THERMAL PERFORMANCE OF BACKFLOW SOLAR AIR HEATING WITH INTEGRATED NANOPARTICLE ENHANCED PCM ABSORBER STORAGE SYSTEM

ALI MOHAMMED HAYDER

A thesis submitted in fulfillment of the requirement for the award of the Doctor of Philosophy in Mechanical Engineering

Faculty of Mechanical and Manufacturing Engineering
Universiti Tun Hussein Onn Malaysia

AUGUST 2019
To the memory of my mother, my father, who would have been glad to see me at this moment.

To my wife and beloved children, Sarah, Malak, Lyan, Hussein for their love and support.

To my brothers and my sisters for their support and encouragement

To all my family members and friends for their love and support

To science,

enlightening us
ACKNOWLEDGEMENT

Alhamdulillah, I am so grateful to Allah for giving me enough strength, inspiration and guidance throughout my Ph.D. study. Many people have redounded directly or indirectly to the completion of this thesis and their assistances are highly appreciated.

First and foremost, I would like to express my deepest gratitude to my supervisor, Dr. Azwan Bin Sapit, for his invaluable guidance and assistance during my Ph.D. journey. Without his patience and motivation, this thesis would not have been completed successfully. He gave me the opportunity to start with him a new constructive experience of research work. I have learned from him many aspects not only in the academic life but also in my living attitude.

Thanks to my co-supervisor Assoc. Prof. Dr. Qahtan Adnan Abed from the Furat Al-Awsat Technical University, for his valuable technical advice.

I would like to acknowledge Universiti Tun Hussein Onn Malaysia (UTHM) for giving me the opportunity to undertake my doctorate program by bestowing upon me university grant scholarship.

The cooperation given by the Engineering Technical College of Al-Najaf; Al-Furat Al-Awsat Technical University is also highly appreciated. Appreciation also goes to everyone involved directly or indirectly towards the compilation of this thesis especially Dr. Yasir Amer Al-Jawahar. Last but not least,

Special thanks I would like present to my brother Hayder whose vineyard and enthusiasm have been always precious to me.

Private gratitude for brother-in-law HJ. Mueen Aljanabi to encourage and support him to me even achieving success.

Finally, I would like to thank my wife Aseel for her encourage, support, patience and unwavering love. I thank my daughters Sarah, Malak, Lyan and my son Hussein for providing cheerful atmosphere at home, their never-ending love, and affection to me.
ABSTRACT

The present study has been executed to clarify the advantage of using latent thermal storage integrated with a back pass solar air heater (SAH). The purpose of this study is to design, fabricate and evaluate the performance of SAH with integrated nanoparticles enhanced phase change material (PCM) absorber storage system. Three different SAH configurations have been designed and studied; without thermal storage, with thermal storage using paraffin wax as a PCM and with thermal storage using \(\text{Al}_2\text{O}_3\)-paraffin wax. A three-dimensional Navier-Stokes equation coupled with the energy balance equation is solved using the computational fluid dynamics (CFD) software program to implement numerical computations. The numerical analysis is conducted to determine the optimum collector dimensions in terms of length (L), width (W) and depth of air flow channel (H
_ch
) at air mass flow rate of 0.03 kg/s and solar irradiance of 1000 W/m
^2
. Results obtained from the numerical analysis indicate that the collector dimensions of (L = 1.8 m, W = 0.7 m, H
_ch
 = 0.07 m) which are the best design. The numerical results show that the SAH with \(\text{Al}_2\text{O}_3\)-paraffin wax have the thermal efficiency ranged between 73 % and 78 % with air temperature difference from 25 °C to 46.6 °C when the solar irradiance of 1000 W/m
^2
 at the air mass flow rates of 0.03 kg/s and 0.06 kg/s, respectively. The experimental setup is constructed using these optimum dimensions for each configuration and validated using the numerical results. All configurations are fabricated and tested outdoor under the Iraq climatic conditions according to ASHRAE standard tests at different air mass flow rates. The two steps method is used to prepare the mixture of nanoparticles with PCM and ultrasonic device is used to suspend the nanoparticles in the PCM. The experimental results show that the SAH with \(\text{Al}_2\text{O}_3\)-paraffin wax has the highest daily performance and thermal efficiency followed by SAH with pure paraffin wax and SAH without storage. Moreover, the discharging time in the SAH with pure paraffin wax of heat stored took 5.5, 5, 4.5 and 4 hours at the air mass flow rate 0.03, 0.04, 0.05 and 0.06 kg/s, respectively. As for the SAH with \(\text{Al}_2\text{O}_3\)-paraffin
wax, the discharge time are 5, 4.5, 4 and 3.5 hours at the air mass flow rates of 0.03, 0.04, 0.05 and 0.06 kg/s, respectively. The experimental results also show that increment in the thermal conductivity of PCM with the dispersion 1wt. % Al₂O₃ which led to raise the outlet air temperature and thermal efficiency of the SAH compared to SAH with pure paraffin wax. In addition, good agreement are obtained when comparing between the numerical and experimental results. It was the average differences in percentage on outlet air temperatures obtained in the numerical and experimental results from 2.11 % to 2.47 % and on the thermal efficiency from 2.70% to 3.50 %, respectively.
ABSTRAK

