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Comparison of multi-stage air treatment process divided by the same temperature and enthalpy difference

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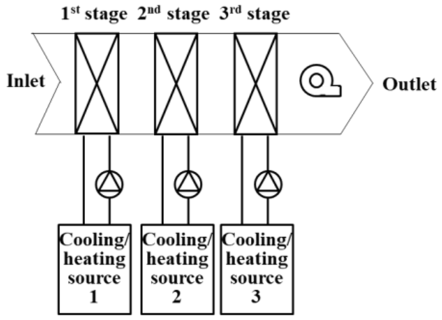
Abstract. The multi-stage air treatment system has been proposed recently, and lower grade chilled/hot water could be used and energy efficiency could be improved. However, it has not been studied which division method of air treatment processes has higher energy efficiency. In this study, the model to calculate the energy consumption of multi-stage air treatment process is introduced, and the effects of two division methods, i.e. multi-stage air treatment process divided by the same temperature difference (ST method) or same enthalpy difference (SE method) between inlet and outlet at each stage, under 9 different air inlet parameters in the 2-stage and 3-stage air treatment processes are analysed and compared. The results show that (1) the system energy consumption of the SE method is generally lower than that of the ST method; (2) there is generally a larger energy consumption reduction rate of SE method when the air relative humidity is 70% compared to relative humidity of 50% and 90%; (3) the difference between ST method and SE method is not great, so both methods can be used for the design of multi-stage treatment system although SE method is normally recommended.

Keywords: Air handling unit, multi-stage air treatment, HVAC, energy efficiency

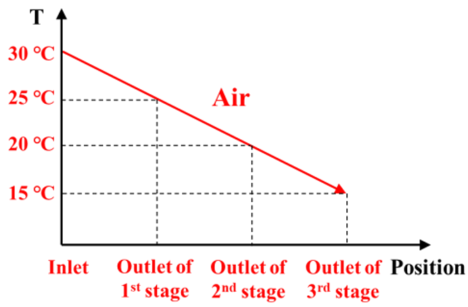
1 Introduction

In the energy consumption of buildings, the energy consumption of air conditioning systems accounts for about 50% [1], so it is necessary to reduce the energy consumption of air conditioning systems [2]. Traditional air conditioning systems only use one chilled/hot water with high-grade temperature to handle all loads, resulting in high energy consumption [3-5].

In order to improve the energy efficiency of the air conditioning system, Zheng and Li [6-8] proposed a multi-stage air treatment system, and the air treatment process was divided into multiple treatment processes, as shown in Fig. 1. At different stages, water at different temperatures (especially lower-grade temperatures) is used. They found that multi-stage air treatment systems have good energy-saving potential and application prospects, so it is necessary to continue promoting the development of multi-stage air treatment systems.



(a) Multi-stage air treatment system



(b) Air treatment process

Fig. 1. Multi-stage air treatment system and its air treatment process [6].

In existing multi-stage air treatment systems, a complete air treatment process is divided into multiple stages by using the same temperature difference between air inlet and outlet at each stage (called ST method), as shown in Fig. 1(b). However, for the air cooling process with dehumidification in summer, its humidity load is relatively large, and the ST method will cause uneven distribution of load at each stage. Another possible division method is based on the same enthalpy difference between the air inlet and outlet at each stage (called SE method), which can ensure that the load of each stage is the same. However, the system performance of the SE method has not been studied, and it is unclear whether the system energy efficiency of the SE method is higher than that of the ST method.

