

# Test and Simulation of the Operational Characteristics of a Water Chiller Based on Dual Evaporation Temperatures

Bing Li\*

School of Environment and Architecture, University of Shanghai for Science and Technology,  
Shanghai, China

\*Corresponding Author

## Abstract

In small-to-medium scaled residential buildings, direct-expansion (DX) air conditioning (AC) system cannot meet indoor occupants' requirements for a healthy, comfortable and energy efficient indoor environment. Based on the annual load of a residential building in Shanghai, a new type of dual evaporation temperatures chiller was proposed based on a dual suctions compressor and two plate heat exchangers as high and low temperature evaporators. The high temperature evaporator produced chilled water at a temperature of about 20°C, and chilled water of 7°C for the low temperature side. High-temperature chilled water was used to remove sensible cooling load, and low-temperature chilled water the indoor latent cooling load by dehumidifying the fresh air, thus realizing independent control of temperature and humidity. The application of high evaporation temperature can effectively improve the energy efficiency of the system. For the novel chiller, the evaporators' heat transfer model was established to calculate the outlet water temperature of evaporators at different operation conditions, and verified through the test of the prototype. Simulation results showed that the coupling effect of the electronic expansion valves (EEVs) on the high and low temperature side was insignificant. In addition, when the opening of low temperature EEV was about 30%, the temperature of the chilled water for dehumidifying reached lowest, suggesting the maximum dehumidifying capacity of the system.

## Keywords

Temperature and Humidity Independent Control; Dual Evaporation Temperatures; Water Chiller; Simulation Study.

## 1. Introduction

Air conditioning ensures the thermal comfort of people in high temperature environment and play a vital role in realizing sustainable development projects [1-5]. With the rapid development of economy, people have growing requirements for comfort, and the amount of air conditioners has increased dramatically, which lead to a large number of greenhouse gas emissions[6-10]. According to the International Energy Agency (IEA), the energy required for space cooling is estimated to triple by 2050[11-12]. Therefore, it was urgent to develop a new type of green and energy efficient air conditioning system.

In traditional air conditioning system, sometimes the cooled air is necessary to be reheated, especially when the latent load is too high, which will further increase the air conditioning load[13-15]. In order to solve the disadvantages of traditional air conditioning, temperature and humidity independent control (THIC) air conditioning system was proposed, also known as separate sensible and latent cooling system[16-18].

The THIC system firstly adopted heat exchange plates with low temperature to deal with latent cooling load, then adopted heat exchange plates with high temperature to deal with sensible

cooling load. This resulted that the chiller performance was improved due to the use of high temperature chilled water[19]. In different THIC systems, the study of dual-evaporation-temperature vapor compression (VC) systems was rare[20].

Ling[21] carried out theoretical research on the performance of separate sensible and latent cooling system composed of two VC cycles. The study found that the system could achieve about 30 percent energy savings compared to traditional air conditioning systems, with the greatest energy saving potential in cold and dry climates. Chen[22] theoretically studied the influence of indoor sensible heat ratio (ISHR) and chilled water temperature on the energy efficiency of thermostatic refrigeration system. The results show that the COP of the system was improved by 3.1%~17.5%. However, the authors focused more on energy efficiency instead of the exactly decoupling of temperature and humidity in the system. The greater the ISHR, the greater the energy saving potential. Zhu[23] proposed a new climate adaptive, adjustable heat-humidity ratio THIC system. By adjusting the proportion of different refrigerants (MR32, R236fa), they found that this new-type THIC air conditioning system was suitable for the residential buildings in southern China to realize customized thermal comfort due to its climate adaptability and high-density. Unlike the climate in west of China, this method is not always proper in other places with a much moister climate. Compared with traditional air conditioning system, dual evaporation temperatures compressor THIC air conditioning system have great energy saving potential, and this kind of system can make use of low grade heat sources such as industrial waste heat, geothermal energy and solar energy[20]. In this paper, a novel dual evaporation temperatures system using dual suctions compressor and two plate heat exchangers for THIC AC application was proposed and the evaporators' outputs were simulated.

## 2. Dual Evaporation Temperatures Chiller

In order to fully understand the operating characteristics of the dual evaporation temperatures chiller, this research will carry out mathematical modeling and calculation for the evaporators of the water chiller based on dual evaporation temperatures so as to obtain the cooling output characteristics of the system under different working conditions.

