Environmental Engineering

Zhaojun Wang
Yingxin Zhu
Fang Wang
Peng Wang
Chao Shen
Jing Liu *Editors*

Proceedings of the 11th International Symposium on Heating, Ventilation and Air Conditioning (ISHVAC 2019)

Volume II: Heating, Ventilation, Air Conditioning and Refrigeration System

Springer

Environmental Science and Engineering

Environmental Engineering

More information about this subseries at http://www.springer.com/series/3172

Zhaojun Wang · Yingxin Zhu · Fang Wang ·
Peng Wang · Chao Shen · Jing Liu
Editors

Proceedings of the 11th International Symposium on Heating, Ventilation and Air Conditioning (ISHVAC 2019)

Volume II: Heating, Ventilation, Air Conditioning and Refrigeration System

Springer

Editors
Zhaojun Wang
Department of Building Thermal Engineering, School of Architecture
Harbin Institute of Technology
Harbin, Heilongjiang, China

Yingxin Zhu
Department of Building Science
School of Architecture
Tsinghua University
Beijing, China

Fang Wang
Department of Building Thermal Engineering, School of Architecture
Harbin Institute of Technology
Harbin, Heilongjiang, China

Peng Wang
Department of Building Thermal Engineering, School of Architecture
Harbin Institute of Technology
Harbin, Heilongjiang, China

Chao Shen
Department of Building Thermal Engineering, School of Architecture
Harbin Institute of Technology
Harbin, Heilongjiang, China

Jing Liu
Department of Building Thermal Engineering, School of Architecture
Harbin Institute of Technology
Harbin, Heilongjiang, China

ISSN 1863-5520 ISSN 1863-5539 (electronic)
Environmental Science and Engineering
ISSN 1431-2492
Environmental Engineering
ISBN 978-981-13-9523-9 ISBN 978-981-13-9524-6 (eBook)
https://doi.org/10.1007/978-981-13-9524-6

This Springer imprint is published by the registered company Springer Nature Singapore Pte Ltd.
The registered company address is: 152 Beach Road, #21-01/04 Gateway East, Singapore 189721, Singapore

Committees

Conference Organizing Committee

President

Prof. Zhaojun Wang, Harbin Institute of Technology, China

Technical Program Chair

Prof. Jing Liu, Harbin Institute of Technology, China

Advisory Chair

Prof. Yingxin Zhu, Tsinghua University, China

Secretary-General

Peng Wang, Harbin Institute of Technology, China

Members

Fang Wang, Harbin Institute of Technology, China
Chao Shen, Harbin Institute of Technology, China
Jiankai Dong, Harbin Institute of Technology, China
Yanling Wang, Harbin Institute of Technology, China
Zhigang Zhou, Harbin Institute of Technology, China
Haiyan Wang, Harbin Institute of Technology, China
Xiumei Bai, Harbin Institute of Technology, China

Student Members

Yuchen Ji, Harbin Institute of Technology, China
Qingwen Xue, Harbin Institute of Technology, China
Xiaowen Su, Harbin Institute of Technology, China

Subei Bu, Harbin Institute of Technology, China
Xin Chen, Harbin Institute of Technology, China
Jing Du, Harbin Institute of Technology, China

International Advisory Committee

Edward Arens, University of California, Berkeley, USA
Chungyoon Chun, Yonsei University, South Korea
Richard Corsi, University of Texas at Austin, USA
Richard de Dear, The University of Sydney, Australia
Lin Duanmu, Dalian University of Technology, China
Xiumu Fang, Harbin Institute of Technology, China
Yi Jiang, Tsinghua University, China
Kwang-Woo Kim, Seoul National University, South Korea
Angui Li, Xi'an University of Architecture and Technology, China
Baizhan Li, Chongqing University, China
Yuguo Li, The University of Hong Kong, China
Junjie Liu, Tianjin University, China
Bjarne W. Olesen, Technical University of Denmark, Denmark
Andrew Persily, National Institute of Standards and Technology, USA
Shin-ichi Tanabe, Waseda University, Japan
Sven Werner, Halmstad University, Sweden
Hiroshi Yoshino, Tohoku University, Japan
Guoqiang Zhang, Hunan University, China
Xu Zhang, Tongji University, China
Jianing Zhao, Harbin Institute of Technology, China