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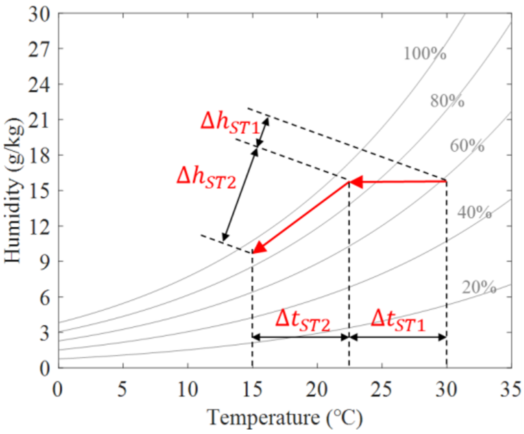
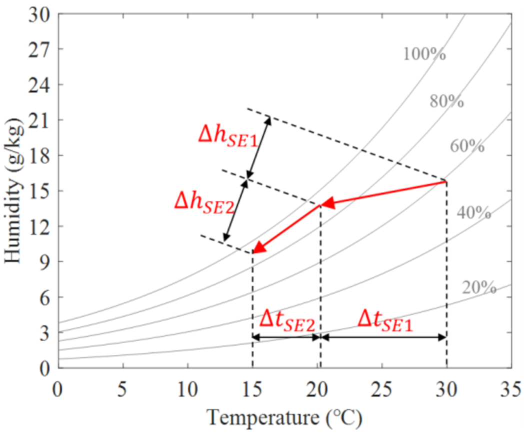
Specifically, Fig. 2 shows the air cooling process of ST method and SE method. From Fig. 2, in the first stage, the temperature of the chilled water of ST method can be higher than that of SE method, and the enthalpy difference between the air inlet and outlet of ST method is smaller than that of SE method. In the second stage, the chilled water temperature of ST method and SE method is basically the same, and the enthalpy difference between the air inlet and outlet of ST method is greater than that of SE method.

For the ST method, although the temperature of the chilled water in the first stage is higher and the cooling source has higher energy efficiency, only a small portion of the load is treated, and most of the load is treated by the lower energy efficiency cooling source in the second stage. For the SE method, compared to the ST method, although the temperature of the chilled water in the first stage is higher and the energy efficiency of the cold source is reduced, a greater portion of the load is treated, resulting in a decrease in the load treated by the lower energy efficiency cooling source in the second stage. Therefore, it is uncertain which method has higher energy efficiency.



(a) ST method



(b) SE method

Fig. 2. Air treatment process of ST and SE method.

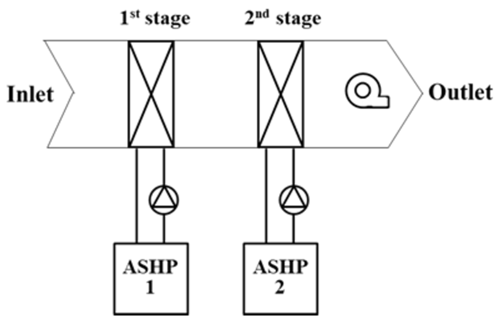
How to design the multi-stage air treatment system with higher energy efficiency is an important question for the energy-efficient air handling unit. Therefore, the energy performance of two common division methods (ST and SE methods) is studied in this study. The model to calculate the energy consumption of multi-stage air treatment process is introduced. And the effects of two division methods under different air inlet parameters in the 2-stage and 3-stage air treatment processes are analysed and compared.

2 Methodology

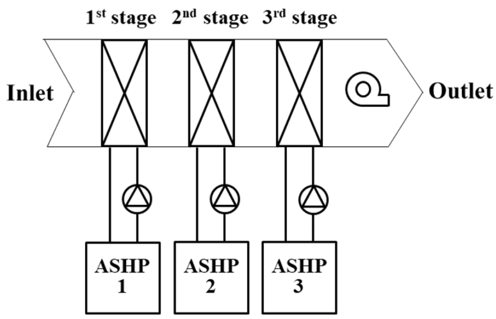
Considering that different numbers of stages and air inlet parameters may have an impact on the performance of the two methods, this section introduces the specific settings of number of stages and air inlet temperature and humidity, as well as the energy consumption calculation model of the multi-stage air treatment system.

2.1 Different number of treatment stages

To avoid the multi-stage air treatment system being overly complex, the commonly used numbers of treatment stages are 2 and 3. Therefore, this study also adopted 2-stage and 3-stage air treatment systems, as shown in Fig 3.



(a) 2-stage air treatment system



(b) 3-stage air treatment system

Fig. 3. Schematic of the 2-stage and 3-stage air treatment system.

In Fig. 3, the cooling/heat sources are air source heat pumps (ASHPs), which produce water at different temperatures and provide it to the corresponding air-water heat exchangers (AWHXs) at each stage. The total AWHX area is designed based on the total load and divided evenly into each stage. And the temperature difference between the supply and return water in each stage is the same and set at 5 °C [9].

2.2 Different air inlet parameters

Because there is no change in humidity during the air heating and dry cooling processes, the ST and SE methods are the same. Therefore, this study focuses on the air cooling process with dehumidification.

