplied into conditioned room by air duct 16. At the same time, cooling air flows through valve 22(down) and then into WSHE 6; after being heated and humidified, it passes valve 25(up) and finally is exited to the outdoor by air duct 17. (2) 4-way valve 5 are power-on, valve 22 and 25 are closed and valve 23 and 24 are open. WSHE 6 is evaporator and WSHE 7 is condenser. Process air flows through valve 23(up) and then into WSHE 6; after being cooled and dehumidified, it passes valve 24(down) and at last is supplied into conditioned room by air duct 16. At the same time, cooling air flows through valve 23(down) and then into WSHE 7; after being heated and humidified, it passes valve 24(up) and finally is exited to the outdoor by