THERMO-ELECTRICAL PERFORMANCE ENHANCEMENT OF PHOTOVOLTAIC / PHASE CHANGE MATERIAL SYSTEMS USING COPPER FOAM MATRIX WITH MULTI-WALLED CARBON NANOTUBES ADDITIVES

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DEDICATION

To my father's soul, may Allah have mercy on him.

To my dear mother, whose vocations have always supported me.

To my brothers and sisters.

To the woman who stood with me, supported me, and endured hardships throughout my journey ..... My wife and the mother of my children Adyan, Raad and Afnan.

To everyone who motivated or advised me even though by a bit word.

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ABSTRACT

Like all other semiconductor devices, photovoltaic (PV) panels are sensitive to temperature. High temperature reduces the bandgap of a semiconductor, thereby increasing the energy of the electrons in the material. The panels' temperature can be reduced using phase change material (PCM), which works as a passive cooling material to absorb heat at a low tilt angle. To further improve the panel's temperature, copper foam matrix (CFM) can be used as an additive to the PCM to enhance its thermal conductivity. The compound's thermal performance can be further enhanced by adding high thermal conductivity materials such as Multi-Walled Carbon Nano-Tubes (MWCNT), however, no report has been published in the literature. Therefore, this study aimed to investigate the effects of the PCM/CFM materials on PV panel temperatures and their electrical performance. The study consisted of two parts, numerical analysis and experiments. The numerical analysis was carried out using ANSYS FLUENT 15.0 to predict and simulate the convection heat transfer mechanism inside the passive cooling container. The experimental part was investigated the unpredictable measurements, such as the enhancements in the electrical efficiency of the PV panels made of the proposed passive cooling materials. Temperature of the panel was measured to validate the numerical simulation. Based on the findings, when the PCM was used, decreasing the PV tilt angle from 90° to 0° will increase the PV cell's temperature from 0.4% to 12%. It also decreases the corresponding cell's electrical efficiency from 5% to 0.2%. Whereas, when the CFM was added to the PCM, the PV cell's temperature was reduced further by 10.43%, and increased the cell's electrical efficiency from 1.79% to 4.5% at a tilt angle of 30°. When MWCNT with a weight concentration ratio of 0.20% was added in the PCM, it further improved the PV cell's temperature and the electrical efficiency by 2.86% and 5.68%, respectively, due to the enhancement of the PCM's thermal conductivity. The improved PV panel was verified by experimental works under actual weather conditions, and it was found that the PV panel electrical efficiency improved by 21%. These findings indicate that using CFM with 0.2% of MWCNT additives within PCM, is an efficient method for electrical performance improvement in PV panel applications passively at low tilt angles.

ABSTRAK

Seperti semua peranti semikonduktor lain, panel fotovolta (PV) sensitif terhadap suhu. Suhu tinggi mengurangkan jurang jalur semikonduktor, dengan itu meningkatkan tenaga elektron dalam bahan. Suhu panel dapat dikurangkan menggunakan bahan perubahan fasa (PCM), yang berfungsi sebagai bahan pendingin pasif untuk menyerap panas pada sudut kemiringan rendah. Untuk peningkatan suhu panel, matriks busa tembaga (CFM) dapat digunakan sebagai bahan tambahan PCM untuk meningkatkan kekonduksian termal. Prestasi haba kompaun dapat ditingkatkan dengan menambahkan bahan kekonduksian terma yang tinggi seperti Tiub Nano Karbon Berbilang Tembok (MWCNT), namun, tiada lapuran diterbitkan dalam literatur. Oleh itu, kajian ini bertujuan untuk mengesan bahan PCM / CFM pada suhu panel PV dan prestasi elektriknya. Kajian ini terdiri daripada dua bahagian, analisis berangka dan eksperimen. Analisis berangka telah dilakukan menggunakan ANSYS FLUENT 15.0 untuk meramalkan dan mensimulasikan mekanisme pemindahan haba perolakan di dalam bekas penyejuk pasif. Bahagian eksperimen telah dilakukan untuk menyelidiki pengukuran yang tidak dapat diramalkan, seperti peningkatan dalam kecekapan elektrik panel PV akibat penggunaan bahan pendingin pasif yang dicadangkan. Pengukuran suhu telah dilakukan untuk mengesahkan simulasi berangka. Berdasarkan penemuan, ketika PCM digunakan, penurunan sudut kecondongan PV dari 90° hingga 0° telah meningkatkan suhu sel PV dari 0.4% menjadi 12%. Ia mengurangkan kecekapan elektrik sel yang sesuai dari 5% hingga 0.2%. Manakala, ketika CFM ditambahkan ke PCM, suhu sel PV telah menurun lebih jauh sebanyak 10.43%, dan meningkatkan kecekapan elektrik sel dari 1.79% menjadi 4.5% pada sudut kemiringan 30°. Apabila MWCNT dengan nisbah kepekatan berat 0.20% ditambahkan dalam PCM, ia telah meningkatkan lagi suhu sel PV dan kecekapan elektrik masing-masing sebanyak 2.86% dan 5.68%, kerana peningkatan kekonduksian terma PCM. Panel PV yang diperbaiki disahkan dengan melakukan kerja eksperimen di dalam keadaan cuaca sebenar, dan didapati bahawa kecekapan elektrik panel PV meningkat sebanyak 21%. Penemuan ini menunjukkan bahawa menggunakan CFM dengan 0.2% bahan tambah MWCNT dalam PCM, adalah kaedah yang berkesan untuk peningkatan prestasi elektrik dalam aplikasi panel PV secara pasif pada sudut kecondongan rendah.