Kajian ini telah dilaksanakan untuk menjelaskan kelebihan menggunakan storan terma laten yang disepadukan dengan pemanas udara suria (SAH) aliran belakang. Tujuan kajian ini adalah untuk merekabentuk, membina dan menilai prestasi SAH dengan sistem storan laten bersepadu berdasarkan sistem penyerapan thermal material berubah fasa yang telah ditambah nanopartikel terpadu (PCM). Tiga konfigurasi SAH yang berbeza telah direka dan dipelajari; tanpa penyimpanan termal, dengan sistem simpanan termal menggunakan lilin parafin sebagai PCM dan dengan penyimpanan haba menggunakan Al₂O₃-lilin parafin. Persamaan Navier-Stokes tiga dimensi disertakan dengan persamaan imbangan tenaga telah diselesaikan menggunakan program perisian dinamik bendalir (CFD) untuk melaksanakan perhitungan berangka. Analisis berangka telah dijalankan untuk menentukan dimensi pengumpul optimum dari segi panjang (L), lebar (W) dan kedalaman saluran aliran udara (H_{ch}) pada kadar aliran jisim udara 0.03 kg/s dan sinar matahari 1000 W/m². Keputusan yang diperoleh daripada analisis berangka menunjukkan bahawa dimensi pengumpul (L = 1.8 m, W = 0.7 m, H_{ch} = 0.07 m) mempunyai reka bentuk terbaik. Keputusan berangka menunjukkan bahawa SAH dengan Al₂O₃-lilin parafin mempunyai kecekapan haba berkisar antara 73 % dan 78 % dengan perbezaan suhu udara dari 25 °C hingga 46.6 °C apabila sinar matahari 1000 W/m² pada kadar aliran jisim udara daripada 0.03 kg/s dan 0.06 kg/s. Persediaan eksperimen dibina menggunakan dimensi optimum untuk setiap konfigurasi dan telah disahkan menggunakan kaedah analisa berangka. Semua konfigurasi dibuat dan diuji di bawah keadaan iklim Iraq menurut ujian standard ASHRAE pada kadar aliran jisim udara yang berlainan. Kaedah dua langkah digunakan untuk menyediakan campuran nanopartikel dengan PCM dan peranti ultrasonik digunakan untuk mengampai nanopartikel dalam PCM. Keputusan eksperimen menunjukkan bahawa SAH dengan Al₂O₃-lilin parafin mempunyai prestasi harian yang paling tinggi dan kecekapan terma diikuti oleh SAH dengan lilin paraffin tulen dan SAH tanpa penyimpanan.
Selain itu, masa pelepasan haba pendam di SAH dengan lilin parafin tulen yang disimpan mengambil 5.5, 5, 4.5 dan 4 jam pada kadar aliran jisim udara 0.03, 0.04, 0.05 dan 0.06 kg/s. Bagi lilin SAH dengan Al₂O₃-lilin Parafin, masa pelepasan adalah 5, 4.5, 4 dan 3.5 jam pada kadar aliran jisim udara masing-masing 0.03, 0.04, 0.05 dan 0.06 kg/s. Keputusan percubaan juga menunjukkan bahawa peningkatan dalam kekonduksian terma PCM dengan pengampaian 1wt. % Al₂O₃ yang menyebabkan peningkatan suhu udara dan kecekapan haba SAH berbanding dengan SAH dengan lilin parafin tulen. Di samping itu, persetujuan yang baik diperoleh apabila membandingkan antara keputusan berangka dan eksperimen. Secara umumnya, perbezaan purata peratusan pada suhu udara keluar yang didapati dalam keputusan berangka dan eksperimen iaitu dari nilai 2.11 % hingga 2.47 % dan perbezaan pada kecekapan terma dari nilai 2.70 % hingga 3.50 %.
TABLE OF CONTENTS

