UNIVERSITI PUTRA MALAYSIA

THERMAL STRATIFICATION ANALYSIS OF TRIANGULAR INTEGRAL COLLECTOR STORAGE SOLAR WATER HEATER

AMMAR ABDUL AZIZ AL-TALIB

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By

AMMAR ABDUL AZIZ AL-TALIB

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

June 2009

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DOCTOR OF PHILOSOPHY

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2009

To the Memories of My Father to Whom I Owe so Much
And
To My Dear & Respectful Mother

Also,

To My Dear Wife and Our Children:
Sidra, Sara, Ibrahim and Hasan

Ammar/2008

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

THERMAL STRATIFICATION ANALYSIS OF TRIANGULAR INTEGRAL COLLECTOR STORAGE SOLAR WATER HEATER

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AMMAR ABDUL AZIZ AL-TALIB

June 2009

Chairman: Professor Megat Mohamad Hamdan B Megat Ahmad, PhD

Faculty: Engineering

The current study outlines the results of testing the effectiveness of using stratification as a collector mechanism for night insulation tool and its effects on the performance of a Triangular Integral Collector Storage (TICS) solar water heater.

The main objective of the present work was the desire to develop a new solar water heater design that can be manufactured in Malaysia with the available local materials and labor. It can solve the problem of night cooling that are usually encountered by most of the Integrated Collector Storage (ICS) solar water heaters. The system, in which this solution is incorporated, was referred to as the Triangular Stratified Integrated Collector Storage (TSICS) system.

Experimental and numerical investigations were conducted on both the TICS and TSICS systems under thermosyphonic mode with no water draw off. The results obtained showed that the hourly efficiency for the TSICS system is higher than that of the TICS system, and the heat loss at night is less for the TSICS system, indicating more favourable outcomes for the stratified system.

FEMLAB software was used to simulate the temperature and velocity distributions in both the TICS and the TSICS systems. The results obtained are in high agreement with the experimental results. In addition, FEMLAB has helped in finding the optimum dimensions for the TSICS system.

Architecturally, two possible ways of installing the TSICS system on a pitch roof design were suggested, and for the purpose of this study, they have been called (1) the ‘Floating’ method of installation and (2) the ‘Pocket’ method of installation, whereupon the details and sketches for both were provided

The methods of Present Worth and Annual Worth were used for the economic analysis to compare the usefulness of using the TSICS system in comparison to the utilisation of conventional electrical water heaters. Results from both methods have led to the conclusion that using the TSICS solar heater- in spite of its higher initial cost- is more economically superior than using the electrical water heater, hence leading to and substantiating the recommendation of the utilisation of TSICS solar heater system.

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

ANALISIS STRATIFICASI TERMA PENGUMPUL PEMANAS AIR BERINTEGRASI BERBENTUK SEGITIGA

Oleh

AMMAR ABDUL-AZIZ AL-TALIB

June 2009

Pengerusi : Professor Megat Mohamad Hamdan B Megat Ahmad, PhD

Fakulti : Kejuruteraan

Pengkajian penyelidikan terkini telah menunjukkan keberkesanan prestasi dan kecekapan penggunaan stratifikasi sebagai alat pengumpul penebat pada waktu malam bagi sebuah pemanas air solar iaitu *Triangular Integral Collector Storage (TICS)*

Objektif utama hasil kerja kajian ini adalah untuk mencipta pemanas air solar baru buatan Malaysia yang dapat dihasilkan dengan buruh dan bahan mentah tempatan di samping menyelesaikan masalah penyejukan waktu malam degan penggunaan pemanas air solar iaitu *Integrated Collector Storage (ICS*). Sistem berintegrasi ini dirujuk sebagai sistem *Triangular Stratified Integrated Collector Storage (TSICS).*

Pengkajian dan penyelidikan secara numerikal telah dijalankan terhadap kedua–dua system, *TICS* dan *TSICS,* dalam keadaan termosifon dan tiada pengaliran air keluar.

Program *FEMLAB* telah digunakan dalam simulasi pengagihan suhu dan kelajuan sistem *TICS* dan *TSICS.* Keputusan simulasi yang diperoleh adalah sama dengan hasil eksperimen. FEMLAB juga telah membantu dalam pencarian dimensi optimum sistem TSICS.

Dari segi reka bentuk, dua cara disarankan untuk pemasangan sistem TSICS pada bumbung dan bagi tujuan kajian ini, kaedah-kaedah tersebut dinamakan sebagai kaedah (1)“Floating” dan (2) kaedah “Pocket”. Butiran dan lakaran kedua-dua kaedah ini dilampirkan.

