Applied Thermal Engineering 121 (2017) 728–736

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Improving defrosting performance of cascade air source heat pump using thermal energy storage based reverse cycle defrosting method

Qu Minglu [a,*], Li Tianrui [a], Deng Shiming [b], Fan Yanan [a], Li Zhao [a]

[a] *School of Environment & Architecture, University of Shanghai for Science & Technology, No. 516, Jungong Road, Shanghai, China*
[b] *Department of Building Services Engineering, The Hong Kong Polytechnic University, Kowloon, Hong Kong Special Administrative Region*

HIGHLIGHTS

- We proposed a TES based defrosting method for cascade air source heat pump.
- The method can shorten defrosting duration and reduce defrosting energy consumption.
- The thermal energy stored can also become a source for indoor space heating.

ARTICLE INFO

Article history:
Received 2 December 2016
Revised 26 April 2017
Accepted 28 April 2017
Available online 2 May 2017

Keywords:
Cascade
Air source heat pump
Defrosting
Thermal energy storage
Experimental study

ABSTRACT

To encourage a wider application of air source heat pumps (ASHPs) to colder areas due to the advantage of a higher energy efficiency, adopting cascade air source heat pumps (CASHPs) is a promising option. When CASHPs are operated in heating mode, frosting/defrosting has been problematic. However, the defrosting methods commonly used by conventional ASHPs cannot be directly applied to CASHPs. Therefore, a thermal energy storage (TES) based reverse cycle defrosting method for CASHPs has been proposed and an experimental study on its operating performances was carried out. Comparative tests when using both the standard hot gas by-pass defrosting method and the TES based reverse cycle defrosting method were carried out. The results suggested that when using the TES based reverse cycle defrosting method, defrosting duration was shortened by 71.4–80.5%, and defrosting energy consumption reduced by 65.1–85.2%, as compared to those when using the standard hot gas by-pass defrosting method. In addition, the thermal energy stored can also become a source for indoor space heating, and 37.7% of the normal heating capacity can be provided to a heated indoor environment when using the TES based reverse cycle defrosting method.

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1. Introduction

Air Source Heat Pumps (ASHPs) have found applications worldwide in recent decades due to its advantages of energy-saving and environment-friendliness. However, the operation of an ASHP unit can be quite problematic when it is operated in an extremely cold region in winter because of a very low evaporating temperature in its evaporator or outdoor coil, leading to a higher discharge temperature, and a sharply decreased heating capacity resulted from a high specific refrigerant volume at compressor suction and thus a low refrigerant mass flow rate. Consequently, a number of methods for improving the operating performances of ASHPs at an extremely low ambient temperature have been developed, including using ejector compression heat pumps [1–3], solar-assisted heat pumps [4,5], two-stage compression heat pumps [6,7], cascade air source heat pumps (CASHPs), etc.

Among these methods, a cascade heat pump system uses a pair of compressors, each working individually with its own refrigerant to obtain a higher condensing temperature and a reduced evaporating temperature. Its advantage lies in that both refrigerants work within their best working temperature ranges. A CASHP is hence suitable for providing space heating under a wide range of outdoor air conditions, including severely cold outdoor conditions. In a CASHP unit, the high temperature (HT) cycle and low temperature (LT) cycle are running independently, connecting by the intermediate heat exchanger, and its operation is complicated than conventional ASHP unit. A large number of experimental and theoretical investigations on CASHPs have thus been carried out, including the reported studies on their operating characteristics [8–11], performance optimization [12–14], and the determination

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* Corresponding author.
E-mail address: quminglu@126.com (M. Qu).

http://dx.doi.org/10.1016/j.applthermaleng.2017.04.146
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of an optimal intermediate temperature [15,16], and their control strategies [17], etc.

Similar to traditional ASHPs, frosting for CASHPs when operated in heating mode is an important issue to be addressed. Frost accumulation on the outdoor coil of a CASHP unit reduces airflow passage area and acts as a thermal insulator, leading to the performance degradation for the outdoor coil, or even the shutdown of the CASHP unit. Therefore periodic defrosting becomes necessary. Currently, the most widely used standard defrosting method for ASHPs is reverse cycle defrosting [18]. Defrosting helps an ASHP unit return to its rated performance. However, the process of defrosting itself consumes energy and causes undesirable fluctuations of indoor air temperature in heated space and other operational problems, such as low-pressure cut-off or wet compression. Therefore, extensive research work has been carried out to improve defrosting operation for ASHPs. Qu et al. [19] quantitatively analyzed the negative effects of melted frost downwards flowing along an outdoor coil surface due to gravity on defrosting performance. Song et al. [20] proposed a horizontally installed multi-circuit outdoor coil to reduce the length of flow path of downwards flowing melted frost, and defrosting efficiency was therefore increased by 9.8%. However, there was still some melted frost remained on the downside surface of each circuit due to surface tension, Song et al. [21] then explored the negative effects of surface tension on a multi-circuit outdoor coil, the experimental results showed that when the remained water cleaned as the surface tension destroyed, defrosting duration could be shorted from 186 s to 167 s, and defrosting efficiency improved from 49.4% to 61.4% compared with the surface tension kept. Zhu et al. [22] proposed a novel Temperature-Humidity-Time (T-H-T) defrosting control method based on a frosting map for an ASHP unit. Field test results showed that the T-H-T method could make accurate defrosting decisions under various environmental conditions. Song et al. [23] investigated the improvement for an ASHP unit by evenly adjusting the refrigerant distribution in its outdoor coil. Nevertheless, studies on developing suitable defrosting methods for CASHPs are seldom seen. Currently, for CASHPs, low temperature (LT) cycle hot gas by-pass defrosting method is commonly used, so that there is no need to reverse the operation of two refrigeration cycles in a CASHP unit. Previous experimental results [24] showed that at a certain outdoor temperature (-9 °C to -12 °C), defrosting duration when using hot gas by-pass may last for over 30 min, resulting from low refrigerant discharge temperature in the LT cycle, because the heat from the input work to LT compressor was not sufficient for melting the frost on outdoor coil surface. Therefore, it can be seen that the defrosting methods commonly used for traditional ASHPs cannot be directly applied to CASHPs, and the lack of an effective defrosting method for a CASHP would hinder its application at extremely cold winter condition. Consequently, it is highly necessary to develop suitable defrosting methods for CASHPs.