DECLARATION ii
DEDICATION iii
ACKNOWLEDGEMENT iv
ABSTRACT v
ABSTRAK vii
TABLE OF CONTENTS ix
LIST OF TABLES xiv
LIST OF FIGURES xvi
LIST OF SYMBOLS AND ABBREVIATIONS xxiv
LIST OF APPENDICES xxvii

CHAPTER 1 INTRODUCTION 1
  1.1 Introduction 1
  1.2 Background of Research 2
  1.3 Problem Statement 3
  1.4 Objectives of Research 3
  1.5 Scopes of Study 4
  1.6 Thesis Outline 4

CHAPTER 2 LITERATURE REVIEW 6
  2.1 Introduction 6
  2.2 Solar Energy Collectors 7
CHAPTER 3 METHODOLOGY 44
3.1 Introduction 44
3.2 Research Methodology Steps 46
   3.2.1 Section One (Numerical Simulation Validation) 46
   3.2.2 Section Two (Numerical Analysis) 46
      3.2.2.1 The CFD Modeling Process 46
      3.2.2.2 Procedures 47
   3.2.3 Section Three (Experimental Setup) 48
3.3 Chapter Summary 51

CHAPTER 4 NUMERICAL ANALYSIS AND EXPERIMENTAL SETUP 52
4.1 Introduction 52
4.2 Numerical Analysis of SAH Model 52
   4.2.1 CFD Theories 53
   4.2.2 Physical Model and Assumptions 53
      4.2.2.1 The Solar Air Heater without Storage (SAHWOS) 54
      4.2.2.2 The Solar Air Heater with Storage (SAHWS) 54
   4.2.3 Governing Equations 55
   4.2.4 Thermal Energy Balance of Corrugated SAH 56
   4.2.5 Boundary Conditions 60
   4.2.6 Grid Independence Test 61
CHAPTER 5 RESULTS AND OBSERVATIONS

5.1 Introduction

5.2 Numerical Analysis Results

5.2.1 Predicting of Collector Dimensions for Optimum Raise of Temperature

5.2.2 Thermal Performance Evaluation of Flat Plate SAH Using Dimensions \([L = 1.8 \text{ m}, W = 0.7 \text{ m}, H_{ch} = 0.07 \text{ m}]\)

5.2.3 Thermal Performance Evaluation of Corrugated SAH without Storage Using Dimensions \([L = 1.8 \text{ m}, W = 0.7 \text{ m}, H_{ch} = 0.07 \text{ m}]\)
5.2.4 Thermal Performance Evaluation of Corrugated SAH with PCM Using Dimensions

