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Comprehensive Analysis of Exhaust Air Heat Pump Heat Recovery Efficiency in Dedicated Outdoor Air System

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Abstract

Exhaust air heat recovery is an important energy saving technology in buildings, which reduces energy consumption on thermal and humid processing of outdoor air. Dedicated outdoor air system with exhaust air heat pump (EAHP) is a newly developing technology, which efficiently recovers waste energy from exhaust air through vapor-compression refrigerant cycle. Some manufacturers claimed that the thermal recovery efficiency of EAHP has been over 100% and is superior to that of the enthalpy wheel total heat exchanger. This paper numerically simulates and compares the performance of both EAHP and enthalpy wheel under different application conditions. The results reveal that the EAHP can recover more waste energy than the enthalpy wheel, but less energy-efficient in the whole dedicated outdoor air system. However, EAHP is still very promising because of its smaller installation size, much wider application temperature range, and no cross-contamination between outdoor air and exhaust air.

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Keywords: Exhaust air heat pump, Enthalpy wheel, Energy efficiency, System simulation;

1. Introduction

With development of population and living conditions, building energy consumption raised rapidly, especially heating, ventilation and air conditioning (HVAC) system [1]. Meanwhile the ventilation accounts for 30% energy consumption but most of them could be recovered from exhaust air [2].

There are some of heat recovery methods for the dedicated outdoor air system (DOAS), such as enthalpy wheel [3], membrane heat exchanger [4], heat pipe [3], and run-around heat recovery system [5]. Because of high efficiency and trouble free operation, enthalpy wheel is widely adopted in building application. Enthalpy wheel wouldn't disintegrate after absorbing water like membrane heat exchanger and it is efficient at heat recovery due to its strong ability for both heat and mass transfer, while heat pipe and run-around system recovery only sensible heat. However, enthalpy wheel has trouble with cross-contamination between exhaust and fresh supply air, odor transfer [6] and frost at low temperature.

Exhaust air heat pump (EAHP) is a novel air source heat pump (ASHP). Like conventional ASHP, EAHP takes limited power driving refrigerant cycle to gain heat from heat source. However, instead of using outdoor air, EAHP in DOAS take the exhaust air as thermal source. The schematic of EAHP is shown in Fig. 1.

In cooling mode, the supply air (SA) coil is evaporator and the exhaust air (EA) coil is condenser. Outdoor air load and power consumption of compressor are taken away by exhaust air. In heating mode, the EAHP changes into heat pump through four-way valve and EA coil becomes evaporator. It recovers both sensible and

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latent heat from return air (RA) to heat the outdoor air (OA). EAHP avoid cross-contamination and odor transfer completely, while its SA and EA channels are separated from each other. Therefore EAHP makes more comfortable and healthy indoor conditions and it is applicable in DOAS of clean room.

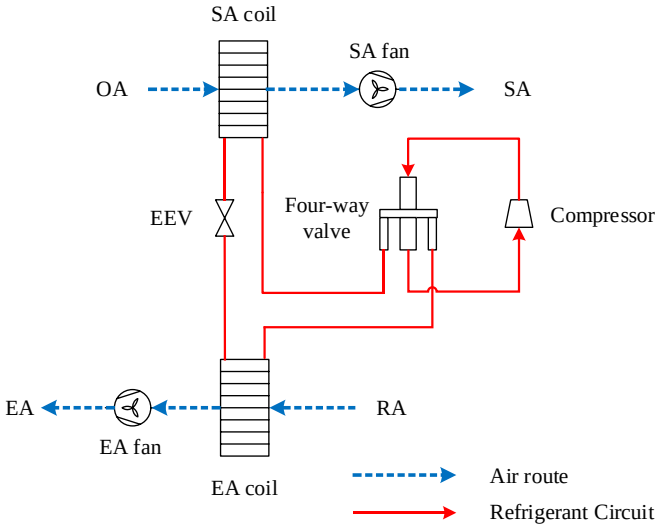


Fig. 1. Schematic of EAHP

In the open literatures, EAHP in DOAS showed strong heat recovery ability. Fracastoro and Serraino [7] did comprehensive calculation through an evaluation model and reported that quite high proportion of thermal demand could be covered by EAHP, although an auxiliary plant is still necessary. The mean seasonal efficiency of EAHP for different building thermal demands at three cities are over 4.6 and EAHP decreases the total energy consumption of HVAC system significantly. Ran et al. [8] tested the EAHP in DOAS when OA was −7 °C. It operated without frost on evaporator and achieved heating COP over 4.2, while SA was over 26 °C. Some manufacturers claimed that the recovery efficiency of EAHP is over 100% and it's the best choice of heat recovery equipment for DOAS.

