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A MODELING STUDY ON THE INHERENT OPERATIONAL CHARACTERISTICS OF A DIRECT EXPANSION BASED AIR CONDITIONING SYSTEM HAVING A TWO-SECTIONED COOLING COIL (TS-DXAC)

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ABSTRACT

In small to medium-scale buildings such as residences, direct expansion (DX) based air conditioning (A/C) systems are widely used for the control of indoor thermal environment. However, to simultaneously control indoor air temperature and humidity, additional equipment or costly measures are necessary. Therefore, in this paper, taking the advantages of multi-evaporator technology, a novel DX based A/C system having a two-sectioned evaporator or cooling coil (TS-DXAC) was proposed, and its inherent operational characteristics were numerically studied through simulation. The evaporator in the TS-DXAC system had two parallel-connected sections, a latent cooling coil section (LCC) and a sensible cooling coil section (SCC), operating at two different evaporating temperatures, with a constant total supply air flow rate passing through the entire two-sectioned evaporator. The simulation results suggested that the TS-DXAC system can achieve a wider combination of total cooling load (TCC) and equipment sensible heat ratio (E SHR), and a higher area ratio of LCC to SCC is beneficial to a larger variation range of TCC and E SHR.

Keywords: direct expansion, two-sectioned evaporator, simulation, variable dehumidification capacity

NONMENCLATURE

Abbreviations	
HX1	The First Heat Exchanger
HX2	The Second Heat Exchanger
EEV	Electronic Expansion Valve
IAQ	Indoor Air Quality
Subscripts	
r	Refrigerant
a	Air
tp	Two-Phase
sp	Single-Phase
sh	Superheated
sc	Sub-Cooling

1. INTRODUCTION

In tropical and sub-tropical buildings, controlling indoor humidity is an important task for A/C systems since this directly affect building occupants' thermal comfort, IAQ and the operating efficiency of A/C systems. Direct expansion (DX) based A/C systems for controlling indoor thermal environment are widely used in small- to medium- scale buildings such as residences and retails.

However, for conventional DX A/C systems, a number of issues, such as the current design trends for A/C systems, varying space load in buildings and commonly used control strategies, lead to that it is difficult to simultaneously control indoor air temperature and humidity by using a DX A/C system due to its inadequate dehumidification ability.

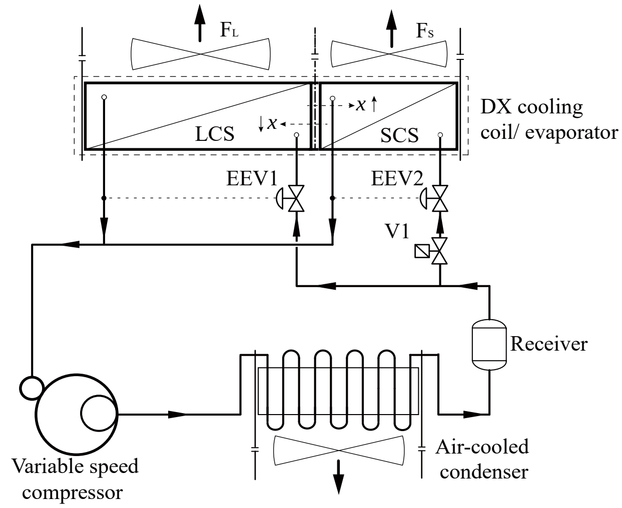
Therefore, to address the inadequacy, many attempts have been made. One of the attempts was to use a DX based separate sensible and latent cooling (SSLC) technology[1] to provide additional dehumidification or moisture removal capacity. A SSLC system was composed of two independent compression cycles, while sensible loads were dealt with by one cycle though high-temperature cooling terminals, and moisture load by the other though latent load terminals. Such a system was complicated, with a high initial cost. Associated with SSLC technology, using desiccant to provide additional dehumidification was also proposed, and the energy to recover the desiccant may come either from condensation heat or from solar energy. Besides, using a dedicated outdoor air system (DOAS) to handle most of the indoor latent load from outdoor air was also an alternative. Then a conventional DX A/C system can adequately to handle the remaining indoor sensible and latent load at a high efficiency.

The other major approach was to apply variable-speed (VS) technology. With VS technology, it was possible to simultaneously vary compressor and supply fan speeds in a DX A/C system to alter the volume of supply air and the evaporating temperature in a cooling coil, which can both directly affect the cooling and the dehumidification capacity of a DX A/C system. But based on the work already done by Deng[2], inherent operational characteristics of a VS DX A/C system are important and should be studied in details. First, the two important parameters, total cooling capacity (TCC) and equipment sensible heat ratio (E SHR), were mutually coupled and constrained within a trapezoid. So it was difficult to develop an efficient control algorithm to match the TCC and the total cooling load (TCL), as well as to match the Equipment SHR and the Application SHR, which was essential to achieve simultaneous control of temperature and humidity. Second, to obtain a smaller E SHR, a lower total supply air flow rate can lead to a very low supply air temperature and a poor air velocity distribution inside a room, negatively impacting on the indoor thermal comfort of occupants.