### 2.1. System Principle of the Dual Evaporation Temperatures Chiller

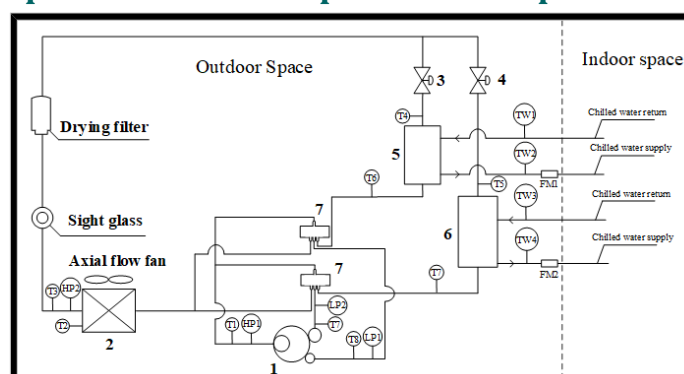


**Fig 1.** Schematic diagram of dual evaporation temperatures chiller

1 dual suctions compressor; 2 fin-tube condenser; 3 EEV for low temperature evaporator; 4 EEV for high temperature evaporator; 5 low temperature plate heat exchange (LT PHE); 6 high temperature PHE (HT PHE); 7 four-way reversing valve

### 2.2. Experimental System of Dual-Evaporation-Temperature Chiller

The performance test experiment was carried out by placing the prototype of dual evaporation temperatures chiller in the psychrometric chamber. The layout of psychrometric chamber is shown in Fig 2.

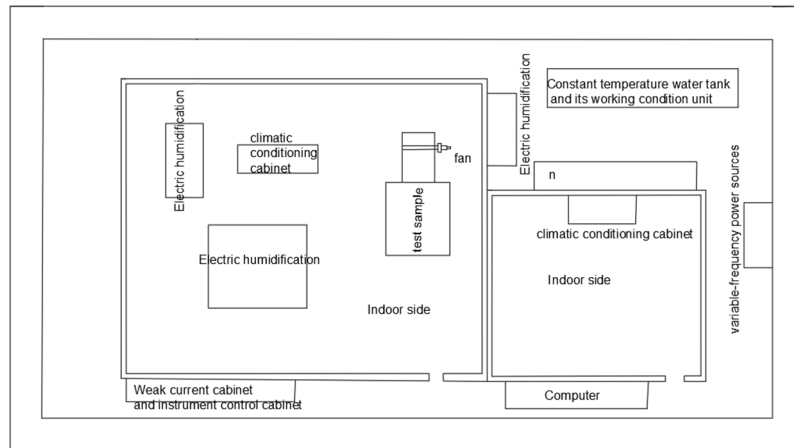


**Fig 2.** Layout of the psychrometric chamber.

### 2.3. Experimental Prototype of Dual Evaporation Temperature Chiller and the Arrangement of Sampling Points

The experimental prototype of dual evaporation temperatures chiller mainly included a dual suctions compressor, two evaporators, a condenser, two EEVs, two four-way reversing valves etc. The parameters of main equipment were shown in Table 2. EEV1 was for the high temperature side and EEV2 the low temperature side, respectively.

### 2.4. Experimental Set of the Dual Evaporation Temperatures Chiller

According to above purposes, the experiment can be divided into two aspects as follows:

- (1) Fixing the opening of the EEVs at the high and low temperature sides, measuring and recording the data in real time at different compressor frequencies.
- (2) Fixing the compressor frequency, measuring and recording the data at varying opening of the electronic expansion valve of the high and low temperature sides respectively.

The outdoor temperature was set at 35 °C for dry bulb and 28 °C for wet bulb temperature. High temperature chilled water flowrate was 2 m<sup>3</sup>/h, and low temperature chilled water flowrate 0.42m<sup>3</sup>/h. The inlet temperature of high temperature chilled water was 21 °C, and the inlet temperature of low temperature chilled water was 11 °C.

## 3. The Establishment of the Model for the Evaporators

In order to simplify the model, the following assumptions were made for the evaporator model:

- (1) Refrigerant and chilled water was countered current during heat exchange;
- (2) The fouling thermal resistance was not considered;
- (3) The pressure drop of refrigerant was ignored.