International Scientific Committee

Alireza Afshari, University of Aalborg, Denmark
Hazim Awbi, University of Reading, UK
Bin Cao, Tsinghua University, China
Guangyu Cao, Norwegian University of Science and Technology, Norway
Shijie Cao, Guangzhou University, China
Ping Cui, Shandong Jianzhu University, China
Lei Fang, Technical University of Denmark, Denmark
Guohui Feng, Shenyang Jianzhu University, China
Jun Gao, Tongji University, China
Naiping Gao, Tongji University, China
Weijun Gao, University of Kitakyushu, Japan
Tomonobu Goto, Tohoku University, Japan

Runa T. Hellwig, University of Aalborg, Denmark
Jan Hensen, Eindhoven University of Technology, the Netherlands
Sabine Hoffmann, Technische Universität Kaiserslautern, Germany
Tianzhen Hong, Lawrence Berkeley National Laboratory, USA
Yiqiang Jiang, Harbin Institute of Technology, China
Xianting Li, Tsinghua University, China
Xiangli Li, Dalian University of Technology, China
Zhengrong Li, Tongji University, China
Zhiwei Lian, Shanghai Jiao Tong University, China
Borong Lin, Tsinghua University, China
Zhang Lin, City University of Hong Kong, China
Xiaohua Liu, Tsinghua University, China
Zhiwen Luo, University of Reading, UK
Jianlei Niu, The Hong Kong Polytechnic University, China
Atila Novoselac, University of Texas at Austin, USA
Yiqun Pan, Tongji University, China
Menghao Qin, Technical University of Denmark, Denmark
Mattheos Santamouris, University of New South Wales, Australia
Chandra Sekhar, National University of Singapore, Singapore
Stefano Schiavon, University of California, Berkeley, USA
Marcel Schweiker, Karlsruhe Institute of Technology, Germany
Li Song, University of Oklahoma, USA
Fu-Jen Wang, National Chin-Yi University of Technology, China
Gang Wang, University of Miami, USA
Leon Wang, Concordia University, Canada
Shengwei Wang, The Hong Kong Polytechnic University, China
Yi Wang, Xi'an University of Architecture and Technology, China
Wei Xu, China Academy of Building Research, China
Da Yan, Tsinghua University, China
U Yanagi, Kogakuin University, Japan
Hongxing Yang, The Hong Kong Polytechnic University, China
Xudong Yang, Tsinghua University, China
Runming Yao, University of Reading, UK
Yang Yao, Harbin Institute of Technology, China
Yonggao Yin, Southeast University, China
Yanping Yuan, Southwest Jiaotong University, China
Zhiqiang (John) Zhai, University of Colorado at Boulder, USA
Hui Zhang, University of California, Berkeley, USA
Jili Zhang, Dalian University of Technology, China
Linhua Zhang, Shandong Jianzhu University, China
Quan Zhang, Hunan University, China
Tengfei (Tim) Zhang, Dalian University of Technology, China

Yinping Zhang, Tsinghua University, China
Yufeng Zhang, South China University of Technology, China
Xudong Zhao, University of Hull, UK
Xiang Zhou, Tongji University, China

Organization

Organized by

Host and Organizer

Harbin Institute of Technology

Co-organizer

Tsinghua University

Supported by

American Society of Heating, Refrigerating and Air-Conditioning Engineers

Journal of Heating, Ventilation and Air Conditioning

Chinese Association of Refrigeration (CAR)

The Chinese Committee of Heating, Ventilation and Air Conditioning (CCHVAC)

List of Plenary Lectures

Speakers	Affiliation	Topic
Yi Jiang	Tsinghua University, China	The Approach for Building Energy Efficiency in Emerging Economies Countries
Bill Bahnfleth	Pennsylvania State University, USA	Promise and Practicalities of Smart Systems
Bjarne W. Olesen	Technical University of Denmark, Denmark	State of the Art of HVAC Technology in Europe
Yingxin Zhu	Tsinghua University, China	How to Create Comfortable and Healthy Indoor Environment?—A New Challenge for Sustainable Building
Katsunori Nagano	Hokkaido University, Japan	Contribution of Heat Pumping Technologies for the Green Environment and Our Life
Rajan Rawal	CEPT University, India	Thermal Comfort for All: Setting up a Stage
Vladimir G. Gagarin	Moscow State University, Russia	Structure and Development of the System of Regulatory Documents in Russia on the Thermal Performance and Energy Saving of Buildings
Zhaojun Wang	Harbin Institute of Technology, China	Thermal Comfort and Thermal Adaptation in the Severe Cold Area, China