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LIST OF ABBREVIATIONS

NOMENCLATURES

A – Area (m^2).

a_E, a_W, a_N, a_S – Coefficient in the discretization equation at the mean point.

BIPV – Building Integrated Photovoltai.

C – Celsius.

C-Si – Crystalline silicon.

CFD – Computational Fluid Dynamics.

CFM – Copper Foam Matrix.

COP – Coefficient of Performance.

Cp – Specific heat (kJ/kg. K).

CPV – Concentrating Photovoltic.

CV – Control Volume.

D – Strength of diffusion.

DSC – Differential Scan Calorimetry.

E_1, E_2 to E_n – Uncertainties of each independently measured variable.

EG – Expanded Graphite.

F – Strength of convection.

F.F. – Fill Factor.

FESEM – Field Emission Scanning Electron Microscope.

FVM – Finite Volume Method.

G – Irradiance (W/m^2).

GE – Governing Equations.

Hm	–	Latent heat (kJ/kg).
h	–	Convection heat transfer coefficient (W/m^2.K).
I	–	PV cell current (Amber).
IEA	–	International Energy Agency.
IPVTS	–	Integrated PV and Thermal Solar System
k	–	Thermal conductivity (W/m.k).
K	–	Kelvin.
LHS	–	Latent Heat storage.
LHTES	–	Latent Heat Thermal Energy Storage.
LTES	–	Low-Temperature Energy Storage.
Mc-Si	–	Multi-crystalline silicon.
MWCNT	–	Multi-Walled Carbon Nanotube.
N	–	Nanoparticles.
P	–	Power (W).
PA	–	Palmitic Acid
PCM	–	Phase Change Material.
PDE	–	Partial Differential Equation.
Pe	–	Peclet number.
PPI	–	Porous Per Inch.
PRESTO	–	Pressure Staggering Option.
PV	–	Photovoltaic.
PV/T	–	Photovoltaic/Thermal.
q	–	Energy (W).
q”	–	Heat flux (W/m^2).
R	–	Function of the independent variables v_1, v_2 to v_n.
R$_A$, R$_B$, R$_C$, R$_D$	–	Thermal resistance four different layers inside a cell.

RTV – Room Temperature Vulcanizing.

S – Heat generation (W).

Sc-Si – Single-crystalline silicon.

SIMPLE – Semi-Implicit Method for Pressure-Linked Equations.

T – Temperature (°C).

TCE – Thermal Conductivity Enhancers.

TES – Thermal Energy Storage.

TF – Thin Film

TTHX – Triplex-Tube Heat Exchanger.

TRNSYS – Transient Systems Simulation Program.

t – Time (s).

U – Uncertainty.

u, v – Components of the fluid velocity in the x and y-direction, respectively.

UDF – User Defined Function.

UTM – Universiti Teknologi Malaysia.