In this paper, the EAHP in DOAS is compared with the enthalpy wheel by numerical modeling approach. We propose a comprehensive comparison of the equipment heat recovery efficiency under different test conditions. In addition, the COP of DOASs that use heat recovery equipment and auxiliary thermal source will be tested with modeling approach as well. Lastly, recommendations for application are summarized.

2. Modeling approach

An EAHP is designed with an in-house simulation software GRAEATLAB [10-11], which has been widely used for refrigeration and air-conditioning component sizing and/or selection, and system performance prediction in China. The compressor and coil models in GREATLAB were calibrated with EAHP lab test data.

A high efficient enthalpy wheel using ion exchange resin as desiccant was used for comparisons in this paper. An efficiency model of enthalpy wheel is developed in GREATLAB according to the ANSI/AHRI Standard 1060 [9] and calibrated with the manufacturer data.

The specifications of EAHP and enthalpy wheel are listed in Table 1 and Table 2, respectively. Operating conditions used in simulation are summarized in Table 3.

Table 1. Specifications of EAHP and modeling approach

Component	specification	Numerical model type
Refrigerant	R410A	REFPROP 9.0

Compressors	Rotary, variable speed	Cubic polynomial curve-fitting model
Expansion device	Electronic expansion valve	Manufacturer curve
Coil	8 mm tubes, helical grooved; louver fins, 2.0 mm fin spacing 22 mm tube pitch, 19.05 mm row pitch	Incremental tube-by-tube model
Fan	Centrifugal fan, variable speed	Manufacturer curve

Table 2. Specifications of the enthalpy wheel

Model	PAC-500T
Material	Ion exchange resin
Wheel diameter	520 mm
Wheel thickness	340 mm
Summer effectiveness*	52% (Latent)/ 66% (Sensible)
Winter effectiveness*	71% (Latent)/ 70% (Sensible)
OACF**	106%
Air pressure drop	100 Pa (Face velocity 2 m/s)
Driven motor	100 W

*The effectiveness is defined without air leakage.

**OACF means outdoor air correction factor, OACF= OA flow/ SA flow.

Table 3. Operating conditions in simulation

Name	Indoor condition		Outdoor condition	
	Dry-Bulb/ °C	Wet-Bulb/ °C	Dry-Bulb/ °C	Wet-Bulb/ °C
Chinese rated cooling*	27	19	35	28
American rated cooling**	24	17	35	26
Chinese rated heating*	20	15	7	6
American rated heating**	21	15	2	-2
American low temperature heating**	21	15	-9	-11
SA air flow rate	1200 m^3/h			
EA air flow rate	1200 m^3/h			

* Chinese Standard [12]

** American Standard [13]

In this work, we choose coefficient of performance (COP) as energy efficiency index for comparison, which is defined as below.

$$COP = \frac{\dot{m}_{SA} \cdot |h_{SA} - h_{OA}|}{P} \tag{1}$$

where P is the total power consumption of the DOAS, including compressor, fans and driven motors.

We use sensible, latent and total heat recovery effectiveness to evaluate the heat recovery capability. The equation of determining effectiveness of air-to-air heat exchangers for energy recovery ventilation is given the ANSI/AHRI Standard 1060 [9].

$$\eta = \frac{\dot{m}_{SA} \cdot (X_1 - X_2)}{\dot{m}_{\min} \cdot (X_1 - X_3)} \tag{2}$$

where X could be dry-bulb temperature (for sensible effectiveness), absolute humidity ratio (for latent effectiveness), enthalpy (for total effectiveness) and the subscript numbers indicate the measurement points. $\dot{m}_{\min}$ is the smaller mass flow rate between SA and RA.

While EAHP releases more heat in condenser as that absorbed in evaporator, the eq. (2) that calculates effectiveness using one side couldn't demonstrate the heat recovery ability of EAHP objectively. In this work, general heat recovery effectiveness for energy recovery equipment is re-defined based on eq. (2).

