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Techno-economic analysis on frosting and defrosting operations of an air source heat pump unit applied in a typical cold city

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ABSTRACT

In recent years, air source heat pump (ASHP) units have found applications worldwide due to their advantages. For an ASHP unit with a multi-circuit outdoor coil, when the refrigerant distribution adjusted with the valves, system defrosting efficiency could be optimized. Meanwhile, adjusting the refrigerant distribution by using valves located at each circuit could improve the frosting evenness value, and system coefficient of performance and the defrosting efficiency are thereby both optimized. However, in open literature, no tech-economic analysis work on frosting/defrosting performances of ASHP units is reported, which limits the development of innovation technologies in this field. Therefore, a techno-economic analysis on frosting/defrosting operations for an ASHP unit used in typical cold regions is given, basing on previous experimental work and series of assumptions. As concluded, the total running costs of the new ASHP unit could decrease as much as 5,327.99 CNY ($ 798.87), or 7.67%, and the total cost about 5,177.99 CNY ($ 776.36), or 6.68%, in 15 years' service life, compared with a traditional one. The payback period of additional first cost of valves is less than 1 year. Conclusions of this study might provide a new analytical tool for scholars, researchers, product developers, and policy designers, and shed new light on the designing and performance optimization of ASHP units.

1. Introduction

Air source heat pump (ASHP) units have found applications worldwide in recent decades due to their advantages of high efficiency, environmental protection, low cost and easily modification, etc. When an ASHP unit operates for space heating at a low ambient temperature and high humidity environment, frost would form and accumulate on the tube surface of its outdoor coil. Frost becomes problematic, and thus periodic defrosting becomes necessary [1,2]. For an ASHP unit, there are many defrosting methods reported, such as compressor shut-down defrosting [3], electric heating defrosting [4], hot water spraying defrosting [5], hot gas by-pass defrosting [6], compressed air blowing defrosting [7], and ultrasonic defrosting [8], etc. Among all the studied defrosting methods, reverse cycle defrosting (RCD) have advantages of easy adjustment, no more energy consumed and floor space added, and safety and stable system, etc. [9]. Currently, it is the most widely used standard defrosting method for ASHP units.

To further improve the RCD performance for an ASHP unit, different studies were conducted by global researchers, such as heating and/or dehumidifying the inlet air of outdoor coil [10,11,12], structure and dimension adjustment for outdoor coil [13,14], fin type and surface treatment [15,16], additional defrosting energy supply with phase change material (PCM) thermal energy storage (TES) system [9,17,18], frosting evenness value (FEV) improvement on the surface of outdoor coil [19,20], control strategies optimization via refrigerant distribution adjustment [21,22], etc. On the other hand, for an outdoor coil in an ASHP unit, multi-circuit structure is usually used in order to enhance its heat transfer and minimize its refrigerant pressure loss [2,14,17–22]. To save the floor space, a multi-circuit is always vertically installed in its practical application.

For an ASHP unit with a vertically installed multi-circuit outdoor coil, it was easy to find the uneven defrosting phenomenon in open literatures [[19],23]. When the other circuit(s) was waiting for the lowest circuit terminating its defrosting procession, the heat transfer between hot tube and fins and ambient cold air would consume a

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Nomenclatures

Variable (Unit)