V – Voltage (V).

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SUBSCRIPTS

av – Average.

C – Freezing.

E – Neighbor in the positive x direction (on the east side).

eff – Effective.

ele – Electrical.

i, j – Location of point in cartesian grid.

m – Melting.

max – Maximum.

mpp – Maximum power point.

n, s, e, w – Refers to cell face, where: n is the control-volume face between P and N, s is the control-volume face between P and S, e is the control-volume face between P and E, and w is the control-volume face between P and W.

Np – Nanoparticle.

NPCM – Composite nano-phase change material.

OC – Open circuit.

P – Central grid point under consideration.

s, m, and L – Referring to the solid phase, mushy zone and liquid phase, respectively.

SC – Short circuit.

t – Turbulent.

x, y – Dimensions of the computational cell (m).

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LIST OF SYMBOLS

ρ – Density (kg/m^3).

Γ – Diffusion coefficient or diffusivity.

μ – Dynamic viscosity.

σ_t – Prandtl number.

α – Thermal diffusivity (m/s^2).

γ – Thermal expansion coefficient (0.001°C^{-1}).

η – Efficiency (%).

θ – Geometry tilt angle.

ε – Porosity of the metal foam.

φ – Concentration ratios (%).

ϕ – Depended variables.

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CHAPTER 1

INTRODUCTION

1.1 Background

Renewable energy option, such as solar energy, is one of the free energy resources, making it an attractive and useful alternative energy choice. Photovoltaic (PV) is the process of converting sunlight directly into electricity using solar cells. PV cells are one of the most popular alternative technologies to generate electricity. PV panels utilizing the photovoltaic effect exhibited by semiconducting materials to generate electricity from sunlight. This electricity generation method is clean and without greenhouse gaseous or particulate emissions that caused pollution [1, 2]. In these day's, the use of PV panel is a fast-growing trend in a different aspect of life, and this has led to producing solar panels with higher efficiency for commercial use than before and more variety of PV panels [3]. Due to the growing interest of manufacturers, businesses, and consumers, the PV cell can be considered as a good choice for the renewable energy source. Countries around the world start to seek renewable energy sources due to the effects of using fossil fuel reserves on the atmosphere. Increases in the consumption of fossil fuels have a negative impact on the environment, such as global warming by the increasing emissions of carbon dioxide (CO2) into the atmosphere has led to global concerns about climate change and environmental sustainability for future generation [4]. Around the world, a lot more household started to own PV panels and use it to produce their home's electricity supply.

As the PV technology has become more mature, so has the interest which has spurred researchers even more. The motivation for using these resources started in many countries such as in Sweden, where the government started awarding grants for people who installed the panels on their home roofs amounting about 30 % the price of the panels [5]. For private consumers, this has made it more attractive and thanks to China overtaking the rest of the world in sheer production of the cells, thus pushing the price down on production costs, the cells are now cheaper than ever before [1]. According to the summary made by the International Energy Agency (IEA) [1], there are numerous different types of solar panels where crystalline silicon (C-Si), the single crystalline (Sc-Si) and multi-crystalline (MC-Si) modules make up about 90% of the industry. The thin film (TF) PV panels which existed today in many forms, only stands for about 10% of the market. The third largest variable are the concentrating photovoltaics (CPV), which makes up about less than 1% of the market. However, with these current PV panels, the electrical efficiency of the solar cells are only between 10% to 16% whereby the rest of the solar radiation failed to be converted into electrical power. This is because the PV silicon cells attached to form a solar panel can only transform to electricity at a specific range of light frequencies. The remaining solar irradiance levels were unused and converted to heat and raised the temperature of the PV panel resulting in the reduction of the performance of the PV panel performance. Like all other semiconductor devices, solar cells are sensitive to temperature. Increases in temperature reduce the band gap of a semiconductor, thereby lead to increasing the energy of the electrons in the material. Due to the temperature-dependent strength of crystalline silicon cells, the coefficient reduces between the range of 0.4 % /K to 0.65 %/ K [6-8], hence, decreasing the operating temperature of the PV panel will results in a significantly improvement of the electrical output.

So, the main problem for the current PV cells is that they heat up above their optimal working temperature and lose out on their power generation capacity which in turn reduces their efficiency. There is an urgent needs for a new method of cooling the silicon-based solar cells and further research is needed to explore this area.