### 3.1. Water Side Energy Equation

The chiller studied in this paper was constructed based on dual evaporation temperatures absorption cycle. According to thermodynamic equilibrium water, the amount of cold lost by water is equal to the amount of cold lost or gained through the heat transfer surface. This gives us the following equation.

$$Q_{w1} = m_{a,w} \alpha_{a,w} c_{pw} (t_{w,out} - t_{w,in}) \quad (1)$$

$$Q_{w2} = A_0 \alpha_w (t_{w1} - (t_{w,out} - t_{w,in})/2) \quad (2)$$

The convective heat transfer coefficient of water side is determined by Nusselt number. The number of Nusselt under different flow states is shown as follows:

$$Re_a = \frac{u_a d_a}{\vartheta_a} \quad (3)$$

When the Reynolds number is greater than 10,000:

$$Re_a = 0.023 Re_a^{0.8} P_{ra}^{0.3} \quad (4)$$

When the Reynolds number is less than 2300:

$$N_{ua} = 1.86 Re_a^{\frac{1}{3}} \cdot P_{ra}^{\frac{1}{3}} \cdot \left(\frac{d_a}{L_a}\right)^{\frac{1}{3}} \cdot \left(\frac{\vartheta_a}{\vartheta_w}\right)^{0.14} \quad (5)$$

When the Reynolds number is greater than 2300 and less than 100,000:

$$N_{ua} = 0.012 (Re_a^{0.87} - 280) \cdot P_{ra}^{0.4} \cdot \left[1 + \left(\frac{d_a}{L_a}\right)^{\frac{2}{3}}\right] \cdot \left(\frac{P_{ra}}{P_{rw}}\right)^{0.11} \quad (6)$$

$$\alpha_a = N_{ua} \frac{\lambda_a}{d_a} \quad (7)$$

## 4. Results and Discussion

The measured outlet water temperature of the chilled water system of the dual evaporation temperatures chiller under different compressor frequencies and different high and low temperature EEVs' openings were compared with the simulated value calculated by the dual evaporation temperatures water-cooled evaporator model.

### 4.1. Results for High Temperature Side Water-Cooled Evaporator

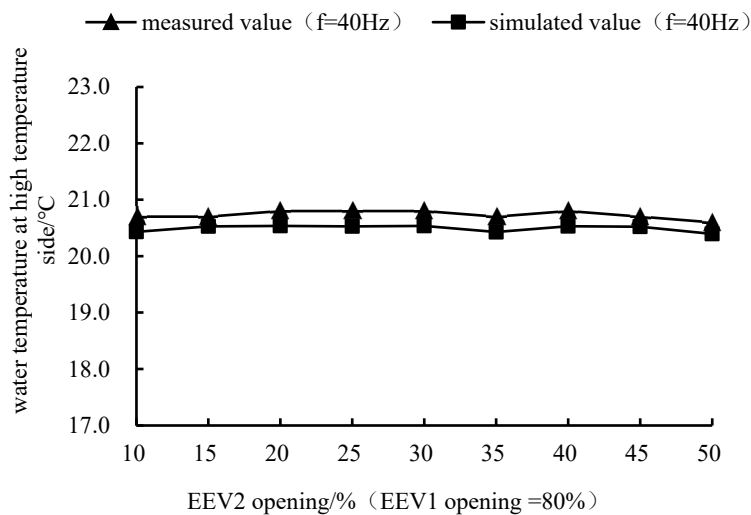


**Fig 3.** Comparison of measured and simulated outlet water temperature at high temperature side (f=40Hz, EEV1 opening=80%)

It could be seen from Fig.3 to Fig.5 that the opening of EEV1 was 80% and 100%. The compressor was rated at 40Hz and 50Hz. With the opening of the EEV on the low temperature side increasing from 10% to 50%, the average temperature of the measured water outlet temperature was 20.73°C, 20.88°C, 20.31°C and 20.55°C. The fluctuation range was 20.7-20.8, 20.8-20.9, 20.2-20.6 and 20.5-20.6, respectively. Therefore, the fluctuation range of outlet

water temperature was small, which indicated that the change of the opening of the EEV at the low temperature side has little influence on the outlet water temperature at the high temperature side. The variation of the simulated value of outlet water temperature obtained from the calculation of the high-temperature water-cooled evaporator model was relatively slight, which was almost a straight line in the figure. The average temperatures of the simulated values were 20.43°C, 20.36°C, 20.48°C and 20.31°C respectively, which was similar with the measured value of outlet water temperature, and the maximum relative error was only 2.5%. Therefore, the simulation calculation results of the high-temperature side water-cooled evaporator model were accurate.