Kaedah “*Present Worth*” dan “*Annual Worth”* telah digunakan dalam analisis ekonomi bagi membandingkan kelebihan menggunakan sistem *TSICS* berbanding dengan pemanas air elektrik yang konvensional dan hasil dapatan daripada kedua-dua kaedah ini membawa kepada kesimpulan bahawa penggunaan pemanas solar (suria) *TSCIS* adalah lebih ekonomi walaupun kos permulaannya lebih tinggi. Ini telah membawa kepada usul penggunaan system TSICS pemanas solar (suria) sebagai system pilihan optimum.

ACKNOWLEDGEMENTS

First and foremost I thank ALLAH the almighty for the blessings and opportunities that He has provided for me to accomplish this study.

I would like to express my sincere thanks to my advisor and committee chairman, Professor Dr. Megat Mohamad Hamdan B Megat Ahmad, who is a constant source of advice, encouragement and all kind of support throughout this study. He was the mentor who taught me how to blend advising with friendship. To Prof. Dr. Megat I say, your supervision and friendship are highly regarded and appreciated. I am deeply indebted and most grateful to Prof. Dr. Kamaruzzaman Sopian, the supervisory committee member, who gave all the support and has offered me all the facilities of the solar park at UKM / Bangi to conduct the experimental work. I wish to express my thanks to Dr. Mahdi B Abdul Wahab, my supervisory committee member for his helpful discussions and advice. I highly appreciate their time and willingness to serve in my supervisory committee.

I wish to extend my thanks to the staff of the Department of Mechanical and Manufacturing Engineering for their friendly dealing and moral support. I also thank my friends and colleagues for sharing their knowledge and encouragement.

Thanks must also go to my family members, my wife, my daughters and sons for their patience, understanding and encouragement until the completion of this work.

I certify that an Examination Committee has met on 18/June/2009 to conduct the final examination of Ammar Abdul Aziz Al-Talib on his Doctor of Philosophy thesis entitled “EVALUATION OF A STRATIFIED INTEGRATED SOLAR WATER HEATER WITH A TRIANGULAR SHAPE”. in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The committee recommends that the candidate be awarded the relevant degree. Members of the Examination Committee are as follows:

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This thesis submitted to the Senate of Universiti Putra Malaysia and has been accepted as a fulfilment of the requirement for the degree of Doctor of Philosophy.

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Date: 11 February 2010

DECLARATION

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

AMMAR ABDUL AZIZ AL-TALIB

Date: 5 / December/ 2008

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF PHOTOGRAPHS

LIST OF FLOW CHARTS

NOMENCLATURE

A/F	Sinking Fund Factor
A/P	Capital Recovery Factor
A_p	Aperture Area (m^2)
B_A	Annual Benefit
B_j	Benefits at the End of Period j
C_A	Annual Cost
C_j	Costs at the End of Period j
C_p	Specific Heat of Water (4.186 kj/kg.^oC)
G	Solar Irradiance Intensity (W/m^2)
g	Gravity Acceleration
I	Integral Hourly Solar Energy Falling on a Tilted Surface ($kW.hr/m^2$)
i	Interest Rate
$\dot{Q}_f$	Rate of Energy Transferred to the Storage Water in the Solar System (W)
m	Mass of the Water in the System
m_c	Mass of Water in the Lower Collection Part of the TSICS System (kg)
m_i	Mass of Water in Node i (kg)
m_T	Mass of Water in the TSICS Effective Storage Tank (kg)
m_{v3}	Mass of Water in the 3rd. Portion of the TSICS System
N	Life Time
P	Pressure
P/F,i,j	Single-Payment Present-Worth Factor for Period j at Discount Rate i

P_e	Peclet Number
Q_u	Useful Heat (W)
T	Time Duration of the Test (sec)
T	Temperature
T_0	Initial Water Temperature at the Morning (K)
T_c	Temperature at the Collection Portion
T_D	Delivery Temperature (^oC)
T_f	Final Temperature (^oC)
T_i	Initial Temperature (^oC)
T_{in}	Inlet Water Temperature (^oC)
T_M	Main Supply Temperature (^oC)
T_{m1}	Mean Temperature of the Water in the TICS System (^oC)
T_{m2}	Overall Mean Temperature for the TSICS System
T_{max}	Maximum Water Temperature Each Day (K)
T_{mc}	Mean Temperature at the Collection Portion
T_{ms}	Mean Temperature of TSICS System Effective Storage Tank
T_{mT}	Mean Temperature of Water inside the Stratification Tank for the TSICS System
T_o	Reference Temperature (^oC)
T_{out}	Outlet Water Temperature (^oC)
T_{Set}	Hot Water Set Temperature (^oC)
T_{wi}	Temperature of Water at Node I (^oC)
T_T	Water Temperature at Time $_T$ (K)
U	Effective Heat Loss Coefficient (W / m^2. ^oC)
U	Velocity Component in the X-Direction
V	Velocity Component in the Y-Direction

