UNIVERSITI PUTRA MALAYSIA

DEVELOPMENT OF A MATHEMATICAL MODEL TO PREDICT THERMAL PERFORMANCE AND COST EFFECTIVENESS OF SOLAR AIR HEATERS

BASHRIA ABD-RUB ALRASOUL ABD ALLAH YOUSEF

DEVELOPMENT OF A MATHEMATICAL MODEL TO PREDICT THERMAL PERFORMANCE AND COST EFFECTIVENESS OF SOLAR AIR HEATERS

By

BASHRIA ABD-RUB ALRASOUL ABD ALLAH YOUSEF

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

March 2007

DEDICATION

To the soul of my only sibling I had **"Mohamed"** who shocked me with his sudden death on 1stof April 2006, while I was waiting for my VIVA. Brother, I had always wished that if you were with me for the rest of my life; because you were and still the twin of my soul, I miss you so much and I feel lonely without you. Now I am just like a leaf falling down from the tree in a huge dessert. Any how it is God willing and the only things that I can say is God bless you and (Ena Li-alah Wa Ena Eli-he Rageon). I am not going to forget you, never ever my beloved brother; you are still my support in this life. I swear that I am still seeing you and hearing your voice and laughter, you still exist in my heart and you will be there forever, so good-by for now my dear brother until we meet again in the heaven inshaalla,

Bashria

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

DEVELOPMENT OF A MATHEMATICAL MODEL TO PREDICT THERMAL PERFORMANCE AND COST EFFECTIVENESS OF SOLAR AIR HEATERS

By

BASHRIA ABD RUB ALRASOUL ABD ALLAH YOUSEF

March 2007

Chairman: Associate Professor Nor Mariah Adam, PhD

Faculty: Engineering

Energy is a subject of vital importance because of our great dependence on them in all aspects of life including social, economy and even in defence. In Malaysia the analyses of solar radiation at several main towns show that solar radiation has potential for drying purpose. This research is concerned with developing an internet-based mathematical model which is able to predict the thermal performance and cost effectiveness for different types of solar air heaters.

The data and knowledge collected from published sources on solar collectors, literature review and the field survey along with personal communications in the solar energy field is used to develop an internet based mathematical model given the code name Mathematical Modeling for Solar Air Heaters (MMSAH). This Mathematical Model incorporates knowledge and able to calculate the parameters required to predict the thermal efficiency and the cost effectiveness of solar air heaters. These parameters are absorber plate temperature, the temperature of the transport fluid inside the duct flow,

the output temperature and the overall heat loss coefficient. It also can calculate the fan power consumption to obtain the net energy gain which is required in the cost effectiveness calculation.

The solution procedure is performed for flat and V-groove absorber in single and double flow mode, with and without porous media. The thermal performance was determined over a wide range of operating conditions. The optimum operating parameters with respect to the efficiency, outlet temperature and cost effectiveness have been determined. For mass flow rate it lies in the range of 0.025 to 0.045 kg/s, for channel flow depth the recommended ranges are 0.025 to 0.035 m for flat plate collector, 0.06 to 0.08 m for V-groove absorber and 0.04 to 0.055 m for lower duct in double flow double duct solar air heater. The optimum collector length for reasonable thermal performance and minimum annual cost per unit thermal energy gain was found to be between 1 and 3 m.

For flat plate collector type it is found that the system thermal efficiency increases by 10-12% in double flow mode without porous media than single flow. An increase of 18% after using porous media in the lower channel than the single flow. For V-groove absorber type it is found that the double flow mode is 4-5% more efficient than the single flow mode. Observation shows that using the porous media in double flow increase the air heater efficiency by more than 7% efficient than the air heater in single mode and a further 2-3% in double flow mode without porous media. It is found that the annual cost of the collector in the double duct double pass flat plate collector with porous media is higher than the annual cost of the collector in double duct double pass flat plate collector without porous media and that is a consequence of using the porous media in which increase the pressure drop lead to increase in annual running cost. However the cost of solar energy (cost-benefit ratio); the annual cost of the collector/the annual thermal energy gain in double flow duct double duct flat plate collector with porous media is less than the cost of solar energy in double flow duct double duct flat plate collector without porous media due to the higher useful energy gained from using porous media which subsequently increase the heat transfer area. Also it is found that the cost-benefit ratio was affected by the flow depth.