Sensible heat recovery effectiveness on SA side and EA side are defined as eq. (3) and (4) respectively.

$$\eta_{S,SA} = \frac{\dot{m}_{SA} \cdot (T_1 - T_2)}{\dot{m}_{\min} \cdot (T_1 - T_3)} \tag{3}$$

$$\eta_{S,EA} = \frac{\dot{m}_{EA} \cdot (T_4 - T_3)}{\dot{m}_{\min} \cdot (T_1 - T_3)} \tag{4}$$

where the measurement points of EAHP and enthalpy wheel could be found in Fig. 2 and Fig. 3, respectively. Similarly, latent and enthalpy heat recovery effectiveness on both side are defined as below.

$$\eta_{L,SA} = \frac{\dot{m}_{SA} \cdot (x_1 - x_2)}{\dot{m}_{\min} \cdot (x_1 - x_3)} \tag{5}$$

$$\eta_{L,EA} = \frac{\dot{m}_{EA} \cdot (x_4 - x_3)}{\dot{m}_{\min} \cdot (x_1 - x_3)} \tag{6}$$

$$\eta_{E,SA} = \frac{\dot{m}_{SA} \cdot (h_1 - h_2)}{\dot{m}_{\min} \cdot (h_1 - h_3)} \tag{7}$$

$$\eta_{E,EA} = \frac{\dot{m}_{EA} \cdot (h_4 - h_3)}{\dot{m}_{\min} \cdot (h_1 - h_3)} \tag{8}$$

3. System performance analysis

As shown in Fig. 2 and Fig. 3, respectively, numerical models of EAHP and enthalpy wheel are proposed in GREALAB.

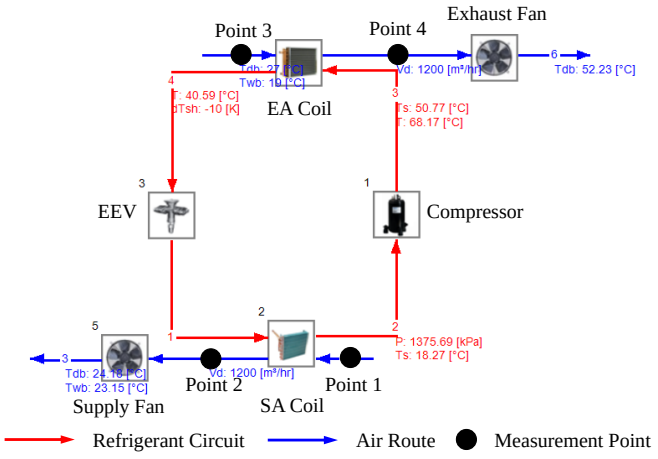


Fig. 2. System model of an EAHP (cooling mode) in GREATLAB

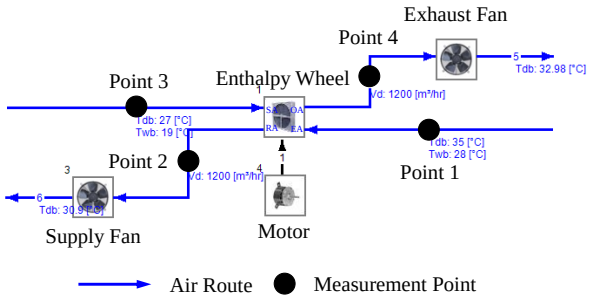


Fig. 3. System model of an enthalpy wheel (cooling mode) in GREATLAB

3.1. Cooling performance of EAHP and enthalpy wheel

In cooling mode, the heat recovery devices are evaluated under two rated conditions. In addition, the performance of EAHP achieving the same cooling capacity (Load 1) and the same SA humidity ratio (x_{SA}) (Load 2) as enthalpy wheel are simulated, respectively. The results are presented in Table 4.

Table 4. Comparison between enthalpy wheel and EAHP in cooling mode

Condition		Enthalpy wheel	EAHP (Load 1)	EAHP (Load 2)
Chinese rated cooling	Cooling Capacity/ W	6230	6230	10387
	Power/ W	677	1370	3536
	Cooling COP	9.2	4.5	2.9
	T_{SA}/ °C	30.9	25.7	22.4
	x_{SA}/ g·kg^{-1}	15.9	18.7	15.9
	T_{EA}/ °C	33.0	46.3	62.7
	η_S at cooling side	63.7 %	130 %	185 %
	η_S at heating side	68.1 %	235 %	441 %
	η_E at cooling side	53.4 %	49.9 %	85.9 %
	η_E at heating side	56.9 %	54.0 %	101 %
American rated cooling	Cooling Capacity/ W	5955	5955	10206
	Power/ W	680	1240	3331
	Cooling COP	8.8	4.8	3.1
	T_{SA}/ °C	29.0	23.9	20.2
	x_{SA}/ g·kg^{-1}	13.5	16.1	13.5
	T_{EA}/ °C	32.0	42.2	58.3
	η_S at cooling side	64.0 %	112 %	156 %
	η_S at heating side	72.6 %	161 %	310 %
	η_E at cooling side	55.2 %	51.5 %	90.9 %
	η_E at heating side	58.3 %	55.4 %	107 %