Vol_A	Volume of the Lower Triangular Region of the TSICS System
Vol_B	Volume of the Lower Rectangular Region of the TSICS System
Vol_C	Volume of the Storage-Stratification Tank of the TSICS System
$\bar{x}$	Mean Value
$\eta_{inst.}$	Instantaneous Efficiency
η_{hr}	Hourly Efficiency
Δx_{max}	Maximum Error
σ_z	Standard Deviation
$\sigma_{\bar{z}}$	Standard Error
α	Water Thermal Diffusivity
β	Coefficient of Volumetric Expansion
θ	Angle of Inclination of the Collector
ν	Water Kinematic Viscosity (m^2/s)
ρ	Water Density (kg/m^3)

ABBREVIATIONS

$AC)_{electricity}$	Annual Cost for the Electrical Water Heater
$AC)_{solar}$	Annual Cost for the Solar Water Heater
APEC	Asia Pacific Economic Cooperation
AW	Annual Worth
$AW)_{electricity}$	Annual Worth for the Electrical Water Heater
$AW)_{solar}$	Annual Worth for the Solar Water Heater
CAD	Computer Aided Design
CFD	Computational Fluid Dynamics
ESTIF	Europe Solar Thermal Energy Federation
EUAB	Equivalent Uniform Annual Benefit
EUAC	Equivalent Uniform Annual Cost
GEF	Global Energy Federation
ICS	Integrated Collector Storage Solar Systems
LPTSICS	Low Profile Triangular Stratified Integrated Collector System
MTA	Mean Ambient Temperature (^{o}C)
$NPC)_{electricity}$	Net Present Cost of the Electrical Water Heater
$NPC)_{solar}$	Net Present Cost of the TSICS System
NPV	Net Present Value
$NPV)_{electrical}$	Net Present Value for the Electrical Water Heater
$NPV)_{solar}$	Net Present Value for the TSICS System
P/A	Uniform Series Present Worth Factor
P/F	Single-Payment Present Worth Factor
SF	Solar Fraction

SDHW	Solar Domestic Hot Water System
SWH	Solar Water Heater
TICS	Triangular Integrated Collector-Storage System.
TSICS	Triangular Stratified Integrated Collector-Storage System
UKM	University Kebangsaan Malaysia.

CHAPTER 1

INTRODUCTION

1.1 Facts about the Sun

Without the Sun, life on Earth would not exist. Our planet would be a frozen dark ball, drifting dead in space. The Sun is needed for light, heat and energy. With the Sun, plants can grow, and animals can eat. The Sun is just a star, just like those usually seen twinkling at night (Rao and Parulekar, 1997).

The Sun is a typical G2 star. G stars are classified as having a temperature in the range of 5000 to 6000 K, and a color ranging from white to yellow. Spectrally, G stars show most predominantly the lines of ionized calcium. Lines from ionized and neutral metals are present. Lines from ionized hydrogen show up weakly (Rao and Parulekar, 1997).

The Sun is about 150 million km away from the earth. Light from the Sun takes about 8 minutes to reach the Earth, knowing that the light is traveling at a speed of 3×10^8 m/s. The distance from the Earth to the Sun varies throughout the year. At perihelion (closest approach) the distance is 147 million km, and at aphelion (farthest) the distance is 152 million km. Due to this distance variation, the Sun will appear about 3% bigger at perihelion than at aphelion. At this point in geological time, perihelion occurs in early January, and aphelion in early

July. The Sun's age is estimated to be around 4.5 billion years. It should remain more or less as it is for another 5.5 billion years, although it will continually be undergoing changes as it consumes its fuel through fusion (Garg and Prakash, 2000).

The Sun is extremely hot. The middle of the Sun is about 16 million degrees. The surface of the Sun (what is seen), the photosphere is only 6000 degrees.