The developed program is capable of handling Malaysian ambient conditions, collector characteristics, and material thermal properties. The criteria for solar collector in Malaysia were used as the input in the program to simulate the performance of the solar air heaters. To assess the accuracy of the developed program, the mathematical model was validated by comparing its output with experimental results. The comparison conducted showed a similar agreement with maximum error of 5%. The technique seems to be promising since a great correlation has been obtained between the experimental and the predicted results ($97.5\% < R^2 < 99.76\%$ and $P < 0.001$).

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PEMBANGUNAN MODEL MATEMATIK UNTUK MERAMAL PERSTASI TERMAL DAN KEBERKESANAN KOS UNTUK PEMANAS UDARA SURIA

Oleh

BASHRIA ABD RUB ALRASOUL ABD ALLAH YOUSEF

March 2007

Pengerusi: **Profesor Madya Nor Mariah Adam, PhD**

Fakulti: **Kejuruteraan**

Tenaga merupakan suatu subjek yang penting disebabkan manusia bergantung kepada tenaga dalam pelbagai aspek kehidupan, yang juga merangkumi aspek sosial, ekonomi dan pertahanan. Analisis sinaran suria di beberapa bandar utama di Malaysia menunjukkan bahawa tenaga suria berpotensi digunakan sebagai sumber untuk pengeringan. Kajian ini adalah berkaitan pembangunan model matematikal berasaskan internet, untuk meramal perstasi termal dan keberkesanan kos berbagai jenis pemanas udara suria.

Data dan maklumat yang diperolehi daripada sumber penerbitan tentang pengumpul tenaga suria, sorotan literatur dan tinjauan lapangan serta komunikasi secara peribadi dengan pakar bidang tenaga suria digunakan untuk membangunkan model mathematikal berasaskan internet, kod *MMSAH*. Model ini merangkaumi pengetahuan dan pengiraan parameter penting untuk meramal kecekapan termal dan keberkesaran kos pemanas udara suria. Parameter yang dimaksudkan adalah suhu plat penyerap, suhu bendalir

pengangkut didalam aliran salur, suhu keluaran dan pekali kehilangan haba keseluruhan dan keupayaan menghitung nilai penggunaan kuasa kipas untuk mendapatkan nilai tenaga pertambahan net.

Prosidur penyelesaian dijalankan untuk peresap leper dan berlurah V untuk mod aliran tunggal dan penduaan, dengan dan tanpa media. Nilai prestasi termal dihitung untuk julat keadaan operasi yang luas. Parameter operasi yang optimum berlandaskan kecekapan adalah suhu keluar dan keberkesanan haba. Julat untuk kadar alir jisim adalah diantara 0.025 hingga 0.045 kg/s, kedalaman aliran alur yang dicadangkan adalah 0.025 hingga 0.035 m untuk pengumpul jenis plat rata; 0.06 hingga 0.08 untuk jenis berlurah V dan 0.04 hingga 0.055 m untuk pemanas udara suria salur bahagian bawah dalam aliran perduaan salur berganda. Panjang optimum pengumpul untuk prestasi termal bersesuaian dengan kos tahunan per tenaga pertambahan termal minimum adalah antara 1m dan 3m.

