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Research Paper

Design and experimental study of an air source heat pump for drying with dual modes of single stage and cascade cycle

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HIGHLIGHTS

- An air source heat pump drying system was designed with dual operation modes.
- The operation mode changes to satisfy heating demands at different conditions.
- A prototype is developed and its performance is experimentally studied.
- The drying air temperature reaches 70 °C at the heat pump's design conditions.
- The comparison of COPs is done for the reference of mode-switch point decision.

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ABSTRACT

The heat pump drying system is a prospect technology for material drying due to its advantages of high efficiency and energy saving. This paper presents a design of an air source heat pump with dual modes for drying. The operation mode changes between a single stage and a cascade cycle to satisfy the heating demand under different ambient temperatures. A prototype of this dual-mode heat pump is developed using R22 and R134a as refrigerants. To verify the feasibility and to investigate the characteristics of this heat pump, an experimental study is carried out. According to the results of this study, the supplying air temperatures satisfied the drying demand (70 °C) when the heat pump operated at its design condition which is an ambient temperature of 0 °C for the cascade cycle and 20 °C for the single stage. With the increase of the ambient temperature, the supplying air temperature, heating capacity and electric power all increased at both operation modes. The difference of electric power between the two modes also increased with the ambient temperature, but the difference of supplying air temperature decreased. Although the variation of compressors' pressure ratio was small within each mode, the pressure ratio of the high stage's compressor changes a lot which was about 3.8 for the single stage and 5.5 for the cascade cycle. With the same supplying air temperature, the lines of coefficient of performance (COP) at different modes crossed each other. The COP of single stage was higher after an ambient temperature of 2 °C for the developed heat pump.

1. Introduction

Material drying is a technology that separates water inside the material by heating. It has been widely used in many areas, such as agriculture, food, medicinal materials, carpentry, etc. [1]. Industrial boilers or devices of direct electric heating are the commonly used heating technology to generate the heat with high temperature. Due to the principle of these heating method, a huge amount of energy consumption is necessary. Considering the challenges of global energy crisis and environmental problems, it is quite important to develop new heating devices that apply a heating technology with high energy efficiency.

A heat pump dryer (HPD) which combines the heat pump with a drying machine is one of the most effective methods that satisfies the requirements. It can recover energy from low-grade or low temperature sources and provide a high-grade or high temperature heating output that can be several times of the recovered low-grade heat. As a result, HPD is considered to be an efficient, energy saving, environmental friendly technology. It can also maintain the quality of materials due to the advantage of closed loop air cycle. Therefore, it is regarded as a hygienic drying machine especially

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Nomenclature

COP	coefficient of performance
C_p	specific heat at constant pressure, kJ/(kg·K)
E	electric energy consumption, kWh
H	heating time, s
m	mass flow rate, kg/s
p	pressure, kPa
Q	heat rate capacity, kW
T	temperature, °C
W	power consumption, kW

Greek symbol

ε	pressure ratio of the compressor

Subscripts

1	supplying air inlet of the condenser
2	supplying air outlet of the condenser
a	air
in	inlet of the compressor
out	outlet of the compressor

suitable for food drying [2]. Due to the above advantages, researches on HPD attracted lots of attentions in the last few years.