The Sun is a giant, natural thermonuclear reactor that converts hydrogen to helium in its core to produce the heat sensed on our faces as sunshine.

The Sun is held together in an equilibrium state by the mutual gravitational attractions between all its atoms acting to compress the solar center and, thus, produce and contain the nuclear reactions taking place there (Garg and Prakash, 2000).

The solar atmosphere outside the energy generating core adjusts itself to carry the enormous amount of energy that emerges from the surface in the form of radiation.

The Sun visible to our eyes does not have a solid surface such as that of the Earth or the Moon. Nevertheless, what is seen is only its very outer layers because the gas is opaque. This outer visible surface is a few hundred kilometers thick on the Sun and is called the Photosphere. This layer is the top of the solar convection zone where the solar energy is carried to the outer surface by convective gas motions over the last quarter of the solar radius. Further inside lies the radioactive zone where the energy is carried principally by radiation, not convection (Garg and Prakash, 2000).

The sun generates approximately 5.6 X 10^{27} calories every minute or 3.9 X 10^{23} kilowatts of power. However, the Earth only intercepts less than one part in two billion of this total or about (1353 watt/m^2). This known as the Solar Constant (Garg and Prakash, 2000 and Rai, 1989).

Earth would not have any life on it without the Sun's energy, which reaches Earth in the form of heat and light (Rai, 1989).

1.1.1 Energy of the Sun

Nuclear fusion releases energy deep down inside the Sun's high-temperature core, which extends from the center to about one-quarter of the radius of the Sun. The layers above the core produce no energy, so the core, which makes up only 1.6 percent of the Sun's volume, produces all of the Sun's energy. Energy moves from the core to the rest of the Sun through two spherical shells that surround the core (Garg and Prakash, 2000).

In Table 1.1, the main three zones of the sun are shown.

Table 1.1. The three main zones of the sun (Garg and Prakash, 2000).

CORE	RADIATIVE ZONE	CONVECTIVE ZONE
Core is the central region where nuclear reactions occur. It occupies 2% of the volume of the Sun, but contains 60% of its mass.	Radiative zone is region where energy leaves the core in the form of streams of photons.	Convective zone is region where energy is carried by convection ,cells-rising and falling currents of hot gas.

1.1.2 Physical Properties of the Sun

In Table 1.2, the main physical properties of the sun and comparisons with the earth are shown:

Table1.2. The main physical properties of the sun, (Garg and Prakash, 2000)

Mass (kg)	1.989e+30
Mass (Earth = 1)	332,830
Equatorial radius (km)	695,000
Equatorial radius (Earth = 1)	108.97
Mean density (gm/cm^3)	1.410
Mean surface temperature	6,000°C
Age (billion years)	4.5

1.1.3 Necessity of Solar Energy

The increasing cost and scarcity of oil, gas, and electricity has focused attention on the need for transition to renewable energy sources. Solar energy can play an essential role in this effort, particularly for domestic and commercial space heating (and cooling) and water heating.

Malaysia as a developing country is reported to perform well in economy and industrialization. At the same time, the usage of energy is increasing year by year. In the year 1995, the total demand for energy was 22,164 kilo ton of energy (ktoe) and it increased to 25,558 ktoe by 1998. The main sources of energy are crude oil and petroleum products, which are depletable energy resources. Although Malaysia currently produces adequate oil for local consumption, but in the long run, the country needs to develop its renewable energy resources in order to ensure the sustainability of energy supply and consequently of the country's sustainable economic development. The total primary energy demand is expected to increase at a growth rate of 7% until the year 2020 (Komathi , 2000)

Solar energy is available freely and abundantly throughout Malaysia. Malaysia has a high solar radiation level that ranges from 6.5 kwh/m^2 in January and 6.0 kwh/m^2 in August, but unfortunately only 2.6 % of this energy is used. (Komathi, 2000).

Government and non-government agencies should take more proactive action to coordinate and promote energy generation based on renewable resources such as inventory of renewable sources, identification of suitable technologies, create incentives for appropriate practical application and a better national renewable energy policy to allow more participation from government, non-government and public. The public should be educated on the real situation of energy resources and problems that going to be tackled if there is no action taken. Awareness among them is the key point to shift from non-renewable sources to renewable sources.

The energy crisis in 1970s stimulated vast amounts of research and development into new and improved renewable energy technologies. Governments across the world created new programs, or strengthened existing ones, that focused on developing alternatives of fossil energy. The 1970s also produced innovative thinking on energy issues and the need to transcend the existing energy paradigm, (Hedger et al., 2001 ; Yergin, 1993).