In this study, the air inlet temperature is set at 27, 30, and 33 °C, and the air inlet humidity is set at 50%, 70%, and 90%. By combining temperature and humidity in pairs, there are a total of 9 air inlet parameters, as listed in Table 1.

Table 1. Air inlet parameters.

Relative humidity	Temperature (°C)		
	27	30	33
50%	Case-27/50	Case-30/50	Case-33/50
70%	Case-27/70	Case-30/70	Case-33/70
90%	Case-27/90	Case-30/90	Case-33/90

2.3 System models

To calculate the energy performance under different system settings, the model of the system equipment is introduced as follows.

For the ASHP, its energy efficiency ratio (EER) is obtained through Carnot efficiency, as expressed in Eq. (1) [10].

$$EER = \frac{t_e+273.15}{t_c-t_e}\eta_C \quad (1)$$

where t_e and t_c are the evaporation temperature and condensation temperature, respectively, °C; and η_C is the Carnot efficiency, which is 0.5 in this study [10].

The electric power of ASHP (P_{ASHP}) can be obtained through load and EER, as expressed in Eq. (2).

$$P_{ASHP} = \frac{Q_{load}}{EER} \quad (2)$$

where Q_{load} is the cooling load, kW.

For the AWHP, the energy balance between air and water and $\varepsilon - NTU$ model are used, as listed in Eqs. (3) and (4) [11].

$$m_a(i_{a,i} - i_{a,o}) = c_w m_w(t_{w,o} - t_{w,i}) \quad (3)$$

$$\varepsilon = \frac{1-\exp[-NTU(1-C_r)]}{1-C_r\exp[-NTU(1-C_r)]} = \frac{t_{a,i}-t_{a,o}}{t_{a,i}-t_{w,i}} \quad (4)$$

where m_a and m_w are the air and water mass flows, respectively, kg/s; $i_{a,i}$ and $i_{a,o}$ are the air inlet and outlet enthalpy, respectively, kJ/kg; c_w is the specific heat capacity of water, kJ/(kg·°C); $t_{w,i}$ and $t_{w,o}$ are the water inlet and outlet temperature, respectively, °C; ε and NTU_{aw} are heat exchange efficiency and number of heat transfer units of the AWHX, respectively; C_r is the heat capacity ratio; and $t_{a,i}$ and $t_{a,o}$ are the air inlet and outlet temperature, respectively, °C.

For the pump and the fan, their electric powers (P_{pump} and P_{fan}) are obtained by Eqs. (5) and (6) [12, 13].

$$P_{pump} = \frac{m_w g \Delta p_w}{1000\eta_{pump}} \quad (5)$$

$$P_{fan} = \frac{m_a \Delta p_a}{1000\rho_a \eta_{fan}} \quad (6)$$

where g is the acceleration of gravity, m/s^2; Δp_w and Δp_a are the pressure drops of the pump and fan, respectively, mH_2O, Pa; ρ_a is the air density, kg/m^3; and η_{pump} and η_{fan} are the efficiencies of the pump and fan, which are set to 0.7 and 0.6 [12, 13], respectively.

The total electric power of the whole system is the sum of the electric power of each device, which can be obtained by Eq. (7).

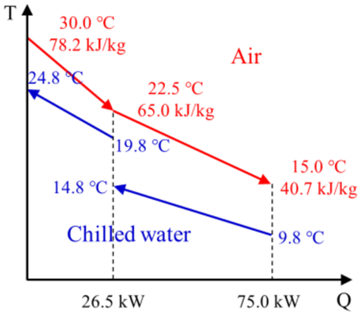
$$P_{sys} = P_{ASHP} + P_{pump} + P_{fan} \quad (7)$$

3 Results

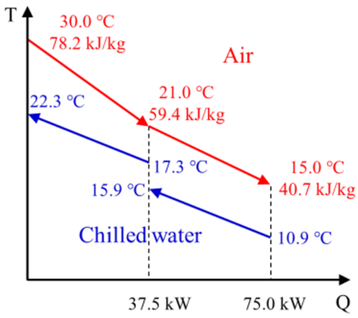
Taking the treated air mass flow of 2 kg/s as an example, the results of ST and SE methods under 9 air inlet parameters in the 2-stage and 3-stage air treatment processes are obtained and analysed in this section.