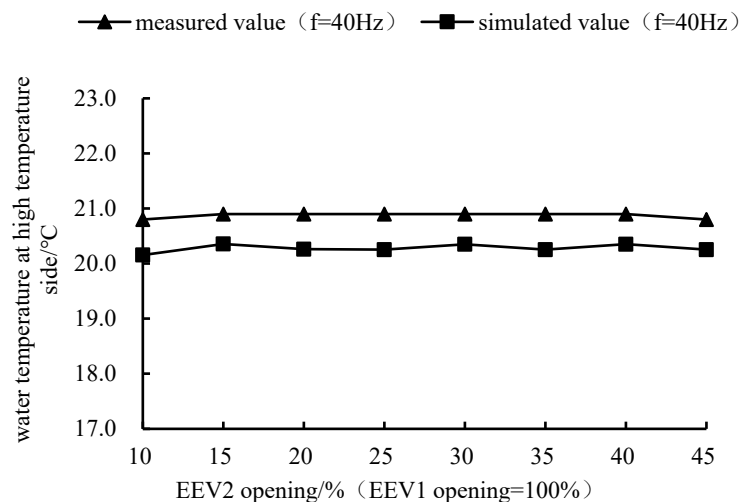


**Fig 4.** Comparison of measured and simulated outlet water temperature at high temperature side (f=40Hz, EEV1 opening=100%)

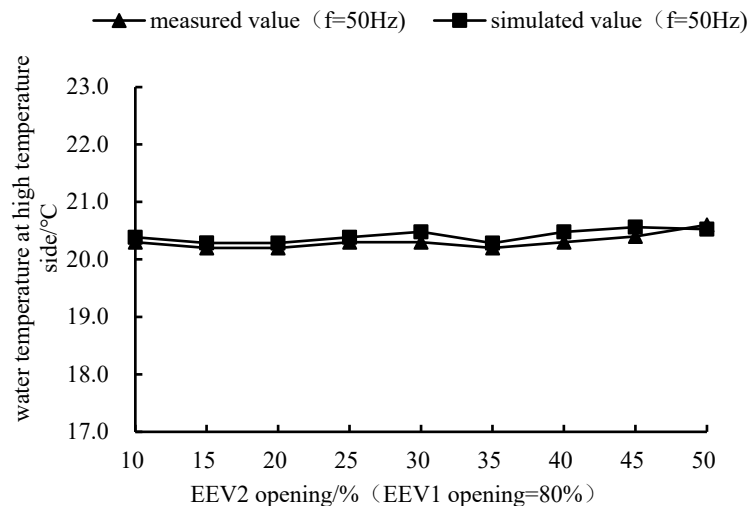


**Fig 5.** Comparison of measured and simulated outlet water temperature at high temperature side (f=50Hz, EEV1 opening=80%)

## 4.2. Discussion

The dual evaporation temperatures chiller is mainly suitable for small-to-medium scaled residential buildings.

This simulation experiment mainly studied the influence of compressor frequency and the opening of EEV1 and EEV2 on the system. When the total cooling load changed, the frequency of the compressor could be varied to adapt to load variation. The higher the frequency of the compressor, the larger its total cooling capacity will be. When the opening of EEV2 increased

from 10% to 80%, the cooling capacity at high temperature side changed little. Taking the opening of EEV1 100% as an example, the fluctuation range of cooling capacity at high temperature side was 2.276 kW to 2.291 kW, only varied by 0.28%. Therefore, it could be considered that when the opening of EEV1 was fixed, the cooling capacity of the high temperature side basically remained the same with the opening of EEV2 changed, but the dehumidifying ability of the system was enhanced. When the opening of EEV1 increased from 30% to 100%, the cooling capacity at the high temperature side increased by 40.6%, the cooling capacity at the high temperature side showed an obvious rising trend, and the radiant cooling capacity was gradually enhanced. In the process of EEV2 opening increasing from 10% to 80%, the cooling capacity of the low temperature side increased first and then decreased. The peak value appeared when the opening of EEV2 was about 30%, and the dehumidifying capacity reached the peak at the fixed compressor frequency, but the cooling capacity of the radiation terminal on the high temperature side almost remained unchanged. When the opening of EEV1 increases from 30% to 100%, the cooling capacity on the low temperature side decreased by 7%, and the cooling capacity on the low temperature side showed a small downward trend. It can be then concluded that the coupling effects between the high and low temperature expansion valves is small. The fresh air system and the radiation terminal are independent of each other. Therefore, it shows the feasibility of applying the radiant air conditioning with dedicated fresh air unit to realizing independent control of temperature and humidity.