The diminishing of non renewable energy resources, and their current rise of price; the availability of solar energy in Malaysia, have pushed for the current study.

1.2 Solar Water Heating Designs

One of the most widespread uses of solar thermal technology is solar water heating. Solar water heating systems (SWHs) have now been used for more than sixty years (MNRE, 2007 and Kalogirou, 2004). In many countries, which include China, Israel, USA, Japan, Australia, South Africa and Cyprus, SWHs are very popular for their use in community, commercial and industrial applications (Chow et al., 2006; Houri, 2006; Kaldellis et al., 2005; Nieuwoudt and Mathews, 2005; Zhiqiang, 2005 and Bhattacharya and Kumar, 2000).

There are a few parts that are basic to most solar water heating systems: collector(s), storage tank, heat transfer medium, and interconnecting plumbing, (Figure 1.1).

The collector intercepts the sun’s rays and converts it into heat which is transferred to the storage tank using a fluid such as water or antifreeze. An expansion tank is used in closed systems to accommodate the slight changes in volume that result when water or antifreeze is heated and expands. If glycol is used, a heat exchanger is needed to transfer the heat from the collector to the water that will exit the tap.

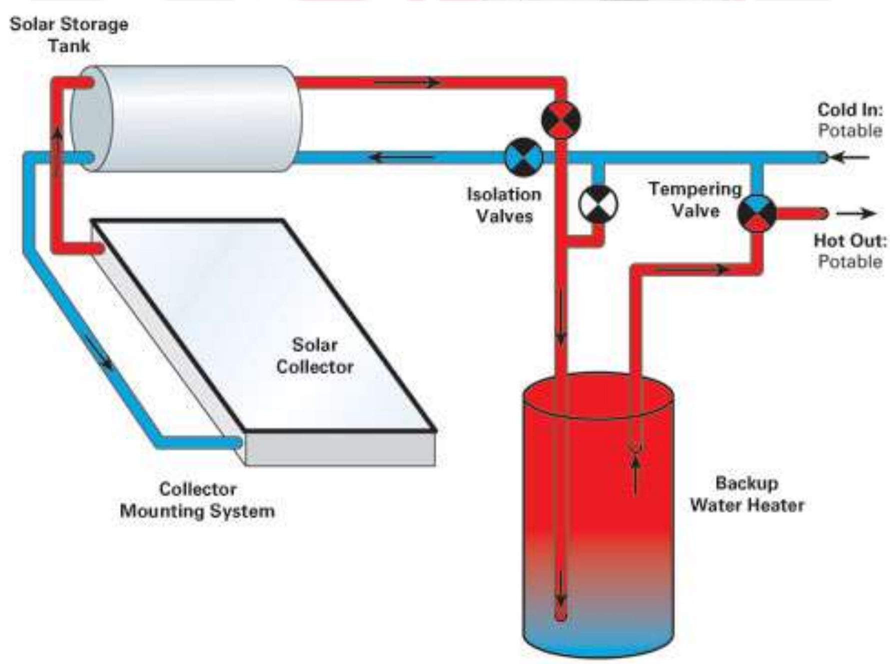

Figure 1.1. The Basic Components of a Solar Water Heater.

A temperature and pressure release valve is a common safety device found at the top of water heaters. If the water gets hotter than it should or the system builds up too much pressure, this valve will open, releasing water until the temperature or pressure drops to safer levels. The simple control system disables the backup heating system (gas or electricity) during daylight hours, giving the sun a chance to heat all of the water in the storage tank.

1.2.1 Classification of Solar Water Heaters

Solar systems for heating water or space can be divided into two classes, which are the passive and active systems. The essential difference is that passive systems need no auxiliary power to operate while active systems are dependent on externally driven fans or pumps.

The first commercial solar water heater, patterned after the fundamental black can, was patented in 1891 by Clarence M. Kemp as an alternative to the wood stove (Bainbridge, 1981).

The principle types of solar water heaters as classified by Graham (1997) are passive systems, integral collector-storage systems and pump circulation systems.

1.2.1.1 Passive Systems

The majority of domestic solar water heaters use thermosyphonic circulation of water between the solar collectors and the storage tank. This requires the storage tank to be mounted above the collector to produce thermally driven circulation between the collector and the tank. The advantage of these systems is that they do not require an electrical connection and have very low Maintenance, (Figure 1.2).