\[ L = 1.8 \text{ m}, \ W = 0.7 \text{ m}, \ H_{ch} = 0.07 \text{ m} \] 89

5.2.5 Thermal Performance Evaluation of Corrugated SAH with Nano-PCM Using Dimensions

\[ L = 1.8 \text{ m}, \ W = 0.7 \text{ m}, \ H_{ch} = 0.07 \text{ m} \] 91

5.2.6 Summary of Numerical Analysis Results 94

5.3 Experimental Analysis Results 95

5.3.1 Solar Air Heater without Storage (SAHWOS) 96

5.3.1.1 The Variation of Temperatures 96

5.3.1.2 Relationship Between Daily Useful Energy and Daily Solar Irradiation 101

5.3.1.3 System Efficiencies and Its Relationship with Outlet Air Temperature 103

5.3.2 Solar Air Heater with Thermal Storage (SAHWS) 105

5.3.2.1 Effect Using Paraffin Wax as a PCM (SAHWP) 105

5.3.2.2 Effect Using Nanoparticles with PCM (SAHWNP) 115

5.3.3 Collector Tests 124

5.3.3.1 Typical Efficiency Curves 124

5.3.3.2 Collector Incidence Angle Modifier 127

5.3.3.3 Collector Time Constant 129

5.3.4 Summary of Experimental Analysis Results 130

5.4 Comparison Between the Numerical and Experimental Results 131

5.4.1 Comparison of Temperatures with Different Air Mass Flow Rates 131

5.4.2 Comparison of Thermal Efficiencies with Different Air Mass Flow Rates 134

5.5 Comparisons with Other PCM Based SAH 136

CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS 137

6.1 Introduction 137
6.2 Conclusions 137
6.3 Significance of the Research 139
6.4 Recommendations for Future Works 140

REFERENCES 142
APPENDICES 158
VITA 170
LIST OF TABLES

2.1 Summary of the previous studies for the effect of different design on the performance of the solar air collector  15
2.2 Summary of the previous studies for the latent thermal energy storage materials with nanoparticles of the solar system  30
2.3 Summary of the previous studies for the sensible thermal energy storage materials with nanoparticles of the solar system  39
2.4 Summary of the previous studies for the hybrid thermal energy storage materials with nanoparticles of the solar system  43
4.1 Thermo-physical properties of aluminum plate  67
4.2 Thermo-physical properties of paraffin wax  69
4.3 Thermo-physical properties of Al₂O₃ nanoparticles  70
4.4 Accuracy of the measuring instruments  80
4.5 The total error and uncertainty of the parameters  81
5.1 Cases tested by simulation to select the optimum collector dimensions in terms of length, width, and height of the air flow channel  84
5.2 Change of thermal characteristic of SAH collectors design for dimensions (L = 1.8 m, W = 0.7 m and H_{ch} = 0.07 m) at solar irradiance of 1000 W/m² and different air mass flow rates  95
5.3 The values of the factor of absorbing energy and the factor of losses energy at different air mass flow rates for all cases  125
5.4 Outcomes of the collector time constant tests  129
5.5 Change of (\(T_{in}, T_{out}, \Delta T, \eta_{th}\)) for different configuration of the SAH at solar irradiance of 800 W/m² and different air mass flow rates  131
5.6 Comparison between numerical and experimental results in terms of (\(T_{out}\) and \(\Delta T\)) for SAHWOS at solar irradiance of 800 W/m² and different air mass flow rates  132
5.7 Comparison between numerical and experimental results in terms of (Tout and ΔT) for SAHWP at solar irradiance of 800 W/m² and different air mass flow rates

5.8 Comparison between numerical and experimental results in terms of (Tout and ΔT) for SAHWNP at solar irradiance of 800 W/m² and different air mass flow rates
LIST OF FIGURES

2.1 Types of thermal energy storage systems 7
2.2 The overall chart of literature review for solar systems with and without thermal energy storage unit 7
2.3 Thermal efficiency curves for four types of solar thermal collectors 8
2.4 Classification of flat plate solar collectors 9
2.5 Classification of evacuated tube solar collectors 10
2.6 Classification of concentrating solar collectors 10
2.7 The experimental setup for the solar air heaters 12
2.8 The hourly variation in the temperature difference during the sunny and cloudy days 12
2.9 Efficiency of the system during the months of year 13
2.10 The different designs of absorber plate surface of SAH collectors 13
2.11 The difference in design of the absorber plate for solar air collector 14
2.12 Cross sectional side view of a thermal storage unit 19
2.13 Schematic drawing of SAH collector with storage 20
2.14 SAH collector to drying agricultural crops 22
2.15 Outlet air temperature for different configurations of the SAH collector 22
2.16 The SAH collector integrated with PCM 23
2.17 Variation of melting temperature versus thermal conductivity of the PCM 24
2.18 Different configurations of the heat exchanger (a) ordinary collector; (b) ordinary collector with a copper coil; (c) ordinary collector with a circular fin 25
2.19 SAH collectors with and without PCM 25
2.20 The SAH collector integrated with thermal storage unit 26
2.21 The SAH collector to dryer red chili 27
2.22 The SAH collector integrated with AC27 as a PCM 27
2.23 SAH collector with vertical and horizontal parts 28
2.24 Schematic diagram for SAH collector with a sensible storage 35
2.25 Schematic diagram for two configurations of SAH collector 36
2.26 The SAH collector with sensible storage 36
2.27 Photo view of dried bitter gourd before and after drying 37
2.28 Experimental setup to modify the conventional solar collector 42
3.1 Overview of the research methodology 45
3.2 Flowchart of the modeling process 47
3.3 Outline of the numerical analysis methodology 48
3.4 Photo of three different configurations of the SAH collector 49
3.5 Phases of mixture preparation (Nanoparticles with PCM) and calculate its thermo-physical properties 49
3.6 Flowchart of the experimental test conditions parameters and energy balance equations for SAH collector 50
3.7 A diagram of all experimental activities conducted in the present study 51
4.1 Schematic view of elements the system configuration of SAHWOS 54
4.2 Schematic view of elements the system configuration of SAHWS 54
4.3 Thermal analysis of the system configuration of SAHWOS 56
4.4 Thermal analysis of the system configuration of SAHWS 57
4.5 CFD meshing of corrugated absorber plate surface without storage 61
4.6 Average absorber plate temperature versus the mesh face for grid independence test 62
4.7 Skewness mesh metrics spectrum and Orthogonal Quality mesh metrics spectrum 62
4.8 Average absorber plate temperature and outlet air temperature versus air mass flow rates for the numerical validation results and experimental results of Aboghrara et al. [40] of corrugated solar air heater 63
4.9 Thermal efficacy versus air mass flow rates for the numerical validation results and experimental results of Aboghrara et al. [40] of corrugated solar air heater 64
4.10 Average absorber plate temperature and outlet air temperature versus air mass flow rates for the numerical validation results and experimental results of Aboghrara et al. [40] of flat plate solar air heater 64
4.11 Thermal efficacy versus air mass flow rates for the numerical validation results and experimental results of Aboghrara et al. [40] of flat plate solar air heater