In general, the EAHP has strong sensible heat recovery capability. Its sensible heat recovery effectiveness is over 100% and the effectiveness of heating side is stronger than that of cooling side, since the condenser rejects not only the heat absorbed from evaporator but also the power consumed by compressor. However, the total energy recovery efficiency of EAHP is quite lower than its sensible heat recovery effectiveness, because it

doesn't utilize the moisture difference between OA and EA in dehumidification.

As a contrast, the enthalpy wheel doesn't have such excellent sensible heat recovery ability as EAHP but its total heat recovery effectiveness is better than EAHP when achieving the same cooling capacity, because enthalpy wheel recovers not only cooling from EA but also absorbs moisture from SA directly. But the cooling capacity of enthalpy wheel is fixed by the enthalpy difference between OA and RA, while EAHP could speed up compressor if higher cooling load from outdoor air is necessary. Therefore EAHP has higher energy recovery efficiency when it achieves larger cooling capacity.

In general, EAHP costs more power and has lower cooling COP as enthalpy wheel. Although enthalpy wheel yields higher air pressure drop than finned-tube coil and consumes more fan power, the compressor of EAHP consumes quite more energy. In addition, the cooling COP of EAHP under American rated condition is higher than Chinese rated condition because the RA temperature and latent heat load in American standard are lower than that in Chinese standard, which remarkably decreases the condensing temperature of refrigerant cycle. Meanwhile, the enthalpy wheel has large cooling capacity and higher cooling COP under Chinese rated condition as it specifies more humid OA and larger enthalpy difference between OA and SA.

In addition to the rated conditions, the off-design performance is also tested via modeling approach. The equipment performance in cooling season is plotted in Fig. 4. The RA state is fixed at Chinese rated condition, while T_{OA} and RH_{OA} are variable. The designed T_{SA} of EAHP is 20 °C when its condensing temperature is lower than 58 °C.

From Fig. 4 we find that the EAHP achieves not only larger cooling capacity as enthalpy wheel but also higher COP under some conditions. The cooling capacity of enthalpy wheel decreases as the enthalpy difference between OA and EA gets close, while its power consumption from fans and motor keeps the same. So its cooling COP decreases rapidly, even lower than that of EAHP.