1.2 Research Motivation

If the used cooling approach in PV systems without economic losses, it would be a good resource for electrical power generation. Different methods of thermal control of PV panels have been developed, to prevent the fall in PV panel's electrical power production capacity caused by the raising of its temperature. These cooling methods can be classified into passive or active cooling methods as shown in Figure 1.1.

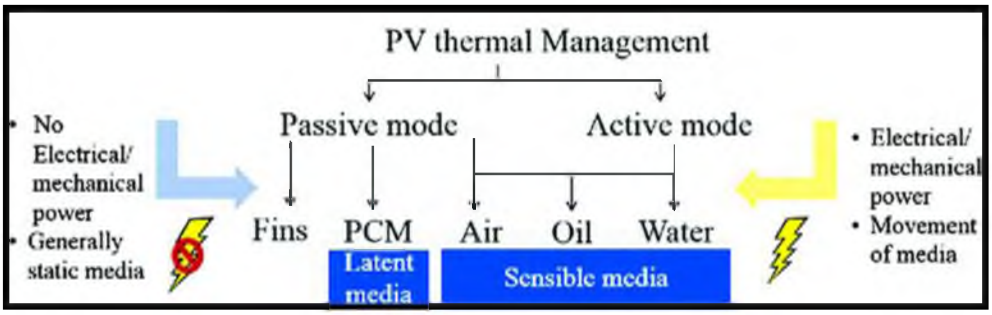

Figure 1.1: Cooling methods in PV

Passive cooling methods usually depend on the free (natural) convection of heat transfer by air circulation in the open space behind the PV panels (no energy consumption), while the active methods of cooling require energy to pump the working fluids on the back layer of the PV panels [9].

Using phase change materials (PCMs) as heat sink materials or as passive cooling materials is an important technology that has gained the attention of many researchers. Some applications of these materials are as photovoltaic panel systems [10], building applications [11], solar water heating [12], greenhouse heating [13], microelectronics [14], space applications [15], and etc., where they have benefited from PCM's latent heat power to cool the equipment. The prediction of the change in heat transfer of the PCM phase during the melting and freezing process was the key to the optimal PCM system design as shown in Figure 1.2 [16]. The PCM is therefore capable of absorbing waste heat from the panel by switching its phase, so the PV panel should be kept at a near-constant temperature and the temperature of the PV panel should also be regulated [17].

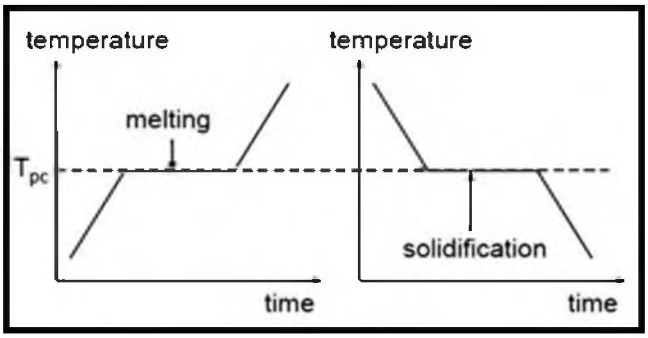

Figure 1.2: The process of PCM's melting and solidification

One of the limitations of using these materials as passive cooling materials is that these materials possess low thermal conductivity, which provides higher thermal resistance which acts as a barrier to the efficient use of PCM in the transit cooling solution. An attempt to improve the thermal conductivity of PCMs is by an integration with a higher thermal conductivity of porous materials such as fins, foams and heat sinks within the PCM.

However, the constraint of using the porous insert for a particular PCM application is that it reduces the PCM efficient volume for latent heat storage due to the solid porous matrix addition that acts as a natural convection barrier for fluid movement. Therefore, the usage of foam material with high open porosity can be seen as an alternative to avoid the PCM volume reduction due to these inserts and maintain the desired thermal conductivity of PCM/Foam matrix for convection and conduction heat transfer performance [18-21]. The local thermal equilibrium between them is still a problem due to the high thermal resistance between the PCM inside the pore and the metal structure of porous material. In order to reduce the thermal resistance, a highly conductive nanoparticles can be dispersed into base PCM for an additional enhancement of the rate of PCM melting and freezing within a porous medium. The addition of the nanoparticles within the PCM must be in a particular ratio to avoid the adverse effect of the Nano-PCM thermal performance with porous media such as sedimentation, heavier fluid, etc [22-25].

