STUDY OF THE EFFECT OF SUNFLOWER OIL AND WATER ON THERMAL STORAGE PROPERTIES OF A FLAT PLATE SOLAR WATER HEATING COLLECTOR

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A thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Physics of Masinde Muliro University of Science and Technology

July, 2025

DECLARATION

CANDIDATE

This thesis is my original work prepared with no other than the indicated sources and support and has not been presented elsewhere for a degree or any other award.

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DEDICATION

This work is dedicated to my dear loving wife Idah and children Levi, Marion and Billy

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I attribute all glory to God Almighty for bestowing upon me life, strength, and resources essential for the achievement of this endeavor.

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ABSTRACT

Solar collectors can convert the solar radiation energy to thermal energy when it hits a surface. A flat plate solar collector is a medium-temperature glazed plate heater manufactured to warm water or air to 80 Cmaximum. The simplest and effective way of tapping solar energy is by domestic water heating. Weather changes also have a big effect on the solar heater output water temperature. Behaviour, complexity and size of a solar water heating system are largely affected by the changes of ambient temperature and solar radiation in different weather conditions. Therefore, there is the necessity to use thermal storage fluids such as sunflower oil that has been documented to be an excellent heat transfer fluid (HTF) in addition to the heat storage fluid also necessitating the use of heat storage fluids such as sunflower oil since it is easily accessible, non-corrosive and non-poisonous. The main objective of the study was to compare the thermal storage capacity parameters of a flat plate solar water heater using sunflower oil versus water as thermal storage fluids. Specific objectives were to: determine instantaneous receiver heat gain by solar collector and compare the thermal storage effect of water and sunflower oil on output temperatures from a flat plate solar collector, evaluate the effect of both fluids on heat loss and heat exchange parameters of a flat plate solar collector, compare the overall system efficiency when using water versus sunflower oil as thermal storage media compare and analyse the KOLEKTOR 2.2 simulation results with the experimental data. Flat plate solar water heating collectors containing sunflower oil, and water as thermal storage fluids were designed and constructed for this study. The absorber plate was made of mild steel welded on galvanized iron riser pipes. The stated objectives were achieved by applying appropriate equations and measuring parameters affecting the thermal storage of a solar water heater such as area of the receiver, incident solar radiation, mass flow rate, wind speed, humidity, ambient temperature, fluid inlet and outlet temperatures. The efficiency of solar water heating systems was deduced by considering the incident solar energy on the collectors and the useful energy output from the systems. This takes into account conductive, convective and radiative thermal losses. The experimental measurements were done using k-type thermocouples connected to a data logger and a computer. Simulation and theoretical modeling were done using KOLEKTOR 2.2 software while experimental data computation and analysis were done using MATLAB. Research findings showed that sunflower oil and air attained a peak temperature of 75℃, while that of water was 65℃ from 12 noon to 3.30 pm. Overall heat loss coefficients for air, water and sunflower oil as -38.40 W/m^{2}K, -20.94 W/m^{2}K and -15.80 W/m^{2}K respectively Sunflower oil has the longest stagnation (steady) temperature duration.F_R of 0.8934, 0.846 and 0.785 for sunflower oil water and air respectively. However, from the KOLEKTOR 2.2 model, the heat removal factor for sunflower oil is 0.937, while water and air have heat removal factors of 0.918, and 0.910 respectively. Both experimental and theoretical results showed that sunflower oil has a higher removal factor F_R and efficiency factor F^1 than water. From the KOLEKTOR model, efficiency factor F^1 values of sunflower oil, water and air 0.922, 0.916 and 0.818 respectively. Sunflower oil is also a better thermal storage fluid than water since has a lower heat loss coefficient than water. Other studies have also shown that sensible heat storage media improve efficiency by reducing thermal losses. The information from this study would be useful for effective utilization of intermittent solar energy for heating applications. Thus reducing water heating expenses, and conserving our environment.

TABLE OF CONTENTS

LIST OF SYMBOLS AND ABBREVIATIONS

A_c-Collector area

A_p-Exposed area of plate

A_r-Area of the receiver

b_o- Incidence angle modifier coefficient

CNT-Carbon nanotube

C_p - Specific heat capacity

DHW-Direct heating of water

F_R-The collector heat removal factor

F_{solar}-Solar fraction

GI- Galvanized iron

HTF- Heat transfer fluid

I_{av}-Average daily solar insolation (kWh/m^2/day)

I_T- Irradiance on the collector

ICS-SWH-Integrated Collector Storage Solar Water Heater

l - Daily hot water energy demand (kWh/day)

m - Mass flow rate

PCM - Phase change material

P_{net}-Net heat flow into the plate

Q_r- Instantaneous energy gained by the receiver

Q_{conv}-Heat losses by convection

Q_{rad}- Radiative heat loss due to the difference of temperature between collector and sky dome

Q_u- Usable energy collected

R_L- Resistance to heat loss from the system

R_{pg}- Total resistance to heat loss between plate and glass
R_{vpg}- Convective heat loss resistances between plate and glass

R_{rpg} - Radiative heat loss resistances between plate and glass

SWH- Solar water heater

T_a - Ambient or outside temperature

T_{cold}- Cold water temperature

T_{hot}- Water delivery temperature

T_p- Plate temperature.

T_r - Receiver temperature.

TES- Thermal energy storage

TSF-Thermal storage fluid

U - Overall heat loss coefficient

V - Volume of water per day (m^3/day)

α - Absorbance of the receiver

ε_{eff} - The collector's effective emissivity
σ - Stefan–Boltzmann constant

η -Overall efficiency in a specific period of time

η_n- The efficiency value for normal incidence in the absence of optical losses through the gap between the receiver and the reflector.

η_{sp}- Capture efficiency (<1)

η_{solar} - Solar system efficiency (usually about 40%) τ_{cov} - Transmittance of any transparent cover utilized to shield the plate from the wind.

ρ- Density of materials

LIST OF FIGURES

CHAPTER ONE

INTRODUCTION

1.1 Background

Solar thermal collectors convert the sun radiation falling at a surface into thermal energy. There are two types of collector namely non-concentrating and concentrating as Kaplan observed in 1985. An example of non-concentrating collectors is the use of flat plate collectors and evacuated tube collectors. Muhammad et al. (2008) and Fareed et al. (2012) state that there are indeed many types of concentrating collectors, such as parabolic trough concentrators (PTC) and compound parabolic concentrators (CPC). The choice of a specific collector is dictated by its concentration level and the desired temperature to be achieved**..** The process of focusing solar radiation onto a singular point using a parabolic dish concentrator can yield temperatures ranging from 500°C to 900°C, and in some instances, even reaching as high as 3000°C. Parabolic trough concentrators, which focus solar radiation onto a linear receiver, generate temperatures ranging from 100°C to 400°C. Non-focusing solar collectors yield temperatures that can be both below and exceed 100°C. For example, unglazed mats functioning as low temperature collectors are employed in the heating of swimming pool water, while perforated plates serve the purpose of preheating ventilation air. Medium temperature collectors encompass glazed flat plate solar collectors, which are adept at heating water or air to temperatures reaching 80°C, as well as evacuated tube collectors that can achieve temperatures of up to 125°C (Zarza, 2002).

The process of heating water for household use represents a straightforward and efficient application of solar energy. The upfront investment for a solar water heating system is considerably substantial, yet it incurs no operational expenses. This represents a naturally occurring solar thermal technology. This system facilitates the conversion of incident solar radiation into thermal energy, which is subsequently conveyed to a transfer medium, exemplified by water. Solar energy stands out as the most proficient among alternative energy sources. A solar heater is an apparatus that harnesses solar energy to generate steam for both domestic and industrial uses. According to Khan et al. (2016), boiling water accounts for around 20% of a typical family's overall energy use. Solar water heating systems represent a cost-effective and readily accessible clean energy solution for homeowners, capable of supplying the hot water necessary for a household. Solar water heaters possess the capability to function effectively across diverse climatic conditions.. Different types of water heaters are shown in **Figure 1.1.**

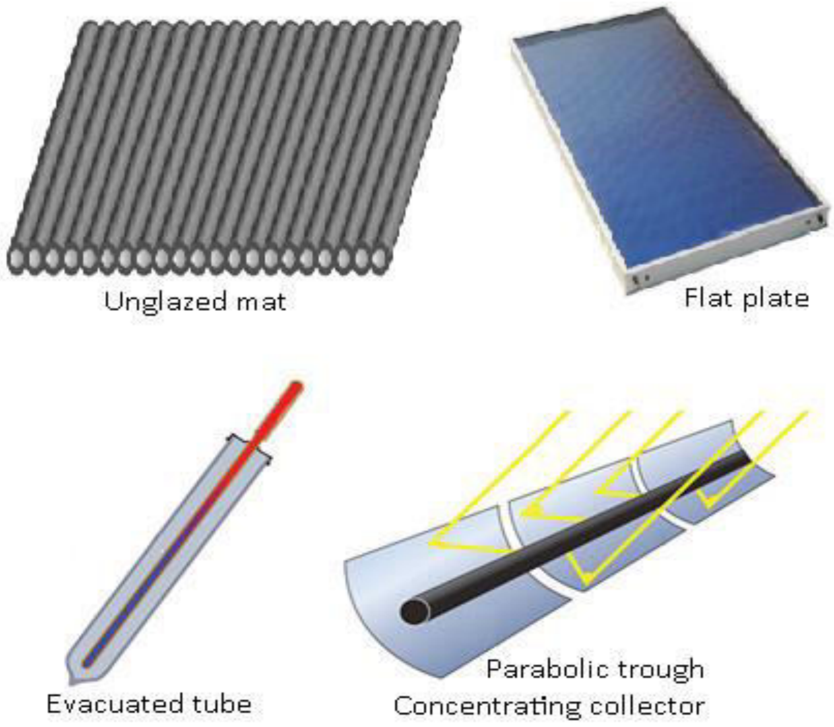

Figure 1.1 Different types of collectors, (Warui *et al*, 2017)

Non-focusing collectors are capable of absorbing both beam and diffuse radiation, thus maintaining functionality even when beam radiation is obstructed by cloud cover. The combination of this benefit, along with their operational simplicity and cost-effectiveness, typically leads to a preference for non-focusing collectors in the heating of fluids (Twidel and Weir, 2006).

Flat-plate solar collectors typically consist of three primary components:

A clear barrier that facilitates the transmission of solar energy while minimizing thermal dissipation from the absorber. The transparent cover must possess several essential characteristics to ensure the effective functioning of the collector. These include the ability to generate a greenhouse effect, minimize external losses, maintain a low thermal conductivity coefficient, and feature a clean external surface.

The collector needs to be properly sealed to inhibit the ingress of water and air into the system. The primary substances employed in the cover consist of glass and transparent plastic. Flat plate water collectors typically feature a single glazing, although they may incorporate an additional layer of secondary glazing. A more intricate glazing system allows for a greater temperature differential to be maintained between the absorber and the surrounding air.

A solar collector comprises a flat metal plate that captures and absorbs solar energy. Typically, an absorber plate should possess elevated thermal conductivity, such as that of copper, to effectively transfer the collected energy to the water while minimizing temperature loss. The absorbent layer captures solar radiation, which is subsequently converted into heat and then conveyed to the fluid designated for its transport.

The absorber layer can be made of two metallic sheets separated by a few millimeters as shown in **Figure 1.2**.

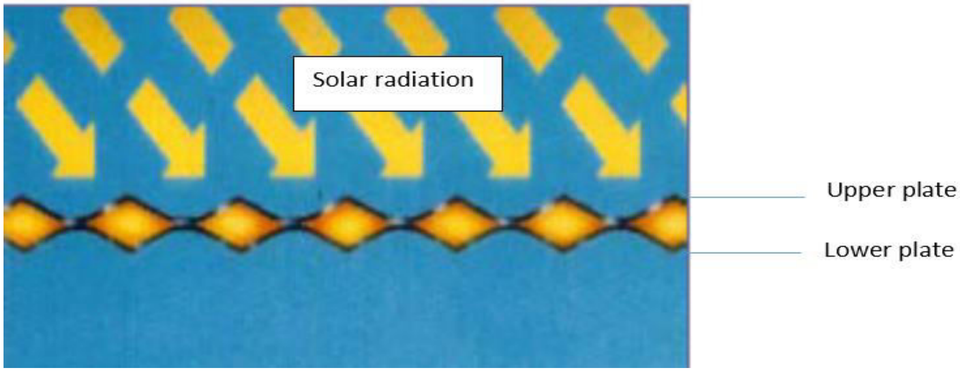

Figure 1.2: Absorbent layer made of metallic sheets, (Musunuri *et al*, 2007)

The absorbent layer can as well be made of a metallic sheet that contains several tubes that carry the fluid as shown in **Figure 1.3.**

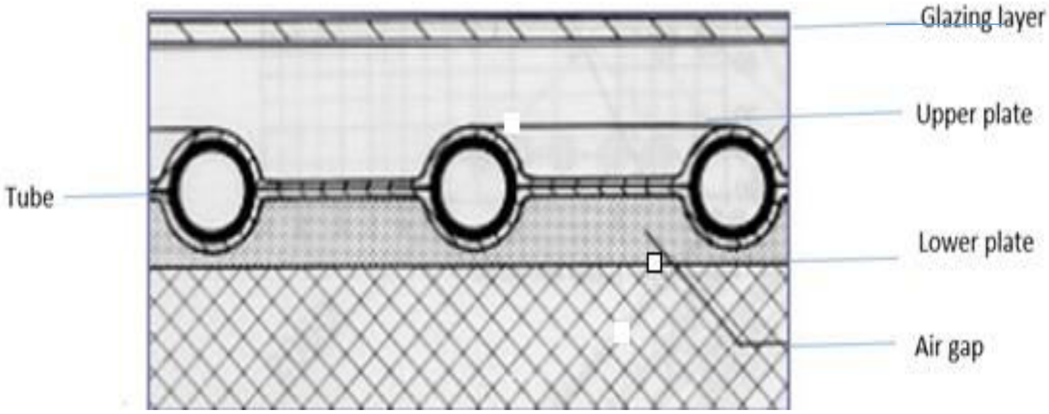

Figure 1.3: Absorber layer made of metallic tubes, (Musunuri *et al*, 2007)

The absorber may be coated with black paint or a selective surface treatment, such as black chrome. The black paint exhibits commendable absorption of solar radiation along with a high emission coefficient. Typical black paints exhibit a reflection of roughly 10% of the incoming radiation. Nonetheless, a black paint coating presents a more economical option compared to the selective material; however, it is prone to degradation due to exposure to ultraviolet radiation. A selective surface coating exhibits a significant absorption coefficient while maintaining a minimal emission coefficient. Consequently, solar panels that are treated with selective surfaces exhibit elevated absorptivity for solar radiation within the visible spectrum while maintaining reduced emissivity in the long-wave infrared spectrum, thereby effectively minimizing radiative heat loss. An insulating layer applied to the rear of the absorber serves to minimize thermal loss. The materials employed for this purpose are typically composed of fiberglass or polyurethane. The insulators exhibit several notable characteristics, including effective performance at approximately 150 oC, resistance to water, and a high degree of durability.

Solar water heating collectors feature metal tubes that are securely attached to the absorber. A heat-transfer fluid traverses the absorber tubes, proficiently extracting thermal energy from the absorber and subsequently conveying that energy to water housed within a storage tank. In warmer climates, solar systems intended for the heating of swimming pool water generally do not incorporate covers or insulation for the absorber. The water in the pool is drawn through the collectors, subsequently being recirculated back into the pool. The fundamental components of a glazed flat plate solar water heater are depicted in Figures 1.4 and 1.5.

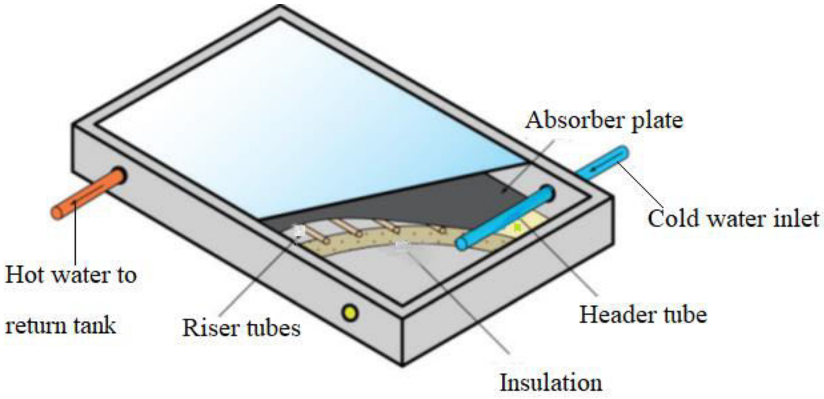

Figure 1.4: Components of a flat plate solar collector, (Foster *et al,* 2010)

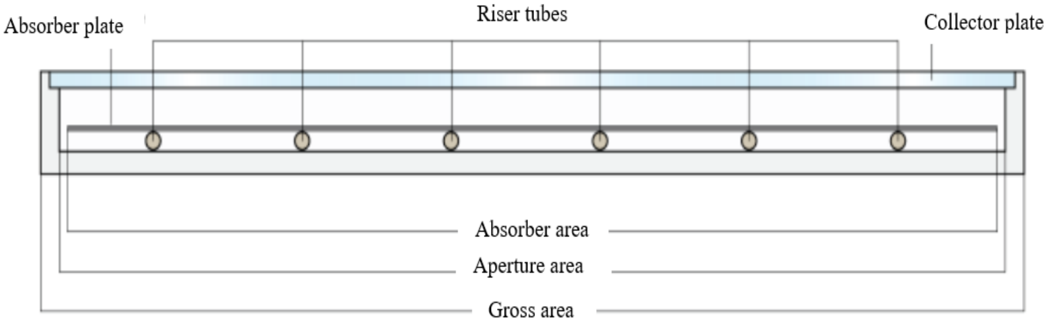

Figure 1.5: Cross-section of flat plate collector showing absorber, aperture and gross area, (Warui *et al,* 2017), (Musunuri *et al*, 2007)

The process of water circulation in a solar water heater occurs through natural convection, driven by the variations in density between the heated water and the cooler water. Solar water heating systems use collector panels to capture solar rays and convert them into useful heat, which can be used to increase the temperature of water.

Solar water storage combined with a solar collector reduces the amount of fuel needed to heat water used by people in their homes. Solar thermal can be used to provide space heating, as well as to provide hot water. Liquid passes through conduits attached on a dark metallic absorbing surface. The dish is contained within an insulated enclosure featuring a transparent panel that permits the entry of sunlight. The elevated temperature water is conveyed to a reservoir, rendering it accessible for residential, commercial, or institutional applications.

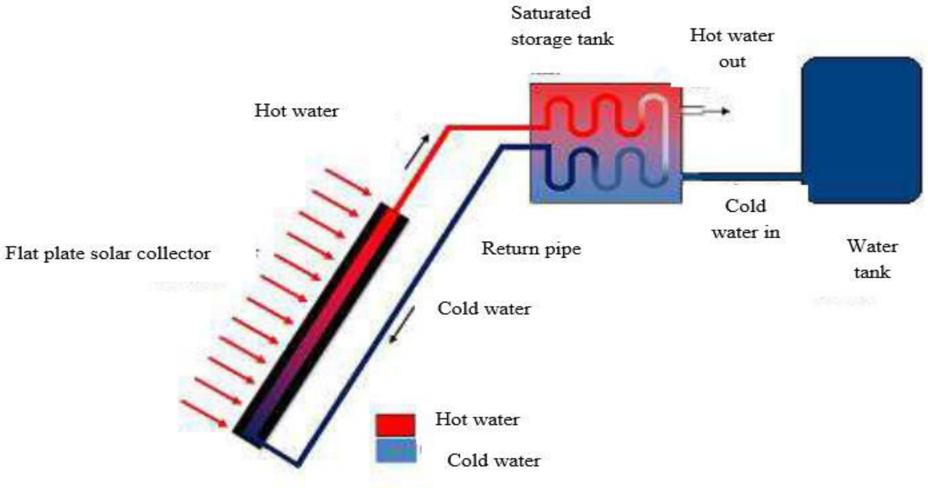

Figure 1.6: Block diagram of the heat exchanger based solar water heater, (Kumar and Jaurker, 2013).

Solar air heating systems blow air through building mounted flat plate collector and into building interior.

The technologies of thermal energy storage (TES) can be classified based on the storage mechanism, which includes the sensible heat, the latent heat, or the thermochemical energy. With respect to sensible heat storage systems, it may or may not be true that the storage medium can or should be a solid or a liquid. The hardware temperature of the storage medium can be adjusted by the logical arrangement of the storage.

The amount of energy stored is defined by:

$$E = mc_p\Delta\mathrm{T} \tag{1.1}$$

where E, m, c_p and ΔT The quantities in question are energy, mass, specific heat capacity, and the change in temperature, respectively.

Conversely, the solid-liquid phase change storage systems are known as latent heat storage systems and in consequence, the systems have become known as phase change materials (PMC). Most latent heat storage systems are designed to be deployed in solar power thermal systems, phase transition between solid and liquid are more favored to phase transition between liquid and gas because the space and pressure changes would be too considerable in the latter process (Fabio, 2013).

The LHS storage capacity Q_s, in J, with a PCM medium, is expressed as, (Tian and Zhao, 2013):

$$Q_s = \int_{T_i}^{T_m} mc_p dT + mf\nabla q + \int_{T_m}^{T_f} mc_p dT \tag{1.2}$$

$$Q_s = m[c_{ps}(T_m - T_i) + f\Delta q + c_{pl}(T_f - T_m)] \tag{1.3}$$

where T_m is the melting temperature, in °C; m is the mass of PCM medium, in kg; c_{ps} is the average specific heat of the solid phase between T_i and T_m in kJ/(kgK); c_{pl} is the average specific heat of the liquid phase between T_m and T_f in J/(kgK); f is the melt fraction; Δq is the latent heat of fusion, in J/kg.

Techmochemical storage Thermochemical storage (TCS) employs thermo-chemical materials (TCM), which store and release heat through a reversible exothermic/endothermic process, (Sarbu and Sebarchievici, 2018); Bruno and Noel, 2013; McLeske, 2009). TCS processes are sorption, adsorption, absorption and chemical decomposition. Sorption The fixation or trapping of a reactive gas by a condensed phase is referred to as sorption. When the condensed medium is solid the process is known as adsorption and absorption process when condensed medium is liquid. The overall thermochemical storage chemical reaction can be written as follows, (Stutz et al., 2016):

$$< S > +mG \leftrightarrow < SmG > +mHr \qquad (1.4)$$

There are varieties of the heats transfer fluids whose use depends on the geographical position of the water heat system. These include air, water, glycol-water, hydrocarbon oil, refrigerants or phase change fluid, silicon, molten sodium nitrate / potassium nitrate mixture, (Ataer, 2006). These heat-transfer fluids transport heat in solar collectors and on the heat exchanger to the heatstorage tanks in the solar water heating system.