## 5. Conclusion

To achieve temperature and humidity independently control in small-to-medium scaled residential buildings, a novel water chiller based on dual evaporation temperatures was proposed. The model for dual evaporation temperature evaporators was established. Simulations and experimental tests were carried out and conclusions can be drawn.

Through the experimental data, it was found that the high temperature EEV's opening had little influence on the outlet water temperature of the low temperature evaporator but would obviously influence that of the high temperature evaporator. As to the low temperature EEV's opening, it significantly influenced the low temperature evaporator's cooling capacity but had little effect on the high temperature evaporator's. Specifically, with the increasing low temperature EEV's opening, the outlet water temperature decreased first, reached the bottom and then increased again. The lowest outlet water temperature suggested the largest cooling capacity for the low temperature evaporator and the peak occurred at the opening of EEV2 being 30%. The lowest outlet water temperature also provided the highest capability of dehumidification. Generally, the coupling effect of adjusting the two EEVs on high and low temperature cooling capacities were insignificant, which would be benefit to developing the temperature and humidity independent control strategies using the proposed chiller.

## Acknowledgments

Thank's for teacher's support.

## References

- [1] Qi S, Wang W, Shen S, et al. Geothermal and solar energy utilization for the development of a sustainable power and cooling production[J/OL]. *Process Safety and Environmental Protection*, 2023: S0957582023000939. DOI:10.1016/j.psep.2023.02.002.
- [2] Ortiz L, Gamarro H, Gonzalez J E, et al. Energy burden and air conditioning adoption in New York City under a warming climate[J/OL]. *Sustainable Cities and Society*, 2022, 76: 103465. DOI: 10.1016/j.scs.2021.103465.

