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Research Paper

A frost-free dedicated outdoor air system with exhaust air heat recovery

Zi-Yang Zhang [a], Chun-Lu Zhang [a,*], Mei-Cai Ge [b], Yue Yu [b]

[a] Institute of Refrigeration and Cryogenics, School of Mechanical Engineering, Tongji University, Shanghai 201804, China
[b] Nantong Huaxin Central Air-Conditioning CO., LTD, Jiangsu, Nantong 226014, China

HIGHLIGHTS

- An efficient DOAS with exhaust air heat recovery is proposed.
- System cooling COP reaches 3.3 and heating COP achieves 4.8 at design conditions.
- In winter, evaporating temperature of exhaust air coil is regulated for frost-free operation.

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ABSTRACT

DOAS (dedicated outdoor air system) has drawn much attention recently. However, it is quite energy-intensive resulted from the big temperature and/or humidity difference between outdoor air and supply air. This paper proposed a new DOAS with exhaust air heat recovery. In cooling mode, there are one evaporator and three condensers in parallel. The outdoor air is cooled and dehumidified by the evaporator. Besides the outdoor condenser, another two are used for supply air reheat and exhaust air heat recovery. In heating mode, the reheat coil is off and two evaporators work for exhaust air heat recovery and ambient heat absorption, respectively. A pressure regulating valve equipped on the indoor evaporator keeps proper evaporating temperature for a frost-free operation. A validated model is applied to fulfill the system design and performance prediction. The results showed that the system cooling COP reaches 3.3 at ambient temperature 35°C/28°C and the heating COP achieves 4.8 at ambient temperature 7°C/6°C, respectively. In winter the proposed system can maintain the desired supply temperature and keep both evaporators frost-free (ambient temperature −20°C to 10°C). The proposed system can efficiently recover waste energy from exhaust air in the whole year and has the extensive applicability, especially in the cold climate where considerable energy savings can be found.

1. Introduction

Nowadays people are paying more attention to the indoor air quality and other healthy issues, thus the DOAS (dedicated outdoor air system) has got wider researches and applications [1–3]. For a typical DOAS, the outdoor air is separately conditioned for dealing with the total latent and partial sensible load [4]. DOAS with the sensible heat load handling device (e.g. chilled beams, radiant cooling systems) can achieve higher indoor air quality compared with the traditional air-conditioning systems.

However, DOAS is quite energy-intensive resulted from the big temperature and/or humidity difference between the outdoor air (OA) and supply air (SA). According to open literatures, related researches mostly focused on the dehumidification process in cooling mode. Vapor-compression systems and desiccants are two main approaches to dehumidification [5]. Desiccants, which can be either solid or liquid, have better dehumidification performance than vapor-compression systems. But higher cost and larger footprint limited their applications [6]. Moreover, additional heat source is required to regenerate desiccants [7]. By comparison, the inexpensive, compact and easily installed vapor-compression systems are widely used, even though the coefficient of performance (COP) of vapor-compression systems is relatively lower. There are two major types: chilled-water system and refrigerant direct-expansion (DX) system. Compared with the chilled-water systems, the DX dehumidification systems are less complex, less expensive and more energy efficient so that they are widely used in both commercial and residential buildings [8].

In cooling mode, a common DX DOAS should have its evaporating temperature lower than a desired dew point temperature for the supply air to remove all latent load of the conditioned space,

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* Corresponding author.
E-mail address: chunlu.zhang@gmail.com (C.-L. Zhang).

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Nomenclature

A	area (m^2)
c_p	specific heat ($kJ\ kg^{-1}\ K^{-1}$)
D	diameter (m)
f	friction factor
G	mass flux ($kg\ s^{-1}\ m^{-2}$)
h	specific enthalpy (kJ/kg); heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
h_d	mass transfer coefficient ($kg\ s^{-1}\ m^{-2}$)
Le	Lewis number
m	mass flow rate (kg/s)
p	pressure (Pa)
Q	heat transfer (W)
R	heat resistance ($m^2\ K\ W^{-1}$)
T	temperature (°C, K)
v	specific volume ($m^3\ kg^{-1}$)
W	humidity ratio ($kg\ kga^{-1}$)