65

4.12 The air processing unit (a) axial fan (b) speed controller

67

4.13 The design of absorber plate surface integrated with storage containers

68

4.14 Thermal energy storage material (paraffin wax)

69

4.15 Suspension of nanoparticles in PCM by ultrasonic water bath (Elmasonic P180H)

71

4.16 View of the (a) pure paraffin wax, (b) Al₂O₃ nanoparticle suspended in paraffin wax with concentration 1wt. %

72

4.17 FESEM image of 1wt. % Al₂O₃ nanoparticles with paraffin wax

75

4.18 K-type thermocouple to temperature measurement

76

4.19 Data logger module AT4532 with 32-channel

77

4.20 Pyranometer (TENMARS TM 207) to measure the solar irradiance

77

4.21 Anemometer (model AM-4826) to measure the wind velocity

78

4.22 Photographic view of the experimental setup show the tilt and details of the collectors

80

5.1 Outlet air temperature versus SAH dimensions at solar irradiance of 1000 W/m² and air mass flow rate of 0.03 kg/s

83

5.2 Air temperature difference versus different air mass flow rate of flat plate SAH for dimensions (L = 1.8 m, W = 0.7 m, Hch = 0.07 m) at solar irradiance 1000 W/m²

85

5.3 Thermal efficiency versus different air mass flow rate of flat plate SAH for dimensions (L = 1.8 m, W = 0.7 m, Hch = 0.07 m) at solar irradiance 1000 W/m²

85

5.4 Side view of the temperature distribution of flat plate SAH for dimensions (L = 1.8 m, W = 0.7 m, Hch = 0.07 m)

86

5.5 The temperature distribution in outlet air cross section of flat plate SAH for dimensions (L = 1.8 m, W = 0.7 m, Hch = 0.07 m)

86

5.6 Air temperature difference versus different air mass flow rate of corrugated SAH without storage for dimensions (L = 1.8 m, W = 0.7 m, Hch = 0.07 m) at solar irradiance 1000 W/m²

87
5.7 Thermal efficiency versus different air mass flow rate of corrugated SAH without storage for dimensions \(L = 1.8\) m, \(W = 0.7\) m, 
\(H_{ch} = 0.07\) m at solar irradiance 1000 W/m\(^2\)
88
5.8 Side view of the temperature distribution of corrugated SAH without storage for dimensions \(L = 1.8\) m, \(W = 0.7\) m, \(H_{ch} = 0.07\) m
88
5.9 The temperature distribution in outlet air cross section of corrugated SAH without storage for dimensions \(L = 1.8\) m, \(W = 0.7\) m, 
\(H_{ch} = 0.07\) m
89
5.10 Air temperature difference versus different air mass flow rate of corrugated SAH with PCM for dimensions \(L = 1.8\) m, \(W = 0.7\) m, 
\(H_{ch} = 0.07\) m at solar irradiance 1000 W/m\(^2\)
90
5.11 Thermal efficiency versus different air mass flow rate of corrugated SAH with PCM for dimensions \(L = 1.8\) m, \(W = 0.7\) m, 
\(H_{ch} = 0.07\) m at solar irradiance 1000 W/m\(^2\)
90
5.12 Side view of the temperature distribution of corrugated SAH with PCM for dimensions \(L = 1.8\) m, \(W = 0.7\) m, \(H_{ch} = 0.07\) m
91
5.13 The temperature distribution in outlet air cross section of corrugated SAH with PCM for dimensions \(L = 1.8\) m, \(W = 0.7\) m, \(H_{ch} = 0.07\) m
91
5.14 Air temperature difference versus different air mass flow rate of corrugated SAH with Nano-PCM for dimensions \(L = 1.8\) m, \(W = 0.7\) m, 
\(H_{ch} = 0.07\) m at solar irradiance 1000 W/m\(^2\)
92
5.15 Thermal efficiency versus different air mass flow rate of corrugated SAH with Nano-PCM for dimensions \(L = 1.8\) m, \(W = 0.7\) m, 
\(H_{ch} = 0.07\) m at solar irradiance 1000 W/m\(^2\)
93
5.16 Side view of the temperature distribution of corrugated SAH with Nano-PCM for dimensions \(L = 1.8\) m, \(W = 0.7\) m, \(H_{ch} = 0.07\) m
93
5.17 The temperature distribution in outlet air cross section for the corrugated SAH with Nano-PCM with dimensions \(L = 1.8\) m, \(W = 0.7\) m, 
\(H_{ch} = 0.07\) m
94
5.18 Hourly solar irradiance and mean temperature of \((T_{amb}, T_{out}, T_g \text{ and } T_p)\) for SAHWOS at \(\dot{m} = 0.03\) kg/s to the entire daytime
97
5.19 Hourly solar irradiance and mean temperature of \((T_{amb}, T_{out}, T_g \text{ and } T_p)\) for SAHWOS at \(\dot{m} = 0.04\) kg/s to the entire daytime
97
5.20 Hourly solar irradiance and mean temperature of \( T_{\text{amb}}, T_{\text{out}}, T_{g} \) and \( T_{p} \) for SAHWOS at \( \dot{m} = 0.05 \) kg/s to the entire daytime