Most of the researches that utilizing a phase change materials for temperature regulation of PV panels in order to enhance its performance are currently only focusing on the usage of PCM, PCM with fins or PCM with nanoparticles. The performance enhancement of PV panels using PCM along with porous media and porous media with nanoparticles to increase the heat absorption from its surface isn't to be investigated yet. Therefore, the current study focuses on the application of phase change material (PCM) as a passive cooling material for PV panels with the combination of nanoparticles and porous media as a heat transfer enhancer for better thermal performance in PV panels to enhance its electrical performance.

1.3 Problem Statement

Utilizing the PCM's latent heat of fusion is considered an essential solution to regulate the PV panel's temperature passively to improve its electrical efficiency because of its ability to absorb the heat energy from the PV panels. But the major problem using these materials, it has less efficient for absorbing heat at low tilt angles of PV panels, which contributes to temperature rises of the PV panels. Therefore, the need arises on how to improve the thermal properties of PCM so that they can be effectively used as a passive cooling material to regulate the temperature of PV panels to improve their electrical performance at low tilt angles. This study aims to examine the effects of PV / PCM system tilt angles on the PCM melting time and the electrical efficiency of the PV panels. A high conductive porous metal, specifically CFM together with PCM, and high conductive nanoparticles MWCNT additive was used as a passive cooling system to improve the electrical efficiency at low tilt angles. The incorporation of CFM within PCM will manage to impede the internal convection inside the PCM, hence increasing the PCM melting process rate due to increasing the effective thermal conductivity of the PCM inside the passive cooling container. While, the inclusion of MWCNT additives within PCM/CFM contributes to increasing the PCM's effective thermal conductivity even further, due to the effect of the tangled tubes' bundles of this type of nanoparticles within PCM inside the CFM pore. To achieve the research goal, the study was carried out firstly numerically to show convection streams and temperature distribution inside the passive cooling material cavity at different tilt angles with the effects of including CFM and MWCNT additives. Secondly, the experimental investigation was carried out to show the effect of using the proposed passive cooling materials on the electrical performance enhancement of the used PV panel. The low thermal performance of PCM as a passive cooling material at a low tilt angle of PV panels contributes to temperature rises of the PV panels, and then reduces the electrical power generated. So, using CFM and MWCNT additives together with PCM is the solution to achieve the enhancement in the thermal performance of the PCM at low tilt angles, due to increasing the effective thermal conductivity of the PCM inside the passive cooling container of PV panels.

1.4 Research Objectives

The study aims to examine the effects of PV / PCM system tilt angles on the PCM melting time and the electrical efficiency of the PV panels. The research aim was achieved through the following objectives:

1. To evaluate the effects of PV panels furnished with metal foams (copper foam matrix) and PCM as a passive cooling system on the PCM melting time, panel temperature, and electrical performance at low tilt angles, experimentally.
2. To evaluate the effect of adding in a high thermal conductivity nanoparticle MWCNT in the compound PCM/CFM material on the PV panel temperature and electrical performance numerically.
3. To assess the improved PV panel in objective 2 on the electrical performance under actual outdoor conditions.

1.5 Research Scope

In this research work,

1. The new passive cooling material is combined with a PV panel, their electrical performance will be tested and compared with the alone PV panel.
2. This study involved numerical (CFD) analysis and the indoor tests for all different cases of the proposed passive cooling materials, to evaluate the thermal performance of the used materials.
3. To assess the validity of using these materials on real weather, the outdoor experimental processes were done on large modules of PV panels, under the Baghdad-Iraq governorate climate for all proposed materials.
4. limitations: the thermal diffusivity of the used nanoparticles within PCM is not considered in this study.

1.6 Significance of the Research

The unique point of this work is the integration of dispersed nanoparticles within PCM and porous materials as a new passive cooling technique in PV panel systems. The integration of these materials together will be improving the PCM thermal specification as a thermal regulation technique in PV panel systems. This research will be dedicated to improving the electrical output of the PV system by decreasing the PV panel surface temperature, which is directly related to PV quality.