As seen, all approaches mentioned above were inevitably complicated, and additional provisions, such as additional vapor compression cycle, or the use of desiccant, must be provided, leading to higher initial and operating costs. Furthermore, additional installation space was also needed to accommodate these additional provisions. Hence, these approaches were not feasible for application to small- to medium-scale buildings, where additional installation space is not available, such as in high-rise residential blocks in Hong Kong. Therefore, a novel DX based A/C system having a two-sectioned evaporator or cooling coil (TS-DXAC) was proposed. The evaporator in the TS-DXAC system will have two parallel-connected sections operating at two different evaporating temperatures, and a constant total supply air flow rate passing through the entire two-sectioned evaporator will be maintained for both enhanced output cooling and dehumidification capacity and improved indoor air velocity distribution. This paper reports the development of the steady-state physical-based model for such a TS-DXAC system, and the inherent operational characteristics which were numerically studied by using the model developed.

2. Development of a steady-state mathematical model for the TS-DXAC system

To facilitate the modeling study, a steady-state mathematical model for the TS-DXAC system, whose schematic diagram is shown in Fig 1, was firstly developed. The major system components included a variable speed compressor, an air-cooled condenser, two DX evaporators, two EEVs and two variable speed supply fans.



LCS: Latent Cooling Section   SCS: Sensible Cooling Section

F_L, F_S: Variable speed fan

Fig 1 Schematics of the configuration for the proposed TS-DXAC system

Taking reference to an existing DX based enhanced dehumidification two-evaporators A/C (EDAC) system model[3], a steady state mathematical model was developed for the TS-DXAC system. The thermal properties of R410A were obtained from Refprop[4] and the State Equations for humid air from ASHRAE Handbook[5]. All equations used in the mathematical model are available from Pan et al[6].

The following assumptions were made:

On the refrigerant-side of the TS-DXAC system:

- Refrigerant: R410A;
- A fixed setting of degree of refrigerant sub-cooling, T_{sc}, at 5°C;

On the air-side of the TS-DXAC system:

- No ventilation air;
- Counter-flow heat exchange between the air and refrigerant in the two cooling coils;

3. Modeling study results and discussion

TCC and E SHR are often used to represent the operational characteristics of a DX A/C system, since they could reflect its overall cooling and dehumidification capacities. In the TS-DXAC system, the following five factors that could affect its output TCC and E SHR are: its compressor frequency F, supply fan volume V, the ratio of the surface area of the latent coiling section (LCS) to the surface area of the sensible coiling section (SCS), *x*, the ratio of the refrigerant mass flow rate through HX2, m_{rHX2}, to the total mass flow rate, m_r, and the ratio of the air mass flow rate through the HX2, m_{aHX2}, to the total air mass flow rate, m_a, calculated by

$$R_r = m_{rHX2}/m_r\ ,\ \ R_a = m_{aHX2}/m_a$$

Respectively. In this modeling study, different combinations of the five factors were used to find out the inherent characteristics of the TS-DXAC system.

Given that different inlet air states to the proposed TS-DXAC system may also affect its TCC and E SHR, the inlet air state was assumed at 26°C and 50% RH. Under this inlet air state, modeling study was carried out at all R_a/R_r combinations listed in Table 2.

Table 2
The combinations of R_a and R_r used in the modeling study

No.	1	2	3	4	5	6	7
R_a (%)	20	30	40	50	60	70	80
R_r (%)	20	30	40	50	60	70	80

Since there were two evaporator sections, a latent cooling section (LCS) and a sensible coiling section (SCS), in the proposed TS-DXAC system, and different surface ratio, *x*, between SCS and LCS, can affect its overall operational characteristics. Hence three *x* values of 6:4, 8:2, 9:1 with all the combinations of R_a and R_r listed in Table 2 were simulated.

Table 3
The combinations of F and V used in the modeling study

x	6:4	6:4
F (Hz)	80	80
V (m^3/s)	0.36	0.6

The TS-DXAC system will be operated at a constant compressor speed, F, and a constant total supply air flow rate, V. But different combinations of F and V can also affect the operational characteristics of the TS-DXAC system. In this modeling study, two different combinations of F and V listed in Table 3 were simulated under a *x* value of 6:4.

To study the inherent characteristics of the proposed TS-DXAC system, the simulated TCC–E / SHR relationships were plotted on a TCC–E / SHR diagram, and compared to those of a conventional VS DX A/C system at the same operation conditions.

As shown in Fig 4, the irregular area of AA' represents the results of TS-DXAC system at *x* = 6:4, F = 80Hz and V = $0.36 m^3/s$. Similarly, the curve of BB' represents that of a conventional VS DX A/C system at the same compressor and but a variable V value from 30% to its maximum of $0.36\ m^3/s$. From Fig 4, it is seen that unlike a conventional VS DX A/C system that could only provide a variable TCC and E SHR on a curve at a constant compressor speed, the TS-DXAC system was able to produce a relative wide range of combinations of TCC and E SHR at the same operation conditions, enabling its dealing with variable latent and sensible space loads. However, it can also be seen that the position of the irregular area of AA' is almost always above curve BB', suggesting that a wide range of E SHR was achieved at the expense of reduced output TCC for the TS-DXAC system.