5.21 Hourly solar irradiance and mean temperature of \( T_{\text{amb}}, T_{\text{out}}, T_{g} \) and \( T_{p} \) for SAHWOS at \( \dot{m} = 0.06 \) kg/s to the entire daytime

5.22 A temperature difference of air versus local time at different air mass flow rates for SAHWOS

5.23 Effect of air mass flow rate on the measured daily average air temperature difference for SAHWOS

5.24 Mean temperature of the air inside the air flow channel at different air mass flow rates for SAHWOS

5.25 The solar irradiance and useful energy for SAHWOS at \( \dot{m} = 0.03 \) kg/s to the entire daytime

5.26 The solar irradiance and useful energy for SAHWOS at \( \dot{m} = 0.04 \) kg/s to the entire daytime

5.27 The solar irradiance and useful energy for SAHWOS at \( \dot{m} = 0.05 \) kg/s to the entire daytime

5.28 The solar irradiance and useful energy for SAHWOS at \( \dot{m} = 0.06 \) kg/s to the entire daytime

5.29 A instantaneous thermal efficiency versus local time at different air mass flow rates for SAHWOS

5.30 Relationship between the efficiency and outlet air temperature for SAHWOS at different air mass flow rates

5.31 Hourly solar irradiance and mean temperature of \( T_{\text{amb}}, T_{\text{out}}, T_{g}, T_{p} \) and \( T_{pcm} \) for SAHP at \( \dot{m} = 0.03 \) kg/s to the entire day

5.32 Hourly solar irradiance and mean temperature of \( T_{\text{amb}}, T_{\text{out}}, T_{g}, T_{p} \) and \( T_{pcm} \) for SAHP at \( \dot{m} = 0.04 \) kg/s to the entire day

5.33 Hourly solar irradiance and mean temperature of \( T_{\text{amb}}, T_{\text{out}}, T_{g}, T_{p} \) and \( T_{pcm} \) for SAHP at \( \dot{m} = 0.05 \) kg/s to the entire day

5.34 Hourly solar irradiance and mean temperature of \( T_{\text{amb}}, T_{\text{out}}, T_{g}, T_{p} \) and \( T_{pcm} \) for SAHP at \( \dot{m} = 0.06 \) kg/s to the entire day

5.35 A temperature difference of air versus local time at different air mass flow rates for SAHP
5.36 Effect of air mass flow rate on the measured daily average air temperature difference for SAHWP

5.37 Mean temperature of the air inside the air flow channel at different air mass flow rates for SAHWP

5.38 The solar irradiance and useful energy for SAHWP at $\dot{m} = 0.03$ kg/s to the entire day

5.39 The solar irradiance and useful energy for SAHWP at $\dot{m} = 0.04$ kg/s to the entire day

5.40 The solar irradiance and useful energy for SAHWP at $\dot{m} = 0.05$ kg/s to the entire day

5.41 The solar irradiance and useful energy for SAHWP at $\dot{m} = 0.06$ kg/s to the entire day

5.42 Mean temperature of $(T_{out}, T_p, T_{pcm})$ for SAHWP at $\dot{m} = 0.03$ kg/s to the discharging period

5.43 Mean temperature of $(T_{out}, T_p, T_{pcm})$ for SAHWP at $\dot{m} = 0.04$ kg/s to the discharging period

5.44 Mean temperature of $(T_{out}, T_p, T_{pcm})$ for SAHWP at $\dot{m} = 0.05$ kg/s to the discharging period

5.45 Mean temperature of $(T_{out}, T_p, T_{pcm})$ for SAHWP at $\dot{m} = 0.06$ kg/s to the discharging period

5.46 A instantaneous thermal efficiency versus local time at different air mass flow rates for SAHWP

5.47 Hourly solar irradiance and mean temperature of $(T_{amb}, T_{out}, T_g, T_p$ and $T_{pcm})$ for SAHWP at $\dot{m} = 0.03$ kg/s to the entire day