1.7 Thesis's Structure

Specifically, this research examines how to improve the thermal performance of PCM as a passive cooling material, which can be utilized to maintain the output power of the PV panel. The thesis contains five chapters.

1. Chapter One introduces the context and background of the research and elaborates on the advantages that can be obtained from the integration of passive cooling materials in the PV system. It also reviews the motivation of the research which is to reduce energy losses by utilizing these materials, with a summary of the main problem statement of this work and the research objectives. Moreover, the research scopes and procedures and significance of the research are discuss in this chapter, and the chapter ends with a description of the thesis structure.
2. Chapter Two provides a technology review of the effect of temperature on the efficiency of PV cells with the ways of the PV panels temperature regulation applied, and presents the different methods of improving the PCM thermal conductivity as passive cooling materials. In addition, this chapter presents the research gap and the proposed work.
3. Chapter Three describes the research methodology of the proposed work, which carried out in two parts, numerical analysis, and experimental investigation. Also presented in this chapter are the materials, laboratory equipment, and testing procedures applied in this study.

4. Chapter Four presents and discusses the numerical and experimental results which carried out throughout this study.
5. Chapter Five provides the main conclusions from this work and some of the recommendations for future work based on the findings of this study.

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LIST OF PUBLICATIONS

Journal with Impact Factor

1. **Abdulmunem, A.R.**, Samin, P.M., Rahman, H.A., Hussien, H.A., Mazali, I.I. and Habibah G. (2021) 'Numerical and experimental analysis of the tilt angle's effects on the characteristics of the melting process of PCM-based as PV cell's backside heat sink', Renewable Energy,173: 520-530. https://doi.org/10.1016/j.renene.2021.04.014. **(Q1, IF: 8.001)**
2. **Abdulmunem, A.R.**, Samin, P.M., Rahman, H.A., Hussien, H.A. and Habibah G. (2021) 'A Novel Thermal Regulation Method for Photovoltaic Panels Using Porous Metals Filled with Phase Change Material and Nanoparticle Additives', Journal of Energy Storage, 39: 102621. https://doi.org/10.1016/j.est.2021.102621. **(Q1, IF: 6.583)**
3. **Abdulmunem, A.R.**, Samin, P.M., Rahman, H.A., Hussien, H.A. and Mazali, I.I. (2020) 'Enhancing PV Cell's electrical efficiency using phase change material with copper foam matrix and multi-walled carbon nanotubes as passive cooling method', Renewable Energy, 160: 663-675. https://doi.org/10.1016/j.renene.2020.07.037. **(Q1, IF: 8.001)**
4. **Abdulmunem, A.R.**, Samin, P.M., Rahman, H.A., Hussien, H.A., Mazali, I.I. and Ghazali, H. (2020) 'Experimental and numerical investigations on the effects of different tilt angles on the phase change material melting process in a rectangular container', Journal of Energy Storage, 32: 101914. https://doi.org/10.1016/j.est.2020.101914. **(Q1, IF: 6.583)**

Indexed Journal

1. **Abdulmunem, A.R.**, Samin, P.M., Rahman, H.A. and Hussien, H.A. (2020) 'Effects of different tilt angles on the thermo-electrical performance of a

PV/PCM system’, Journal of Engineering Science and Technology, 15(3): 1731 - 1746 . **(Indexed by SCOPUS)**

2. **Abdulmunem, A.R.**, Jabal, M.H., Samin, P.M., Rahman, H.A. and Hussien, H.A. (2019) ’Analysis of energy and exergy for the flat plate solar air collector with longitudinal fins embedded in paraffin wax located in Baghdad center’, International Journal of Heat and Technology, 37(4): 1180-1186. https://doi.org/10.18280/ijht.370428. **(Indexed by SCOPUS)**

3. **Abdulmunem, A.R.**, Abed, A.H., Hussien, H.A., Samin, P.M. and Rahman, H.A. (2019) ’Improving the performance of solar air heater using high thermal storage materials’, Annales de Chimie - Science des Matériaux, 43(6): 389-394. https://doi.org/10.18280/acsm.430605. **(Indexed by SCOPUS)**