C_{ASHP}	First cost of an ASHP unit (CNY)
$C_{e,unit}$	Unit price of electricity (CNY/kWh)
$C_{f,i}$	Total first cost of the new ASHP unit (CNY)
$C_{f,V}$	First cost of valves (CNY)
$C_{i,V}$	Installation cost of valves (CNY)
$C_{r,C}$	Total running cost in cooling season (CNY)
$C_{r,comp,DF}$	Running cost of compressor during defrosting (CNY)
$C_{r,comp,F}$	Running cost of compressor during frosting (CNY)
$C_{r,DF}$	Running cost at defrosting operation (CNY)
$C_{r,F}$	Running cost at frosting operation (CNY)
$C_{r,FDH}$	Total running cost in heating season with frosting formation (CNY)
$C_{r,ITE,DF}$	Corresponding electricity cost of indoor thermal energy consumed (CNY)
$C_{r,id,fan,DF}$	Running cost of indoor air fan during defrosting (CNY)
$C_{r,od,fan,DF}$	Running cost of outdoor air fan during defrosting (CNY)
COP_C	System COP at cooling operation
COP_{DF}	System COP at defrosting operation
COP_F	System COP at frosting operation
$P_{ave,od,fan}$	Average power consumption of outdoor air fan (kW)
P_C	Compressor power consumption at cooling operation (kW)
P_{DF}	Compressor power consumption at defrosting operation (kW)
P_F	Compressor power consumption at frosting operation (kW)
P_H	Compressor power consumption at heating operation(kW)
$P_{id,fan}$	Power consumption of indoor air fan (kW)
$P_{od,fan}$	Power consumption of outdoor air fan (kW)
$Q_{id,air,DF}$	Indoor air thermal energy consumed at defrosting operation (kJ)
$Q_{id,air,F}$	Indoor air thermal energy supplied at frosting operation (kJ)
T_{CD}	Duration of cooling season in a year (day)
T_{DC}	Duration of a frosting/defrosting cycle (minute)
T_{DD}	Duration of defrosting operation in a cycle (s)
T_{DF}	Duration of frosting operation in a cycle (minute)
T_{FDH}	Duration of heating season with frost formation in a year (day)
$T_{ind,in}$	Average measured air temperature at the inlet of indoor coil (°C)
$T_{ind,out}$	Average measured air temperature at the outlet of indoor coil (°C)
T_{NFDH}	Duration of heating season without frost formation in a year (day)
T_{ODC}	System operating duration in cooling season (hour)
T_{ODH}	System operating duration in heating season without frost formation (hour)
T_{OT}	Operating cycle times in a day (time)
T_Y	Service life of the new ASHP unit (year)
$V_{i,air}$	Volumetric flow rate of air passing through the indoor coil (m^3/s)
$\rho_{i,air}$	Density of air in the indoor heated space (kg/m^3)

Abbreviations

ASHP	Air source heat pump
CNY	Chinese yuan
COP	Coefficient of performance
EEV	Electronic expansion valve
FEV	Frosting evenness value
PCM	Phase change material
RCD	Reverse cycle defrosting
TES	Thermal energy storage

lot of energy [24]. Not only system defrosting efficiency would be degraded, but also the defrosting duration prolonged and affected the indoor thermal comfort level [25,26]. As previous experimental and numerical studies demonstrated, the downwards flowing melted frost along the surface of outdoor coil was one of important reasons of uneven defrosting [27,28]. At the same time, RCD at a lower FEV was another reason. It was reported that, when the FEV was increased from 82.6% to 96.6%, defrosting efficiency could increase from 42.0% to 48.7% [19]. After the negative effects of melted frost were eliminated, defrosting efficiency increased by about 5.7% as the FEV increased from 79.4% to 96.6% [19]. Furthermore, it was proved that system frosting COP increased from 4.10 to 4.26 as the FEV increased from 75.7% to 90.5% [29]. Among all the previous experimental studies, series of valves were used to adjust the refrigerant distribution, guiding by the tube surface temperatures at circuit exits. And thus, frosting at different FEVs was reached [19,25–27].

However, for a new technology or innovation, a techno-economic analysis is very important and always given before it being scaled up to wide applications [30,31,32]. The total cost of proposed new ASHP unit is increased by the additional investment of valves, so the payback period is predicted to be longer. To solve this problem, the economy has to be improved based on the characteristics of the ASHP unit. Although many methods were used to improve the operating performance of ASHP unit [33,34], especially to optimize its RCD performance [35,36], scare of literatures with techno-economic analysis on them was reported [37]. In particular, Horton et al. gave an economic analysis when they evaluated at a high performance cold climate heat pump [38]. As reported, the maximum additional cost of the system changes, for the Minneapolis location (USA), were $ 430 for the vapor injected system and $ 391 for the oil flooded system. These estimates were assumed that a 3-year simple payback period was accepted by the customer. Using a lifetime of 20 years for ground-coupled and air-coupled heat pump systems, their performance were compared basing on the experimental COP results by Esen et al. [39,40]. The economic analysis clearly shows that ground-coupled system is economically preferable to the air-coupled one. In addition, Dong et al. discussed the economy of an ASHP unit with a PCM-TES system added to improve its RCD performance [18]. As concluded, before the replacement of the PCM in the TES system, using the novel RCD method, the running cost could save approximately 650 CNY ($ 97.47) in 7 years' service life. Recently, a techno-economic analysis of ASHP applied for space heating in northern China was also carried out, with the pollution emission comprehensively considered [41]. Although authors neglected the unavoidable frosting/defrosting problem in north China, the low temperature ASHP heating system was demonstrated having better economical performance than coal-fired boiler, gas boiler, direct electric heating mode, and combined heat and power generation systems.

Clearly, many ASHP units studies around energy performance improvement were reported, but few of them considered the economic performance [42,43]. Therefore, to analysis the economic performance of the new ASHP unit, with valves installed in its multi-circuit outdoor coil, an economic analysis on its novel frosting/defrosting operations is given in this study. Firstly, results of designed frosting/defrosting experiments will be presented, as well