Preface

The International Symposium on Heating, Ventilation and Air Conditioning (ISHVAC) series was initiated by Tsinghua University of China in 1991. It has been a premier International Conference on Heating, Ventilating, and Air Conditioning (HVAC) in China and has played a significant role for presenting newly found research results and exchanging ideas among colleagues from academics, research organizations, and industry in the field. The 11th ISHVAC (ISHVAC 2019) was held from July 12 to 15, 2019, in Harbin, China, hosted by Harbin Institute of Technology (HIT), and Prof. Zhaojun Wang from HIT was President of ISHVAC 2019.

In developed countries, buildings use 40% of the primary energy, while in developing countries like China, buildings use 1/3 of the primary energy. Thus, energy used in buildings is very significant and a majority of the energy used in buildings is by HVAC systems that should create thermally comfortable and healthy indoor environment for their occupants. However, the indoor environment created is far from ideal because of poor design, operation, and occupant intervention. Therefore, ISHVAC 2019 focused on not only HVAC but also indoor environmental quality, health, thermal comfort, human activities, energy efficiency, renewable energy, etc. The conference provided a great opportunity to exchange new ideas and the state-of-the-art sciences and technologies, to identify solutions to problems in built environment, and to build partnerships among engineers, architects, environmental scientists, facility managers, HVAC system manufacturers, and policy makers.

The themes of this conference include indoor and outdoor environment; heating, ventilation, air conditioning, and refrigeration; and building and energy. More than 600 full papers were received, 543 full papers were accepted, and 407 papers were included in the proceedings. There were eight keynote lectures, 15 workshops, 56 parallel sessions, and one poster session. More than 500 experts and scholars from 20 countries or regions attended the conference, of which more than 80 were foreign guests. The participation of many internationally renowned experts and scholars has raised the level of ISHVAC 2019. The conference had the following features:

- The conference invited prominent Indian and Russian scholars to present in plenary sessions, and their presentations were of significance to the study of global climate and energy consumption.
- Many outstanding scholars were invited to organize 15 workshops, focusing on hot issues including thermal environment and thermal comfort, indoor environmental quality, pollutant transmission and control, human behaviors and building energy consumption simulation, smart heating, evaporative cooling, and heat pump.
- During the conference, the Asian HVAC Alliance was established. We hope that the ISHVAC series would become a grand event in the field of HVAC in Asia in the future, like CLIMA conferences in Europe and ASHRAE conferences in North America.

We would like to appreciate the International Advisory Committee and Scientific Committee for their hard work and efforts in reviewing papers and providing support needed. We also would like to thank the co-organizer Tsinghua University and co-sponsors such as ASHRAE, Journal of HV&AC, the Chinese Association of Refrigeration, and the Chinese Committee of Heating, Ventilation and Air Conditioning (CCHVAC).

Harbin, China Zhaojun Wang
Beijing, China Yingxin Zhu
Harbin, China Fang Wang
Harbin, China Peng Wang
Harbin, China Chao Shen
Harbin, China Jing Liu
Editors of the Proceedings of ISHVAC 2019

Contents

An Experimental Study on the Energy Use during a TES-Based Reverse Cycle Defrosting Method for Cascade Air Source Heat Pumps

Minglu Qu, Tongyao Zhang, Rao Zhang, Jianbo Chen, Zhao Li and Tianrui Li

Abstract Adopting cascade air source heat pumps (CASHPs) is a possible way to widespread application of air source heat pumps in cold area. When CASHPs are operated in winter, frosting/defrosting may become problematic. Thermal energy storage-based reverse cycle defrosting (TES-based RCD) method for CASHPs has been developed to provide heat to defrosting and continuously heat indoor space. In this paper, the energy use during the TES-based RCD for CASHPs was experimentally studied. It was found that most of the heat supplied was dissipating to the ambient air, accounting for 44.3%, and the defrosting efficiency was 30.2%. Meanwhile, most of the heat came from the TES-heat exchanger (TES-HE), accounting for 40%. This study can be utilized to guide the design optimization for the TES-HE and promote energy-saving for TES-based RCD method.