Saborio [3] established a general guideline for comparing heat pump and conventional recirculating dryer based on the energy consumption of specific moisture extraction rate (SMER). This guideline could be easily modified to take effects of local conditions such as electricity price into account. Chua [4] carried out an experimental study of a two-stage heat pump drying system and found 35% more heat could be recovered via a two-stage evaporator system. According to the experimental results and economic analyses by Wang et al. [5], the application of a heat pump dryer to dry hawthorn cake was proven to be feasible. The thermal characteristics of a heat pump dryer for ginger drying at 50 °C within 200 min was analyzed by Chapchaimoh et al. [6] using air and nitrogen as drying medium. According to their results, the SMER of ginger drying in air was 0.06 kg water/MJ compared with 0.07 kg water/MJ in nitrogen. Further, a review of heat pump systems for drying application was presented by Goh et al. [7]. Minea overviewed different types and applications of HPD in different areas [1,2]. Recently, an infrared heater was successfully combined with a heat pump for food drying by Aktsa et al. [8]. The maximum COP of the whole system reached 2.96. Apart from the characteristic studies of different HPD types, an advanced exergoeconomic evaluation method was developed and validated experimentally by Erbay et al. [9,10]. They showed that the efficient improvements by system components modification could be effectively determined through the exergoeconomic evaluation. The condenser was deemed to be the most important system component from the efficiency improvement point of view.

For different types of HPD, the refrigerants selection for the heat pump is quite important. Because, it not only affects the performance greatly, but also restricts the application of an HPD as it has to satisfy the international standard of global warming potential (GWP) and Ozone Depression Potential (ODP). With the changes of the compressor and expansion device, performances of heat pump tumble dryers with refrigerants of R290, R441 and R407C are compared experimentally by Ballomare et al. [11]. It was concluded that the technological focus on components was quite important for refrigerant replacement. The performances of household heat pump dryers with CO_2 and R134a were compared theoretically and experimentally in [12]. The results showed that the heat pump dryer with CO_2 had a negligible decreases of power consumption and a limited (9%) increase in the cycle time. Moreover, an experimental study on the control of a heat pump's capacity was performed with the composition changing of refrigerant mixtures which are R32/134a [13]. A mechanical steam compression dryer was also developed by Palandre et al. [14] and its performance was compared with a R134a heat pump dryer. The results of this study demonstrated that mechanical steam compression dryer had a higher efficiency and shorter drying time.

According to the reported studies on the HPD above, the recovered heat by a heat pump were commonly from the exhausted moist air out of the drying chamber. In these systems, both of the heat pump's evaporating and condensing temperature are decided or influenced by the drying process or demands. As a result, a special design of the heat exchangers is necessary for different drying application. And the control strategy of the HPD is another important technique to guarantee the system efficiency and stability [15]. This type of HPD might be mainly used in small and medium drying applications. Apart from the moist drying air, the ambient air is another usable low-grade heat source. Considering the system stability and investment, the air source heat pump (ASHP) as a mature technology will be also a good choice for drying applications. It can be easily combined with the dryer and need no more special design of the evaporator. One biggest problem of ASHPs is how to guarantee the heating capacity with the decrease of ambient air temperature. Different methods to improve the performance of ASHPs at low ambient temperature have been reported over the past years including solar-assisted heat pump [16,17], two-stage compression heat pump [18,19], vapor-injected compression heat pump [20,21] and cascade heat pump [22,23].

Although many studies have been reported on HPD and ASHP separately, the application of ASHP for drying process was seldom reported. Moreover, most of the studies on ASHPs were focused on the performance improvements under cold ambient temperatures in winter without paying the attention to the mean annual efficiency. As known, the ambient temperature variates a lot with the change of season. An air source heat pump for drying application should also keep high efficiency in different season except for satisfying the heating demands. This paper develops a heat pump that has dual operation modes of single stage and cascade cycle. The operation mode can be shifted according to the ambient temperatures to ensure certain heat production and efficiency. Moreover, a prototype of the designed heat pump is developed and an experiment rig based on HPD is built. An experimental study of this heat pump is carried out on the basis of the standard of heat pump water heater (GB/T21362-2008). The performance variation of the designed heat pump for drying is analyzed under different operation modes and ambient temperature conditions.

2. Design and develop of the heat pump for drying

2.1. Principle of the heat pump drying system

Fig. 1 illustrates the flow chart of the drying system using an air source heat pump with dual modes: single stage and cascade cycle. Fig. 2 is the corresponding *p-h* diagrams. The heat pump's operation mode is decided by the ambient temperature to guarantee