1.2.1.2 Integral Collector-Storage Systems

Integral systems, (Figure 1.3) combine the water storage tank and the collector into one unit. These systems are simple and effective, however, due to high heat loss at night they only provide hot water during the day and early evening. The products range from simple glazed low-pressure plastic tanks to high quality steel tank systems with selective surface coatings to minimize heat loss.

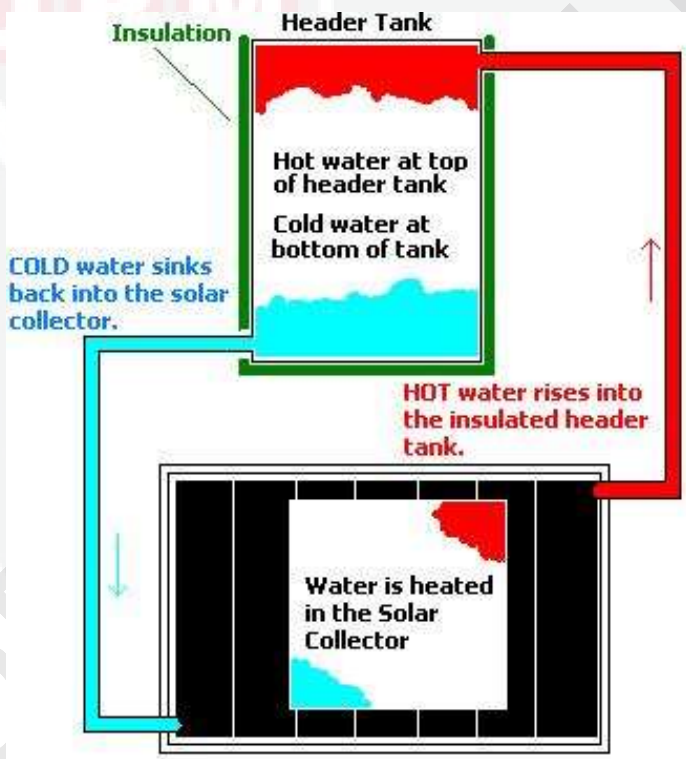

Figure 1.2. Components of a Thermosiphonic Solar Water Heater.

These systems make up the major portion of the large market in Japan (Graham,1997). The main limitation with this system concept is the night cooling and reverse circulation during nights and during low solar radiation.

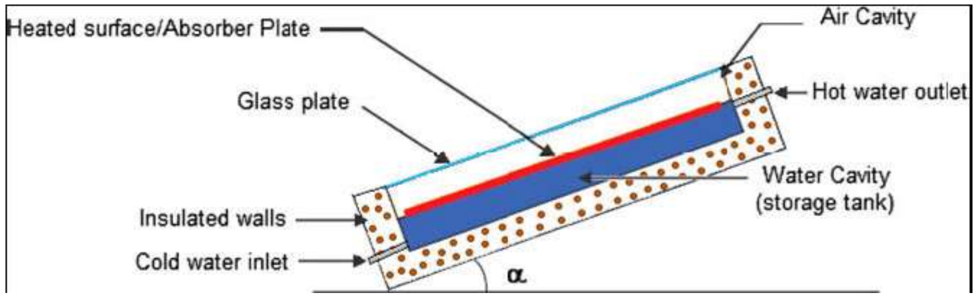

Figure 1.3. A Schematic Diagram of a Rectangular Integrated Collector-Storage (ICS) Solar Water Heater, (Garnier, 2006).

1.2.1.3 Pumped Circulation Systems

Pumped circulation, solar collector arrays connected to conventional enameled Steel hot water tanks (Figure 1.4) have been widely used for domestic solar water heating in North America and Europe (Graham, 1997). The development of this design concept was driven by the need to provide freeze protection in these climates. The market share of such systems dropped significantly during the 1990's due to the lower cost of externally mounted thermosyphonic systems. However production of pumped systems has started to increase in recent years, due to an increasing number of consumers who are not willing to accept the visual impact of an external roof-mounted tank, even though such systems are cheaper and have better performance. New design concepts for pumped systems have resulted in increased use of this configuration however, it is primarily suited to large commercial systems.

Another classification used for solar water heaters are the open or closed loop systems (Syhari, 2004). An open system means the water circulating through the collector is the same water to be used. A closed system circulates the separate heated fluid from the collector through a small loop that includes a heat exchanger, usually located in the storage tank.