Keywords Defrosting · Energy use · Thermal energy storage · Cascade air source heat pump

1 Introduction

To advance the operating performance of ASHP in cold regions, employing cascade air source heat pumps (CASHPs) is a feasible way. In CASHPs, the two refrigeration cycles, i.e., the high temperature (HT) cycle and low temperature (LT) cycle, adopting different refrigerant, are connected by a cascade heat exchanger. Extensive experimental and theoretical studies on CASHPs have been carried out recently [1–4].

When adopting CASHP unit in cold regions, frosting and defrosting may also be problematic. Nevertheless, seldom research was conducted to develop suitable

M. Qu (✉) · T. Zhang · R. Zhang · J. Chen · Z. Li · T. Li
School of Environment and Architecture, University of Shanghai for Science and Technology, No. 516, Jungong Road, 200093 Shanghai, China
e-mail: quminglu@126.com

Z. Wang et al. (eds.), *Proceedings of the 11th International Symposium on Heating, Ventilation and Air Conditioning (ISHVAC 2019)*, Environmental Science and Engineering, https://doi.org/10.1007/978-981-13-9524-6_1

defrost method for CASHPs. To handle this problem, Qu et al. [5, 6] proposed thermal energy storage-based reverse cycle defrosting method (TES-based RCD) for CASHPs to provide heat to both defrosting for LT cycle and indoor heating for HT cycle.

On the other hand, in order to shorten defrost duration and improve defrosting efficiency, it is therefore necessary to identify the energy consumption and energy supply in the defrosting process. Previous research has been conducted to investigate the energy use during reverse cycle defrosting for ASHPs [7, 8]. However, energy use during TES-based RCD for CASHPs is seldom seen. Therefore, an experimental study is conducted to investigate the energy use during a TES-based RCD method for CASHPs in this paper. This study can be utilized to guide the design optimization for the TES-HE and promote energy-saving for TES-based RCD method.

2 Experimental Prototype and Procedures

2.1 Experimental Prototype

In this research, the prototype CASHP unit was modified from a conventional CASHP unit with heating capacity of 10 kW and shown in Fig. 1, and the introduction of this system including the PCM-HE is described in Refs. [5, 6]. Commercial composite organic phase-change material (PCM) RT 10 whose melting point 6.17 and melting latent heat 134.9 kJ/kg was adopted. Its thermophysical

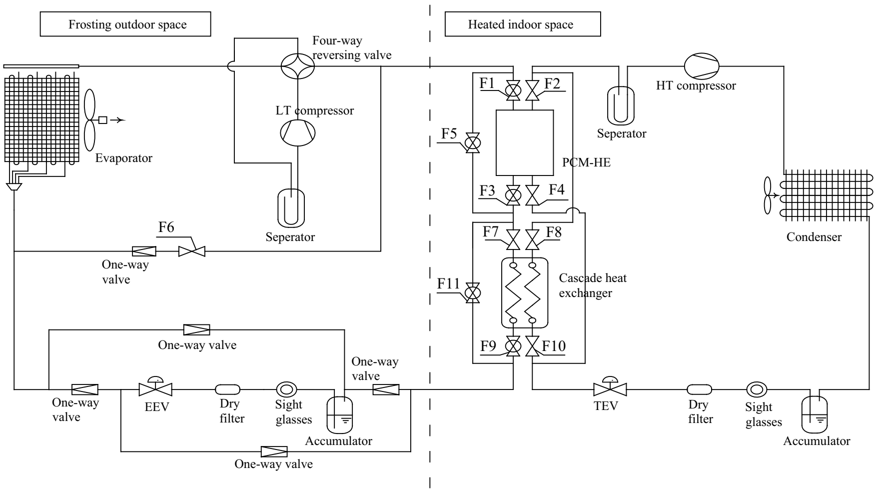

Fig. 1 Schematics of the prototype

properties can be found in Ref. [6]. In this research, 16.7 kg of RT10 was used; thus, about 2255 kJ of latent heat could be stored.