- [3] Shao J, Huang Z, Chen Y, et al. A practical application-oriented model predictive control algorithm for direct expansion (DX) air-conditioning (A/C) systems that balances thermal comfort and energy consumption[J/OL]. *Energy*, 2023, 269: 126748. DOI:10.1016/j.energy.2023.126748.
- [4] Yang L, Weng W, Deng S. A modeling study on a direct expansion based air conditioner having a two-sectioned cooling coil[J/OL]. *Applied Energy*, 2020, 278: 115688. DOI:10.1016/j.apenergy.2020.115688.
- [5] Li Z, Dong P, Zheng Z, et al. Experimental study on the operational characteristics of a dual evaporation temperatures based water chiller[J/OL]. *Journal of Building Engineering*, 2023, 72: 106616. DOI:10.1016/j.jobbe.2023.106616.
- [6] Ma L, Zhao Q, Zhang H. Performance analysis of a new hybrid system composed of a concentrated photovoltaic cell and a two-stage thermoelectric generator[J/OL]. *Sustainable Energy, Grids and Networks*, 2021, 27: 100481. DOI:10.1016/j.segan.2021.100481.
- [7] Arif S, Taweekun J, Ali H M, et al. Development of a cost effective approach toward energy efficient buildings by design, fabrication and economical analysis of air conditioning pods: A case study of a bus station in Thailand[J/OL]. *Case Studies in Thermal Engineering*, 2023, 41: 102534. DOI: 10.1016/j.csite.2022.102534.
- [8] Demir M H, Cetin S, Haggag O, et al. Independent temperature and humidity control of a precooled desiccant air cooling system with proportional and fuzzy logic + proportional based controllers [J/OL]. *International Communications in Heat and Mass Transfer*, 2022, 139: 106451. DOI: 10.1016/j.icheatmasstransfer.2022.106451.
- [9] Liu S, Liu X, Jang H, et al. Performance analysis of a temperature and humidity independent control system with high temperature chilled water cooling and condensing heat regenerating for office buildings [J/OL]. *Energy Conversion and Management*, 2024, 308: 118400. DOI:10.1016/j.enconman.2024.118400.
- [10] Li T, Wang J, Jin F, et al. Techno-economic and environmental performance of a novel poly-generation system under different energy-supply scenarios and temperature and humidity independent control[J/OL]. *Case Studies in Thermal Engineering*, 2023, 50: 103447. DOI:10.1016/j.csite.2023.103447.
- [11] Zhu G X, Bao Y Q, Yu Q Q. A control strategy for air-conditioning loads participating in frequency regulation based on model predictive control[J/OL]. *Sustainable Energy, Grids and Networks*, 2024, 38: 101369. DOI:10.1016/j.segan.2024.101369.
- [12] Ling J, Hwang Y, Radermacher R. Theoretical study on separate sensible and latent cooling air-conditioning system[J/OL]. *International Journal of Refrigeration*, 2010, 33(3): 510-520. DOI: 10.1016/j.ijrefrig.2009.11.011.
- [13] Fartade S, Vaid Y, Nagarhalli P, et al. Augmentation in heat transfer by addition of double-pipe heat exchanger in automobile air-conditioning system[J/OL]. *Materials Today: Proceedings*, 2022[2023-01-11]. <https://www.sciencedirect.com/science/article/pii/S2214785322069425>. DOI:10.1016/j.matpr.2022.11.093.
- [14] Shao J, Zhong Z, Xu X. Investigation on weights setting rule for weights-based fuzzy logic control algorithm utilized in direct expansion air-conditioning systems[J/OL]. *International Journal of Refrigeration*, 2022, 138: 71-83. DOI:10.1016/j.ijrefrig.2022.03.005.
- [15] Yan H, Chen Y, Min Y. Performance analysis of small-scale direct expansion air conditioning system with indirect evaporative cooler as dedicated ventilator[J/OL]. *Building and Environment*, 2022, 208: 108603. DOI:10.1016/j.buildenv.2021.108603.
- [16] Niu R, Fan Y, Geng L. Adaptability of a temperature and humidity independent control air-conditioning system in green office buildings[J/OL]. *Journal of Building Engineering*, 2021, 42: 102432. DOI:10.1016/j.jobbe.2021.102432.
- [17] Zhao J, Shi L, Li J, et al. A model predictive control regulation model for radiant air conditioning system based on delay time[J/OL]. *Journal of Building Engineering*, 2022, 62: 105343. DOI: 10.1016/j.jobbe.2022.105343.

- [18] Qin W, Hu Y, Lei J, et al. Comfort design and optimization of direct expansion multi-connected radiant air conditioning based on 3D flow field simulation[J/OL]. *Displays*, 2021, 69: 102054. DOI:10.1016/j.displa.2021.102054.
- [19] Zhang F, Yin Y, Cao B, et al. Performance analysis of a novel dual-evaporation-temperature combined-effect absorption chiller for temperature and humidity independent control air-conditioning[J/OL]. *Energy Conversion and Management*, 2022, 273: 116417. DOI:10.1016/j.enconman.2022.116417.
- [20] Zhang T, Liu X, Jiang Y. Development of temperature and humidity independent control (THIC) air-conditioning systems in China--A review[J/OL]. *Renewable and Sustainable Energy Reviews*, 2014, 29: 793-803. DOI:10.1016/j.rser.2013.09.017.
- [21] Taheri S, Hosseini P, Razban A. Model predictive control of heating, ventilation, and air conditioning (HVAC) systems: A state-of-the-art review[J/OL]. *Journal of Building Engineering*, 2022, 60: 105067. DOI:10.1016/j.jobbe.2022.105067.
- [22] Chen T, Yin Y, Zhang X. Applicability and energy efficiency of temperature and humidity independent control systems based on dual cooling sources[J/OL]. *Energy and Buildings*, 2016, 121: 22-31. DOI:10.1016/j.enbuild.2016.04.001.
- [23] Zhu Y, Yin Y. Performance of a novel climate-adaptive temperature and humidity independent control system based on zeotropic mixture R32/R236fa[J/OL]. *Sustainable Cities and Society*, 2022, 76: 103453. DOI:10.1016/j.scs.2021.103453.