3.1 Two-stage treatment process

Taking Case-30/70 as an example, Fig. 4 shows the 2-stage air treatment process of ST and SE methods.



(a) ST method



(b) SE method

Fig. 4. Air 2-stage treatment process of the ST and SE method.

For the ST method, the first and second stages have the same air inlet and outlet temperature difference of 7.5 °C. However, due to the small amount of dehumidification in the first stage, the load of the first stage is smaller than that of the second stage. Specifically, the first and second stages handle 35.3% and 64.7% of the total load, respectively.

For the SE method, the first and second stages have the same air inlet and outlet enthalpy difference of 37.5kW, meaning that the first and second stages have the same load. Due to the larger load in the first stage of the SE method compared to that of ST method, it has a lower air outlet temperature. Therefore, the required chilled water temperature decreases from 19.8 °C to 17.3 °C. On the contrary, under the same heat exchanger area, the load in the second stage of SE method is smaller than that of ST method, so the chilled water temperature increases from 9.8 °C to 10.9 °C.

Due to the different water temperatures and loads of ST and SE methods, the electric power of the compressor will be greatly affected. Fig. 5 shows the electric powers and EERs of the compressors of the air 2-stage treatment process.

The first stage of ST method has the highest chilled water temperature, resulting in the highest EER of the compressor, reaching 5.62. Meanwhile, the second stage of ST method has the lowest chilled water temperature, and the EER of compressor is only 3.88. Because the load in the second stage is greater than that of the first stage, the total EER of compressor is closer to that of the second stage, at 4.36. In contrast, the SE method has a higher total EER of compressor of 4.48, an increase of 2.8%.

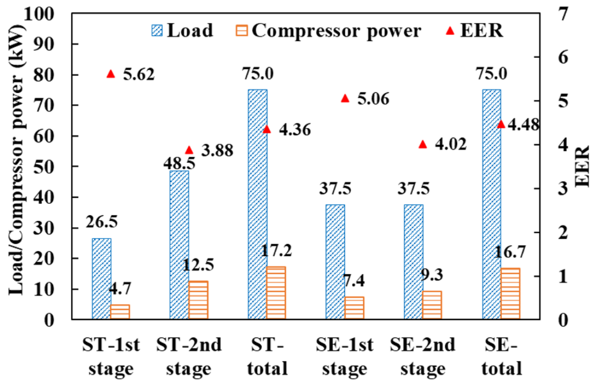
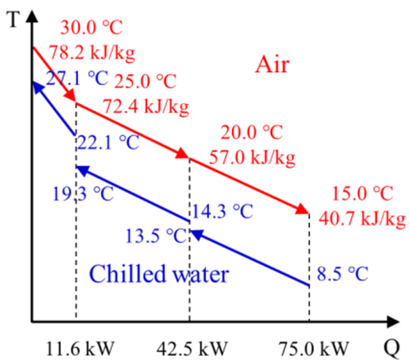


Fig. 5. Energy performance of air 2-stage treatment process.

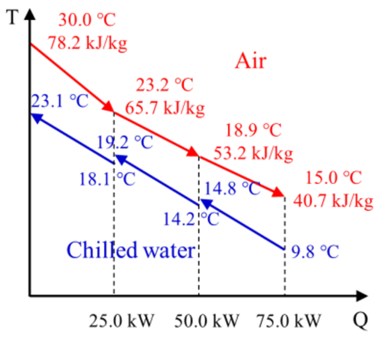
3.2 Three-stage treatment process

Fig. 6 shows the 3-stage treatment process of Case-30/70. For the ST method, the 3-stage treatment process is similar to the 2-stage treatment process, with the first stage only treating 15.5% of the total load, which is much smaller than the 33.3% in the SE method. The benefit is that the temperature of the chilled water has significantly increased to 22.1 °C, which is 4.0 °C higher than the SE method. Then, dehumidification occurs in both the second and third stages, so their loads are similar, with 30.9 and 32.5 kW, accounting for 41.2% and 43.3% of the total load, respectively.

For the SE method, although the load being treated in each stage is the same, the temperature difference between the air inlet and outlet in each stage is different, which is 6.8 °C, 4.3 °C, and 3.9 °C, respectively. The reason is that the dehumidification quantity in the second and third stages is greater than that in the first stage.