When selecting a heat-transfer fluid, it is essential to take into account the following characteristics: The coefficient of expansion pertains to the changes in length (or, in certain instances, volume, when specified) of a material in relation to a unit variation in temperature. Viscosity is the measure of how difficult a liquid is to shear and it hence dictates the flow behavior of the liquid. Thermal capacity refers to how a substance can store the heat energy. The freezing point is a definite temperature where a liquid changes into solid state and the boiling point is a definite temperature where a liquid changes into a gas. The flash point is the point at which the vapor over a liquid can be ignited in the presence of air, but also considers the compatibility with structural materials, and the changes in conditions that can occur.

For instance, in a cold climate, solar water heating systems require fluids that possess exceptionally low freezing points (Basecq et al 2013). Liquids subjected to elevated temperatures, such as those found in desert climates, ought to exhibit a significant boiling point. The viscosity and thermal capacity levels dictate the energy required for pumping. A fluid characterized by high specific heat and low viscosity presents a more favorable scenario for pumping, as it encounters reduced resistance to flow and possesses a greater capacity for heat transfer (Ogonuriola et al, 2008).

Sunflower oil has been identified as an effective heat transfer fluid (HTF) and heat storage medium at moderate domestic temperatures, owing to its accessibility, non-corrosive properties, and compliance with food-grade standards (Mawire et al, 2015). The application of vegetable oils as sophisticated heat-storage mediums has been advocated, (Mawire and Vanierschot, 2023; Mawire et al, 2020; Hoffmann et al. 2018).

Sunflower oil has the following properties within a temperature range of 293.15-433.15K, density $\boldsymbol{\rho}$ of 919.6-904.7 kg/m^3: heat capacity c_p 2.124-2.700 J/gK, dynamic viscosity 63.941-3.166 mPas, thermal conductivity 0.161- 0.167, boiling point 229-230°C, freezing point −5°C, flash point 250°C.

It is important to note that sunflower oil mainly contains linoleic acid which has freezing point −5°C and boiling temperature of 229-230°C at a pressure of 16mmHg.

The varying percentage components of sunflower oil which are; oleic acid, stearic acid and palmitic acid affect its thermo-physical properties, (Edwin *et al*, 2013).

Effect of sunflower oil on heat loss and heat transfer parameters as a thermal storage medium in a flat plate solar water heater has not been studied. The suitability of sunflower oil in the solar water heater should investigate its effectiveness in heat transfer mechanism, thermal retention and the overall efficiency improvement in the solar water heating system.

1.2 Statement of the Problem

The solar water heater systems tend to suffer thermal losses due to the intermittent weather conditions such as the intensity of incident solar radiation, wind velocity and ambient temperature. Such conductive, radiative and convective thermal losses reduce precision of the output temperature and performance of solar thermal collectors. The solar thermal storage technologies lack an effective knowledge of how sunflower oil can be used in solar water heaters as thermal energystorage liquid. Sufficient information is also lacking on heat loss coefficient and heat removal factor of sunflower oil and water as a thermal storage media in solar water heaters. However, the parameters play a great role in thermal performance of solar water heating system.

This has impacted negatively on water quality that can be consumed by human beings. This pollution of water has been attributed to the dis job of sewage materials in water bodies like lakes and rivers, the contaminated dust particles in air as well as running off the surface during the rains. Introduction of this cold untreated contaminated water is causing great risk to health in the form of outbreaks of typhoid and cholera. Cold hard water has also brought about problems as it causes formation of scum when used to wash clothes.

The domestic and institutional use in Kenyan schools, colleges and Universities and business premises such as the hotels have a high hot water demand. As a result, this has resulted to excessive use of fossil based fuels and firewood whose consumption has destructive environmental degradation effects like deforestation and global warming, as a result of high emission of carbon IV oxide. Electrical energy is also expensive to use in water heating to its many inhabitants. The described issues can be solved within the context of effective utilization of solar-thermal energy conversion and storage on the basis of solar water heaters using relevant thermal storage media.

1.3 Significance of the Study

Utilization of thermal storage and heat transfer fluids such as sunflower oil and water can greatly improve the overall efficiency of solar water heaters. It is therefore important to assess the impacts of the thermal storage fluids on the thermal performance parameters of a solar collector. These parameters entail output temperature, heat loss and heat exchange features. The study on solar thermal storage is useful in obtaining suitable output temperatures from the solar heaters during low solar radiation periods and at night. Investigation of thermal performance and thermal energy storage comparative study of sunflower oil, water and air will provide useful information on the choice of such fluids for thermal energy storage in solar water heaters. Solar water heating systems reduce energy costs associated with water heating and promote the use of clean energy, hence leading to economic and environmental conservation benefits.

The results from this study will therefore be useful in continuous provision of cheap safe hot water for domestic, institutional and commercial uses.

1.4 Objectives

The main objective of the study was to compare the thermal storage capacity parameters of a flat plate solar water heater using sunflower oil versus water as thermal storage fluids. The specific objectives were to:

i. To determine instantaneous receiver heat gain by the solar collector and compare the thermal storage effect of water and sunflower oil on output temperatures from a flat plate solar collector.
ii. To evaluate the effect of water and sunflower oil on heat loss and heat exchange parameters of a flat plate solar water heater.
iii. To compare the overall system efficiency when using water versus sunflower oil as thermal storage media.
iv. To compare and anayse the KOLEKTOR 2.2 simulation results with the measured experimental data.

CHAPTER TWO

LITERATURE REVIEW

2.1 Flat Plate Solar Collectors

Solar water heaters demonstrate a remarkable ability to significantly lower annual operating expenses by 50% to 80% by harnessing the abundant energy provided by the sun. This resulted in the creation of thermal solar systems designed for use in residential settings, with an emphasis on space heating applications. A thermal solar collector that is both economical and incorporates Direct Heat Storage (DHS) has been developed (Steinmann, 2015; Kazimierz, 2005). When a surface engages with a fluid that has a bulk temperature differing from that of the surface, a heterogeneous temperature field emerges. The fluctuations in temperature across this domain lead to changes in density, which can, via buoyant forces, cause the fluid to move in relation to the surface, thereby promoting heat transfer in a phenomenon referred to as natural convection (Witter, 2005).

The development of the flat plate collector for water heating dates back to 1767, credited to Saussure, as referenced by Iksan et al. (2023) and Faudi and Kerswani (1973). Nevertheless, the utilization of flat plate collectors experienced considerable growth during the 1900s throughout the United States, especially in California. According to history, the flat plate solar thermal collector was first envisioned in the late 1950s by Hottel and Whillier. This solar collector is a good example of a simple design to produce and has received great popularity in the current market. It consists of a dark flat plate absorber, a transparent glass cover, a heat transport fluid and insulation attached to the backside. The medium passing through the absorber tubes may be divided into two basic types: gaseous fluids and liquid fluids. Air-based collectors are commonly employed for the purpose of heating structures and facilitating the drying of agricultural commodities. Collectors employing liquid can be classified into two distinct categories: glazed and unglazed. Liquid-based collectors are generally utilized for the purposes of domestic water heating and space heating applications, (Horace, 2019).

Maatouk, 1987, conducted an examination of the characteristics of optical materials and coatings, concluding that a low emittance coating material for glazing is essential for minimizing radiative loss from the upper surface of the flat plate collector to the atmosphere. Furthermore, he advocated for the use of selective coatings over nonselective ones for the absorber plate to enhance the performance of solar collectors. It is imperative to consider additional thermal losses resulting from both conductive and convective mechanisms that warrant attention.

The primary function of a thermal storage fluid in a solar water heater is to safeguard the system and its users against the extremes of overheating and freezing. Although numerous technologies exist that facilitate draining or passive heat loss, particularly during low-temperature periods for direct systems, a significant technological advancement is the emergence of indirect systems. Flat plate solar thermal collectors incorporate pipes designated as headers and risers, which vary in size and orientation to enhance heating efficiency, (Kainth and Sharma, 2015). These systems are typically employed as direct mechanisms for heating potable water and frequently incorporate tempered glass to endure the impact of storm debris and hail. Among these systems are evacuated tube collectors, which employ a vacuum along with various materials to minimize heat loss. Although the reduction in heat loss can be considerable, the evacuated tube collectors (ETC) demonstrate diminished efficiency in direct sunlight applications and have encountered reliability challenges (Philip, 2014). Consequently, the advocacy for the utilization of a flat plate solar water heater warrants significant emphasis.

2.2 Use of Thermal Storage Fluids in Solar Collectors

Orange peel flat plate solar collectors have been adapted on thermal storage technologies which include; a, b, c, d, e, f and j.

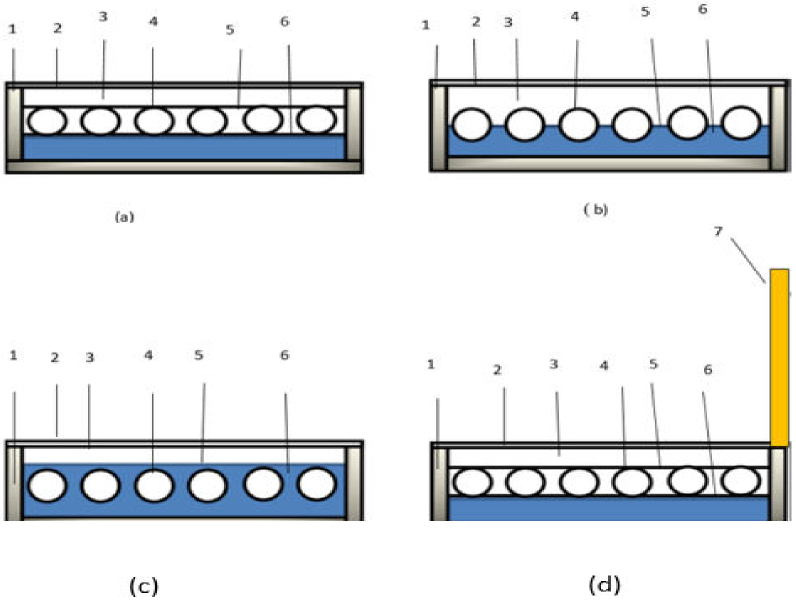

Figure 2.1: Schematic representation of a flat plate solar collector with TSF in thermal storage technologies, (Faud and Kerswani, 1973)

where: (a) below tubes, (b) half perimeters of the tubes, (c) immersed tubes, (d) with reflector, (1) insulation, (2) glass cover, (3) air space, (4) tubes, (5) absorber plate, (6) TSF, (7) reflector.

In 1985 the first large-scale project using flat plate solar collectors and water as a thermal storage resource was set up in Nykvarn, Sweden. In this project, the presence of a large A_c of 7500 m2 and a large water storage tank of 1500 m3 was also an impressive feature. The storage tank temperature was between 55^0c and 90^0c. According to Marshall and McLeskey (2009), the optimum storage volume of water to maintain a square meter of is about 100 liters of water. However, it is justified to investigate the heat loss coefficient and the heat removal factor of water as a thermal storage fluid. There is a need to investigate ways of improving the thermal efficiency of flat plate solar water heaters especially during periods of low solar radiation intensity.

With solar collectors, solar radiation energy received on a surface can be converted into thermal energy. A medium-temperature device that is designed to heat water or air up to 80^0 C is called a glazed flat plate solar collector. Another easy and efficient way of harnessing solar energy is through domestic water heating. The weather conditions largely influence the temperature of the output water of the solar heater. The features, complexity and size of a solar water heating system are largely influenced by the changes in ambient temperature and solar radiation during various weather conditions. Therefore, there is the need to utilize thermal storage fluids like sunflower oil because it has already been established as an efficient heat transfer fluid (HTF) and a heat storage medium in residential medium-temperature applications because of its availability, non-corrosive nature, and non-toxicity.

The remaining experimental reports of the effect of cloud cover on the efficiency of the storage collection apparatus were carried out in different weather conditions. The observations described a sunny January day when the average solar radiation was 698 Wm-2 and average ambient temperature was 11.59^0 C; a sunny January day when the average solar radiation was 701 Wm-2 and the average ambient temperature was 24.84 C and a partly cloudy day in March when the average solar radiation was 747 Wm-2 and average ambient temperature was 24.5^0 C. The research findings indicated that the storage-collector system discharged energy at about 14: 30 in January, 16: 00 in February and 17: 00 in March. The storage-collector was more effective on a semi-cloudy day than on a clear day, as the temperature of the phase change material was higher than the one of the absorber plate (Khalifa and Jabbar, 2013). The results of the research make it very clear that weather conditions largely determine the output temperature of a solar collector. Through the use of thermal storage media, the efficient management of this can be attained.

The mode of enhancing the heat transfer mechanism by using highly porous aluminum foam mixed with paraffin has been explored. A second serpentine conduit was also added to the phase change material at night to enable it to release solar energy stored in daytime. This situation was investigated by the numerical analysis of the temperature distributions in an integrated PCM solar collector with and without the existence of aluminum foam. The findings revealed that the performance of the heat transfer can be highly enhanced when paraffin-impregnated aluminum foams are involved as was reported by Chen et al. in 2010. As shown in this paper, paraffin wax is effective when combined with aluminum foam. The uses of other thermal storage fluids are also worth considering.

In 2010 an experimental project was conducted to use sodium carbonate dicarbohydrate (Na 2CO 3 10H 2 O) as a phase change material in solar collectors. This collector performance was compared to the traditional system that did not feature PCM. The performance of the collectors were predicted based on experimental evidence by different computational models. Such models include artificial neural networks (ANN), adaptive-network-based fuzzy inference systems (ANFIS), and support machine learning (SVM). The results show that the thermal storage collector is very efficient compared with the conventional systems. In addition, Varol et al. (2010) declare that the SVM model was more precise in its capability to forecast the system performance as compared to ANFIS and ANN. Despite the efforts to improve the performance of solar collectors by incorporating the phase change material, the actual readings of heat removal factor and the heat loss coefficient of sodium carbonate dicarbohydrate as a thermal storage media in solar collectors were not recorded.

Paraffin as a phase change substance is of interest in the analysis of a storage system. This system was integrated on the absorber of a flat plate solar collector that is two cavity of rectangular shape. Four days spent in Tunisia determined the thermal efficiency of an integrated storage collector that has been developed to utilize latent solar energy. The influence of the collector inclination as well as the impact of heat flux on the liquid fraction and the solid liquid interface of the phase change materials were also studied using numerical modeling. We found that the total energy efficiency of this collector in the experiment was approximately 27 per cent less than the efficiency standards of commercial solar water heaters. However, as it was shown by Boudila et al. (2013), the phase change material is far more efficient to improve the capabilities of solar collector during the night. To attend to the performance characteristics of the phase transition materials and sensible heat storage fluids, an extensive study is required.

A flat plate solar collector with paraffin attached directly to the back of the absorption plate allows storage of thermal energy. The absorption plate increased the surface area of PCM reservoir and hence increase the area of heat transfer. Experimental effects of phase change materials on the behaviour of a solar water heating system which consisted of a rectangular cavity were also analysed. It also analysed the influence of mass flow rate and the tilt mechanism of the collector on the overall performance of the solar collector. The calculated values indicated that the efficiency of the storage-collector unit is 52.72 and the required temperature of the hot-water is 38.1 degrees to fulfill the daily output of 0.5kg/min flow rate and pressure of 101 to 201. Thus, the technology is simple to integrate the traditional solar collector without or very minimal costly modifications being made (Lin et al, 2012). The research has also failed to analyze the heat loss coefficient and the heat removal factor of paraffin wax in parallelogram solar water heater.

A solar collector is heated with electricity to warm water using a phase change material known as paraffin. In field experiments, the influence of rate of water flow and the impact of the solar energy in the process of melting and solidification of materials in the phase transition was investigated. The thermal energy was emitted to the phase change material by a copper rod inserted in the center of the PCM box, with the same distance to the walls of the PCM box and with the same thickness of the PCM material that covers the rod. Consequently, the findings revealed that the amount of useful heat obtained was considerably improved with an increase in the rate of water mass flow as indicated in the study conducted by Mettawee and Assassa (2006). The experiment would have helped to explain how the water flow rate influences the temperature generated at the outlet of a specific solar water heater.

The use of phase change materials in the solar collector of domestic hot water systems was studied in 2007. It is made up of two rectangular cavities. Figure 2 shows that PCM was placed in the lower cavity and water in the upper cavity. The collector was covered with a clear insulating substance.

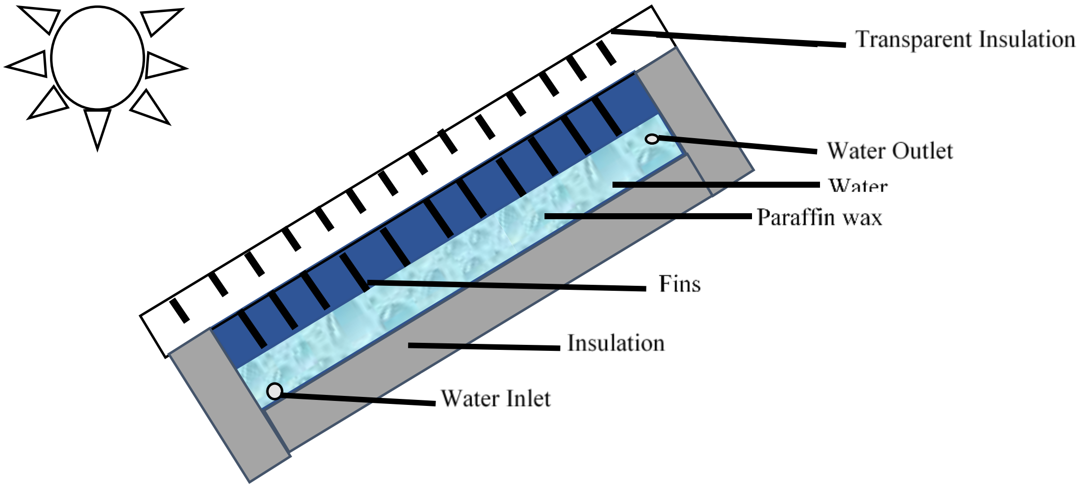

Figure 2.2: Integrated-collector-storage solar water heater with fins inside the wax, (Reddy, 2007)

The aim of the investigation was to enhance the thermal efficiency of the storage collector by examining the effect of different fin designs by attaching them to the phase change material using different pitches to enhance the efficiency of heat transfer. These results indicated that nine-fin thermal efficiency was greater than the no-fin thermal efficiency as indicated by Reddy in 2007. The heat loss coefficient and heat removal factor of the thermal storage fluids of solar collectors with different fin configurations was not studied in the paper.

The impact of different mass flow rates of collector tilt angle and an HTF on the thermal efficiency of the storage-collector system was reported in detail in 2012. The researchers did not overlook the weld of 37 fins beneath the absorber plate of the solar collector containing phase change material (PCM). These results indicated that the hot water outlet reached the maximum temperature at 10^{o} tilt rate of 4 kg/min (Lin et al 2012). No comparative analysis was conducted in this study to identify the thermal effectiveness of the phase transition materials over other fluids that are utilized in sun water heating systems.

The impact of the phase change materials on the performance of a solar residential hot water system has been assessed using a three-dimensional numerical model. Storage collector is a compound parabolic focusing reflector and a cylindrical storage tank. Fig.2.3 Phase change medium is physically enclosed on the receiver tube. Two types of phase transition materials (RT-42 graphite and myristic acid) were investigated and three layers of phase transition materials were examined. The findings revealed that the thermal energy contained in the phase transition material myristic acid was stored in the collector compared to that stored in the sensible storage unit during the day. The

PCM storage unit is, on the contrary, more effective at nocturnal hours to both kinds of PCMs.

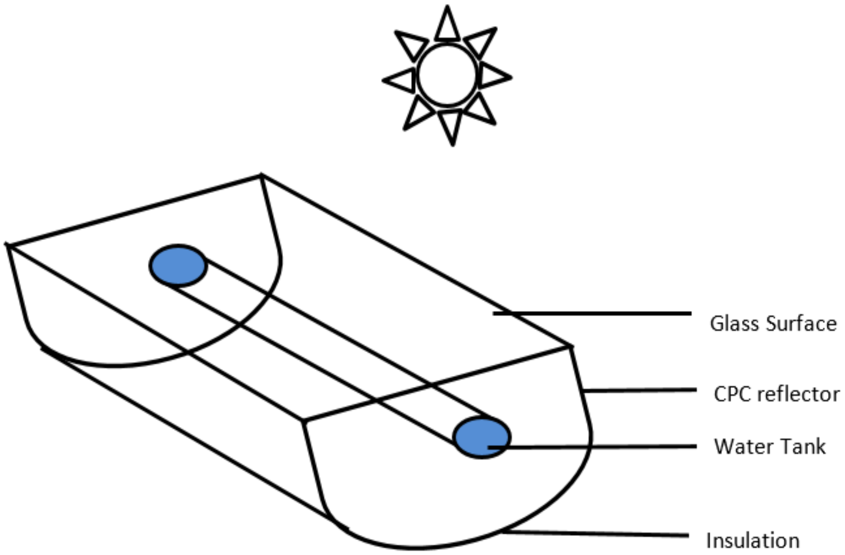

Figure 2.3: Cross-sectional schematic of the compound parabolic concentrating collector integrated with PCM, (Chaabane *et al* 2014)

The heat loss coefficient, heat removal factor and fin efficiency associated with the phase change materials integrated into the compound parabolic concentrating collector metrics have however not been explored.

Research into thermal storage has considered the use of paraffin wax in a new type of cylindrical evacuated system of solar collector. This is a system that will always provide hot water, irrespective of the unpredictable weather patterns, such as those times when the sun radiation is low. To determine the levels of performance in five different cases, the researchers performed an experiment that utilized the solar collector without PCM as a control group. There were four samples used in the experiment with varying proportions of the constituents of phase change viz. 23.43 and 57.6 by volume paraffin and 25.28 and 100 by volume water which was used as thermal storage medium. It was discovered that water is capable of retaining and then releasing thermal energy in a far superior manner. According to Riffa et al., the thermal efficiency was at a peak when the evacuated solar collector tubes were full of partial volume of water, as was the case in 2006. The heat loss coefficient of flat plate solar heaters with a different percentage of paraffin has to be analyzed as this field of heat transfer has not yet been examined in the given work.

PCM incorporation into a flat plate solar collector, which is used to substitute the collector absorber, has been investigated to assess the performance of the DHW system using PCM. To increase the incorporation of the phase change materials in the solar collector, the scientists incorporated four kinds of phase change materials, sodium acetate trihydrate, RT 65 paraffin, stearic acid and penta glycerin. Additionally, they had studied and reviewed all the physical properties of the different phase change materials like thermal conductivity, absorptivity, storage capacity and longevity of the PCMs. The findings indicated that the properties of three of four composites would be appropriate to be implemented into the solar collector other than sodium acetate trihydrate (Haillot et al, 2011). The most important thing is to consider the highest effective temperature of the output of the solar water heaters, considering the fluids used as thermal stores in the analysis..
Haillot et al. (2012) conducted a quantitative evaluation of the introduction of phase change materials in solar collectors, to optimize the performance of the household hot water system, and the choice and production of the materials. The researchers decided

to use compressed and expanded natural graphite with RT65 composites to improve the thermal efficiency of the home hot water system. Further, they were able to offer empirical data to test the numerical model. The findings revealed that the efficiency of the system increased during summer weather, and reduced during winter (Lin et al, 2012). Although this study has produced valuable results, it has failed to test how the heat loss coefficient and the heat removal factor of the solar heater would respond to changing weather conditions.