Untuk pengumpul jenis plat leper didapati kecekapan termal sistem meningkat sebanyak 10- 12% untuk mod aliran penduaan tanpa media berliang berbanding jenis tunggal. Penambahan menjadi 18% jika aliran penduaan dengan media jenis berliang di bahagian bawah terusan, berbanding jenis tunggal. Untuk pengumpul berlurah V, didapati mod aliran penduaan adalah 4-5% lebih cekap daripada mod aliran tunggal. Pemerhatian menunjukkan dengan penggunaan media dalam aliran penduaan, kecekapan pemanas udara menjadi 7% lebih cekap daripada pemanas mod aliran tunggal, dan 2-3% lebih cekap dalam aliran penduaan tanpa media. Keputusan juga mendapati kos tahunan pengumpul untuk salur penduaan laluan dua kali dengan media berliang adalah lebih tinggi daripada kos tahunan pergumpul salur penduaan laluan dua kali, kerana akibat penggunaan media berliang yang menyebabkkan tekanan menurun, seterusnya menyebabkan kos tahunan meningkat. Kos tenaga suria (nisbah kos- faedah); kos tahunan pengumpul penambahan tenaga termal tahunan dalam pengumpul aliran penduaan plat leper dengan media berliang adalah lebih rendah daripada kos tenaga suria dalam pengumpul salur aliran penduaan sesalur penduaan plat leper tanpa media berliang disebabkan tenaga berguna didapati daripada mengguna media berliang boleh meningkatkan luas pemindahan haba. Didapati juga nisbah kos-faedah dipengaruhi kedalaman aliran.

Program yang telah dibangunkan berupaya mengendali keadaan ambien untuk Malaysia, ciri pengumpul dan sifat termal bahan. Kriteria pengumpul tenaga suria untuk Malaysia digunakan sebagai input program untuk menghitung prestasi pemanas udara suria secara simulasi. Untuk memastikan kejayaan program yang dibangunkan, model matematik disahihkan dengan membuat perbandingan dengan output keputusan eksperimen. Perbandingan menunjukkan persamaan dengan ralat maksimum 5%. Teknik ini boleh dikatakan menggalakkan kerana nilai korelasi eksprimen dengan keputusan eksperimen jangkaan adalah bagus ($97.5\% < R^2 < 99.76$ dan $P < 0.001$).

ACKNOWLEDGEMENTS

After my great thanks to Allah, I wish to express my sincere appreciation to Associate Professor Dr. Nor Mariah Adam, chairman of my supervisory committee, for her guidance, encouragement, continual support, insight and patience throughout this research. I would also like to express my sincere gratitude to Prof. Dr. Mohamed Daud, Associate Prof. Dr. Megat Mohamed Hamdan Megat Ahmad and Associate Prof. Dr. Husaini Omar for their sharing of ideas and opinions.

I wish to express my sincere gratitude to Prof. Kamaruzzaman Sopian at the Solar Energy Research Institute, Universiti Kebangsaan Malaysia, and to Prof. Dr. Mohamed Nur Ahmed at Kolej Yayasan MARA Kula Lumpur for their time, advice, critical discussions and comments.

I am certainly grateful to the researchers at the Solar Energy Park, UKM namely Elradi, Mofadel, Nazri, Salah and the entire researcher group for their help and sincere guidance.

My appreciation goes to my friends and colleagues for their encouragement and advice during the period of my study. My thanks go to my sincere friends Zeinab Othman, Eman Naser-Eldein, Ameera Othman, Awad Elmahi and Omer Merghani in Sudan for their constructive support to my mother while I am away, I am very grateful to them. Warm thoughts go to my mother and my brother Mohamed in Sudan (who I lost him suddenly while waiting for viva) for being a source of encouragement, moral support and their patience. My special appreciations and warm thanks go to my husband Dr. El-Mahdi for his constant support, encouragement, understanding and patience during the period of this research and to my little princess my daughters Ghadeer and Tala who is the source of light in my life. Sweetheart Ghadeer and Tala I wish you a great life full of faith, knowledge and happiness, so please be as the best as you can in your life, this is the only desire your Mummy wants from you.

Last but not least, most profound thanks go to Juba University, Sudan, for giving me this opportunity and for their funding support for the research studies. I would like to thank them all.