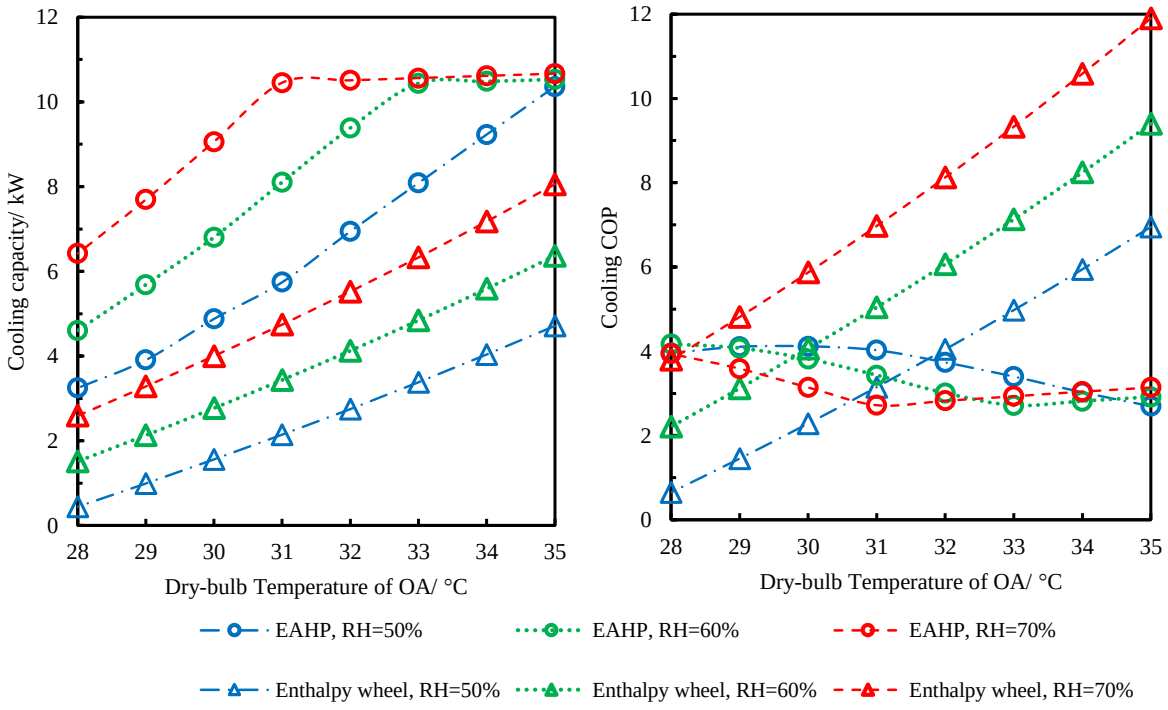


Fig. 4. Equipment performance comparisons in cooling season under variable OA conditions

The part load performance is tested under the transition season (spring and fall) conditions when outdoor air is warm and humid. The test condition is assumed as T_{RA}=24 °C, RH_{RA}=60 % and RH_{OA}=80 %. The EAHP designed T_{SA} is 19 °C when its compressor speed is not lower than 20% of the maximum speed. The results are plotted in Fig. 5.

In the transition season, EAHP has enormous advantage as enthalpy wheel for both cooling capacity and cooling COP under most conditions. Since there are only small the temperature and moisture differences bewteen OA and RA in the transition season, the heat recovery ability of enthalpy wheel is limited. When T_{OA} is over T_{RA}, OA will be even heated by enthalpy wheel and will increase cooling load from outdoor air. However, the cooling capacity of EAHP is not constrained by the enthalpy difference bewteen OA and RA and its cooling COP has little fluctuation in the transition season.

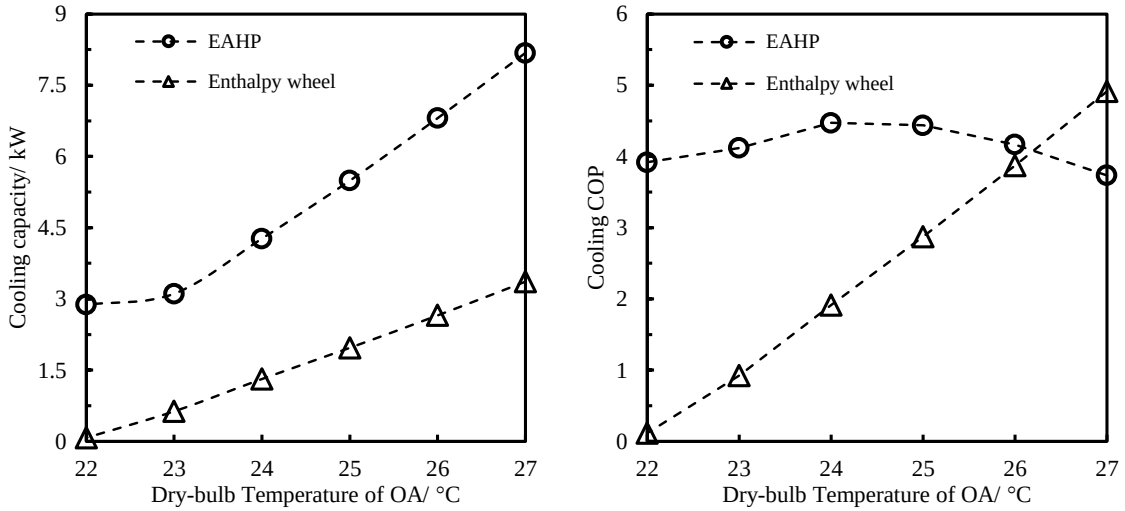


Fig. 5. Equipment performance comparisons in transition season under variable OA conditions

In short, enthalpy wheel is good at latent heat recovery and low power consumption, while EAHP takes advatage on sensible heat recovery and adjustable cooling capacity. It makes enthalpy wheel performs better with hot and humid outdoor air, while EAHP has a more balanced performance under off-design conditions.