A mathematical model was also designed to investigate the effects of PCM-slurry on the efficiency of a flat plate solar collector and to compare the efficiency with a normal solar collector. This finding showed that the increase in solar collector efficiency was dependent on the prevailing boundary conditions and climatic parameters. Furthermore, the increase in instantaneous efficiency ranged between 5 to 10 per cent, but the efficiency of the PCM-slurry solar collector increased by 20 to 40 per cent in comparison of the traditional water-based solar collector (Serale et al, 2014). But, the thermal efficiency of a flat plate solar collector using PCM-slurry along with other sensible heat storage fluids (like sunflower oil) has yet to be conducted with a comprehensive comparative analysis.

The effect of PCM concentration on thermal storage has been evaluated by loading the rectangular solar water heater with water and different (10%, 15%, 20%, 25 and 30) concentrations of PCM slurries. A simulation model was created to investigate solar collection efficiency of the integrated solar heater storage collector by using water and water-PCM slurries. The results showed that a solar water heater with water has a slightly better ability to absorb heat than the water-PCM slurry system when used in the PCM storage system (Eames and Griffiths, 2006).

The thermal efficiency of a flat plate solar collector using PCM-slurry and various vegetable oils including sunflower oil shall be compared. There is an exploration of the combination of a solar collector with salt hydrate. The high density stationary heat transfer oil-based material that had a density superior to that of the liquid phase change materials was observed to be in contact with a layer of immiscible PCM. To the one of the metal plates, the researchers applied an optional HTF coating, which increased its ability to absorb solar energy. The radiation penetrated the plate, the oil and the phase change material. A reflector in the form of an infold is better at collecting solar energy during charging, and then release it into a finned channel on a heat exchanger as shown in Figure 2.4. This reflector was also used as a shield to reduce heat losses at the moment of discharge (Chaabane et al., 2014).

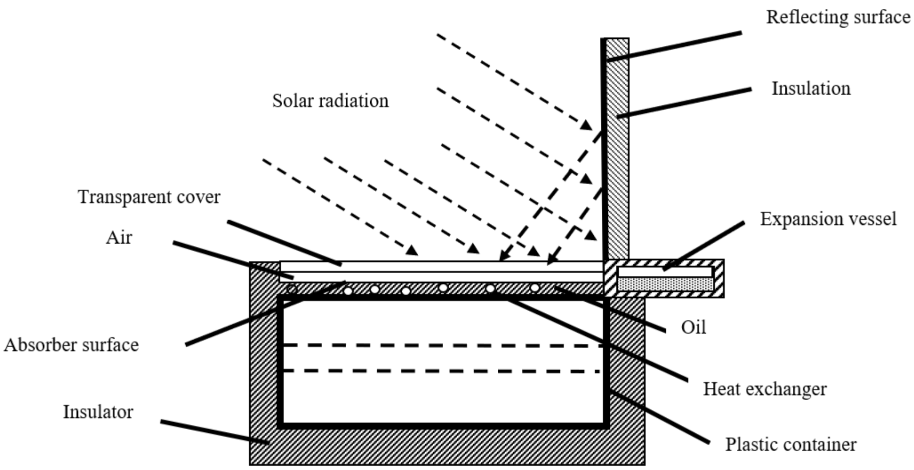

Figure 2.4: Schematic diagram of the integrated solar collector storage system based on a phase-change material, (Rabin, 1995)

According to the results, the transition phase change temperature lies between 15 and 35 degrees Celsius, and the PCM layer thickness of 20-100 mm makes it suitable in heating greenhouses. The abovementioned aspect had not been adequately considered when forecasting PCM heat flow, particularly concerning the heat losses and retention issues in the heat flow study method.

Later investigations of thermal storage using phase change materials reused the new technique of inverting a solar collector, a PCM filled storage tank purposely placed below it. The PCM was charged using a special HTF (Mobilterm 605), and the heat transfer to the PCM was facilitated by the solar collector. The serpentine copper tubing, which is supposed to dissipate heat was pumped through the phase change material using water as shown in figure 2.5. The authors experimentally studied the energy and exergy of the system when charging the system. The net energy and exergy efficiencies presented in this paper are 45 percent and 2.2 percent, respectively..

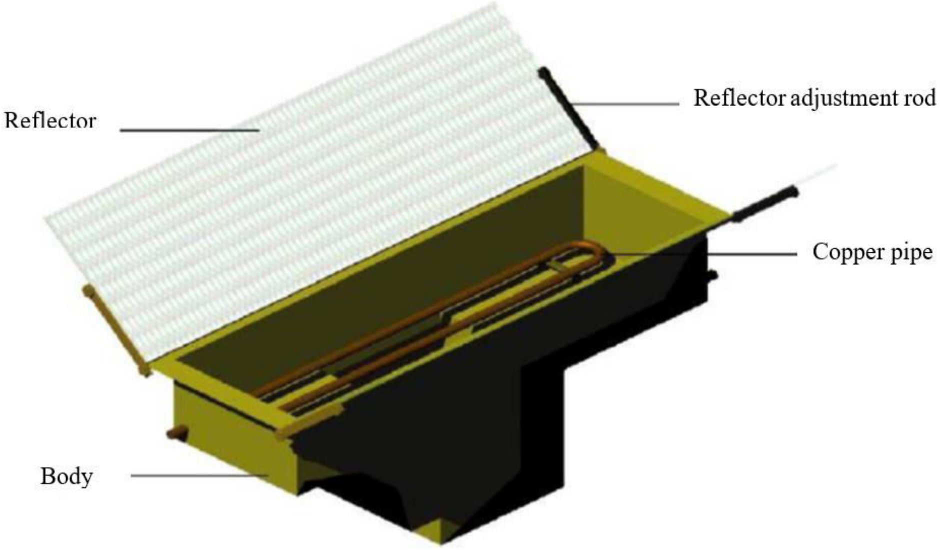

Figure 2.5: Solar collector with a PCM filled storage tank**,** (Koca *et al*, 2008).

The impact of sensible heat storage fluids, such as sunflower oil, on the energy and exergy efficiency of solar collectors with analogous configurations warrants investigation.

Extensive experimental and modeling research has been conducted on flat plate solar collectors, as will be demonstrated in the subsequent subsections of this chapter. The differentiation between experimental and modeling work is not absolute, as some researchers conducted both and reported their findings in a single study. Consequently, the modeling subsection will reference experimental work, whereas the experimental subsection will discuss modeling work.

2.3 Experimental Work

In the study carried out by Maatouk (1987), the transmission of radiative and conductive heat through single and double windows and their thicknesses was investigated at different temperatures. The higher the quantity and thickness of the glazing, the lower the heat flux through the glazing at high temperatures. The investigator puts this down to the greater emissivity of the plate absorber at higher temperatures, which the investigator has overcome by adopting double glazing (Maatouk, 1987). The impact of the thickness of the glass on the heat loss coefficient of flat plate solar collectors is not considered in this work.

Tasdemiroglu (1991) did an in-depth analysis of the experimental assessment of space heating, Ankara, Turkey. This experimental work involved a design of a two plate collector series, a layout of liquid to liquid heat exchanger, storage tank, liquid to air heat exchanger, two circulation pumps and a few valves. Thermocouples were used to measure temperatures systematically using a digital multimeter. This included the fluctuation of temperatures at the interfaces of the main system, the temperature of the surrounding rooms, and the temperature of the world outside. The quantity of solar energy the collectors captured was also measured. The data was taken over a period of seven months, between October 1988 and April 1989, during which thermal performance was measured and thus daily efficiencies of 36 and 45 percent of direct and indirect modes were obtained, respectively (Tasdemiroglu, 1991). This piece of work ought to have examined how thermal energy can be preserved in solar water heating systems.

Abubakar and Egbo, (2014) conducted an experimental study of the thermal efficiency of the solar flat plate water heater (Model TE 39) within the climatic conditions of Bauchi (latitude: 10.50 C N, longitude: 10.00 C E).

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The experimental setup was as shown in **Figure 2.6**.

Figure 2.6: Experimental set up for Performance Evaluation of Flat Plate Solar Collector (Model Te39, (Abubakar and Egbo, 2014)

The fluid temperature was measured at the input and outlet of the collector at five-minute intervals. The experiment was conducted daily from 11:00 to 13:00 hours for a length of 28 days. The findings indicate that the output water temperatures were influenced by the prevailing weather conditions, particularly solar radiation intensity and cloud cover, with the collector attaining peak efficiency of 70.5 percent at 12:05

PM. This indicates that employing this flat plate solar collector for residential heating in the climatic circumstances of Bauchi will be efficacious.

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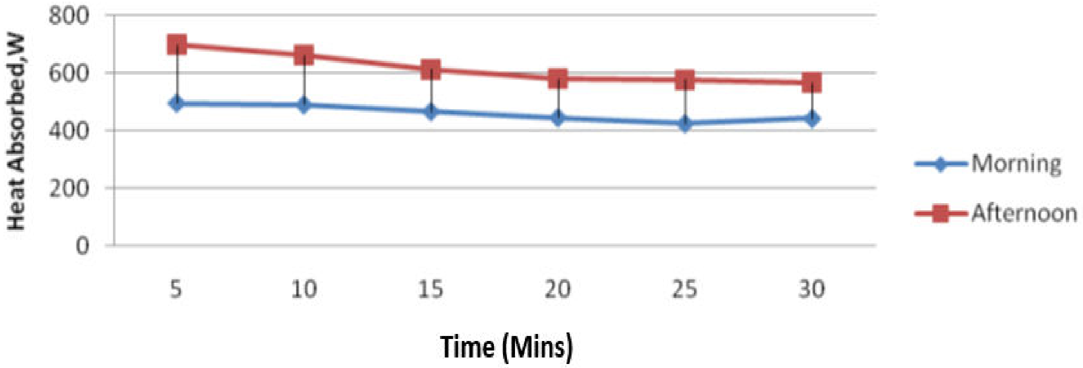

Figure 2.7: Relationship of Heat absorbed and Time of the day (1100-1230), (Abubakar and Egbo, 2014)

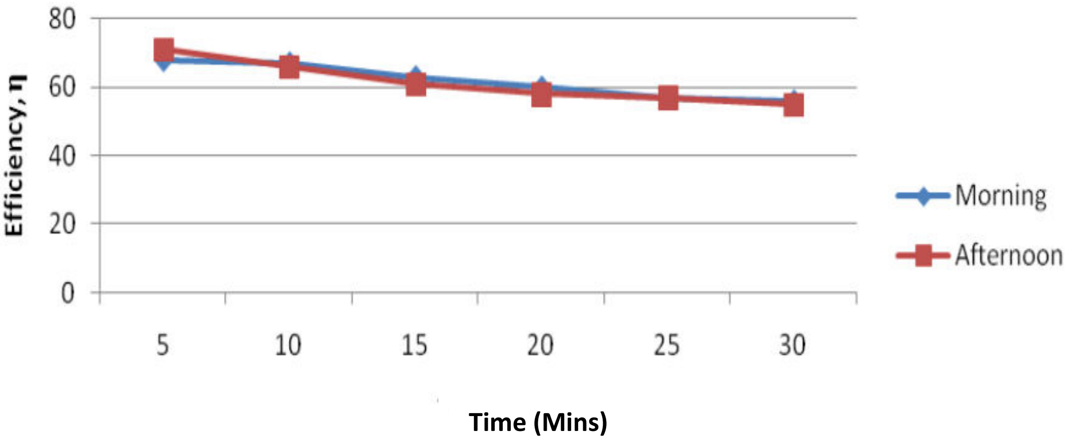

Figure 2.8: Relationships between efficiency with time of the day, (Abubakar and Egbo, 2014)

Figure 2.8 shows a close picture of the efficiency of the flat plate collector, based on the experimental data recorded in the morning (11:00-11:30 AM) and the afternoon (12:00-12:30 PM). The plate collector with the maximum number of points was 70.5 and the least was 55.9. It was observed that the efficiency of the collector was highest at the beginning of the experiment and it declined slowly with time. The difference in temperature between the outlet and inlet fluids of the collector decreases, and this decreases the amount of heat that the collector absorbs and thus decreases the performance of the flat plate collector. The morning performance of the flat plate collector is far much better than the afternoon performance (Abubakar and Egbo, 2014). Therefore, it is now acutely needed to find methods of improving thermal efficiency of flat plate solar collectors through the use of thermal energy storage technologies.

In 2015, the effectiveness of flat plate solar panels with tracking system was estimated in the region near the city of Shtip by means of experimental construction. The aim of the investigation was to establish the performance of a solar monitoring device. These two fixed flat plate solar collectors consisted of single fixed unit and another rotating at 30 degrees south with dual-axis. The findings of the experiment revealed that the energy gathered by the mobile collector improved significantly on daily basis when compared to the one gathered by the fixed collector. The two-axis tracking system collector demonstrated a substantial increase in performance, as the gain peaked over 20 percent in the afternoons of March and April. The complex computational fluid dynamics (CFD) model proved to be highly consistent with test results in the setup with the fixed collector as reported by Chekerovska and Filkoski in 2015. Besides tracking, it is also required to analyze the impact that changes in weather conditions have on the thermal performance of flat plate solar collectors, and the ways the heat produced in the solar collector system can be retained..

In 1977, a flat plate solar collector was subjected to a number of experimental research works. During this period, a building was designed at the technical university in Denmark to enhance the effectiveness of heating during winter days and to utilize the sun as the primary heat source. The insulated walls helped to ensure that the house was using 2300 kWh of energy per year to heat the house. Even year-round hot water will be provided by a flat plate collector heating system. The size of the flat plate collector was 42 m the 2 and it was connected to an insulated 30 m 3 water tank. The radiation that is absorbed by the solar collector and the amount of energy retained in the tank were calculated using an advanced model computer. The inputs included wind speed, ambient temperature and solar radiation that year, which were then used to estimate this parameter at each hourly time. Great care was taken to drain the water in the collector to avoid the chances of the panels being frozen in extreme cold weather and cloudy days. The complete consideration of the total heat balance of the residence indicated that 7300 kWh of energy had accumulated throughout the year; 30 percent of this energy was allocated to space heating, 30 percent to water heating, and the rest had been wasted as heat in the accumulator tank (Esbensen and Korsgaard, 1977). This paper failed to express the spectacular output of flat plate collectors in the form of instant usable heat energy and performance.

In 2005 a study project was conducted to determine the efficiency of nontraditional solar water heating system using nontraditional working fluid. The experiment has been conducted using a well-designed flat plate solar panel that remained fixed during the experiment. This was fixed with an exchanger that was installed in a water storage drum. The operating range of the collector at lower temperature was between the ambient temperature and 10^0C. The alternate working fluid has been defined as acetone, which circulates in a closed-loop system. The heat exchanger was made in this system to allow the efficient exchange of thermal energy between water and acetone. There were minor changes in the intensity of the sun over the day; at 8.30 am the sun had an intensity of 550 W/m2, at noon the sun had an intensity of 850 W/m2, and at 6.00 pm, the sun had an intensity of 640 W/m2. The absorber plate temperature did not change significantly during the early hours but went up to 90 C during two hours and settled at 72 C in the afternoon. The maximum temperature of the acetone was reached at 1:00 pm to 2:00 pm. The temperature of the water was significantly changed and it increased to 62 C. This equipment was able to achieve a total efficiency of 45 percent when water was used as the working fluid in the collector. These findings suggest that future systems would benefit through the use of alternative working fluids with high latent heat of evaporation and low boiling point, including acetone, methanol or ethanol, to operate solar collectors (Manickavasagan, 2005). The heat loss coefficient and heat removal factor of acetone, methanol, and ethanol as thermal storage fluids were not studied in this paper.

Research has been done on the design and the materials used in the construction of a thermal solar panel. Cross-corrugated absorber plate was experimentally investigated in detail, with an exhaustive mathematical analysis. This solar heat panel is made up of two plates; the top plate has a wavy shape just like the bottom plate. The lower plate was laid perpendicular to the direction of air flow in order to maximize the efficiency of heat transfer. The conclusion made after assessing the thermal performance of these plates was that the use of selective coating and glass coverings would not give any favorable results (Lin et al, 2006). There is a need to explore methods of enhancing thermal energy storage in the solar collectors.

Newer developments have been achieved in developing a solar system comprising a solar panel and a newly developed tracking system. The setting of this system was where there was cloudy weather. The non-tracking solar panel did not have the same energy acquisition and efficiency as this tracking option. The three orientations of the panels were assembled in a new experimental methodology (Ayoub 2012). This study, conducted by Zhong and his colleagues in 2011, involved the calculation of optimal performance and a theoretical analysis of the system through a mathematical model that was introduced by Ayoub as cited by Shariff et al. (2014).

This experiment has not considered other environmental factors, such as wind speed, solar radiation level and the tracking angles that affect the performance of solar panels.

One study (2010) examined the thermal efficiency of solar water heaters using coconut coir, a locally available plant material in the tropical areas, as an insulating material. It has investigated the relative thermal efficiency of this collector compared to another, which are similar in construction and design, and which operated under the same conditions. This experiment used glass wool as thermal insulation material, and eight additional randomly selected designs that used a variety of materials as heat insulation, with reference to performance data provided by literature sources. The production cost of coconut coir collector in material is one-fourth of the glass wool collector. The results of the study show that the collector with the use of coconut coir is safer in terms of thermal performance than the conventional models, as reported by Andoh et al. (2010). It is important to note that other vegetable products like vegetable oil can also play a very important role in thermal energy conservation in solar water heaters; hence, additional research is required.

In 2011, a detailed study was done regarding the hybrid solar thermal panels on experimental basis. These hybrid collectors were able to convert a fraction of the solar energy entering it into electricity, and simultaneously convert the rest of the energy into heat. It was a more efficient hybrid system than traditional thermal panels, or photovoltaic panels. There are two types of solar panels, PVT-A which consists of one crystalline silicon solar cell fabricated on a complex flat plate heat exchanger and PVT-B which consists of an absorber assembly of square copper channels with Cd-Te. Then it was put in a frame and referred to as a solar collector. This represented a new architecture attached to a home solar water heating system. The aim was to calculate the performance of hybrid collectors in relation to a traditional one (Dupeyrat et al., 2011). The paper is a fairly extensive study of solar thermal panels which can be developed to include photovoltaic systems. Moreover, thermal storage material can be added to enhance performance of thermal energy by solar panels.

In 2013 a research study was published with the title of Thermal Performance of Two Phase Thermo-syphon Flat-Plate Solar Collectors using Nano-fluid. In this study, design and development of a solar heat pipe collector were considered in order to determine its functionality in actual outdoor testing. The thermal performance of the wickless heat pipe solar collector was evaluated using pure water and nano-fluid of different concentration of carbon nanotube (CNT) contained nano-fluid (0.15% by volume, 0.45% by volume, 0.60% by volume, and 1% by volume) and changing the tilt angle (20, 32, 40, 50 and 60 degrees). In the experimental work, CNT nanoparticles of the type 10-12nm in diameter and 0.1-10 micrometers in length were used. Figures 2.9 and 2.10 show the schematic test beds that are related to the solar collector as well as wickless heat pipes.

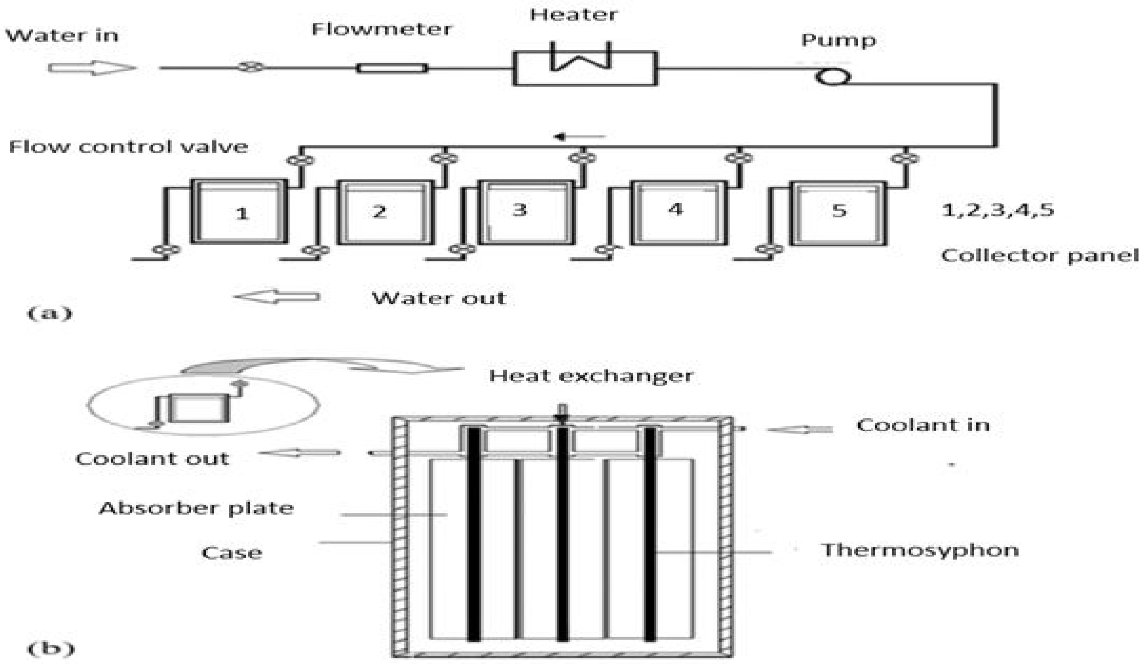

Figure 2.9 (a) Schematic diagram of solar test facility, (b) thermo-syphon solar collector. (Sandesh *et al,* 2013)

The inquiry produced the most effective concentration of CNT nano-fluid for improved performance. A comparative analysis was performed regarding the thermal performance of the heat pipe solar collector employing CNT nano-fluid as opposed to pure water. The results of the experiment are depicted in Figures 2.10(a) and 2.10(b).