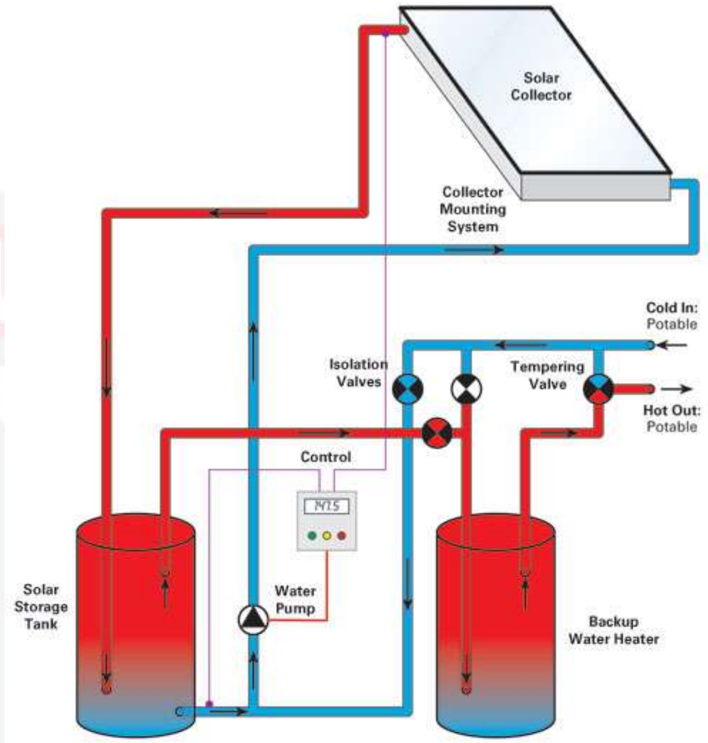

Figure 1.4. A Pump Circulation Solar Water Heater.

1.2.2 Types of Hot Water Solar Collectors

There are basically three types of collectors: flat plate, evacuated tube, and concentrating. A flat-plate collector, the most common type, is an insulated, weather proofed box containing a dark absorber plate under one or more transparent or translucent covers.

Evacuated-tube collectors are made up of rows of parallel, transparent glass tubes. Each tube consists of a glass outer tube and an inner tube, or absorber, covered with a selective coating that absorbs solar energy well but inhibits radiative heat loss. The air is withdrawn (evacuated) from the space between the tubes to form a vacuum, which eliminates conductive and convective heat loss. Concentrating collectors for residential applications are usually parabolic Troughs that uses mirrored surfaces to concentrate the sun's energy on an Absorber tube (called a receiver) containing a heat transfer fluid. Most commercially available solar water heaters require a well-insulated storage tank.

1.3 The Present Work Objectives

The solar domestic hot water system (SDHW), composed of one or several flat plate collectors and a storage tank covered with opaque thermo insulating material, is known all over the world.

However, its use has not become generalized in spite of the improvements introduced in recent decades. These systems have certain limitations that make their use difficult (Amilcar et al., 2001).

(a) They require high initial investment compared with some conventional systems such as those based on the use of electricity.

(b) They do not guarantee the permanent supply of hot water.

(c) They can suffer damage due to freezing effects in winter time.

(d) If they are active systems, they require auxiliary energy to drive the pump and the control system.

The Integrated Collector-Storage (ICS) solar water heaters are simple compared to their conventional counterpart. They have lower initial and operating cost with free maintenance. In spite of the mentioned advantages, such systems still have lower long-term performance due to their high heat losses during the night or the time when there is no solar insolation. Some solutions for decreasing these losses had been suggested and studied, as will be shown in the literature review. The suggested solutions have given good improvements in the performance but they have either added to the initial cost or changed the system to an active one (Amilcar et al., 2001).

The following can be listed as the objectives of the present study:

- To develop a new design of solar water heater that can be manufactured in Malaysia with the available local materials and labor and can solve the problem of night cooling accompanied with most of the ICS Solar Water Heaters with simple components and affordable price.
- To develop an Integrated solar water heater in which the absorber plate can performs the dual function of absorbing the solar energy and storing the heated water, besides a modification in tank shape to achieve stratification.
- To solve the problem of night cooling in an integrated solar water heater depending on thermosyphonic flow and stratification only, without using any moving parts, electronics or controls and to compare the results with other researchers work in the field.