3.2. Heating performance of EAHP and enthalpy wheel

In heating mode, the enthalpy wheel and EAHP are evaluated under three conditions, where OA dry-bulb temperatures are 7 °C, 2 °C and –9 °C, respectively. The design SA temperature of EAHP is 28 °C and the compressor speed could slow down to avoid frosting if evaporating temperature is lower than –1 °C (it indicates the outer wall temperature will be higher than 0 °C). The simulation results are listed in Table 5.

The EAHP shows great advantage in high SA temperature. Different from the cooling mode, the EAHP recovers not only sensible heat but also latent heat from RA and all thermal energy are used to heat OA. By comparison, in enthalpy wheel OA is heated by the sensible heat recovered from RA and couldn't be over T_{RA}, meanwhile the OA is humidified and polluted by the moist from RA.

Another advantage of EAHP is frost free operation at low temperature condition because of its adjustable heating capacity. So EAHP has wider using range and it could be one important solution to heating outdoor air under low temperature conditions.

Table 5. Comparison between enthalpy wheel and EAHP in heating mode

Condition		Enthalpy wheel	EAHP
Chinese rated heating	Heating Capacity/ W	5291	8277
	Power/ W	7.5	1758
	Heating COP	7.5	4.0

	T_{SA}/ °C	11.1	28
	T_{EA}/ °C	16.4	8.2
	x_{EA}/ g·kg^{-1}	7.5	6.4
	η_S at cooling side	74.0 %	96.8 %
	η_S at heating side	64.6 %	161.5 %
	η_E at cooling side	74.7 %	87.2 %
	η_E at heating side	65.0 %	97.2 %
American rated heating	Heating Capacity/ W	8579	10244
	Power/ W	708	2267
	Heating COP	12.1	4.5
	T_{SA}/ °C	7.7	28
	T_{EA}/ °C	15.1	6.11
	x_{EA}/g·kg^{-1}	6.0	5.5
	η_S at cooling side	75.0 %	82.9 %
	η_S at heating side	63.9 %	134 %
	η_E at cooling side	76.0 %	64.5 %
	η_E at heating side	64.4 %	72.4 %
American low temperature heating**	Heating Capacity/ W	--	13299
	Power/ W	--	2934
	Heating COP	--	4.53
	T_{SA}/ °C	--	24.4
	T_{EA}/ °C	1– 1.1 (Frosted)	2.55
	x_{EA}/ g·kg^{-1}	--	4.4
	η_S at cooling side	--	64 %
	η_S at heating side	--	109 %
	η_E at cooling side	--	59.3 %
	η_E at heating side	--	67.2 %

3.3. Cooling performance of DOAS using outdoor air as auxiliary cold source

Because enthalpy wheel couldn't change capacity by itself, an auxiliary ASHP is necessary to DOAS using enthalpy wheel. The system model is proposed in GREATLAB (Fig. 6). As a comparison, we design a novel EAHP in DOAS using outdoor air as auxiliary cold source (Fig. 7). The evaporator of EAHP has been enlarged by the same evaporating area as ASHP. Two DOASs use the same outdoor coil and outdoor fan. The design SA temperature is 20 °C and the test results under Chinese rated condition are shown in Table 6.

The auxiliary cold source could improve the cooling COP of EAHP from 2.9 to 4.0, because its condensing temperature has been decreased from 57.6 °C to 49 °C. By comparison, the DOAS using an enthalpy wheel and auxiliary ASHP achieves higher cooling COP, 4.7. It is benefited from low power consumption by enthalpy wheel, while the cooling COP of ASHP is 3.5.