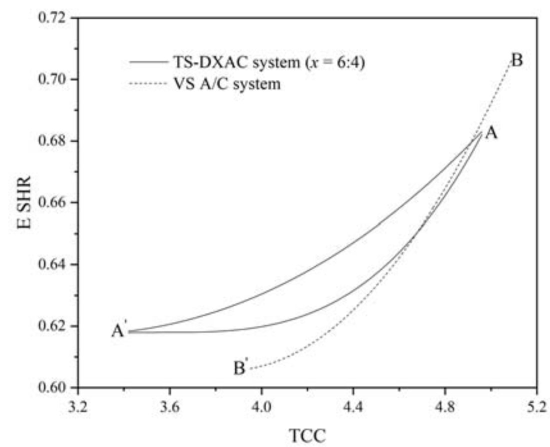


Fig 4 The operation characteristics of different DX A/C system at the same compressor input frequency

Furthermore, the overall operational characteristics of the TS-DXAC system, at three different *x* values of 6:4, 8:2, 9:1, at all the combinations of R_a and R_r shown in Table 3 were also simulated and the results are shown in Fig 5.

In Fig 5, the irregular areas of AA', BB' and CC' represent the simulated results of the TCC/E SHR relationship for the TS-DXAC system at *x* = 6:4, 8:2 and 9:1, respectively. As shown, the variations in *x* value would significantly influence the shapes of these irregular areas. When *x* was increased from 6:4 to 9:1, the high limit of TCC value stayed almost unchanged at 4.9 kW, while the low limit of TCC value was decreased for 3.4 kW to 1.9 kW, leading to a 100% increase in the range between high-low limits for TCC from 1.5 kW at *x* = 6:4 to 3 kW at *x* = 9:1. On the other hand, the high-low limits for E SHR decreased simultaneously when *x* was increased from 6:4 to 9:1, but the range of E SHR stayed almost unchanged. Therefore, the simulated results suggested that using a higher *x* could lead to a larger variation range of TCC and E SHR, and the variation of *x* would influence TCC more than E SHR. Similar to Fig. 4, all these irregular ranges are almost always above curve DD' which represent the operational characteristics of a conventional VS DX A/C system.

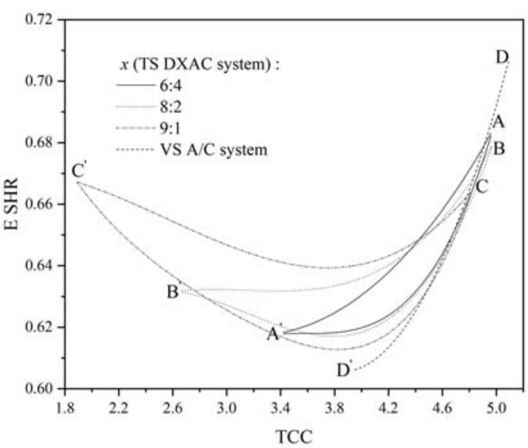


Fig 5 The operation characteristics of the TS-DXAC system at different values of *x*

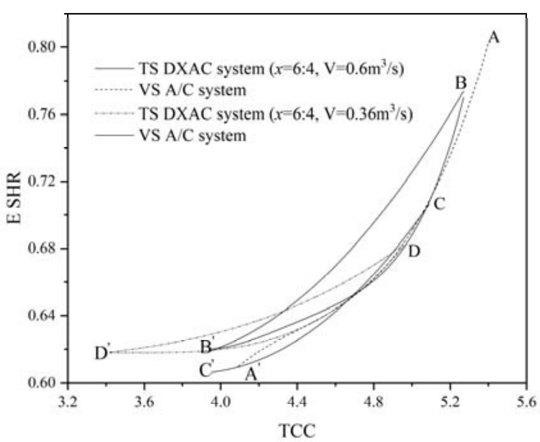


Fig 6 The operation characteristics of different DX A/C system at different supply air volume

As a comparison, Fig 6 shows the characteristics of the TS-DXAC system and a conventional VS DX A/C system at the same compressor frequency but different supply air volume. As seen, the relationship between AA' and BB' was similar to that of CC' and DD', and the range of BB' was almost always above the curve AA'. In addition, a higher supply air volume could achieve higher TCC and E SHR values and a wider range of high-low limits for E SHR, while the range of high-low limits for TCC stayed almost unchanged.

4. Conclusions

The proposed TS-DXAC system was numerically studied by simulation and the study results are presented in this paper. The results showed that the TS-DXAC system was able to provide variable dehumidification capacity. The modeling study also suggested that different surface ratio, *x*, would affect the range of TCC and E SHR, and a larger value of *x* could result in a larger range.

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