5.48 Hourly solar irradiance and mean temperature of $(T_{amb}, T_{out}, T_g, T_p$ and $T_{pcm})$ for SAHWP at $\dot{m} = 0.04$ kg/s to the entire day

5.49 Hourly solar irradiance and mean temperature of $(T_{amb}, T_{out}, T_g, T_p$ and $T_{pcm})$ for SAHWP at $\dot{m} = 0.05$ kg/s to the entire day

5.50 Hourly solar irradiance and mean temperature of $(T_{amb}, T_{out}, T_g, T_p$ and $T_{pcm})$ for SAHWP at $\dot{m} = 0.06$ kg/s to the entire day

5.51 A temperature difference of air versus local time at different air mass flow rates for SAHWNP
5.52 Effect of air mass flow rate on the measured daily average air temperature difference for SAHWNP

5.53 Mean temperature of the air inside the air flow channel at different air mass flow rates for SAHWNP

5.54 The solar irradiance and useful energy for SAHWNP at \( \dot{m} = 0.03 \) kg/s to the entire day

5.55 The solar irradiance and useful energy for SAHWNP at \( \dot{m} = 0.04 \) kg/s to the entire day

5.56 The solar irradiance and useful energy for SAHWNP at \( \dot{m} = 0.05 \) kg/s to the entire day

5.57 The solar irradiance and useful energy for SAHWNP at \( \dot{m} = 0.06 \) kg/s to the entire day

5.58 Mean temperature of \((T_{out}, T_p, T_{pcm})\) for SAHWNP at \( \dot{m} = 0.03 \) kg/s to the discharging period

5.59 Mean temperature of \((T_{out}, T_p, T_{pcm})\) for SAHWNP at \( \dot{m} = 0.04 \) kg/s to the discharging period

5.60 Mean temperature of \((T_{out}, T_p, T_{pcm})\) for SAHWNP at \( \dot{m} = 0.05 \) kg/s to the discharging period

5.61 Mean temperature of \((T_{out}, T_p, T_{pcm})\) for SAHWNP at \( \dot{m} = 0.06 \) kg/s to the discharging period

5.62 A instantaneous thermal efficiency versus local time at different air mass flow rates for SAHWNP

5.63 Efficiency curve of the SAH collector at different configurations in air mass flow rate of 0.03 kg/s

5.64 Efficiency curve of the SAH collector at different configurations in air mass flow rate of 0.04 kg/s

5.65 Efficiency curve of the SAH collector at different configurations in air mass flow rate of 0.05 kg/s

5.66 Efficiency curve of the SAH collector at different configurations in air mass flow rate of 0.06 kg/s

5.67 Variation between incidence angle modifier \( K_{\alpha \tau} \) and the incidence angle \( (T_{in}, T_{out} \text{ and } \Delta T) \) versus air mass flow rates in comparison between numerical and experimental results for SAHWOS
5.69 \((T_{in}, T_{out} \text{ and } \Delta T)\) versus air mass flow rates in comparison between numerical and experimental results for SAHWP 133

5.70 \((T_{in}, T_{out} \text{ and } \Delta T)\) versus air mass flow rates in comparison between numerical and experimental results for SAHWNP 134