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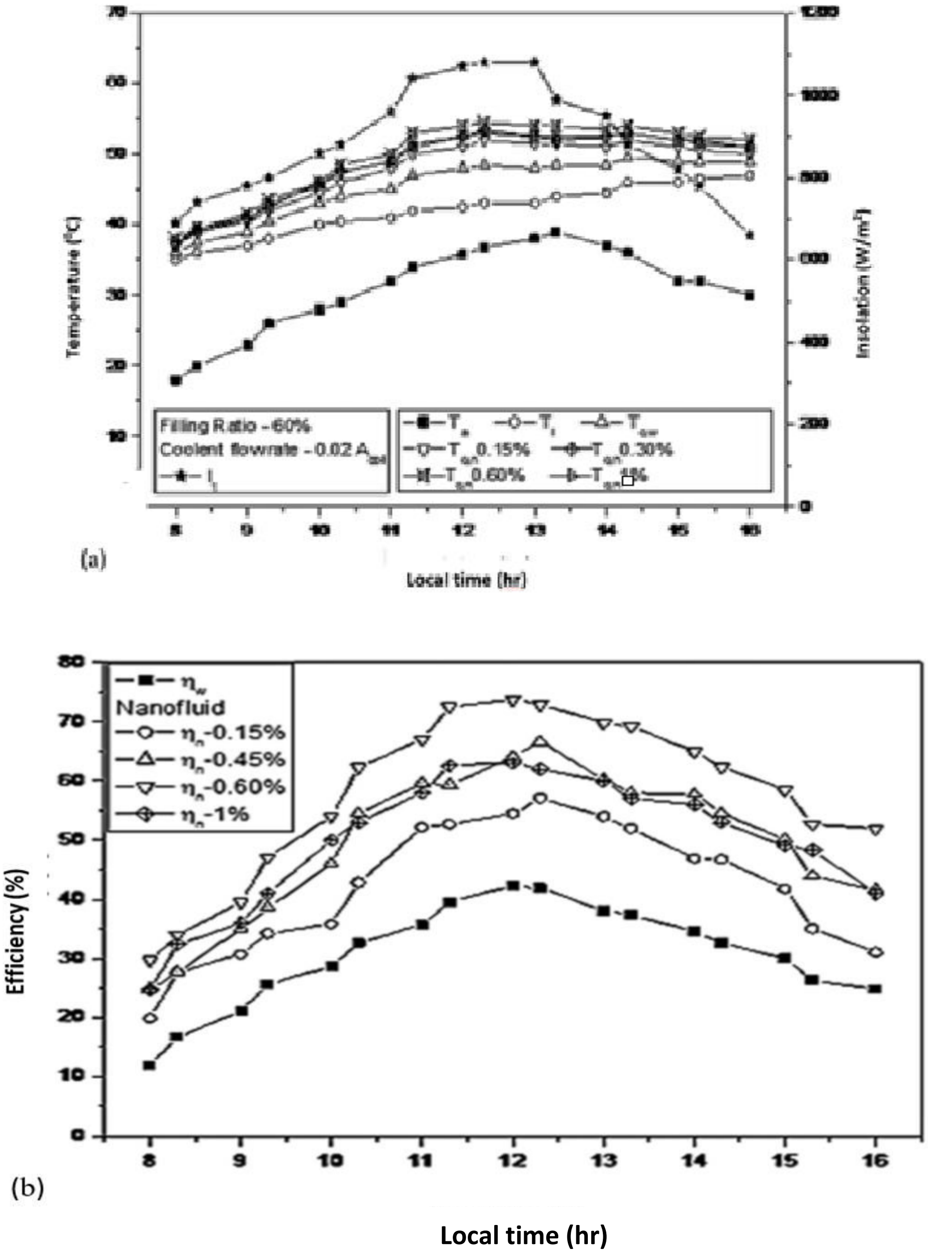

Figure 2.10: Daily variation of temperature and efficiency as functions of local time, (Sandesh *et al,* 2013)

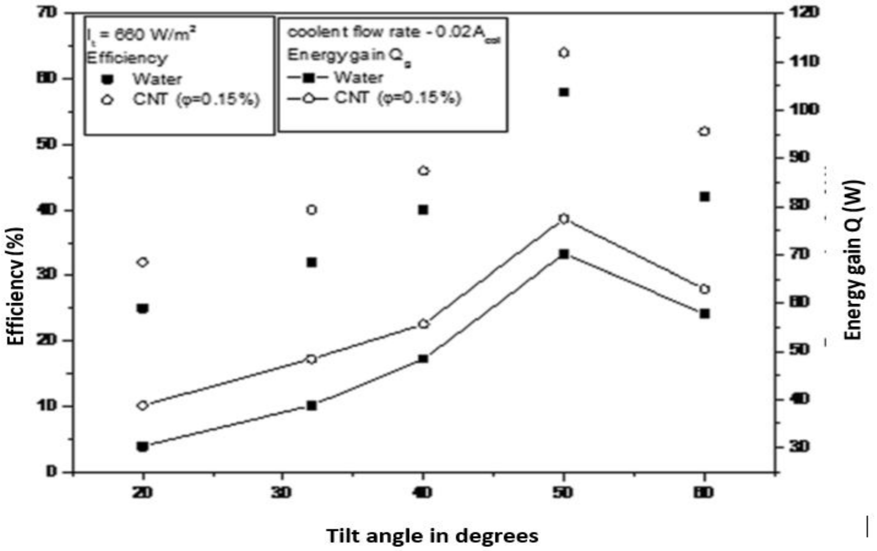

Figure 2.11: Effect of tilt angle on collector instantaneous experimental Efficiencies, (Sandesh *et al,* 2013)

Therefore, they have made the following conclusions as a result of their investigation:

The solar heat pipe collector with CNT nano-fluid as the working fluid can be seen to be very efficient compared to the heat pipe with pure water as the working fluid.

The solar heat pipe collector performance improves as concentrations of CNT nanoparticles in water are enhanced, but it reduces with CNT concentration beyond 0.60 percent. They established that peak instantaneous efficiency was 73 per cent when the nanofluid volume concentration was 0.60 per cent.

Heat pipe collectors perform better in water and nanofluids with an increase in the tilt angle, but worse when the tilt angle exceeds 50 o (Sandesh et al., 2013).

Effects of nanoparticles on thermal storage fluids, especially vegetable oils such as sunflower oil, in solar collectors should be analyzed thoroughly.

The latest developments in integrated technology of heat pump and solar collector provide a possible model of how to effectively utilize solar energy as a reliable heating system to be used in water warming needs in regions with limited sunlight exposure. The choice of a heat pump as a method of solar water heating depends on many factors, especially the properties of their refrigerants. Because of environmental considerations, refrigerants that have high global warming potential have been studied and a number of such chemicals are being gradually phased out. To these problems, new refrigerants are under investigation and a comprehensive analysis of conventional refrigerants like carbon dioxide, ammonia and propane is being conducted. Besides the choice of working fluid, much scholarly attention has been directed at improving the performance of different parts of the SWH system (Ruchi et al., 2013). This paper has not discussed the fin efficiency of heat pumps installed in the solar collectors.

A quantitative research was conducted in 2013 to establish how riser diameter and inclination influence system parameters of a two phase closed loop thermosiphon solar water heater. The following parameters of the system were defined: the rate of the circulation mass, the heat flux the collector captures, the driving pressure, the overall pressure drop, the rate of heat transfer in the risers, and the efficiency of the collector. After taking the differences of riser diameter and angle into account, a scheme of a two-phase thermosiphon solar water heater, which can be operated at different angles, was proposed, with water as the working fluid. The findings indicated that the higher the inclination, the higher the latitude of the location needed to get the optimal source of solar heat. The two-phase characteristics of mass transfer on the large scale are also clearly apparent at lower inclination values and mass flow rates across all the riser tube diameters. Consequently, it was noted that optimum inclination angles and optimum diameters of solar heat flux, circulating mass flow rate and a heat transfer coefficient in a two-phase thermosiphon system were not compatible. According to Nay and Songjing, this study brings forth more insights and significant volumes of information to be incorporated during the design of the two stage thermosiphon solar heaters in 2013. This study also did not examine how to enhance the thermal storage of solar water heaters using thermal storage mediums.

Njoroge et al. (2014) have carried out an experiment to evaluate the effectiveness of solar air heaters with a high-density polyethylene paper as the top-covering and the layer of brown sand as an absorber. They experiment as shown in Figure 2,12.

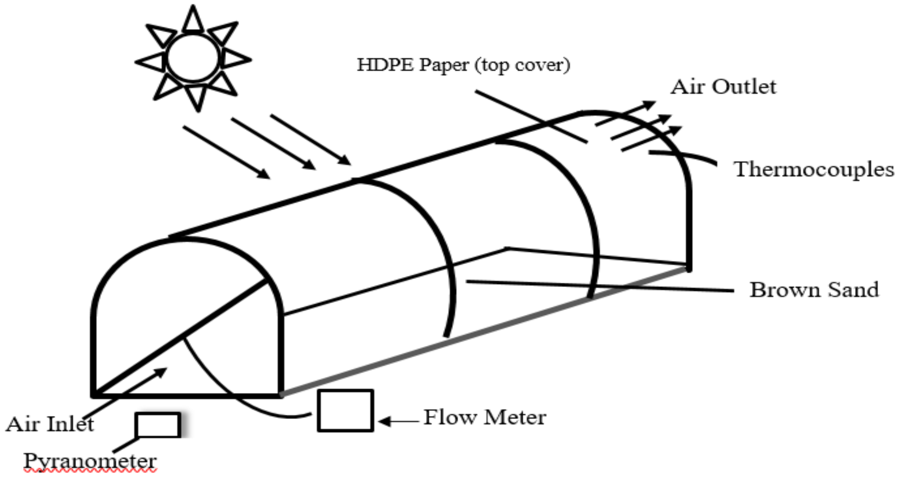

Figure 2.12: Experimental Prototype Model of a Solar Air Heater, (Njoroge *et al,* 2014)

Their results showed that, an increase in air mass flow rate enhances the performance of a solar air heater. The factors that affect the effectiveness of the solar air heater include collector length, collector depth, absorber plate properties, glass cover plate properties, wind speed and others. Heat transmission to the circulating air will increase with increasing the surface area of the absorber plate, but it will also increase the pressure drop across the collector, increasing power consumption to move air through the collector. Different materials, shapes, sizes, and configurations can be used to achieve performance enhancement (Njoroge et al., 2014). Further studies are needed in order to determine the effect of polythene cover thickness on the thermal efficiency of the system.

Effects of glazing thickness on the effectiveness of solar collectors has been examined by testing four similar in size and dimensions solar collectors with low iron glazing with 3 mm, 4 mm, 5 mm and 6 mm. The results indicate the 4mm thick glass is the most efficient with a value of 35.4 percent, whereas the 6mm thick glass is the least with an efficiency of 27.8 percent (Bakari et al, 2014). The aspect of thermal energy storage object has not been addressed in the solar collectors.

Another experimental study and test of the flat plate solar water heater is fixed (as shown in Figure 2.13) at different flow rates using circulating pump.

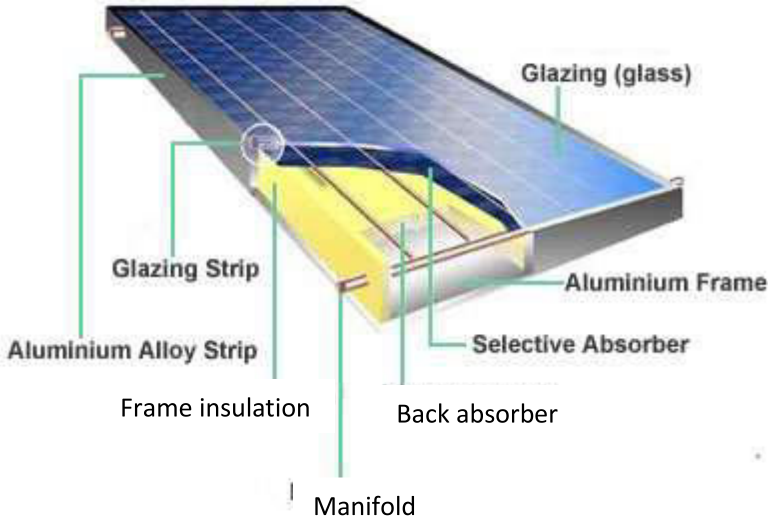

Figure 2.13: Flat plate Solar Water Heater, (Tripathi and Aijaz, 2014)

The measurements were performed on a day marked by high solar intensity to guarantee optimal performance and heat absorption. The peak exit temperature of water reached 50 °C at 13:00, as illustrated in Figure 2.14, signifying an efficiency of 17%. The study revealed that the community's total prevalence of food allergy is 8.6 percent (Tripathi and Aijaz, 2014).

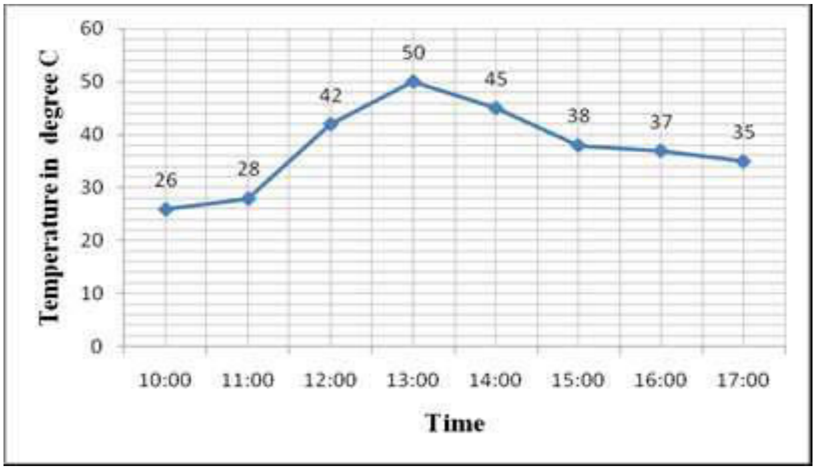

Figure 2.14: Time and temperature with water flow rate 15 liters/minute,

(Tripathi and Aijaz, 2014)

It is worth mentioning that the heat loss coefficient and heat removal factor within the solar collector remain unexamined.

A novel methodology for evaluating the efficacy of a flat plate solar collector through the transmittance factor ‘Fτ’ was established in 2018. The execution of this was carried out utilizing the experimental configuration depicted in Figure 2.15. The transmittance factor ‘Fτ’ was derived solely from the glazing, in contrast to the comprehensive test configuration employed in the incident angle modifier. ‘Fτ’ was assessed at varying surface angles and at different times throughout the day to comprehend the influence of the solar azimuth angle. The values of ‘Fτ’ were observed to be elevated in conjunction with ‘Kτα’. The transmittance factor ‘Fτ’ serves as a predictive measure for the thermal efficiency of the collector at any given time throughout the day. Additionally, it can be correlated with other latitudes through a linear equation derived from a standard thermal efficiency testing procedure. Nonetheless, the research failed to take into account the influence of additional variables, such as the fluid flow rate within the system, (Kadyan et al, 2018). The study did not explore the enhancement of thermal storage in solar collectors through the use of sensible heat storage fluids.

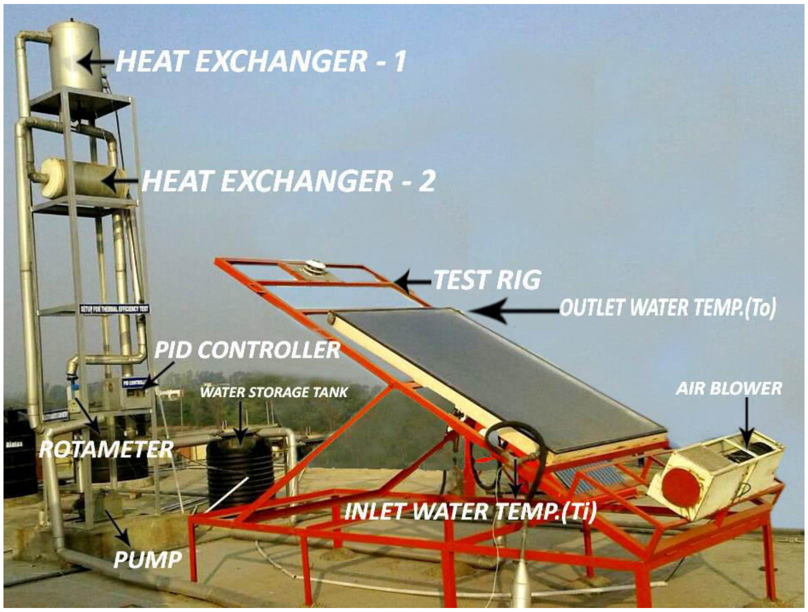

Figure 2.15: Photograph of Flat Plate Collector Test Rig, (Kadyan *et al*, 2018)

Harakasingh et al. (1996) designed a flat plate collector solar cooker which employs natural convection and has short-term thermal energy storage with coconut oil. The solar cooker used a double glazed flat plate collector with a selective surface as the source of energy. The heat transfer medium was coconut oil, the thermo-syphon loop was topped off with an oil bath, and two cooking pots were immersed in the working fluid to improve the heat transfer between the working fluid and the cooking pots.

On hot days, temperatures of 15^0 c can be achieved, between 10.00 and 14.00, when there is a lot of sun. Fig. 2.16 shows an indirect solar cooker that has a flat plate collector where vegetable oil is used as a heat transfer medium and an oil/pebble bed thermal energy storage system that works on the principle of thermo-syphon (Schwarzer and DaSilva, 2003). The reflectors were used to heat the oil inside the collector and it was then taken to the cooking unit through a natural flow system. By using manually operated valves the oil flow rate was directed to either the storage tank or the pots. This type of a solar cooker can be installed into a kitchen. The main advantages of this solar cooker are that it is suitable to cook indoors, has a thermal storage tank, keeping food warm over long periods, and is suitable to cook dinner, and quickly reaches high temperatures in the working fluid, which allows using rapid cooking techniques: frying and roasting (Mawire, 2019).

Figure 2.16: Indirect flat plate collector solar cooker with TES, (Schwarzer and DaSilva, 2003)

Solar cookers that use standard flat-plate solar collectors have a significant limitation: their performance is reduced by reversed cycles at night, and cloudy day conditions. In addition, the downsides also include the high costs associated with construction and the challenges of non-removable pots, which complicate the operation of sanitation and food service. Evacuated tube solar collectors (ETSCs) have many benefits compared to other types of solar collectors. The pluses are in eliminating the need to track the sun as these systems work with direct and diffuse sunshine. They can reach high temperatures, allowing them to cook where shade is available or within a building due to the spatial separation between the collection component and the oven unit. Additionally, they have very high thermal conductivity, and heat transmission between evaporator and condenser parts approach an isothermal state (Mawire, 2019). However, the question of the heat loss coefficient and heat removal factor, of sunflower oil, is not answered.

Through the silica-gel/water pair, a seasonal adsorption thermal energy storage system has been proposed as illustrated in the setup provided in Figure 2.17. In summer when the system is charging, the thermal energy of the solar collectors is transported to three adsorbent beds, thus facilitating the desorption phase. During winter, the low temperatures in the solar collector favor the evaporation of water in the evaporators and condensers, and at the same time transfer the heat of adsorption to the heating system of the building (Hauer, 2007). However, heat removal factor and heat loss coefficient of silica-gel/water mixture in solar collectors have not been studied..

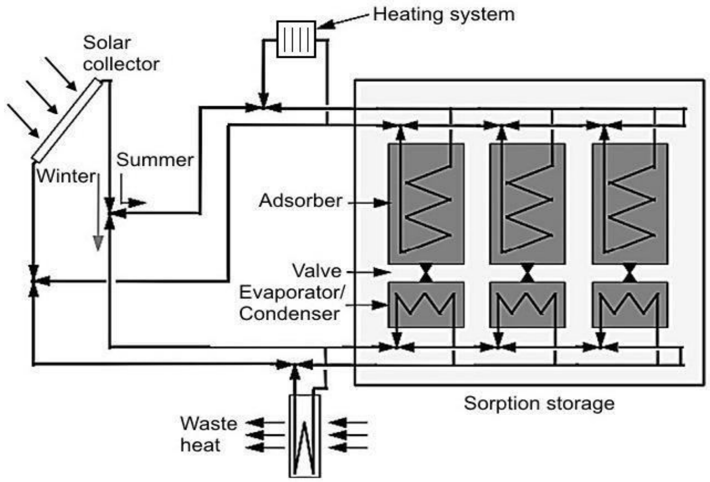

Figure 2.17: Seasonal adsorptional thermal storage system, (Hauer, 2007)

2.4 Modeling of solar collectors

In 1975, a thorough study of the modeling of a solar heating and cooling system was done at Colorado State University. An approximation of one full year of the system was simulated using a computational model, using data acquired during a normal meteorological year. This prototype showed the ability to imitate several design features, including a flat plate collector, a main storage tank, a heat storage tank, an auxiliary heater, an absorption air conditioner with a cooling tower, and heat exchangers that connected the collector and the storage tank. The study has revealed that the area where the collection is done, the inclination of the collector and the amount of cover plates used on the collectors have an effect as observed by Oonk et al in 1975. The thermal storage fluids of solar water heaters were not studied in this work.

A typical curve represents that of a directly heated thermosiphon solar water heater made based on the collected data during an extended 30 day testing period. Application of this curve generated an annual solar fraction that was nearly similar to the value created by the numerical simulation. This paper describes a definite and effective design approach to direct thermo siphon solar water heaters, as defined by Hobson and Norton in 1989. The relationship between the thermal storage efficiency and the thermal storage fluid was not investigated in the research study.

In 1991, an extensive discussion of numerical techniques in the thermal dynamics of a solar collector was carried out. Complex and fluctuating heat transfer characteristics of the solar collector were fully evaluated. In this numerical simulation, various elements of the systems were assessed such as component size and configurations, the relationship between inlet velocity and fluid inlet temperature, and effects of various external factors. This analysis is related to an air collector with the shape of rectangular ducts. Empirical correlations were used to determine the heat transfer caused by free convection in the air gap regions, and solar irradiation was assumed to be fixed on an hourly basis..

Collector dynamic modeling is a factor that determines the performance of a flat plate collector. Temporal variability of the meteorological observations was introduced into the flat plate collector. Dynamic modeling produced better output than steady-state models. The Runge-Kutta method and the Taylor Series expansion method were used to compute the differential equations used in the dynamic model. The temperatures of the fluid and plate, and the cover were defined by three different equations. The model was contrasted with an experimental study based on experiment data of a liquid cooled flat-plate solar collector that has corrugated transparent fiberglass cover. The results obtained with the dynamic model indicated a highly remarkable agreement with the experimental results of the flat plate collector. The experimental collector and the theoretical model had a difference in temperature of about 3 C. This model was coupled with a kind of 1 kW ammonia-water absorption type of refrigeration system which is defined by composition containing 30 percent ammonia by weight and fluid temperature in inlet of 30 C. The benefits of the dynamic modeling results were even higher than the benefits of the aforementioned experimental results of the given system (Oliva et al., 1991). Nevertheless, the coefficients of the relationships between heat losses and the factors which influence heat extraction in the ammonia-water mixture are not adequately studied.

The optimization of the design parameters of a thermosiphon solar water heater was critically analyzed in relation to the towns of Amman and Aqaba in Jordan by using the TRNSYS simulation system. The results indicate that the solar percentage of the system can be increased by 10-25 percent by attentively choosing each of the considered parameters (Zueva and Magiera, 2001). Studies have also shown that the solar fraction of a system installed in Aqaba, with its arid climate, is less sensitive to the specific parameters than the solar fraction of a similar system that is installed in Amman with more moderate climatic conditions (Shariah and Shalabi 1991). This analysis has not considered the application of thermal storage medium to retain heat in the solar collector to be used over a long period.

An elaborate mathematical model has been developed of a solar collector with heat exchanger. The researchers developed an analytical solution of the collector surface thermal dynamics subjected to Cauchy boundary conditions based on internal heat sources which matched with the incident solar energy (Zueva and Magiera, 2001). This research has not evaluated the fin efficiency of a solar collector with heat exchanger.