I certify that an Examination Committee met on 22 March 2007 to conduct the final examination of Bashria A. A. Yousef on her Doctor of Philosophy thesis entitled "Development of Mathematical Mode to Predict Thermal Performance and Cost Effectiveness of Solar Air Heaters" in accordance with University Putra Malaysia (Higher Degree) Act 1980 and University Putra Malaysia (Higher Degree) Regulations 1981. The committee recommends that the candidate be awarded the relevant degree. Members of the Examination Committee are as follows:-

Ir. Barakawi Sahari, PhD
Professor
Institute of Advanced Technology
Universiti Putra Malaysia
(Chairman)

Ir. Md. Yusof Ismail, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Abdel Magid Salem Hamouda, PhD
Professor
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Ir. Yusof Ali, PhD
Professor
School of Graduate Studies
Universiti Kebangsaan Malaysia
(External Examiner)

____

HASANAH MOHD GHAZALI, PhD
Professor/Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 21 JUNE 2007

This thesis submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for degree of Doctor of Philosophy. The members of the Supervisory Committee are as follows:

Nor Mariah Adam, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Mohamed Daud, PhD
Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Megat Mohamed Hamdan Megat Ahmad, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Husaini Omar, PhD
Associate Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

____

AINI IDERIS, PhD
Professor/Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 17 JULY 2007

DECLARATION

I hereby declare that the thesis is based on my original work except for quotation and citation which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UPM or other institutions.

BASHRIA A. A. YOUSEF

Date: 22 March 2007

CHAPTER 1

INTRODUCTION

The increased costs during the past decade for fossil fuels used for drying purposes have led to a search for alternative methods that consume less fuel energy. Solar energy is one of the most promising renewable energy sources in the world; it is the world's most abundant permanent source of energy. According to Sopian *et al*., (1999) the amount of solar energy intercepted by Earth is 170 trillion kW, 30% of this amount is reflected to space, 47% is converted to low temperature heat and reradiated to space, and 23% powers the evaporation/precipitation cycle of the biosphere, where less than 0.5% of this energy is presented in the kinetic energy of wind and waves and in the photosynthesis storage in plants. Compared to fossil fuels solar energy is non- polluting, has no moving parts to breakdown, and does not require much maintenance (Nidal, 2003).

Solar collectors are employed to convert incident solar radiation into thermal energy at the absorbing surface, and transferring this energy to a fluid (commonly water or air) flowing through the collector (Paisarn, 2003). Solar air heater uses air as the transporting fluid. It is extensively used in industrial and agricultural applications without the optical concentration. The solar air heater has minimal use of materials and the direct use of air as the working substance reduces the number of required system components, resulting in simpler design and less maintenance together with less corrosion and leakage problems compared to liquid solar systems (Ammari, 2003; Yeh *et al*., 1999; Mohamed, 1997). On the other hand, air type solar collectors have two inherent disadvantages i.e. low thermal capacity of air and low absorber to air heat transfer coefficient (Karim and Hawlader 2004). Consequently several studies to determine the thermal performance of solar air heaters have been conducted, theoretically and/or experimentally, and different modifications are suggested and applied to improve the heat transfer coefficient between the absorber plate and air (Ong, 1995a, 1995b; Metwally *et al*., 1997; Yeh *et al*., 2002; Froson and Nazha, 2003).

In Malaysia the analysis of solar radiation in several main towns shows that, solar radiation has potential to be used for drying purposes and other applications (Mohd. *et al.,* 1996). Typically, open air sun drying has been used to dry plants, seeds, fruits, meat, wood and other agricultural and forest products. For large scale production, limitations of open air drying have surfaced (Sopian *et al.*, 1999).

As such, this study focuses on solar air heaters and subsequently on developing an internet based mathematical modeling that could be used as a tool to predict the thermal efficiency and the cost effectiveness for six different designs of solar air heaters. The use of the internet offers attractive features that are useful at the development and delivery stages, as well as expanding and sharing knowledge from any location in the world. The developed model is fully implemented to run on the web and provides an easy and attractive way to share knowledge.

The knowledge gained from the said sources on solar collectors would be incorporated in mathematical modeling given the code name Mathematical Modeling for Solar Air

Heaters (MMSAH). This mathematical modeling incorporates knowledge and able to conduct the following:

i. Calculate the important parameters to predict the thermal efficiency, these parameters are absorber plate temperature, the temperature of the transport fluid inside the duct flow, the output temperature and the overall heat loss coefficient.
ii. Calculate the fan power consumption to obtain the net energy gain which is considered important in the cost effectiveness calculation.
iii. Determine the optimum operating parameters with respect to the efficiency, outlet temperature and cost effectiveness. These parameters are mass flow rate, channel flow depth and the collector length.
iv. Rank the six chosen type of solar air heaters in order of high energy gain with reasonable cost and appropriate outlet temperature.