2.2 Experimental Condition and Procedures

During the frosting/TES heating process, the air dry-bulb temperature and RH inside the heated indoor space were maintained at 22 ± 0.1 °C and 50 ± 3% relative humidity, and those inside the frosting outdoor space at −9 ± 0.3 °C and at 85 ± 3% relative humidity, respectively. The operating procedures and the details of instrumentation can be found in Ref. [6].

2.3 Data Reductions

During TES-based RCD process, the heat was applied in five parts, i.e., melt the frost on the evaporator surface, vaporize the retained water on the evaporator surface, heat the evaporator, dissipate to the ambient air, and heat the melted frost. The determination of each part was introduced in the following.

The heat used to melt the frost layer, Q_m, can be obtained by:

$$Q_m = m_{\mathrm{fr}} L_{\mathrm{sf}} \tag{1}$$

where m_{fr} is the total mass of frost layer formed on the evaporator, whose calculation method can be found in Ref. [7], kg, L_{sf} the latent heat of frost melting, kJ/kg. The heat used to vaporize the retained water, Q_v, was:

$$m_v = m_{\mathrm{fr}} - m_{\mathrm{me}} \tag{2}$$

$$Q_v = m_v L_v \tag{3}$$

where m_v and m_{me} are the mass of vaporized melted frost and the mass of collected melted frost at the end of a defrost duration, respectively, kg. L_v is the latent heat of evaporation of water.

The heat used to heat the evaporator metal, Q_{Me}, could be evaluated by:

$$Q_{\mathrm{Me}} = C_{\mathrm{pMe}} \times (m_{\mathrm{Cu}} + m_{\mathrm{Al}}) \times \Delta T_{\mathrm{Me}} \tag{4}$$

in which ΔT_{Me} is the temperature difference of the evaporator metal during the TES-based RCD process, °C. C_{pMe} is the averaged specific heat of copper and aluminum.

The heat dissipated to the ambient air, Q_a, could be obtained by:

$$Q_a = C_{\mathrm{pa}} \times \rho_a \times V_a \times (t_{\mathrm{out}} - t_{\mathrm{in}}) \tag{5}$$

where C_{pAl} and ρ_a are the specific heat and density of air, respectively, kJ/(kg K), kg/m^3, V_a the volumetric flow rate of the air across the evaporator, m^3/s, and t_{out} and t_{in} the air temperature at the inlet and outlet of the evaporator, respectively, °C.

The total heat supplies to defrost can be calculated from the LT refrigerant side, Q, as shown:

$$Q = \int_0^{t_d} m_r \left(h_{\mathrm{Eva},o} - h_{\mathrm{Eva},i}\right) \mathrm{d}t \tag{6}$$

where $m_{r,}$ is refrigerant mass flow rate, kg/s, $h_{\mathrm{Eva},i}$ and $h_{\mathrm{Eva},o}$ the enthalpies of LT refrigerant at both inlet and exit of the evaporator, respectively, kJ/kg, obtained from the measured compressor discharge pressure and the measured inlet and outlet temperatures, t_d the defrost duration, s.

The heat used to heat the melted frost, Q_r, was obtained from the difference of the total heat supplied and the other four parts of heat:

$$Q_r = Q - Q_m - Q_v - Q_{\mathrm{Me}} - Q_a \tag{7}$$

To evaluating defrosting operation, defrosting efficiency, η_d, is an important parameter [7]. It can be evaluated by:

(8)

On the other hand, during TES-based RCD, the heat supplied to defrost was actually came from the energy stored in the PCM-HE, the LT compressor power input, and the energy stored in the metal of the PCM-HE and the tubes.

Heat supplied to LT cycle from the PCM-HE, Q_{PCM}, was calculated by:

$$Q_{\mathrm{PCM}} = \int_0^{\mathrm{td}} m_r \left(h_{\mathrm{PCM},o} - h_{\mathrm{PCM},i}\right) \mathrm{d}t \tag{9}$$

where $h_{\mathrm{PCM},i}$ and $h_{\mathrm{PCM},o}$ the enthalpies of LT refrigerant at both inlet and exit of the PCM-HE, respectively, kJ/kg, obtained from the measured pressure and the measured inlet and outlet temperatures.