An analysis of the transient state has been carried out by developing a model of a flat plate solar panel. A one-dimensional mathematical model was used to simulate the transitory processes in panels in the research. The model developed using MATLAB gives a complete simulation of the whole system including the collector and the storage tank. The correctness of the results of the model was checked in a carefully organized series of experiments carried out over a few days. The findings were impressive, showing that there is a significant change in the temporary fluid temperature at the outflow of the collector. Accurate assessment of the variable temperatures was done through a MATLAB program which exhibited a satisfactory convergence factor in its calculations of the overall efficiency and heat loss of the system as observed by Saleh in 2005. This research did not examine the improvement of thermal performance of solar collectors through the use of thermal storage materials.

An analysis of a solar water heating model to be implemented in a building was performed to allow exergy analysis and establishment of the performance of the system in operation. This system was made up of a flat plate collector, a heat exchanger and a circulation pump. The different temperatures of water entering the solar collector were assessed in detail, analyzing their impact on efficiency of the system components, and implications upon the important thermodynamic parameters. Experimental data was taken in Izmir Province, Turkey and confirmed this analysis. The reported values of energy efficiency ranged between 2.02% and 3.37 percent. They were acquired in eight test runs in the full system between approximately 1:10 PM to 3:35 PM as reported by Gunerhan and Hepbasli in 2007. The letter did not discuss how the solar water heater efficiency could be enhanced by use of thermal storage material.

A solar system consisting of a complex with a flat plate collector attached to a roof of a house, a storage unit was examined and utilised, including a phase change material (PCM). A closed-loop system existed between the collector and PCM storage unit whereby they were closely interrelated. In this paper we concentrated on how solar energy can be used to gather and store the power to distribute space heating to homes, and in our scenario we are considering a house located in Blacksburg, Virginia as the location of the experiments. This was facilitated by the weather conditions of this place that provided 88 percent of the heating and hot water demand of this area. The flat plate solar panels were modeled in ABAQUS software version 6.3. The simulation results were computed at an annual level and analyzed at the hourly level. The test was directed at outlet temperature of the fluid coming out of the collector and the storage tank. In conducting this study, a thorough examination of several parameters, including the quantity of energy acquired by the panel and that which was utilized by the panel, was beyond the scope of the study, as well as the amount of energy necessary to power household appliances of hot water. The collector can supply warm water at frequent intervals and can also supply a non-negligible percentage of space heating demands in various months: 33 percent in January, 58 percent in December, 86 percent in November, 88 percent in February and 100 percent in other months. Hassan and Beliveau (2008) report that the system was proved to generate a year round supply of energy that satisfied the 88 percent space and water heating requirements of the household. No comparative study is carried out in this study to determine the thermal energy storage capacity of the phase transition materials and vegetable oils, including sunflower oil.

The mathematical model is developed to analyze the thermal performance of a flat plate solar collector, based on Hottel-Whillier-Bliss equation in a computational framework. Findings made can be considered as having a positive correlation with the findings of other academic studies. The collector efficiency η was graphically represented as a function of (TiTa)/I as indicated in Figure 2.18.

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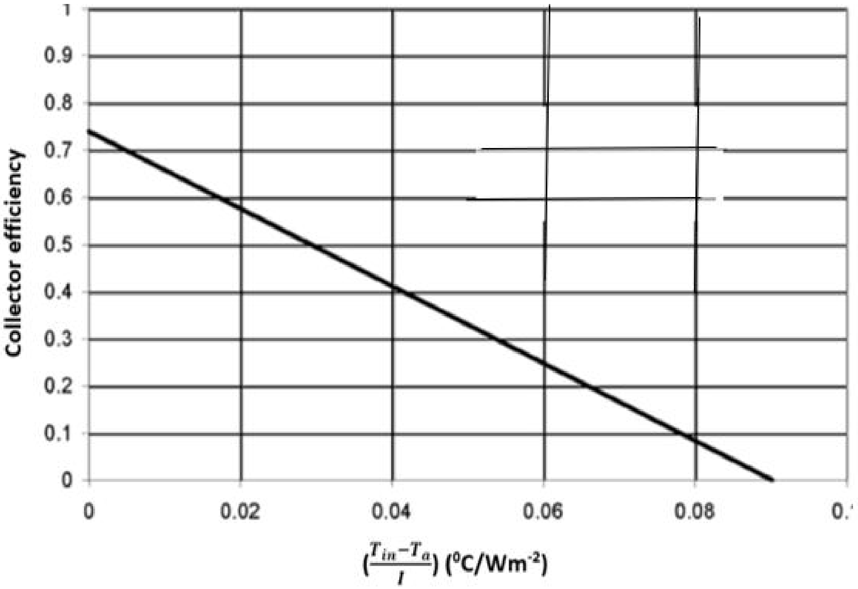

Figure 2.18: Performance of a typical flat-plate thermal collector (ambient temperature 25°C), (Fabio, 2008)

The gradient of this line (- FR U) signifies the rate at which heat is dissipated from the collector. For instance, collectors equipped with cover sheets will exhibit a reduced slope compared to those lacking such protective measures, (Fabio, 2008). An investigation into the efficacy of a hot water solar oven for low-temperature thermal processes has been carried out utilizing the apparatus depicted in Figure 2.19.

Figure 2.19: Experimental hot water solar oven set up, (Bello and Odey, 2009)

The collector was delineated in accordance with the methodology of concrete plates. The energy balance was conceptualized through the application of the Hottel-Whiller-Bliss generalized performance equations. The daily average thermal performance characteristics of the complete system units are illustrated in Figure 2.20.

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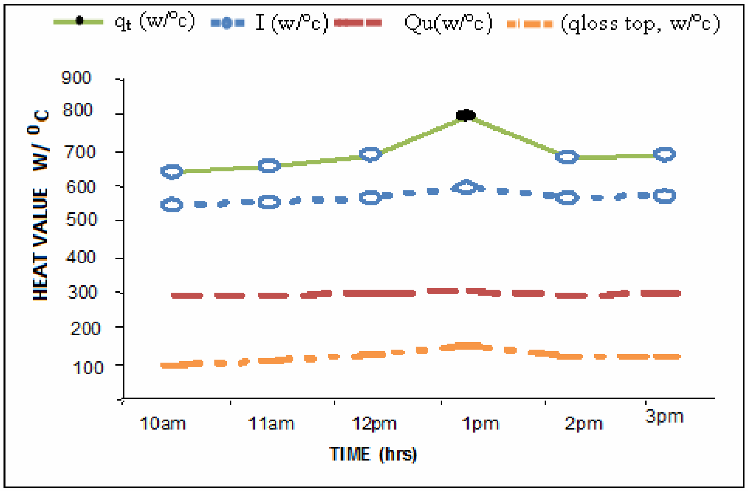

Figure 2.20: Collector heat gain and losses as a function of time,

(Bello and Odey, 2009)

This represents a particularly efficacious method of solar thermal conversion. Nonetheless, it is imperative to consider strategies for mitigating thermal loss. In 2008, Currie et al. devised a straightforward and economical Integrated Collector Storage Solar Water Heater (ICS-SWH) utilizing simulations reflective of Scottish climatic conditions. The system is characterized by a rectangular design that integrates both the solar collector and the storage tank into a cohesive unit, as illustrated in Figure 2.21.

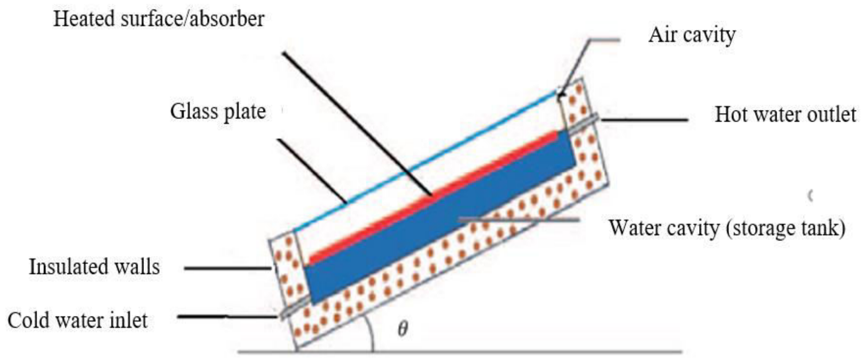

Figure 2.21: Cross-sectional representation of the SWH, (Bello and Odey, 2009)

The ICS-SWH was experimentally and numerically studied over a 3-month period to determine the results with respect to a newly developed macro model. The macro model was improved by making a distinction between finned and non-finned collectors. The macro model was useful in the analyses of the water bulk temperature variations with different SWH collector materials, addition or missing fins, interior temperatures and exterior weather conditions considered at a given aspect ratio. The results obtained through this new instrument numerically showed a striking similarity to the experimental results. The results were corroborated by using the methods of statistics and extreme range assessment. An initial testing with the R2 test has shown that the model is very effective in predicting water bulk temperature. Mean bias error (MBE) and root mean square error (RMSE) were used to evaluate errors in the assessment. The MBE gives a very clear understanding of inclinations to overfit and underfit the selected best fit line, but the RMSE measures the extent of error variability. The identified minimum and maximum ranges of MBE and RMSE of the collectors were between -1.41 and 1.23 and between 0.15 and 1.65 respectively, which showed that the model was highly accurate when estimating the bulk temperature of water. Large scale range tests were done to prove the validity of the program. The results obtained over 8 hrs under steady heat flux of 50 W/m 2 and 600 W/m 2 yielded almost parallel curves of theoretical and experimental data with remarkably low mean bias error (MBE) and root mean square error (RMSE) of -0.43 and 0.53, respectively (Bello and Odey, 2009). Heat removal factor and heat loss coefficient concerning the solar water heating system was not studied..

The complexities of thermal and flow dynamics were demonstrated through the development of a detailed one-dimensional numerical model of a solar flat plate collector. It is based on the progression of the system that Duffie and Beckman developed in 1991 and was validated by an empirical study carried out under steady-state conditions on two separate collectors (Cadafalch, 2009). The effectiveness of solar water heaters is limited to temporary conditions dependent on changing weather conditions that affect their overall output.

The application of heat pipes alongside solar collectors to enhance the rate of heat transmission has been explored. In order to assess the thermal efficiency of a heat pipe flat plate solar collector coupled to a cross-flow heat exchanger, a new theoretical model is created. The results of the analysis were ingeniously compared to the results of previous studies (Xaio et al., 2012). This work did not involve the use of thermal storage fluids to enhance the thermal efficiency of solar collectors.

In 2013, a prototype model was thoroughly calculated and experimented in Tunis, Tunisia with the aim of understanding the unique air heating requirements peculiar to the region. The prototype device also consisted of floor heating active layer, a hot water tank and a flat plate collector system, which was all fitted in a single space. The different heat transfer paths were investigated by a simulation program designed in TRNSYS. The experimental tests were conducted during two months in March and April of 2013 as per the local weather conditions available then. The validity of the simulation software was assessed according to the comparison of the results of the computations to the experimental data.

Based on this program, a study was done to enhance the design features of the prototype house such as A_c, mass flow rate, volume of the storage tank and active layer thickness. As per the analysis, the solar collector was ideal as it had the mass flow rate of 100 kg/m; area of 6 m2; and the storage tank capacity of 450 liters. The long-term performance of the mathematical model was assessed during the last stages of the study based on data recorded during a typical Tunisian weather year. It was found by research and analyses that Tunisia had the potential of solar water heating (Mehdaoui et al, 2014).This research, though, did not investigate how flat plate solar water heaters could be improved by using thermal storage in times of a low solar energy.

A 2014 study in Gabes, Tunisia assessed the performance of flat plate collectors. The collector provided warm water at the designated place. To explore the dynamic behavior of the collector, the researchers simulated and examined many of the factors that might interact with it, such as the output water temperature and the overall heat loss coefficient. They report that the flow rate depends on the number of tubes in the collector, and the rate of heat transfer depends on the number of tubes when the working fluid flows through the tubes. The modeling results show that the output temperature peaks and beginning to decrease. The mass flow rate, which is constant, as in Figure 2.22 of 0.008 kg/s, means that the fluid velocity directly depends on the number of tubes.

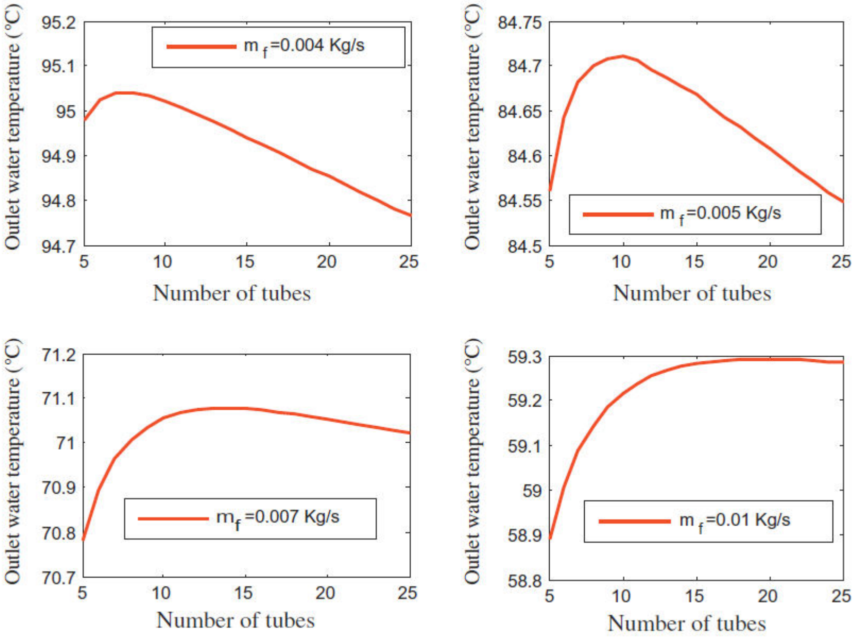

Figure 2.22: Outlet water temperature verses number of tubes for various mass flow rates, (Hamed *et al,* 2014)

Figure 2.23 illustrates the overall heat loss coefficient as a function of time, revealing a peak at noon followed by a subsequent decline. The peak value during the summer and winter seasons is 3.38 W/m²K at a mass flow rate of 0.005 kg/s (Hamed et al., 2014). This research did not examine the heat removal component**.**

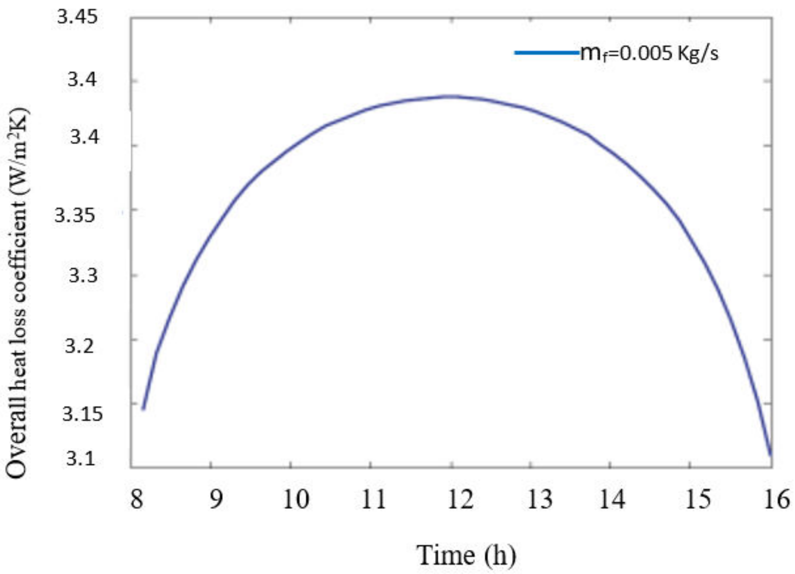

Figure 2.23: Collector overall heat loss coefficient verses time, (Hamed *et al,* 2014)

Extensive examination of the numerical simulation techniques that can be used to determine the performance of solar collectors through the finite volume method has been conducted. The thickness of the absorber plate, the distance between collection tubes, their length and diameter and the insulating thickness were considered. An inquiry was conducted using a constructed collector and a numerical simulation of the built system was then conducted. The findings of the simulation and the experiments were contrasted. The results showed that a thicker absorber plate will make the collector more useful or that the closer the collection tubes are to each other will make the collector useful. In one of the scenarios examined, the intensity of the sun was 700 W/m2, the wind velocity was 4m/s, and the thickness of an absorber plate was 0.1mm to 2.1mm thick. This made the collector efficiency increase significantly, by 46.6 to 64.0. When the distance between the collecting tubes was lowered to 50 mm efficiency increased to 66.0 per cent, compared to 52.8 per cent at 170 mm. To a significant degree, 55 to 64 percent, the efficiency could be increased, by shortening the length of the collecting tube and, at the same time, by increasing its diameter. Based on the study, the insulating thickness of the panel did not have a significant effect on efficiency. Jiandong et al. (2015) noted that the findings led to the optimization of design parameters of flat plate collectors. This study did not look into the fin efficiency, heat removal factor, and heat loss coefficient of the solar heating system.

A Computational Fluid Dynamics (CFD) program was used in the study to predict the circumstances for different types of absorber plates, each with its own unique shape and arrangement, in order to achieve higher efficiency than traditional solar collectors. Using UGS NX, a three-dimensional model of the solar flat plate collector was generated in STEP format and imported into ANSYS Workbench. ANSYS ICEM was then used to mesh the model. According to Kumavat (2016), ANSYS FLUENT software was used to produce the results.
There was no investigation into heat retention in solar collectors that used thermal storage fluids.

Figure 2.24 is the design which has been used to study the optimization of the heat exchanger of the flat plate indirect solar water heating system. In order to reduce the startup cost as well as the operating cost, the objective of the study was to determine how different factors affected the thermal efficiency of the system. The temperature of the outlet service water served as a performance meter that measured the level of energy consumed by the sun. Continuity, momentum equations and energy equations of the fluids in the system were solved numerically with FLUENT software at steady state. Computational fluid dynamics was developed and tested (with high cautiousness) in three dimensions and compared to previous experimental results.

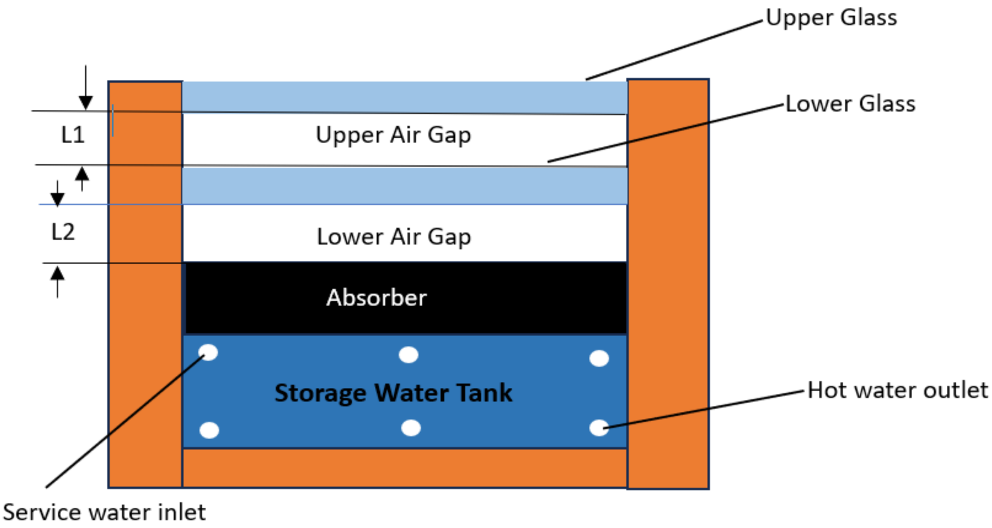

Figure 2.24: Heat exchanger for indirect flat plate solar water heater, (Juleri *et al*, 2016)

The optimal design of the heat exchanger was explored to improve the thermal energy absorbed by the service water. The selected system is characterized by the following parameters:

1. Double glazing featuring a glass thickness of 3 mm
2. An absorber area measuring 0.7 m by 1.35 m, featuring a thickness of 10 mm composed of metallic nickel chrome (M-N-chrome).

The storage tank has dimensions of 81 x 135 x 10 cm, accommodating approximately

109 liters of water, constructed with a 2 mm thickness of iron sheet.

4. Wooden insulation walls with a thickness of 50 mm
5. Copper service water tubes with a thickness of 1 mm.

An established k-ω turbulent model was employed in the optimization process of the heat exchanger. The surface-to-surface radiation model has been included. The effects of heat exchangers with one or two rows and different lengths have been studied. Additionally, pipes with elliptical and circular cross sections were included in the study. Two mass flow rates were chosen: 500 and 650 liters per hour. According to the results, the single row HX, which was 10.8 m long and produced high service water outlet temperatures with low pumping power for both the ellipse and type B tubes (Juleri et al, 2016). The heat loss coefficient, heat removal factor, and fin efficiency were not considered in this study.

2.5 Theoretical Considerations

2.5.1 Useful Formulations and Expressions on Thermal Performance Analysis of Flat Plate Solar Collectors

Flat plate solar water heaters must be glazed using selective materials of low emittance and high transmittance throughout the solar range, keeping up against degradation by ultraviolet light (Raja et al, 2018; Alghoul et al, 2005)

The area of a solar water heater necessary to achieve the desired fluid temperature is predicated on the radiant flux that impinges on the plate as indicated in Equation (2.1), (Warui et al.,2017).

$$I = \tau_{cov} A_P I_T \tag{2.1}$$

where I_T is the irradiance on the collector, A_p is the exposed area of the plate and τ_{cov} is the transmittance of any transparent cover that may be used to protect the plate from the wind.

Radiant energy received by the collector is dependent on the area and intensity of the solar radiation as in the form, (Kumar, 2017):

$$Q_i = I_T A_C \tag{2.2}$$

The immediate energy acquired by the receiver Qr can be calculated as, (Kumar, 2017; Fabio, 2013; Struckmann, 2008; Duffie and Beckham, 2006):

$$Q_r = (\tau\alpha)_{eff} I_T A_C \tag{2.3}$$

where $(\tau\alpha)_{eff}$ is the effective optical fraction of the energy absorbed, I_T is the solar radiation incident on the tilted collector, and A_C is the collector aperture area.

Equation (2.3) hence demonstrates the impact of effective transmittance absorbance product on instantaneous heat that is acquired by the receiver.

Solar collectors normally undergo convective and radiative heat losses. However, the glazing prevents the long-wavelength infrared thermal energy from escaping. The convective heat Q_{conv} losses due to the temperature difference between the absorber plate and the ambient is given by the following equation, (Matuska and Zmrhal, 2009):

$$Q_{conv} = UA_r(T_r - T_a) \tag{2.4}$$

A_r = the area of the receiver, U = the total heat loss coefficient, T_r = temperature of the receiver and Ta = ambient temperature. Heat is lost by radiation

Q_{rad} due to the temperature difference between the collector and the sky dome, (Amira *et al,*2019; Matuska and Zmrhal, 2009):

$$Q_{rad} = \varepsilon_{eff}\sigma A_r({T_r}^4 - {T_a}^4) \qquad (2.5)$$

The heat loss coefficient is the combination of losses due to the surfaces of collector and the edges. Most of the loss at the top can be attributed to optical loss, convection accounts for a slight loss, radiation loss too is partial at the top(Balotaki, 2017).