1.1 Problem Statement

Although solar air heater has vast potential, it has not received much attention like the solar liquid collectors (Parker, 1993; Karim and Hawlader, 2004). Air type solar collectors have two problems, low thermal capacity of air and low absorber to air heat transfer coefficient, at the same time the most essential parameter of solar air collector design is the heat transfer coefficient between the absorber and the flowing air since the collector efficiency is strongly affected by this parameter, which in turn is dependent on collector type and operating conditions. Thus different modifications have been suggested and applied to improve the heat transfer coefficient between the absorber plate and the air and several designs are discussed. However, the importance of having an optimum flow channel depth, length and mass flow rate in solar air heaters has not been much identified and studied.

Hollands and Shewen (1981) while optimizing the flow passage geometry have suggested to keep the pressure drop and mass flow rate constant and to maximize the internal heat transfer coefficient by variation of the flow duct geometry. Bejan *et al.*, (1982) have minimized the entropy generation caused by heat transfer from the absorber plate to the fluid and by fluid friction in order to find optimum flow duct geometry.

There exist many different designs of solar air heaters in literature. The single important characteristic of the thermal behavior of solar air heaters is the depth of flow path of the air usually called flow channel depth. It is because both the pressure drop in the duct as well as forced convective heat transfer coefficient depends on the flow channel depth. The collector performance may be improved by employing higher flow rates but at the cost of additional pumping power, which is the recurring cost to the end user (Ratna *et al.*, 1991). The end user would like to have this recurring cost at its minimum without significantly affecting the collector performance.

Choudhury *et al.*, (1995) stated that the main hindrance to the immediate large-scale introduction of solar air heaters for different practical applications is price, and efforts must be made to improve the efficiency and simultaneously decrease the cost of previously existing or newly designed collectors if they are to be incorporated into utility systems to satisfy energy need without sacrificing reliability.

Duffie and Beckman, (1991) stated that "The design of a solar collector is concerned with obtaining minimum cost energy. Thus, it is desirable to design a collector with efficiency lower than is technologically possible if the cost is significantly reduced. In any event, it is necessary to predict the thermal efficiency". Therefore the prediction of thermal efficiency of solar collector is important and improves the design.

Therefore from the literature review in solar air heaters and the field survey along with personal communications it is found that:

i. The performance of solar air heaters depends upon the physical design of the collectors, heat losses, air circulation rates, and prevailing ambient conditions (Ammari, 2003)

ii. Although solar air collectors are a very important component in the solar drying, they have not received much attention like solar liquid collectors (Parker, 1993; Karim and Hawlader, 2004)

iii. There is limited work on the effect of the air flow passage dimensions on the efficiency and pressure drop and hence on the cost effectiveness of the solar air heaters

iv. The design of a solar collector is concerned with obtaining minimum cost energy. There is a need to predict the performance of a collector (Duffie and Beckman, 1991, Sopian (Pers. Comm., 2005))

v. The concept of a dryer powered by solar energy is becoming increasingly feasible because of the reduction in price of solar collectors and drastic increase cost in fuel coupled with the increasing legal implications on atmospheric pollution caused by conventional fossil fuels used for drying (DOE, 2002; Nidal, 2003)

vi. There were many solar collector designs conducted currently for fulfillment of the different requirements in developed and rural areas.

In general all studies in literature review lacked to the following

i. Determination of the optimum operating parameters; these parameters are mass flow rate, channel flow depth and the collector length
ii. Calculation of cost effectiveness
iii. Taking into consideration the fan power consumption to obtain the net energy gain which is considered important in the cost effectiveness calculation
iv. Limited work on the pressure drop in the flow duct
v. Literature lacks the study on costing for V-groove absorber in single or double pass and the investigation study on double pass V-groove absorber with porous media has not been conducted before either theoretically or experimentally.