(a) ST method



(b) SE method

Fig. 6. Air 3-stage treatment process of the ST and SE method.

In addition, Fig. 7 shows the electric powers and EERs of the compressors of the air 3-stage treatment process. The EERs of the compressors in the first and second stages of the ST method are greater than those of the SE method, but the treated load is only about half. And the largest load is treated in the third stage with the lowest compressor EER, the total EER of compressor is actually lower than the SE method. Specifically, the total EERs of compressor of ST and SE methods are 4.30 and 4.48, respectively, indicating a 4.2% increase in the total EER of compressor of SE method compared to that of ST method.

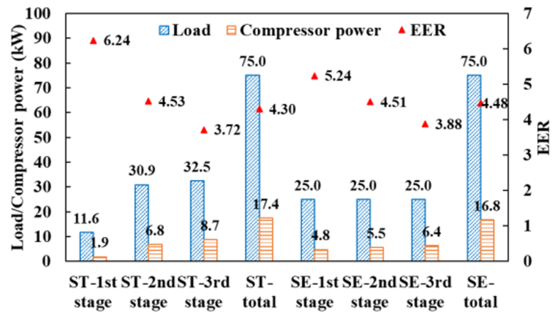


Fig. 7. Energy performance of air 3-stage treatment process.

3.3 Different air inlet parameters

To study the results under different air inlet parameters, Table 2 lists the system electric powers of 9 air inlet parameters in the 2-stage and 3-stage air treatment processes.

Table 2. Electric powers under different air inlet parameters.

Working conditions	2-stage			3-stage		
	ST (kW)	SE (kW)	Change rate	ST (kW)	SE (kW)	Change rate
Case-27/50	9.35	9.50	1.6%	9.52	9.48	-0.5%
Case-27/70	15.39	15.06	-2.2%	15.48	15.12	-2.3%
Case-27/90	20.33	20.31	-0.1%	20.30	20.26	-0.2%
Case-30/50	14.75	14.66	-0.6%	14.84	14.80	-0.3%
Case-30/70	21.98	21.53	-2.1%	22.16	21.49	-3.0%
Case-30/90	27.96	27.96	-0.0%	27.75	27.73	-0.1%
Case-33/50	21.31	20.82	-2.3%	21.08	20.85	-1.1%

Case-33/70	29.76	29.22	-1.8%	29.84	29.02	-2.8%
Case-33/90	37.09	37.12	0.1%	36.59	36.55	-0.1%

From Table 2, the electric power of SE method is generally lower than that of ST method. Compared to relative humidity of 50% and 90%, there is generally a larger change rate when the relative humidity is 70%. The reason is that when the relative humidity approaches 0% or 100%, the difference between ST method and SE method will decrease. Specifically, when the relative humidity is 0%, it is a dry cooling process, and the ST and SE methods are the same, with only sensible heat being treated. When the relative humidity is 100%, dehumidification also occurs in the first stage of the ST method, and the proportion of treated load will increase. At this time, the difference between ST method and the SE method will be reduced.

In addition, there is no significant difference in the results of the 2-stage and 3-stage treatment processes. Their similar result is that the system electric power of SE method is generally smaller than that of ST method, but the difference between the two methods is not significant. Specifically, the maximum energy consumption reduction rates are 2.3% and 3.0% in the 2-stage and 3-stage air treatment processes, both of which are small.

4 Conclusions

For the multi-stage air treatment system, the effects of different division methods of air treatment process have not been studied. In this study, the air treatment process divided by the same temperature difference and same enthalpy difference between the inlet and outlet at each stage is studied. The energy consumption calculation model of multi-stage air treatment process is established, and 2 different treatment stages and 9 different air inlet parameters are selected, and their effects under these different conditions are analysed and compared. The conclusions obtained are as follows.

(1) Compared with that of the ST method, the system energy consumption of the SE method is generally smaller, so the SE method is normally recommended. But the difference between ST method and SE method is not great, so both methods can be used for the design of multi-stage treatment system.

(2) For different numbers of treatment stages, there is no great difference in the results of the 2-stage and 3-stage treatment processes, and their maximum energy consumption reduction rates of SE method are 2.3% and 3.0%, respectively.

(3) For the different air inlet parameters, compared to relative humidity of 50% and 90%, there is generally a larger reduction rate of system energy consumption when the relative humidity is 70%.

Acknowledgement

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