Heat from the LT compressor, W_{com}, was obtained from the measured electric input of the LT compressor.

$$W_{\mathrm{com}} = P\eta \tag{10}$$

where compressor power consumption, kW, acquired by power meter on the enthalpy difference chamber control cabinet and η the electrical efficiency of the compressor, 0.6.

The heat from the coil and tube metal, Q_{store}, could be then evaluated by:

$$Q_{\mathrm{store}} = Q - Q_L - W_{\mathrm{com}} \tag{11}$$

3 Experimental Results

Main experimental results were shown in Table 1. The calculated mass of accumulated frost was 2.515 kg. The collected melted frost in the measuring cylinder was 2.352 kg. The defrosting duration was 510 s, and the total heat supplies to defrost obtained by Eq. (6) was 4099.5 kJ.

3.1 Heat Consumptions

Figure 2 presents the average copper tube surface temperature of the evaporator during TES-based RCD process. As seen, the tube surface temperature began to increase gradually from −5.4 to 0 °C at about 60 s, with the hot refrigerant gas flew into the evaporator (condenser). Afterward, the temperature remained for a while, which can be considered as frost-melting period, until the tube surface temperature increased sharply at 180 s, suggesting most of the frost layer was melted. Thereafter, the supplied heat was utilized to heat and vaporize the melted frost and remained water. At the end of the TES-based RCD process, the tube surface temperature of the evaporator reached 32.5 °C.

Table 1 Main experimental results and the energy consumption

Item	Value
Mass of accumulated frost (kg)	2.515
Mass of collected melted frost in the measuring cylinder (kg)	2.352
Mass of retained water (kg)	0.163
Defrosting duration (s)	510
Heat used to melt the frost layer (kJ)	840.0
Heat used to vaporize retained water (kJ)	398.2
Heat used to heat the melted frost (kJ)	288.3
Heat used to heat evaporator metal (kJ)	757.1
Heat dissipated to ambient air (kJ)	1815.9
Total heat supply to defrost (kJ)	4099.5
Defrosting efficiency (%)	30.2

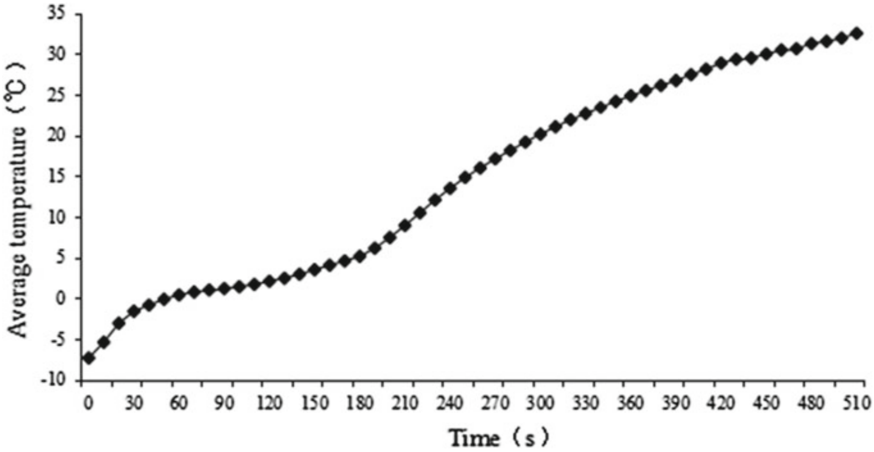

Fig. 2 Average copper tube surface temperature of the evaporator during TES-based RCD process

Figure 3 illustrates measured air temperatures at the inlet and outlet of the evaporator during TES-based RCD process. The air temperature at the outlet of the evaporator was −10.3 °C, with the heat dissipated to the ambient air by natural convection from the evaporator coil; it raised gradually to 2.5 °C at the end of the TES-based RCD process. Meanwhile, the air temperatures at the inlet of the