The absorbed heat energy in the fluid can be calculated to be described as: (Iksan et al, 2023; Amira et al,2019):

$$Q_{u\_} = A_c F_R[S - U_L(T_r - T_a)] \qquad (2.6)$$

where Q_u is the heat absorbed by the fluid, A_c is the collector surface area, U_L Where H is the heat loss coefficient and the S the heat taken up by the collector.

Equation (2.6) indicates that the heat taken up by the working fluid is exclusively determined by heat removal factor and the heat removal factor.

Hoses attached to the absorber plate carry a heat-carrying fluid, which is often water, glycol, or air. The fluid is heated as it passes through the pipes. The quantity that matches a portion of the useable energy recovered after heat loss is the intensity of energy used by the working fluid. Instantis The portion of incoming solar radiation that is collected and used is known as thermal efficiency (Amira et al., 2019; Fabio, 2013; Garg et al., 2011).

$$\eta = \frac{Q_u}{I_T A_C} \qquad (2.7)$$

$$\eta = (\tau\alpha)_{eff} - \frac{UA_r}{I_T A_C}\left(T_r - T_a\right) - \frac{\varepsilon_{eff}\sigma}{I_T A_C}({T_r}^4 - {T_a}^4) \qquad (2.8)$$

The efficiency and the useful heat gain can be expressed in terms of heat removal factor in the form:

$$\eta = F_R\{(\tau\alpha)_{eff} - \frac{UA_r}{I_T A_C}(T_{in} - T_a) \qquad (2.9a)$$

$$\eta = F_R\{(\tau\alpha)_{eff} - F_R U_L \frac{(T_{in} - T_a)}{I_T} \qquad (2.9b)$$

$$Q_u = \eta I_T A_C \qquad (2.10a)$$

$$Q_U = I_T A_C F_R\{(\tau\alpha)_{eff} - \frac{UA_r}{I_T A_C}(T_{in} - T_a)\} \qquad (2.10b)$$

Collector efficiency has also been expressed as Andoh *et al*, 2010):

$$\eta = \frac{Q_u}{I_T A_C(\tau\alpha)} \qquad (2.11)$$

It is important to note that solar radiation intensity as well as the size of a collector significantly affect the thermal energy gain, heat loss, heat removal factor and heat loss coefficient and efficiency of a solar collector as illustrated in Equations (2.1) to (2.11).

The heat that the working fluid can effectively utilize can be articulated as a function of the inlet temperature, T_{in}, and the outlet temperature, T_{out}, as demonstrated in the works of Amira et al. (2019), Fabio (2013), Gang et al. (2011), Struckmann (2008), Fraisse et al. (2007), Duffie and Beckham (2006), Santiago and Jimenez (2002), and Shariah (1991).

$$Q_u = \dot{m}c_p(T_{out} - T_{in}) \qquad (2.12)$$

where c_p , and *m* the specific heat capacity in a constant pressure, and mass flow rate of the working fluid, respectively.

Equation (2.12) indicates that the flow rate of fluid through the solar collector influences the heat gain which is usable.

The heat removal factor FR can then be written as (Daghigh et al., 2011; Baldini et al., 2009; Santiago and Jimenez, 2002):

$$F_{\mathrm{R}}=\frac{\dot{m}c_p(T_{out}-T_{in})}{I_T A_C\,\{(\tau\alpha)_{eff}-\frac{UA_r}{I_T A_C}(T_{in}-T_a)\}} \tag{2.13}$$

As stated by Iksan et al. (2023), Raghu et al. (2000), and Matuska and Zmrhal (2009), the collector heat removal factor can alternatively be expressed as follows:

$$F_R=\frac{\dot{M}c}{A_a U}[1-\exp\left(\frac{-A_a UF'}{\dot{M}c}\right)] \tag{2.14}$$

Where $M^{\cdot}$ is mass flow rate of fluid through the solar collector, in kg/s; *c* specific thermal capacity of fluid, in J/kgK; and Aa aperture area of solar collector, in m_2.

Within the system, thermal conductivity is expressed as (Andoh et al, 2010):

$$Q_c=-kA\frac{dT}{dx} \tag{2.15}$$

where Q_c is the conducted heat, *k* thermal conductivity, *A* the cross sectional area of the heat flow and $\frac{dT}{dx}$ the temperature gradient.

Thermal conductivity values in Equation (2.15) is useful in selecting appropriate absorber and insulation materials for a solar collector.

2.5.2 KOLEKTOR 2.2 Design Model

This model of a solar flat plate liquid collector illustrates the mathematical solutions of the one-dimensional heat transfer balances. The model considers a broad set of input parameters such as the complex geometrical, thermal, and optical properties of each constituent of the solar collector and the relevant operating and environmental conditions. The model results can be taken as direct values, the usable heat gain, Q_u, the efficiency, expressed in a fraction of the reference A_c (aperture area A_a), and the output temperature of the heat transfer fluid, T_{eut}. The model can also be used to obtain the optimized results on heat transfer coefficients, temperature of major surfaces in the collector scheme, temperature of stagnation, etc. What is defined mathematically as a solar collector is the external energy equilibrium of the absorber, which is how much heat the absorber surface takes in comparison to the surrounding environment, and the internal energy equilibrium of the absorber, which is how much heat the absorber surface releases to the heat transfer liquid. In the expression of unavailable thermal power a resolution is provided by the Rossi-H (Model) which is given in the form of the fundamental Hottel-Whillier equation:

$$\dot{Q_U} = A_C F_R \{(\tau\alpha)_{eff} I_T - U(T_{in} - T_a)\} \tag{2.16}$$

External energy balance on the absorber is then determined in an iteration loop making a first estimate of the temperature on each of the principal surfaces, starting with temperatures dependent on input temperature T_{in} and ambient temperature T_a. In the estimation of external balance first iteration cycle, Tabs is estimated based on relation with T_{in}.

$$T_{abs} = T_{in} + 10 \qquad (2.17$$

External balance loop results in total heat loss coefficient U of the collector.Mean fluid temperature T_m is given in the form:

$$T_m = T_{in} + 10 \tag{2.18}$$

Radiation heat exchange heat exchange between the external surface of glazing and sky is given as: (Matuska T., 2009)

$$Q_{g1-s} = \varepsilon_{g1}\sigma\left[T_{g1}^4 - T_s^4\right] \tag{2.19}$$

where ε_{g1}, is the interior glazing emissivity, σ is the Stefan–Boltzmann constant, T_{g1} and T_s are the interior glazing and sky temperatures respectively, (Matuska and Zmrhal, 2009).

The sky temperature used in this model tool design is as expressed by (Swinbank, 1963) under clear sky conditions.

$$T_s = 0.0552T_a^{1.5} \tag{2.20}$$

where T_a is the ambient temperature.

The Stefan-Boltzmann law gives the radiation heat transfer between the absorber front surface and between interiors of the glazing and absorber.

$$Q_{rad,abs-g2} = \frac{\sigma T_{abs}^4 - T_{g2}^4}{\frac{1}{\varepsilon_{abs,g}} + \frac{1}{\varepsilon_{g2}} - 1} \tag{2.21}$$

Where T_{abs} is the absorber surface temperature, T_{g2} is interior glazing surface temperature, $\varepsilon_{abs,g}$ is emissivity of front absorber surface and ε_{g2} is emissivity of glazing interior surface.

Convective heat transfer coefficient h between the exterior glazing cover surface and ambient environment is of the form:

$$h = a + bw \tag{2.22}$$

Where, a, b and w are thermal diffusivity, bond width and wind velocity respectively. In the design of the model tool of the KOLEKTOR 2.2 the convective correlation format by McAdams has been utilised as follows:

$$h = 5.7 + 3.8w, \text{ for w<5m/s.}$$

$$h = 6.47 + w^{0.78}, \text{ for w>5m/s.} \qquad (2.23)$$

Nusselt number NUL characterizing the heat transfer in closed gas layer between absorber and glazing by natural convection is defined as a ratio of characteristic dimension of this layer its thickness L_x.

$$NU_L = \frac{h_x L_x}{k_x} \qquad (2.24)$$

Where h_x, and k_x are convection heat transfer coefficient of gas layer and thermal conductivity of still gas of mean temperature. $T_x = T_{abs} - g2$ in the gas layer, in W/mK respectively. Thermal conductivity of the tray-glazing system varying with the average temperature as a second-order polynomial expression of formula:

$$k_{g1-g2}(t) = k_0 + k_1 t + k_2 t^2 \qquad (2.25)$$

where k_0, k_1, and k_2 are sky, interior and exterior glazing cover thermal conductivities, (McAdams, 1954).

The general heat loss factor U calculated in terms of aperture area is the expression:

$$U = \frac{\left[U_g + U_s + U_b \frac{A_s}{A_c}\right] A_c}{A_a} \qquad (2.26)$$

U_g, U_s, U_b are the heat losses coefficients sitting on glazing cover, sides and bottom of the collector respectively. A_a, A_c and A_s are aperture, gross collector and side areas respectively.

Collector efficiency factor F is the parameter describing to what extent heat that is absorbed on an absorber surface reaches the heat transfer fluid. It is an express ratio

$$F' = \frac{U_0}{U} \tag{2.27}$$

where U_0 is heat loss coefficient from liquid to ambient, in W/m^{2}K.

However, the efficiency factor is expressed in different forms depending on the collector configuration. For instance, for the configuration used in this study shown in **Figure 2.25** collector efficiency factor is expressed as:

$$F' = \frac{U^{-1}}{W\{[U(D_e+F(W-D_e)]^{-1}]+[\pi D_i h]^{-1}\}} \tag{2.28}$$

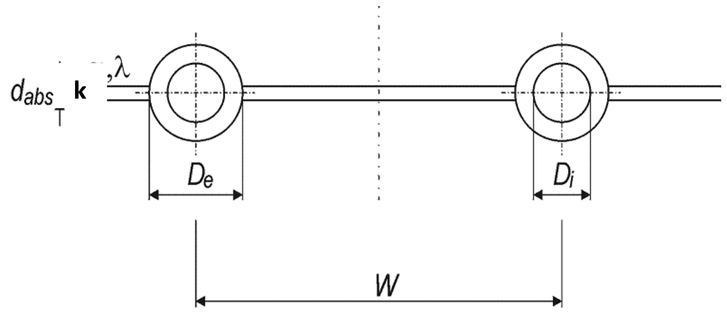

Figure 2.25: Absorber–pipe side bond configuration, (Matuska and Zmrhal, 2009)

The collector heat removal factor is expressed in (2.14)

The efficiency is determined using Hottel-Whilier-Bliss solar collector efficiency expression in equation (2.29), (Matuska and Zmrhal, 2009).

$$\eta = F_R\{(\tau\alpha)_{eff} - F_R U \frac{(T_{in}-T_a)}{I_T} \tag{2.29}$$

Although considerable research has been conducted on solar water heaters, a comparative comparison of thermal storage using sunflower oil and water in solar collectors has been examined. This project aims to employ locally available fluids to enhance the solar water heating system.

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CHAPTER THREE

MATERIALS AND METHODS

3.1 Experimental Work

This research was conducted through experimental measurements, simulation and modeling using KOLEKTOR 2.2 software and MATLAB, while experimental data computation and analysis were done using MATLAB. This research was conducted in Maseno University, in Kisumu County, Kenya where the prevailing weather conditions affecting thermal performance of a solar collector were measured. These experimental measurements were done and averaged at 30-minute interval from April to October in the year 2022.

A prototype solar water heating system was designed, it consisted of three main sections; a water supply tank, the solar water heater, and a hot water storage tank. The supply tank provided cold water to the solar water heater and the hot water coming out was stored in the tank. The hot water storage tank surface was insulated using styrofoam and polished to minimize conductive and radiative thermal energy losses. The prototype water heating system was as shown in **Figure 3.1**.

Figure 3.1: Layout of flat plate solar water heating systems

The cold water in the reservoir tank is pumped into the solar water warming system and the hot water pumped out of the solar water warming system by natural convection because the density of the hot water is lower than that of cold water. The hot water is now forced to the surface and flows onwards through the hot water pipe into the storage tank.

In this study, three flat plate solar water heaters containing water and sunflower oil and air as thermal storage fluids were designed with the following parameters:

(a) Collector Box Parameters

The flat plate solar collector box which was constructed had the following specifications: Collector gross dimensions of 127 cm long, 98cm wide, and 7 cm deep, with 20^0 slope. The collector box interior surface was made of metallic sheet with wood of thickness 2.5 cm as an insulating material. The collector had a fluid volume capacity of 30 litres. The collector's external surface was protected by an aluminium-painted metallic sheet. A transparent glass glazing of 4mm thickness is used to cover the collector box. The experimental flat plate solar water heater collector box is shown in **Figure 3.2.**

Figure 3.2: Solar collector box

b) Absorber Parameters

A Steel absorber plate was welded on 15 GI riser pipes, each 118 cm long and spaced at 5cm intervals. The absorber–frame gap and absorber- glazing gap were 2 cm each. The absorber plate and tubes were assembled and joined as in **Figure 3.3.**

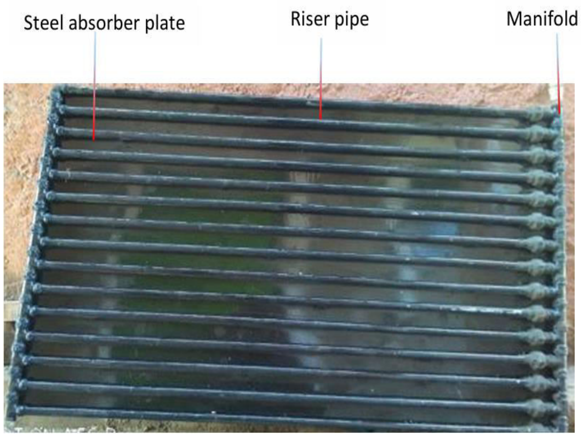


Figure 3.3: Absorber plate with pipes

The pipes welded on the absorber plate were immersed in sunflower oil and water which are thermal storage fluids.

3.1.1 Determination of Instantaneous Heat Gain and Effect of Water and Sunflower Oil on Output Temperature

(a) Instantaneous Heat Gain of a Flat Plate Solar Water Heater

Here we determined the instantaneous usable heat gain by the solar water heater as a function of absorbance-transmittance product, solar radiation intensity and receiver area, by using equation (2.3). This involved measuring: the incident solar radiation I_T using a solarimeter of model LSL200 and the dimensions of the receiver to find its area A_r. Effective absorbance-transmittance product was obtained from the KOLEKTOR 2.2 design model. Solar radiation intensity, fluid inlet and outlet temperatures were measured at 30 minutes interval from 1000hrs to 1630hrs. The experimental measurements were done from February to August.

(b) Comparison of the Effect of Sunflower Oil and Water on Peak Output Temperature

The objective of this section is to compare peak output temperature of water from the flat plate solar collector containing sunflower oil and water as thermal storage fluids. The effectiveness of these thermal storage fluids was analyzed in comparison with a conventional flat plate solar water heater without any thermal storage medium. Output temperatures of the flat plate solar water heaters were measured by the k-type thermocouples attached to a datalogger kept inside a laboratory, the outlet pipes of the solar water heaters containing water and sunflower oil. The temperatures of the heated water from these solar water heaters were measured at 30-minute time interval under prevailing weather conditions.

3.1.2 Comparison of the Effect of Sunflower Oil and Water on Heat Loss and Heat Exchange Parameters

(a) Overall Heat Loss from the Solar Collector

In determining the heat loss from the solar collector, we measured the mass flow rate, inlet and output temperatures of water, and determined the absorbed or usable heat Q_u of water from the solar collectors containing water and sunflower oil as thermal storage media using equation (2.12). The overall system heat loss was then obtained by finding the difference between the heat energy gained by the receiver, Q_r and Q_u

(b) Heat Removal Factor and Heat Loss Coefficient

Here we determined the heat removal factor F_R and heat loss coefficient U by measuring inlet water temperature T_{in}, ambient temperature T_a and incident solar radiation intensity I. These solar water heater parameters were obtained from graphs of the instantaneous efficiency of the solar water heater versus $\frac{(T_{in}-T_a)}{I}$ as shown in **Figure 2.18.** The heat removal factor and heat loss coefficient are always calculated using the Hottel-Whillier-Bliss equation as in equation (2.13). The KOLEKTOR 2.2 design tool was used to obtain the value of the effective transmittance-absorbance product needed in the determination of the heat removal factor of the solar water heating system as 0,874. The thermal fluids under the study were also examined with regard to instantaneous heat loss.

(c) Determination of effect of sunflower oil and water on the collector's efficiency factor or fin efficiency

This parameter was determined by measuring the tube spacing, bond thickness, external and internal diameters of absorber tubes. It was then obtained from equation (2.27), in relation to the overall heat loss coefficient evaluated from the Hottel-Whillier-Bliss equation.

3.1.3 Comparison of the Overall System Efficiency when using Water versus Sunflower Oil as Thermal Storage Media

In this section we determined the efficiency of each solar water heating system containing sunflower oil, and water as thermal storage fluids. The impact of sunflower oil and water on thermal storage in flat plate solar water heaters was then assessed by comparing the efficiency of the solar collector containing each of the thermal storage fluids under study, with efficiency of the conventional flat plate solar water heater without any thermal storage medium. The efficiency of the flat plate solar water heating system was evaluated by determining both solar receiver heat gain from equation (2.3) and the heat gained by the heated water from the solar collector using equation (2.11). The determination of receiver heat gain was done by measuring incident solar radiation intensity using the solarimeter, measuring collector dimensions to determine the area of the collector. However, heat gained by the heated water from the solar water heater was obtained by measuring input and output water temperatures, and mass flow rate. Instantaneous efficiencies were evaluated at 30 minutes interval during the research period. The experimental procedure was summarized a shown in the flowchart shown in **Figure** 3.4.

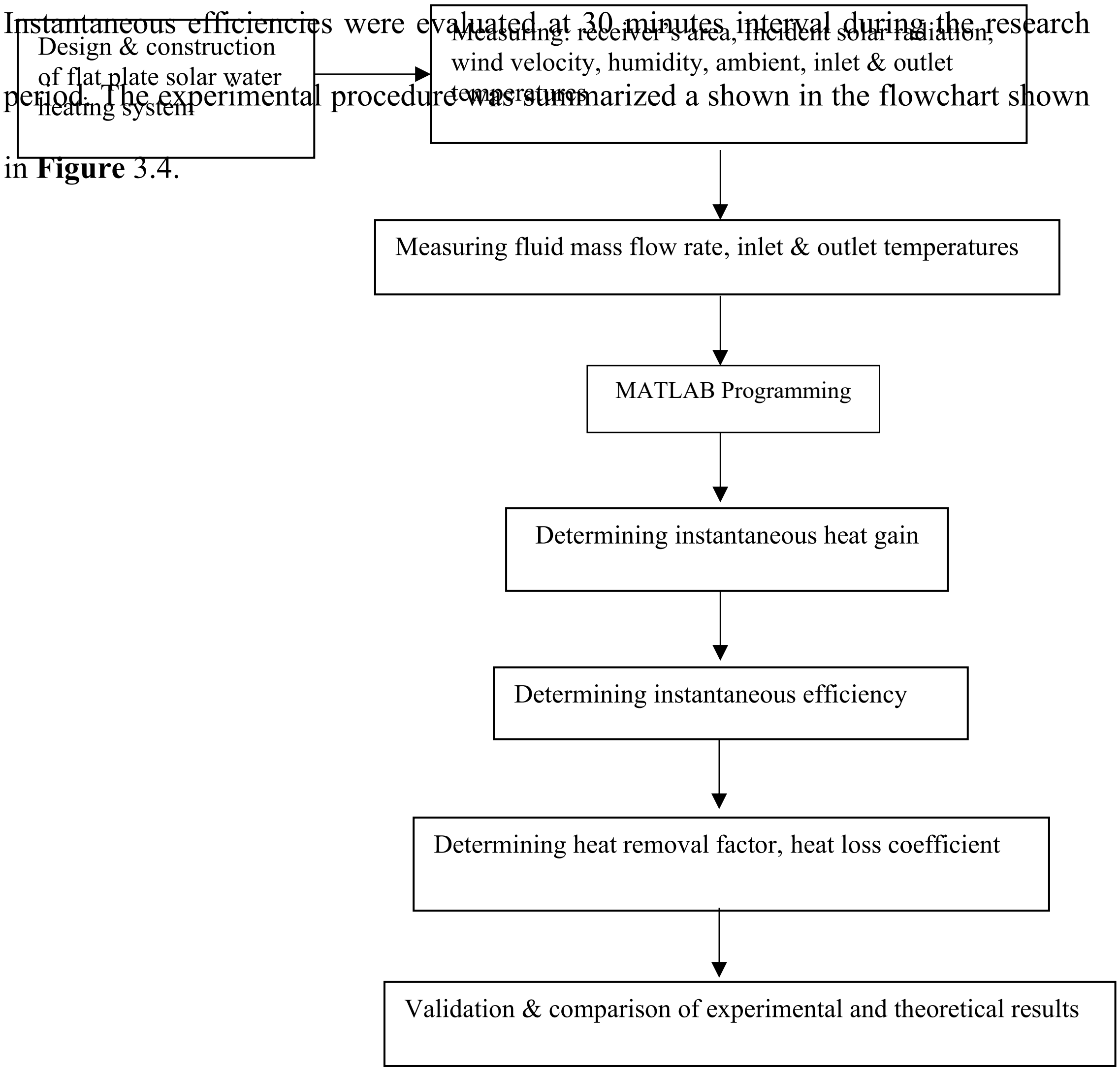


Figure 3.4: Flow chart of the experimental procedure

Experimental data computation and analysis were done using MATLAB as shown in the flow chart in **Figure 3.5**.