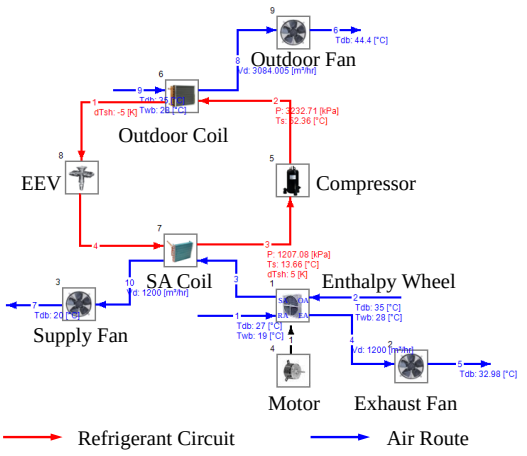


Fig. 6. GREATLAB model of DOAS using an auxiliary ASHP and an enthalpy wheel

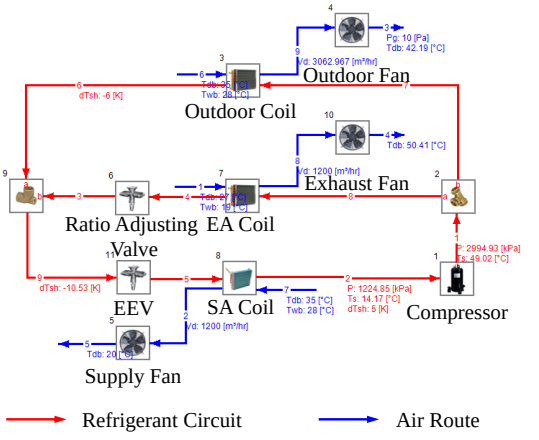


Fig. 7. GREATLAB model of an EAHP in DOAS using outdoor air as auxiliary cold source

Table 6. System performance comparison in cooling mode

Condition		Enthalpy wheel + Air source heat pump	EAHP + Auxiliary cold source
Chinese rated cooling	Cooling Capacity/ W	13578	13352
	Power/ W	2873	3322
	Cooling COP	4.7	4.0
	T_{SA}/ °C	20	20
	X_{SA}/ g·kg^{-1}	13.0	14.0
	T_{EA}/ °C	33.0	50.41
	Sensible cooling recovery/W	1754	8403
	Latent cooling recovery/ W	4549	0
	Heat rejection of outdoor coil/ W	8835	6755

3.4. Summary

After comprehensive comparisons, a summary is given in Table 7. The simulation results indicate that the EAHP and enthalpy wheel have their own advantages. While enthalpy wheel has powerful latent heat recover ability and higher energy efficiency, EAHP has advantages in capacity adjustment, frost-free and odor-free operation. When there is no special requirement for the COP of DOAS at rated condition, EAHP is more recommended as enthalpy wheel for the DOAS because it has less limitations in application.

Table 7. Summary of characteristics of EAHP and enthalpy wheel

	EAHP	Enthalpy wheel
Sensible heat recovery effectiveness	Excellent	Fair
Latent heat recovery effectiveness	Good in heating mode No latent heat recovery in cooling mode	Excellent in both cooling and heating mode
Total heat recovery effectiveness	Good	Good
Cooling and heating capacity	Adjustable	Passive changed by working condition
COP	Good in heating mode Fair in cooling mode	Excellent at rated condition Poor in transition seasons
Installation space occupation	Small	Large
Cross-contamination and odor transfer	No	Yes
trouble free operation	Yes	Frost at low temperature conditions

4. Conclusions

In this work, a comprehensive comparison between EAHP and enthalpy wheel in DOAS using numerical modeling approach is proposed. The study came to the following main conclusions.

1) EAHP has strong heat recovery capability. Its sensible heat recovery effectiveness could be over 100% and total heat recovery effectiveness is comparable to that of enthalpy wheel. However, its cooling and heating COPs are lower than enthalpy wheel at rated conditions.

2) EAHP shows good performance under off-design conditions and it is more efficient in the transition season as enthalpy wheel.

3) EAHP has wider operation range than enthalpy wheel because EAHP could recover energy from exhaust air under any conditions and its capacity is adjustable. Moreover, EAHP can operate without frost on the evaporator in heating mode.

4) Using outdoor air as auxiliary cold source could improve the COP of EAHP to 4.0. However, it is less efficient than the combination of air source heat pump system and enthalpy wheel.

Nomenclature

COP	coefficient of performance	*T*	temperature, ^{o}C
h	enthalpy, J kg^{-1} K^{-1}	*RH*	relative humidity, %

$\dot{m}$	the mass flow rate, kg s^{-1}	x	humidity ratio, kg (H_2O) kg^{-1} (dry air)
s	entropy, J K^{-1}	X	air parameters

Greek symbols

η_S	sensible heat recovery effectiveness	η_E	total heat recovery effectiveness
η_L	latent heat recovery effectiveness		

Subscripts

DOAS	dedicated outdoor air system	OA	outdoor air
EA	exhaust air	RA	return air
EEV	electronic expansion valve	SA	send air
EAHP	exhaust air heat pump		

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