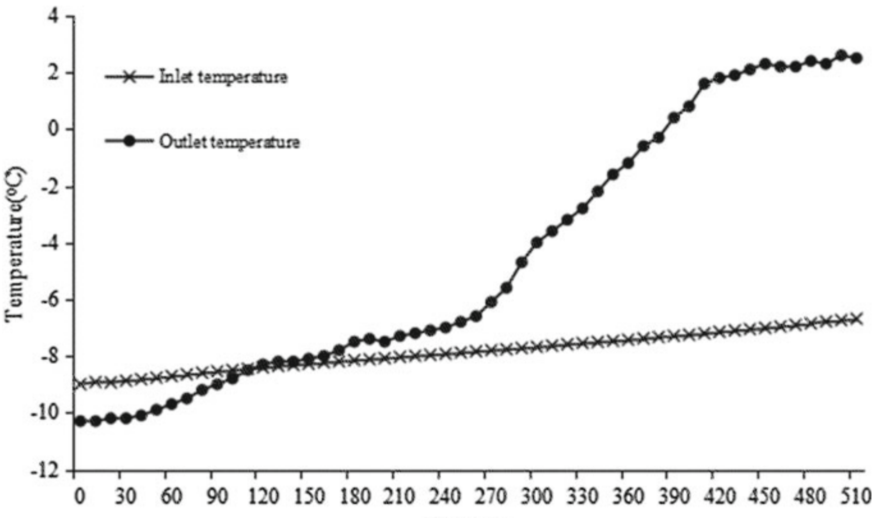

Fig. 3 Measured air temperatures at the inlet and outlet of the evaporator during TES-based RCD process

evaporator began to grow ion from the evaporator coil; it raised gradually to 2.5 °C in at the end of the TES-based RCD process. Meanwhile, the air temperatures at the inlet of the evaporator began to grow from −8.9 to −6.7 °C, with the defrosting proceeded.

Figure 4 shows the measured air velocity of the evaporator during TES-based RCD process. The air velocity was zero due to the shutdown of the evaporator fan and the block of the frost layer on the coil surface at the first 180 s. Thereafter, with the most frost layer melted, the ambient air temperature was therefore heated by the evaporator coil. The ambient air began to rise due to thermal pressure, and the air velocity increased remarkably along with the rise of the coil surface temperature. It reached 0.71 m/s at the end of the TES-based RCD process.

Given the experimental results, the heat consumption during TES-based RCD process was obtained from Eqs. (1–8) and listed in Table 2 and Fig. 5. The largest proportion of the heat supplied went on dissipate to ambient air, 44.3%, which was

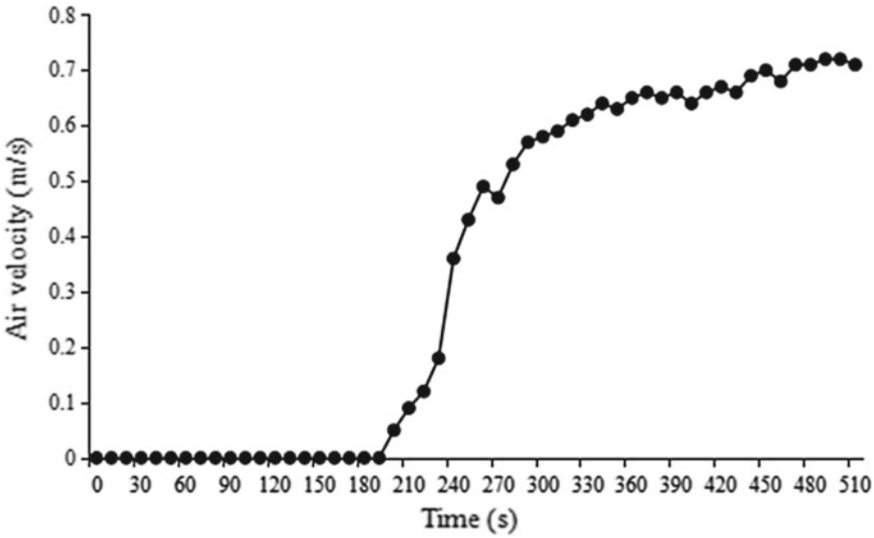

Fig. 4 Measured air velocity variations of the evaporator during TES-based

Table 2 Energy supplies

Total heat supplies to defrost (kJ)	4099.5
Heat from the PCM-HE (kJ)	1637.7
Proportions of heat from the PCM-HE (%)	40.0
Heat from the LT compressor (kJ)	969.5
Proportions of heat from the LT compressor (%)	23.7
Heat from the coil and tubes metal (kJ)	1492.3
Proportions of heat from the coil and tubes metal (%)	36