- To conduct a simulation study by using FEMLAB, in order to compare the experimental results with the simulation results and to visualize the stratification effect in the TSICS system, beside finding its optimum dimensions.
- To do economical analysis for comparison between the TSICS system and the conventional electrical water heater by using the annual cost method and the present worth method to prove the economical superiority of the TSICS system.
- To study the architectural concepts of installing the TSICS system on flat surfaces and pitched surfaces, and providing the required schematic drawings.

In the present study, a modification for the ICS systems which have been designed and studied by Ecevit et al. (1989) and shown in Figure 3.6, and also by Soponronnarit et al. (1994) and shown in Figure 3.7, and then by Mohamad (1997) which is shown in Figure 3.8, has been made.

The performance of the proposed Triangular Stratified Integrated Collector-storage (TSICS) system has been compared with that of the Triangular Integrated Collector-Storage (TICS) system with its optimum geometric design as given by Soponronnarit et al. (1994), with the intention to prove the effectiveness of the triangular cross section with the stratification tank as a passive low cost solution to the night heat loss problem, and can be locally manufactured in Malaysia with the available materials and labor.

Also, the diminishing of non renewable energy resources, and their current rise of price beside the availability of solar energy in Malaysia, have pushed for the current study.

1.4 Thesis Layout

In chapter 1, an introduction to the sun and its importance for life of humans, beside its composition, zones, age and temperature are explained.

The availability of solar energy in Malaysia and the necessity of using it as an alternative to the non renewable energy resource is also discussed.

The classifications of solar water heaters and their alternative designs have also been demonstrated. The basic ideas behind the modification of the conventional Integrated collector-Storage (ICS) systems are introduced and the objectives of the present study are presented.

In Chapter 2 a preview of previous works relevant to the present study is presented. The review includes the concept of thermal stratification as a mean of improving the thermal storage efficiency. The effect of increasing CO_2 gas and its influence on global warming is also discussed. Comparison of the market scale for the solar water heaters in different countries and the wide range of designs used for different climates and demand requirements are demonstrated.

Numerical simulation for the velocity profile and temperature distribution inside the TICS and TSICS systems by using the FEMLAB software are presented in this chapter as well. In the FEMLAB software, the finite element method is used to solve the governing equations subjected to the applied boundary conditions. Also, simulations for a proposed system entitled as the Low Profile Triangular Stratified Integrated Collector System (LPTSICS) are shown.

Also presented in this chapter are the two different methods used for the economical analysis. The present worth Method and the Annual Worth Method are used to prove the economical superiority of the proposed TSICS system in comparison with the conventionally used electrical water heaters. Cash flow diagrams are drawn for the two systems for the purpose of comparison beside a solution for the problem of alternatives with different lives are explained, and the results are presented.

At the end of the chapter, the Architecture suggestions for the installation of the TSICS system on a flat and pitch roof are described. Two methods are presented, the floating method and the pocket method. Sketches and explanations are provided as well.

Chapter 3 presents the experimental set up and procedures. The Malaysian energy policy objectives, and its agreement with the current study is also explained. In addition, the types of ICS systems studied earlier by other researchers are demonstrated, and a description and sketches for the TICS and TSICS systems covered in this study are presented. The measuring instruments and experimental procedures are explained as well.

The analysis of the experimental data is presented and the Procedures to calculate the mean water temperature in the TICS and TSICS systems are explained, Besides, calculations for the efficiency and heat losses in the two systems are described.

The FEMLAB simulation results for velocity and temperature are presented as well for the systems under consideration.

Appendix A, is related to the chapter and is provided to show more simulation results for different dimensions and different solar radiation intensities.

Presented in this chapter also, is the error analysis for the experimental data. Definitions for the accuracy, precision and uncertainties on measurements are explained. Difference between the systematic and random errors in the experimental data is presented. The terms of mean value, maximum error, standard deviation and variance are all defined.

Moreover, the error analysis for all the temperature readings at the different points in the TICS and TSICS systems are shown.

The experimental results and their discussions are shown in Chapter 4. Results obtained from the experiments conducted on the two systems with and without glass cover are shown. Comparisons between the two systems under different operating conditions are also presented. Comparisons for the performance of the TSICS system with systems of different configurations studied by other researchers are shown, and explanations are given as well.

Moreover, the simulation results and their comparison with the experimental results are presented .

Also, presented in this chapter are the results of economical analysis by using the present worth and annual worth methods to compare the TSICS system with the conventional electrical water heater.

At the end of the chapter, the installation of the TSICS system on a flat and pitch roof by using the floating method and the pocket method are described . The related sketches and explanations are provided as well.

Conclusions and recommendations for further work are presented in Chapter 5.

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