Greek symbol

η	efficiency

Subscripts

a	air
d	dry air
fr	frost
in	inlet
lat	latent heat
m	metal
o	outlet
r	refrigerant
s	surface
sens	sensible heat
w	water

which usually results in poor system efficiency. Besides, extra energy consumption on the supply air reheating makes the system COP even worse. Many researchers have made efforts to improve efficiency of conventional DX systems. Liang proposed a DX system in combination with a membrane-based total heat exchanger [7], whose COP is one time higher than a conventional system. Another DX system proposed by Liang using an auxiliary condenser to reheat supply air was claimed to have a COP of 6.8 under nominal operating conditions [9]. Li proposed a DOAS using multi-stage dehumidifying coils and a heat pipe to recover exhaust energy. It was revealed that this system could reduce annual energy use by 13.6% compared with a conventional system [10]. Some other energy efficient methods applied in desiccant and water-based dehumidification systems were also proved energy effective. Ham proposed a liquid desiccant system characterized by a membrane enthalpy exchanger, an indirect evaporative cooler, and a sensible heat exchanger, could save 12% of primary energy compared to a conventional system [11]. An experimental study about a small capacity DOAS with sensible and latent energy recovery wheels, revealed that 30% of the total cooling load could be provided by the energy recovery wheel [12]. Mahmud et al. [13] designed and built a novel run-around membrane energy exchanger and tested its effectiveness in air-conditioning system applications. 50%–55% maximum effectiveness was found. A secondary heat pipe heat recovery system proposed by Wang et al. was proved to save energy by 2.5% in summer and 22.1% in winter [14]. We could summarize that most methods to improve system performance is to employ heat recovery equipment, such as enthalpy wheels, membrane based heat exchangers, run-around coils [15] and heat pipes. However, some of the methods above have unavoidable drawbacks. For example, wheels have cross contamination issues between exhaust air (EA) and supply air, flat-plate heat exchangers and run-around coils are faced with freezing problem in winter [16]. Therefore, a DOAS with good performance in terms of dehumidification, and able to avoid those problems mentioned above, is definitely desired by the market.

When we turn to heating mode in winter, the DX DOAS is changed into a heat pump then. Low temperature outdoor air is heated to the desired supply temperature. Partial or the entire space heating load is handled by the DOAS. However, low ambient temperature will cause a lower evaporating temperature and easily get the outdoor heat exchanger frosted. Thus it is difficult in stably providing desired volume of fresh air or desired air supply temperature. This tricky problem hasn't got properly addressed to the authors' view. Most frost-related researches focused on the defrosting methods for an ordinary air source heat pump (ASHP), in which the condenser inlet air consists of mostly return air and a smaller fraction of outdoor air. Therefore, the ASHP absorbs less heat from ambient environment and has a relatively higher evaporating temperature thus its frosting risk is lower than a DOAS. For the ASHP, it was proved that widely used reverse cycle defrosting method will cause at least 15% capacity degrade [17] while hot gas bypass method will lead to much longer defrosting time [18]. Recently some efficient defrosting methods was also put forward, such as exhaust and outdoor air mixing methods [19], auxiliary electric heaters before and after outdoor evaporator tubes [20], and solid dehumidification combined with storage energy regeneration methods [21]. Useful as those methods are, a defrosting method or frost-free system specifically aimed at DOAS remains to be developed all the same.

Based on those issues to be addressed, in this work we propose a new dedicated outdoor air system with exhaust air heat recovery. An exhaust air heat pump (EAHP) is employed to recover exhaust air energy. It has been proved to have shorter payback period compared with other exhaust air heat recovery methods [22]. Besides, in winter EAHP could delay even avoid frost issue which frequently happens on other heat recovery equipment. Considered that the EAHP alone isn't able to deal with all the space cooling and moisture load and often require an auxiliary plant [23], an outdoor heat exchanger is still adopted as heat sink or heat source. In cooling mode, there are one evaporator and three condensers in parallel. The outdoor air is cooled and dehumidified by the evaporator. Besides the outdoor condenser, another two are used for supply air reheat and exhaust air heat recovery, respectively. In heating mode, the reheat coil is off and two evaporators work for exhaust air heat recovery and ambient heat absorption, respectively. Note that the two heat sources here are at different temperatures, thus a pressure regulating valve is equipped on the indoor evaporator to keep proper evaporating temperature for a frost-free operation. In this way, the new dedicated outdoor air system can operate in an efficient way and mitigate frost issues as well.

In terms of the proposed new DOAS, we developed the system simulation model using in-house developed simulation software GREATLAB [24] and well designed the system. The simulation model was validated with experimental data. Moreover, we analyzed the system performance under design and off-design