With the wide applications of thermal energy storage (TES) to HVAC systems, a TES based reverse cycle defrosting method has been developed [25,26], and the experimental results showed that this TES based defrosting method could provide adequate heat for defrosting, leading to a shortened defrosting period, an increased operating stability and a higher level of indoor thermal comfort for occupants.

This paper reports on an experimental study of a TES based reverse cycle defrosting method for CASHPs. Firstly, an experimental prototype CASHP unit where the TES based reverse cycle defrosting method may be applied to, and its test procedures are detailed. This is followed by reporting the results of controlled comparative tests using both standard hot gas by-pass defrosting method and the TES based reverse cycle defrosting method. Finally, a conclusion is given.

2. Experimentation

2.1. The experimental prototype CASHP unit

Fig. 1 shows the schematics of the prototype CASHP unit where the TES based reverse cycle defrosting method can be applied to. It was modified from a 10 kW heating capacity CASHP unit and was installed inside an existing psychrometric room. The psychrometric room was separated into a heated indoor space and a frosting outdoor space by a thermally insulated partition. As seen in Fig. 1, a TES based heat exchanger (TES-HE) and eleven solenoid valves (F1-F11) were added to the CASHP unit. The prototype was designed to operate under an outdoor air temperature of -25 to 20 °C. There were two refrigeration cycles in the prototype CASHP unit, a LT cycle using R410A to absorb the heat from ambient air and to transfer the absorbed heat to a high temperature (HT) cycle using R134a. The HT cycle consisted of a fixed speed compressor, a condenser (for heat exchange between R134a and indoor air) and a thermostatic expansion valve (TEV). The LT cycle consisted of a DC inverter-driven compressor, an electronic expansion valve (EEV), an air cooled evaporator, and a DC inverter-driven evaporator fan. Both cycles shared a common intermediate heat exchanger (HE) for heat transfer between R134a and R410A, and the TES-HE for heat exchange between refrigerants (R410A/R134a) and a thermal storage material used. The specifications of the key components in the prototype are listed in Table 1. The components in the HT cycle were installed inside the heated indoor space and that in the LT cycle inside the frosting outdoor space. The components shared by both cycles, i.e., the TES-HE and the intermediate HE, were installed in the indoor space.

The TES-HE, whose construction details are shown in Fig. 2, was designed as a thermally insulated shell-and-tube storage unit with the thermal storage material on the shell side and the refrigerants being circulated inside two separate spiral refrigerant tubes, to maximize the heat transfer between refrigerants and thermal storage material. R134a flowed through the inner refrigerant tube and R410A the outer refrigerant tube for continuously supplying heat to the indoor space, with the flow direction indicated in Fig. 2.

Water was used as the thermal storage material due to its advantages of high specific heat and thermal conductivity. Based on the evaluated amount of heat required for effective defrosting, 15.6 kg of water was used. Given that the water temperature difference before and after heat discharge was 30 °C, a total of $\sim$1966 kJ of heat could be stored in the TES-HE.

With the availability of the TES-HE, some of the heat made available during normal heating operation in the LT cycle of the prototype CASHP unit can then be stored in the TES-HE and used for defrosting when needed. This can then help provide adequate heat to enable a quick defrosting to eliminate the operating problems associated with conventional reverse cycle defrosting. On the other hand, when conventional reverse cycle or hot gas by-pass defrosting in the LT cycle is in progress, the HT cycle is usually powered off and no heating is thus provided to an indoor space. To the contrary, however, when the TES based reverse cycle defrosting is used, the HT cycle can continuously supply heat because sufficient thermal energy is available from the TES-HE.

The existing psychrometric room had a separate air conditioning (A/C) system and sensible and latent load generating units (LGUs), so that suitable experimental conditions in both indoor and outdoor spaces can be maintained.

The refrigerant pressures were measured using pressure transmitters with an accuracy of ±0.3% of full scale reading. Six pre-calibrated T-type thermocouples (of ±0.3 °C accuracy) were used for measuring water temperatures at three different levels of the TES-HE: top, middle and bottom. The power consumption of the

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