5.71 Efficiency versus air mass flow rate in comparison of numerical and experimental results for SAHWOS 135

5.72 Efficiency versus air mass flow rate in comparison of numerical and experimental results for SAHWP 135

5.73 Efficiency versus air mass flow rate in comparison of numerical and experimental results for SAHWNP 136

5.74 Comparison of thermal efficiency with other studies for SAHWP 136
LIST OF SYMBOLS AND ABBREVIATIONS

$I$ - Global Solar Irradiance (W/m²)
$I_T$ - Solar Irradiance on the Tilt Surface (W/m²)
$h_{conv}$ - Convection Heat Transfer Coefficient (W/m² K)
$h_{rad}$ - Radiation Heat Transfer Coefficient (W/m² K)
$h_{cond}$ - Conduction Heat Transfer Coefficient (W/m² K)
$T_{out}$ - Output Temperature (°C)
$T_{in}$ - Inlet Temperature (°C)
$T_{amb}$ - Ambient Temperature (°C)
$T_p$ - Absorber Plate Surface Temperature (°C)
$T_g$ - Glass Cover Surface Temperature (°C)
$T_{sky}$ - Sky Temperature (°C)
$T_m$ - Mean Temperature (°C)
$T_b$ - Bottom Temperature (°C)
$T_{PCM}$ - PCM Temperature (°C)
$T_{out,t}$ - Outlet Temperature at the Time (°C)
$T_{in,init}$ - Outlet Temperature When Solar Radiation is Interrupted (°C)
$k$ - Thermal Conductivity (W/m K)
$U_L$ - Overall Heat Loss Coefficient (kJ/kg K)
$U_t$ - Top Heat Loss Coefficient (kJ/kg K)
$U_b$ - Bottom Heat Loss Coefficient (kJ/kg K)
$U_e$ - Edges Heat Loss Coefficient (kJ/kg K)
$S$ - The Absorbed Solar Irradiance by a Collector (W)
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_p$</td>
<td>Specific Heat Capacity (kJ/kg K)</td>
</tr>
<tr>
<td>$Q_u$</td>
<td>Useful Energy of Collector (W)</td>
</tr>
<tr>
<td>$Q_s$</td>
<td>Stored Thermal Energy of Collector (W)</td>
</tr>
<tr>
<td>$\dot{m}_{air}$</td>
<td>Air Mass Flow Rate (kg/s)</td>
</tr>
<tr>
<td>$v_{air}$</td>
<td>Air Velocity (m/s)</td>
</tr>
<tr>
<td>$w_v$</td>
<td>Wind Velocity (m/s)</td>
</tr>
<tr>
<td>$A_g$</td>
<td>Cross Section Area of Glass Covers (m$^2$)</td>
</tr>
<tr>
<td>$A_p$</td>
<td>Cross Section Area of Absorber Plate Surface (m$^2$)</td>
</tr>
<tr>
<td>$A_c$</td>
<td>Cross Section Area of Collector (m$^2$)</td>
</tr>
<tr>
<td>$A_{ext}$</td>
<td>Cross Section Area of the Duct (m$^2$)</td>
</tr>
<tr>
<td>$l$</td>
<td>Absorber to Glass Cover Distance (m)</td>
</tr>
<tr>
<td>$g$</td>
<td>Gravitational Constant (m$^2$/s)</td>
</tr>
<tr>
<td>$D_H$</td>
<td>Hydraulic Diameter of the Air Flow Channel (m)</td>
</tr>
<tr>
<td>$H_{ch}$</td>
<td>Depth of Air Flow Channel (m)</td>
</tr>
<tr>
<td>$W$</td>
<td>Width of the Collector (m)</td>
</tr>
<tr>
<td>$L$</td>
<td>Length of the Collector (m)</td>
</tr>
<tr>
<td>$P_c$</td>
<td>Perimeter of the Collector (m)</td>
</tr>
<tr>
<td>$R_e$</td>
<td>Reynolds Number (Dimensionless)</td>
</tr>
<tr>
<td>$P_r$</td>
<td>Prandtl Number (Dimensionless)</td>
</tr>
<tr>
<td>$R_a$</td>
<td>Rayleigh Number (Dimensionless)</td>
</tr>
<tr>
<td>$N_u$</td>
<td>Nusselt Number (Dimensionless)</td>
</tr>
<tr>
<td>$F_R$</td>
<td>Removal Factor (Dimensionless)</td>
</tr>
<tr>
<td>$F'$</td>
<td>Collector Efficiency Factor (Dimensionless)</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Density (kg/m$^3$)</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Stephan Constant (W/m$^2$ K)</td>
</tr>
<tr>
<td>$\tau$</td>
<td>Transmittance (Dimensionless)</td>
</tr>
<tr>
<td>$\alpha_t$</td>
<td>Thermal Diffusivity (m$^2$/s)</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Absorptance (Dimensionless)</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>Emissivity (Dimensionless)</td>
</tr>
</tbody>
</table>
REFERENCES


76. Y. Deng, J. Li, and H. Nian, “Polyethylene glycol-enwrapped silicon carbide nanowires network / expanded vermiculite composite phase change materials :


87. N. S. Dhaidan, J. M. Khodadadi, T. A. Al-hattab, and S. M. Al-mashat, “Experimental and numerical investigation of melting of phase change material / nanoparticle suspensions in a square container subjected to a


106. S. M. Shalaby, H. F. Abosheiaash, S. T. Assar, and A. E. Kabeel,


151. Weiguang Su, Jo Darkwa and Georgios Kokogiannakis, “Development of microencapsulated phase change material for solar thermal energy storage,”
163. V. Piriyawong, V. Thongpool, P. Asanithi, and P. Limsuwan “Preparation and