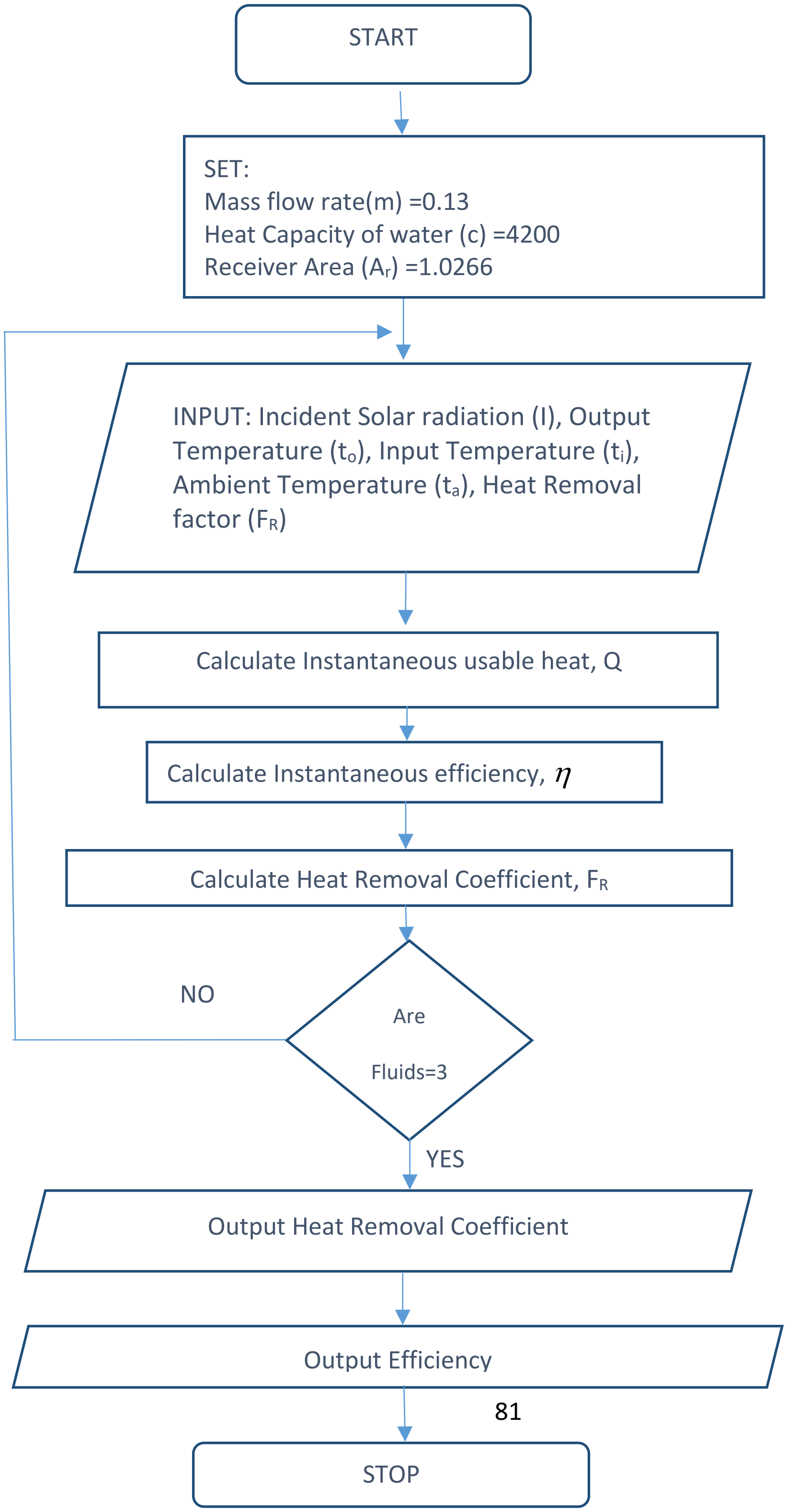


Figure 3.5: Flow chart for MATLAB program

3.2 Comparison and Analysis of Experimental Data against KOLEKTOR 2.2 Simulation Results under Dynamic Weather Conditions.

The theoretical simulation was done using the KOLEKTOR 2.2 software model which solves one-dimensional heat transfer balances for a flat plate solar water heater working under transient conditions. The simulation process was as shown in the flowchart shown in **Figure 3.6.**

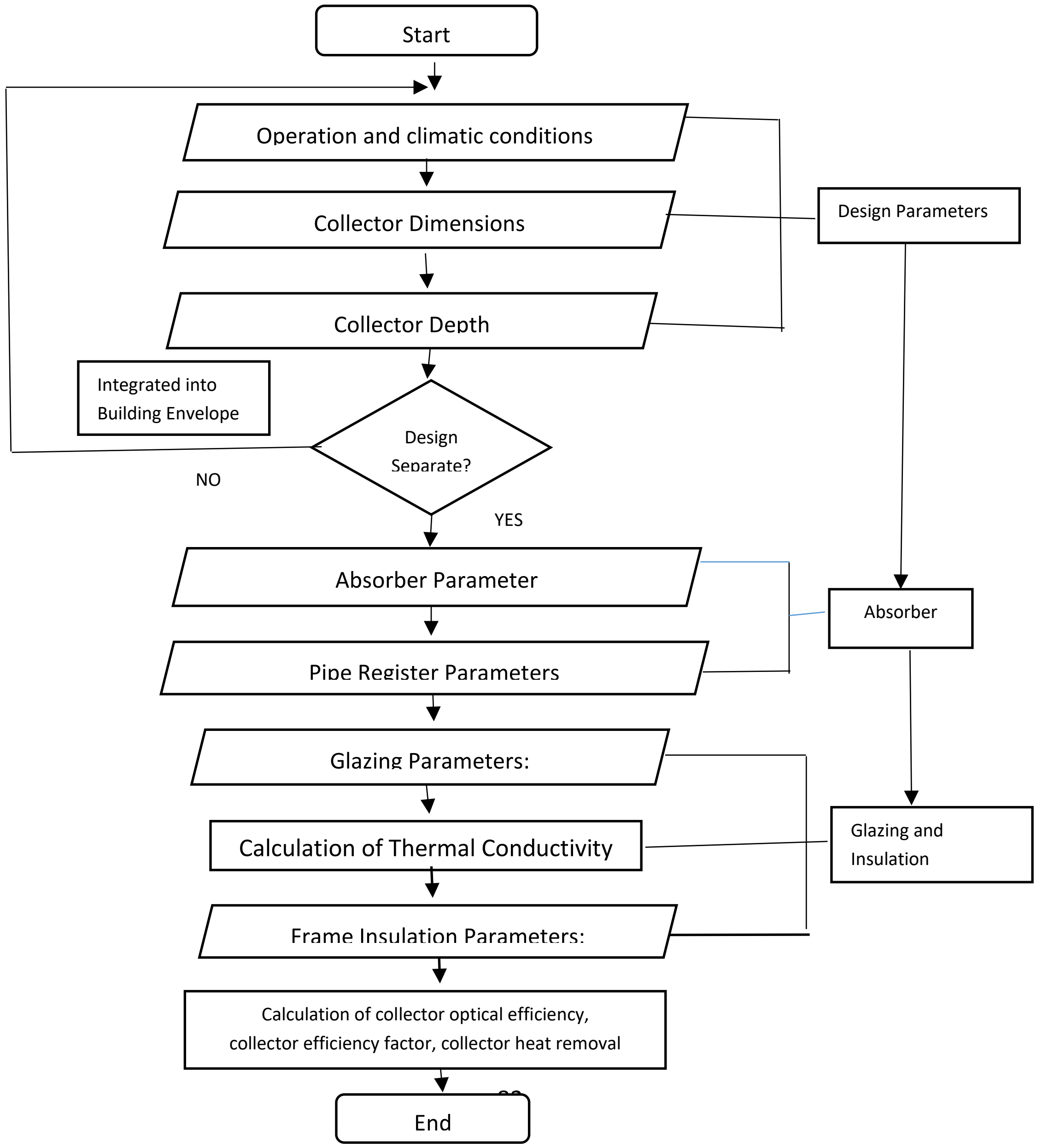
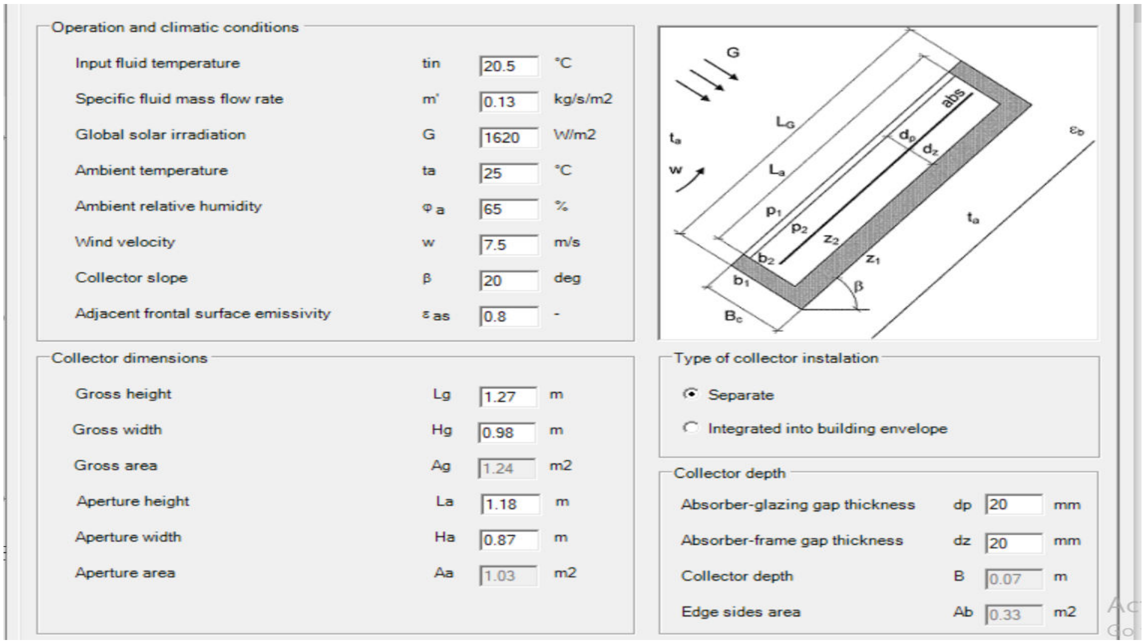


Figure 3.6: Flow chart of KOLEKTOR 2.2 simulation process

The model input parameters include geometrical, thermal and optical properties of portions of the solar collector, climatic and operation conditions. The following are the modelling conditions and parameters used in the study of the KOLEKTOR 2.2 design tool:

(a) Operational and Climatic Conditions

The design parameter inputs in the model consists of operating weather conditions. Ambient temperature fluid inlet and outlet temperatures were measured by type k thermocouples attached to a datalogger. Solar radiation intensity, humidity, and wind velocity were also measured. Gross length, gross width, aperture length, and collector depth were also measured. These parameter values were fed into the KOLEKTOR 2.2 design model tool as displayed in **Figure 3.7.**



Operation and climatic conditions

Input fluid temperature	tin	20.5	°C
Specific fluid mass flow rate	m'	0.13	kg/s/m2
Global solar irradiation	G	1620	W/m2
Ambient temperature	ta	25	°C
Ambient relative humidity	φ a	65	%
Wind velocity	w	7.5	m/s
Collector slope	β	20	deg
Adjacent frontal surface emissivity	ε as	0.8	-

Collector dimensions

Gross height	Lg	1.27	m
Gross width	Hg	0.98	m
Gross area	Ag	1.24	m2
Aperture height	La	1.18	m
Aperture width	Ha	0.87	m
Aperture area	Aa	1.03	m2

Type of collector instalation

● Separate
○ Integrated into building envelope

Collector depth

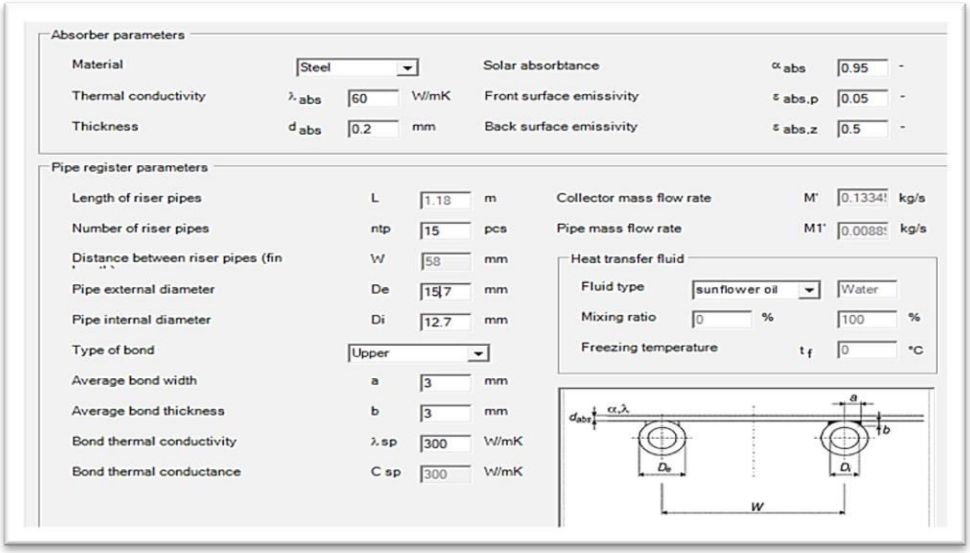
Absorber-glazing gap thickness	dp	20	mm
Absorber-frame gap thickness	dz	20	mm
Collector depth	B	0.07	m
Edge sides area	Ab	0.33	m2

Figure 3.7: Design parameters of the flat plate solar water heater KOLEKTOR 2.2 design model

(b) Absorber Parameters

These entail the nature of the absorber material, its thickness and thermal conductivity, solar absorbance, front and back surface emissivity values. The absorber parameters also consist of the number of riser pipes, length of the riser pipes, the distance between the pipes, external and internal diameters, type of bond, bond thickness, bond width, bond thermal conductivity, and bond thermal conductance. Collector mass flow rate, pipe flow rate, type of heat transfer fluid, fluid mixing ratio, and fluid freezing point were determined and fed into the KOLEKTOR 2.2 model.

The absorber parameter specifications used in the theoretical simulation are shown in **Figure 3.8.** Heat transfer and thermal storage fluids tested were sunflower oil, water, and air



Absorber parameters

Material		Steel	
Thermal conductivity	λ_{abs}	60	W/mK
Thickness	d_{abs}	0.2	mm
Solar absorbtance	α_{abs}	0.95	-
Front surface emissivity	$\varepsilon_{abs,p}$	0.05	-
Back surface emissivity	$\varepsilon_{abs,z}$	0.5	-

Pipe register parameters

Length of riser pipes	L	1.18	m
Number of riser pipes	ntp	15	pcs
Distance between riser pipes (fin	W	58	mm
Pipe external diameter	De	15.7	mm
Pipe internal diameter	Di	12.7	mm
Type of bond		Upper	
Average bond width	a	3	mm
Average bond thickness	b	3	mm
Bond thermal conductivity	λ.sp	300	W/mK
Bond thermal conductance	C sp	300	W/mK
Collector mass flow rate	M'	0.1334	kg/s
Pipe mass flow rate	M1'	0.0088	kg/s

Heat transfer fluid

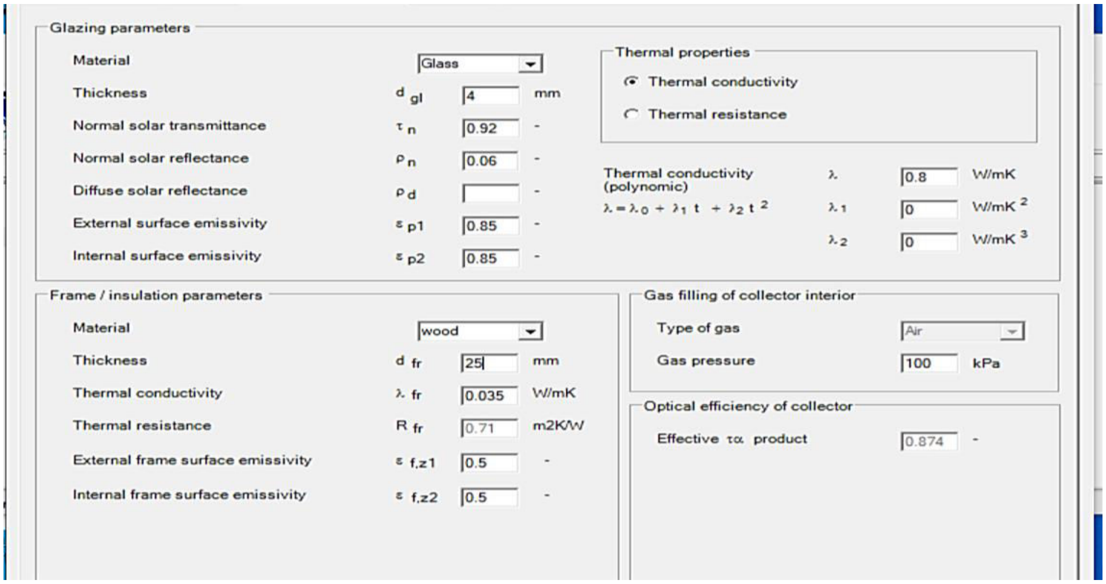
Fluid type	sunflower oil			Water	
Mixing ratio	0	%		100	%
Freezing temperature			t_f	0	°C

Figure 3.8: Absorber parameters of the flat plate solar water heater KOLEKTOR 2.2 design model

c) Glazing, and Frame Insulation Parameters

The glazing parameters fed into the KOLEKTOR 2.2 model are the nature of the glazing material, its thickness, normal solar transmittance, normal solar reflectance, diffuse solar reflectance, internal, and external emissivity values, and its thermal conductivity. Frame or insulation parameters in this study are the nature of the material, its thickness, thermal conductivity, thermal resistance, internal and external frame surface emissivity values. This parameter also entails the type of gas in the collector, gas pressure and collector optical efficiency.

Glazing and wooden frame insulation parameters used in the KOLEKTOR 2.2 mathematical model are illustrated in **Figure 3.9.** The collector optical efficiency in terms of transmittance-absorbance product was 0.874.



Glazing parameters

Material		Glass	
Thickness	d_{gl}	4	mm
Normal solar transmittance	τ_n	0.92	-
Normal solar reflectance	ρ_n	0.06	-
Diffuse solar reflectance	ρ_d		-
External surface emissivity	ε_{p1}	0.85	-
Internal surface emissivity	ε_{p2}	0.85	-

Thermal properties

● Thermal conductivity

○ Thermal resistance

Thermal conductivity (polynomic) $\lambda = \lambda_0 + \lambda_1 t + \lambda_2 t^2$	λ	0.8	W/mK
	λ_1	0	W/mK^2
	λ_2	0	W/mK^3

Frame / insulation parameters

Material		wood	
Thickness	d_{fr}	25	mm
Thermal conductivity	λ_{fr}	0.035	W/mK
Thermal resistance	R_{fr}	0.71	m2K/W
External frame surface emissivity	$\varepsilon_{f,z1}$	0.5	-
Internal frame surface emissivity	$\varepsilon_{f,z2}$	0.5	-

Gas filling of collector interior

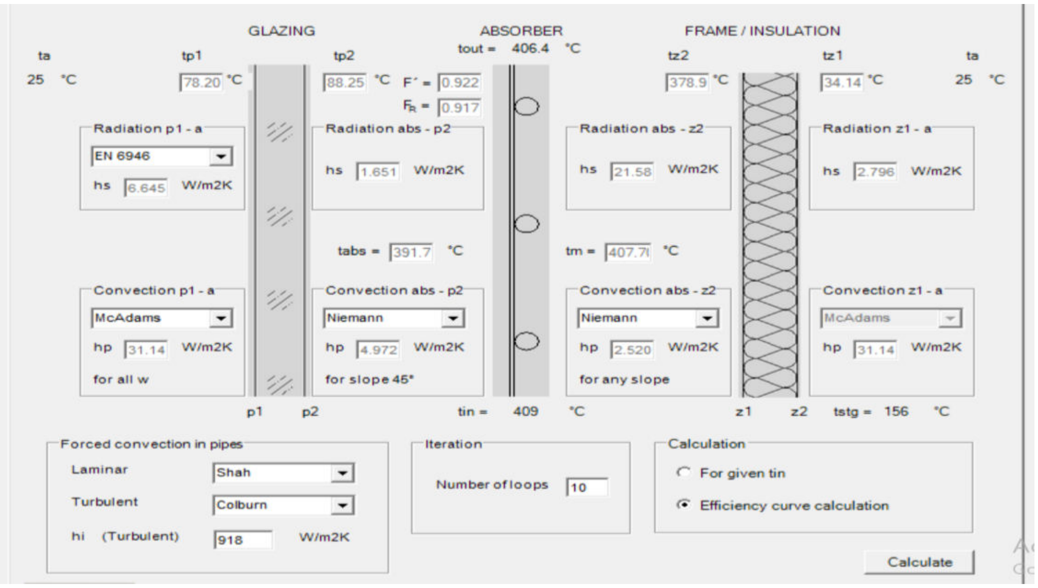
Type of gas	Air	
Gas pressure	100	kPa

Optical efficiency of collector

Effective $\tau\alpha$ product	0.874	-

Figure 3.9: Glazing parameters of the flat plate solar water heater KOLEKTOR 2.2 design model

Typical efficiency curve calculations for heat removal factor: F_R and absorber or collector efficiency factor F^I were as illustrated in **Figure 3.10**.



ta 25 °C
tp1 78.20 °C
tp2 88.25 °C
tout = 406.4 °C
F' = 0.922
F_R = 0.917
tz2 378.9 °C
tz1 34.14 °C
ta 25 °C

Radiation p1 - a: EN 6946, hs 6.645 W/m2K
Radiation abs - p2: hs 1.651 W/m2K
Radiation abs - z2: hs 21.58 W/m2K
Radiation z1 - a: hs 2.796 W/m2K

tabs = 391.7 °C
tm = 407.7 °C

Convection p1 - a: McAdams, hp 31.14 W/m2K, for all w
Convection abs - p2: Niemann, hp 4.972 W/m2K, for slope 45°
Convection abs - z2: Niemann, hp 2.520 W/m2K, for any slope
Convection z1 - a: McAdams, hp 31.14 W/m2K

tin = 409 °C
tstg = 156 °C

Forced convection in pipes
Laminar: Shah
Turbulent: Colburn
hi (Turbulent): 918 W/m2K

Iteration
Number of loops: 10

Calculation
○ For given tin
● Efficiency curve calculation

Figure 3.10: Flat plate solar water heater KOLEKTOR 2.2 design model calculation.

From the KOLEKTOR 2.2 software, the overall heat loss coefficient, *U* was obtained. Determination of this overall heat loss coefficient entails heat loss coefficients of the glazing cover U_g, side U_s and base U_b of the collector, as well as the aperture, gross collector and side areas.

The parameter that defines the efficiency of heat transfer between an absorber surface and a heat transfer fluid, i.e., the collector efficiency factor F', was calculated using the KOLEKTOR 2.2 model, which relied on the collector configuration used in the study as illustrated in Figure 3.10. This efficiency factor comprises total heat loss coefficient, interval between the tube centres, external and internal tube diameter.

Collector heat removal factor was determined using total mass flow rate of fluid m 0x through solar collector, 0.13 kg/s; *c* specific thermal capacity of fluid, in J/kgK; aperture area A_a of the solar collector, in m^2.

The solar water heater system efficiency was then determined applying the Hottel-Whilier-Bliss solar collector efficiency equation.