Therefore there is a need for a systematic approach to deal with solar air heater as a problem on optimum flow channel depth, pressure drop, mass flow rate, convective heat transfer coefficient, configuration and cost effectiveness to facilitate design thus collector performance promoting use of solar air heater.

Having mentioned the shortcomings, this work presents mathematical solutions for the followings:

i. Ranges of optimum operating parameters of mass flow rate, flow depth and length
ii. Study on costing of flat collector and V-groove absorber in single and double pass
iii. Study on thermal performance of double pass V-groove absorber with porous media
iv. Fan power consumption for net energy gain in cost effectiveness calculation

1.2 Objective

1- To develop a mathematical model to predict the thermal efficiency and the cost effectiveness for double pass V-groove absorber with porous media which has not been conducted before either theoretically or experimentally

2- To develop an internet based tool to be used for the prediction of the thermal efficiency and the cost effectiveness for different types of solar air heaters namely single pass flat plate collector, single pass V-groove absorber, double pass double duct flat plate, double pass double duct V-groove, double pass flat plate with porous media and double pass V-groove absorber with porous media

3- To determine the optimum operating conditions mass flow rate, air flow depth and collector length which has a direct effect on the efficiency, outlet temperature and cost effective design

4- To determine the effect of using the porous media in the lower duct in double flow double duct solar air heater to overcome the low heat transfer coefficient between the absorber plate and the airstreams

1.3 Expected Outcome of the Study

The expected outcome of this research is an internet based Mathematical Modeling for Solar Air Heater acronym MMSAH. The system can be used for predicting the thermal performance with cost effectiveness for the six types of solar air heaters. The system should be of interest to designers, engineers, students who can use the model for tutorials and consumers who like to compare the cost effectiveness of different solar air heaters configurations. Finally the internet based computer program will be available at all times to all parts of the world and that will expand its application.

1.4 Thesis Layout

This thesis is divided into seven chapters. Chapter One focuses on the research problem, objective and the expected outcome of the study. Chapters Two is literature review and Chapter Three is theoretical consideration on the developed mathematical model. Chapter Four focuses on the methodology of study. Chapter Five focuses on the results and discussion while Chapter Six focuses on the validation; finally Chapter Seven presents the summary of conclusions and recommendations.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

For thousands of years human civilization has used non concentrated solar energy to produce light and heat and to grow food; then technologies evolved and developed to concentrate sunlight and convert it to produce electricity, steam and hot water for industrial processes. In 1744 Joseph Priestly used a concentrating lens to heat mercuric oxide and discovered oxygen in the process. Antoine Lavoisier, built a solar furnace that achieved a temperature of circa 1750^{o}C. Augastien Mouchot devised several solar powered steam engines in the late 1800 using silver plated reflectors, that could be turned to track the path of the sun and the solar receiver is further connected to a steam boiler (Johansson *et al.,* 1993)

During the early part of this century, solar water heaters were wide used in southern United States of America but by the middle of the century, emergence of cheap oil and gas supplies in the 1930s resulted in decline of sales of solar collectors and the industry slowly disappeared (Michael, 1992). The French physicist Edmond Becquerel was the first to describe the photovoltaic (PV) effect in 1839, but it only remained a curiosity of science for the next three quarters of a century. Only in 19th century, Becquerel found that certain materials could produce small amounts of electric current when exposed to light (Michael, 1992).

2.2 Solar Systems

The main types of active solar systems are solar thermal collectors, solar concentrators and photovoltaic cells.

2.2.1 Solar Collectors

Solar collectors are discrete units that collect, store and distribute solar energy for water heating, space heating, drying purpose and space cooling. Many types of solar collectors have been developed, the simplest and most popular of which is the flat plate collector (Michael, 1992). It consists of the absorber plate that absorbs sun light and transfers the heat to the transport fluid. The absorber plate is topped by one or more transparent cover and the rest of the system is surrounded by thermal insulation as shown in Figure 2.1 (CanREN, 2005).