CHAPTER FOUR

RESULTS AND DISCUSSION

The performance of a solar thermal conversion system greatly depends on the solar radiation intensity incident on a given geographical location. Hence the measured the solar radiation for our experimental site was done and presented as shown in **Figure 4.1.**

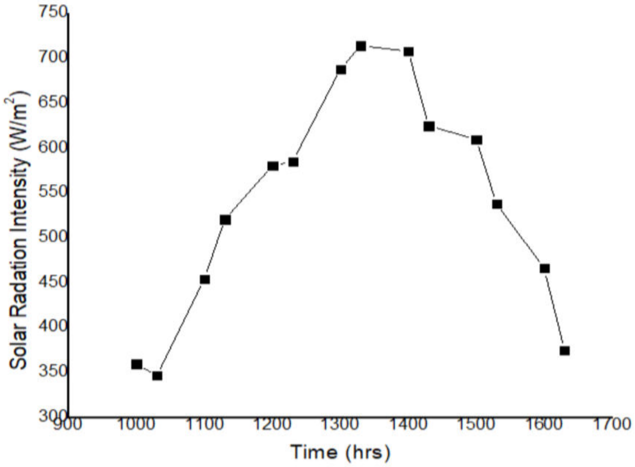


Figure 4. 1 Instantaneous solar radiation intensity

Solar radiation and energy trends are therefore useful for the solar-thermal energy application in deciding the periods when the desired temperatures can be obtained from various heating devices for the suitable needs.

This research was conducted in Kisumu County in Kenya whose monthly global hourly irradiation (GHI) is shown in **Figure 4.2**.

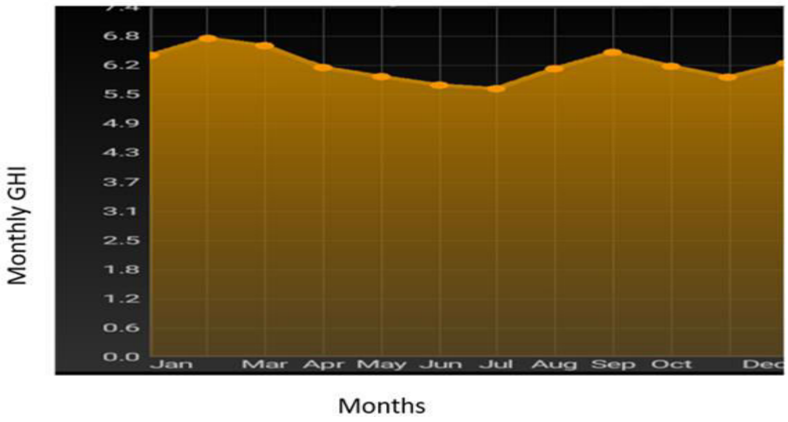


Figure 4. 2: Monthly global hourly irradiation for Kisumu- Kenya (Lat.-0.084, Long. 34.531)

Application of solar energy can therefore be utilized in Kenya due to high global solar irradiation associated with the regional geographical location. Use of this clean abundant renewable energy should therefore be promoted for heating purposes due to its environmental conservation benefits.

4.1 Determination of Instantaneous Receiver Heat Gain and Comparison of the Thermal Storage Effect of Water and Sunflower Oil on Output Temperatures

4.1.1 Receiver Heat Gain by Flat Plate the Solar Collector

The instantaneous heat energy gained by our solar water heater receiver from experimental and theoretical results within 1000hrs to 1630 was determined and presented as shown in **Figure 4.3** and **Figure 4.4.**

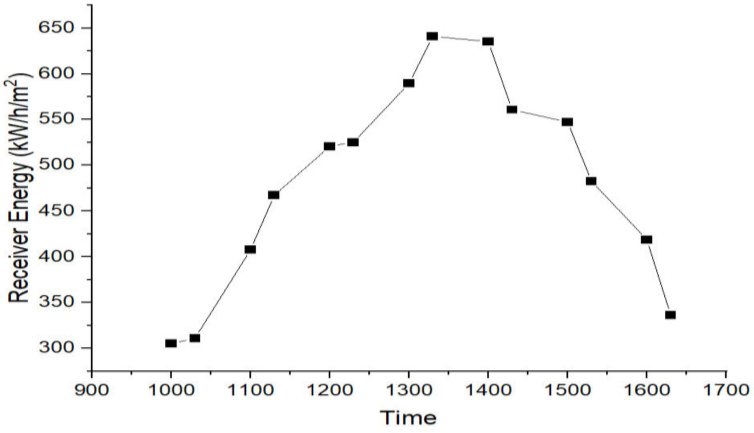


Figure 4. 3: Experimental Instantaneous receiver heat gain

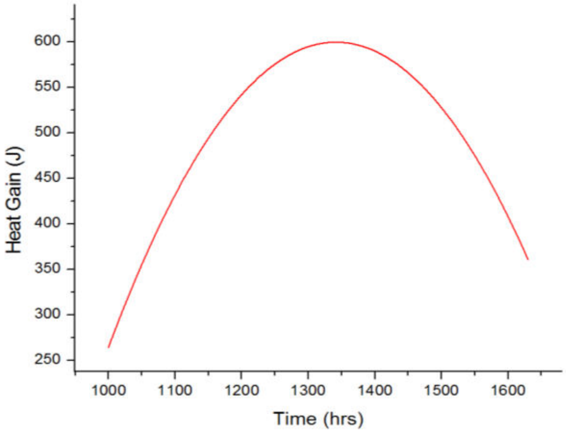


Figure 4. 4: Theoretical Instantaneous Receiver Heat Gain

From the experimental and theoretical heat gain graphs, it can be seen that much of the usable heat is obtained from 1230hrs to 1430hrs with the maximum being from 1300hrs to 1400hrs. Variation of the experimental and the KOLEKTOR 2.2 simulation results on the receiver heat gain was within 4.5%.

4.1.2 Effect of Sunflower Oil and Water on Output Temperature

Solar heating system output temperature is highly influenced by the intensity of the solar radiation and ambient temperature which is subject to weather changes. The temperature of the output is also a factor of the subsequent thermo-physical characteristics of the sensible heat storage material: specific heat capacity and thermal conductivity. The characteristics of air, water and sunflower oil as thermal energy storage (TES) fluid in a flat plate sunflower-based solar water were comparatively investigated. Their output temperatures rose with incident solar intensity in the morning till 1400hrs and then decreased after 1430hrs, as indicated in the experimental and theoretical graphs provided in Figure 4.5 and Figure 4.6 respectively.

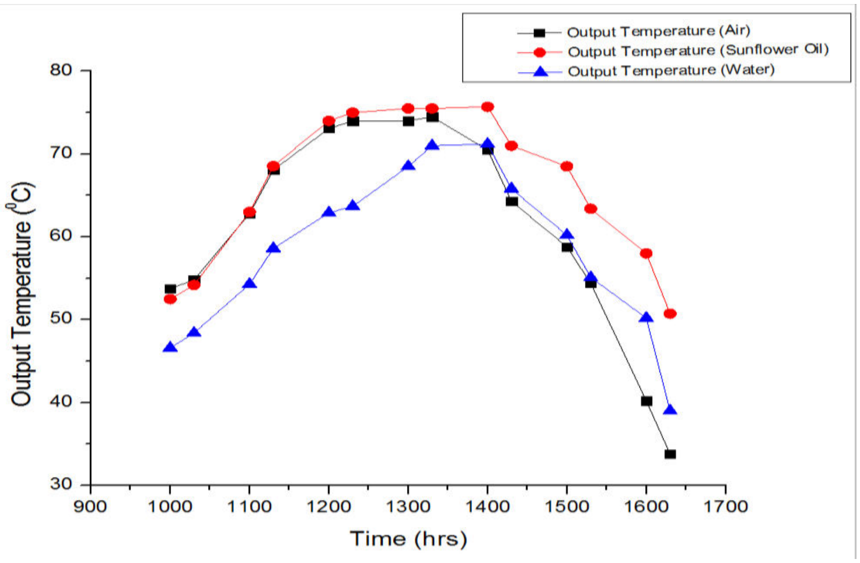


Figure 4. 5: Experimental instantaneous outlet temperatures due to thermal storage fluids

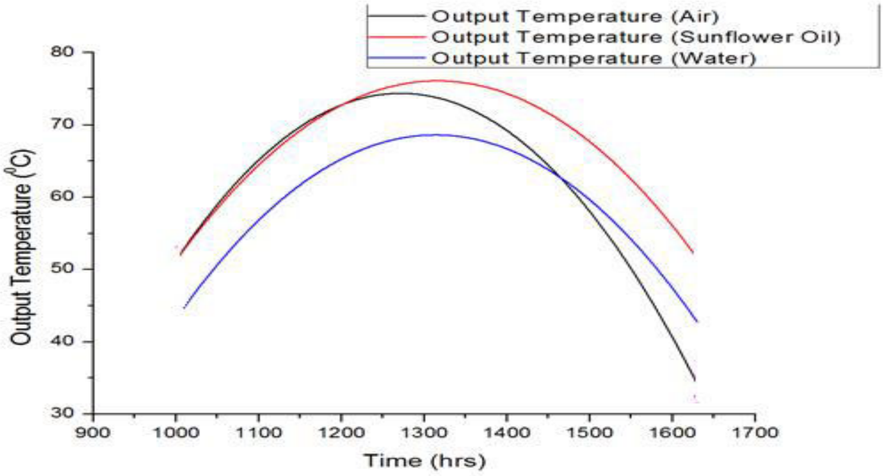


Figure 4. 6: Theoretical instantaneous outlet temperatures due to thermal storage fluids

The peak output temperature attained by the experimental flat plate solar water heater with sunflower oil as TSF was 75.7°C. However, the peak output temperatures for water and air were 71.2°C and 74.0°C respectively. It is also important to note that the rates of thermal energy gain and energy loss are faster in air than in water as thermal storage fluids in solar water heaters. The low output temperature for water as a sensible heat storage fluid is due to its high specific heat capacity as compared to other fluids. The rate of heat loss in sunflower oil as a thermal storage medium was much lower than in water. For instance, at 1600hr the storage fluid output temperatures for sunflower oil, water and air were 58.0°C, 50.2°C and 40.2°C respectively. Thus sunflower oil is a better thermal storage and heat transfer fluid than water and air.

Instantaneous temperature rise, which is a variation between the water inlet temperature and outlet temperature from the flat plate solar water heater is a quick way of testing solar thermal conversion performance of the solar heating device. Instantaneous temperature rise of water from the solar water heating system with thermal storage fluids.is therefore a measure of usable thermal energy gain due to such thermal storage media. The experimental result analysis on the instantaneous temperature rise of water from the flat plate solar water heater is shown in **Figure 4.7.**

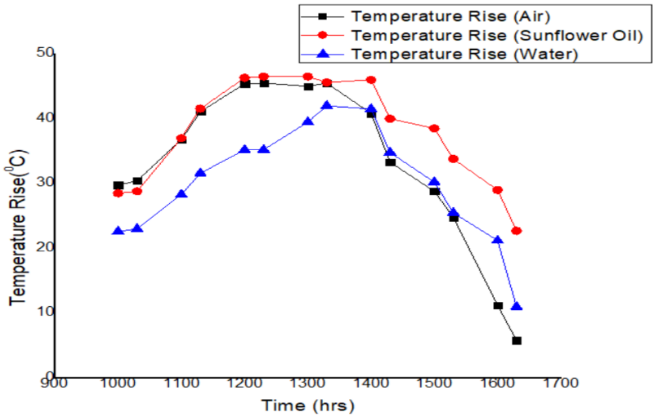


Figure 4. 7: Experimental instantaneous temperature rise by air, water and sunflower oil thermal storage fluids

Theoretical results analysis showing the instantaneous temperature rise from the inlet water temperature is shown in **Figure 4.8.**

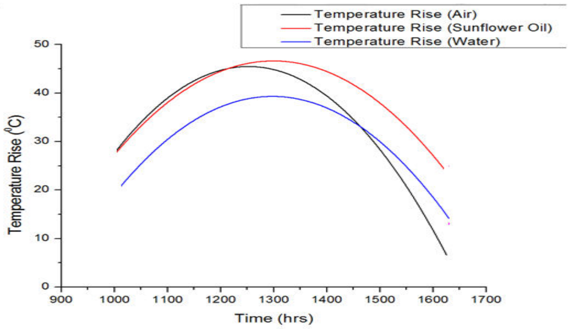


Figure 4. 8: Theoretical Instantaneous Temperature Rise by air, water and sunflower oil thermal storage fluids

The maximum temperature rise in comparison with the inlet water temperature of the flat plate solar water heater due to air, sunflower oil, and water as thermal storage media are 45.5°C, 46.5°C and 42.0°C respectively. The low temperature increase due to water as a thermal storage fluid is due to its high thermal energy absorption since it has higher specific heat capacity, thermal conductivity and thermal diffusivity than sunflower oil. From the temperature variation curves, it can be seen that solar thermal energy is at its peak between 1230hrs to 1400hrs due to strong incident solar radiations. Both graphs drawn from experimental and theoretical results show sunflower oil improves the solar-thermal energy conversion by the solar water heater. The variation of experimental and theoretical temperature values is within ±2.4%.

4.2 Evaluation of Effect of the Thermal Storage Liquids on Thermal Energy Loss and Heat Exchange Parameters.

4.2.1 Effect on heat loss

There were variations in receiver usable heat gain and output heat of the working fluid due to thermal losses associated with conduction, convection, and radiation within the solar water heating system. The thermal losses associated with air, water, and sunflower oil as thermal storage media were investigated both experimentally and theoretically. The research findings were presented in the graphs shown in **Figure 4.9 and Figure 4.10**.

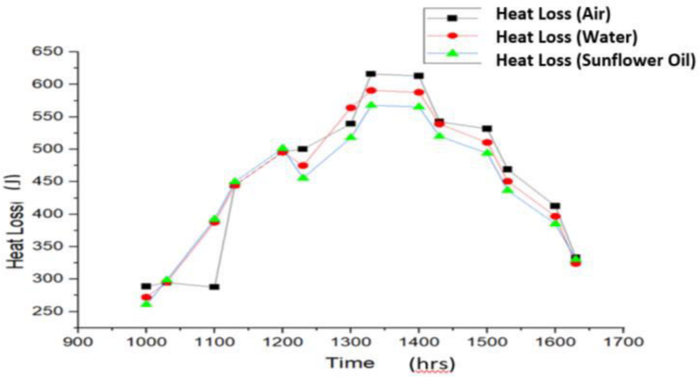


Figure 4. 9: Experimental Instantaneous thermal losses within solar collector associated with air, sunflower oil and water as thermal storage media

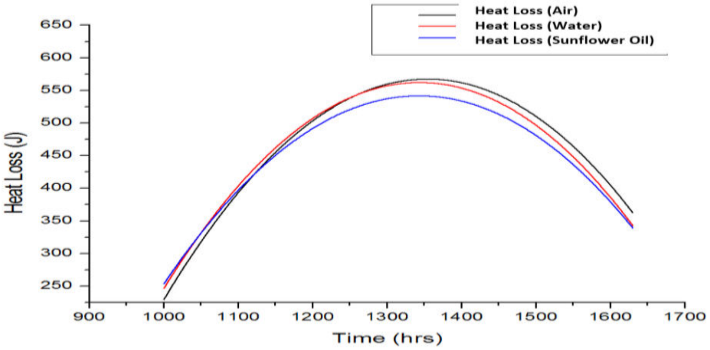


Figure 4. 10: Theoretical Instantaneous thermal losses within solar collectors associated with air, sunflower oil and water as thermal storage media

From the graphs of instantaneous heat losses from the solar water heaters containing the thermal storage fluids under study, it is evident that using thermal storage media reduces thermal losses in solar collectors. For instance at 6.30 pm the output temperature from the collector containing sunflower oil, water and air were 56℃, 48 ℃ and 28℃ respectively. Thus agreeing with the results on the effectiveness of thermal storage media by other researches. The higher thermal loss due to water occurs since thermal conductivities of water and sunflower oil are 0. 598-0.667W/mK and 0.161-

0.167W/mK respectively within a temperature range of 20℃- 80℃. Water also losses more heat due to its higher thermal diffusivity than sunflower oil, (Oyirwoth *et al,* 2023) established that sunflower oil has a long thermal retention ability.

4.2.2 Effect of Thermal Storage Fluids on Collector Heat Loss Coefficient and Heat Removal Factor

Figure 4.11 and Figure 4.12 respectively depict the experimental and theoretical efficiency curves, which can be used to estimate the heat loss coefficient and heat removal factor of the solar water heaters using the equation, which is referred to as the Hottel-Whillier-Bliss equation.

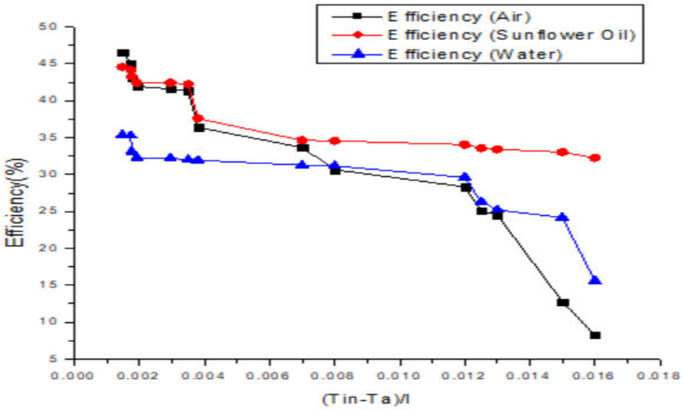


Figure 4. 11: Experimental overall collector efficiency curve.

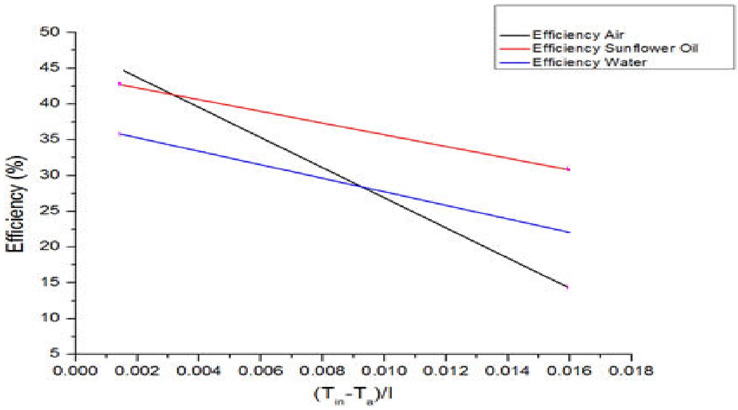


Figure 4. 12: Theoretical Overall Collector Efficiency Curve.

The external energy balance equation formulated by the mathematical model incorporates an iterative cycle where initial values of temperatures of all main surfaces are estimated based on initial values of temperature of the tin and ambient temperature ta as an input. External balance loop yields in overall heat loss coefficient U of the collector. The research results revealed that the overall heat loss coefficients U of air, water and sunflower oil were -38.40 W/m2K, -20.94 W/m2K and -15.80 W/m2K respectively in the experimental and theoretical range of variation of ± 8.5. The product of the solar collector system of effective transmittance and absorbance was 0.874.

The collector heat removal factor FR, may be expressed corresponding to the ratio of the actual useful energy gain of the collector to the useful gain at the fluid temperature, at which the absorber surface will be. Collector heat removal factor F_R can therefore be synonymous with the performance of a standard heat exchanger, the performance of which is also a ratio of actual heat transfer to the maximum possible heat transfer. Maximum possible useful heat gain in a solar collector occurs when the whole absorber is at the inlet fluid temperature (no temperature increases along the riser pipes, minimized heat loss), (Matuska and Zmrhal, 2009) From the experimental results our solar water heater has a heat removal factor F_R of 0.8934, 0.846 and 0.785 for sunflower oil anwater and air respectively. However, from the KOLEKTOR 2.2 model, the heat removal factor F_R for sunflower oil is 0.937, while water and air have heat removal factors of 0.918, and 0.910 respectively. Both experimental and theoretical results showed that sunflower oil has the highest heat removal factor within experimental error of ±4.6%, hence sunflower oil is effective for the heat exchange mechanism

4.2.3. Effect of Sunflower Oil and Water on Efficiency Factor of a Solar Collector

The thermal power output was determined based on mean fluid temperature tm which was found by using measured input temperature and output temperature. The effective thermal power output of the collector at this average fluid temperature equals the sum of efficiency factor F^1 as defined in 2.4.2 of the literature review. The parameter is the ratio of the efficiency of the heat transfer between the absorber surface and the heat transfer fluid, The equation (2.27.) is a definition of the efficiency factor. The factor of collector or absorber efficiency can then be simply given as the ratio of the heat loss coefficient of the liquid to the ambient U_0 to the sum of the total heat loss coefficient U. Based on the KOLEKTOR 2.2 model efficiency factor F^1 of sunflower oil, water and air 0.922, 0.916 and 0.818 respectively. The experimental efficiency factor was determined to be 0.878, 0.856, and 0.778 within a 5 percent variation to the theoretical outcome. This study has shown that sunflower oil is better as a heat transfer fluid compared to water and air. It has been reported that sunflower oil is suitable for good for high temperature charging during thermal storage leading to high energy, high exergy and exergy factor, (Mawire *et al.*2015).

4.3. Comparison of Water and Sunflower Oil on Overall Solar Water Heater System Efficiency

The efficiency of a solar heating system is therefore determined by the temperature of the output fluid which is used to determine the performance of the solar-thermal energy conversion system.

The usable thermal power production of the collector as a fraction of the incident sunlight on the collector front face is called the efficiency of the collector. How well a solar water heater works is related to the conduction, convection and radiation heat losses. The useful energy collected following such thermal losses is a fraction of the amount of energy taken up by the working fluid. The total heat loss coefficient U takes into account the loss at the collector sides, at the rear of the collector and in the collector glazing.

Figure 4.13 showed the instantaneous efficiency curves (experimental and theoretical) of the thermal storage fluids between the periods of 1000hrs and 1600hrs.

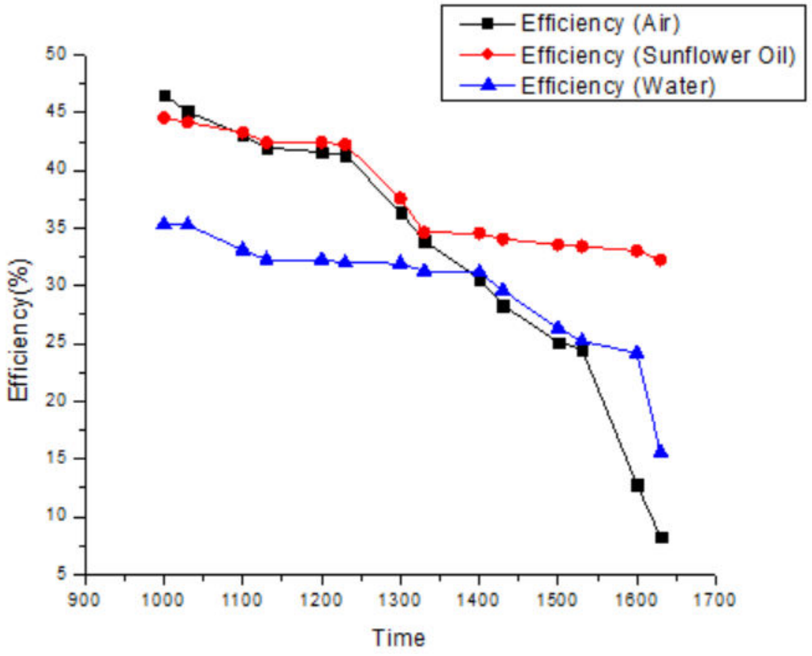


Figure 4. 13: The experimental instantaneous efficiency curves for the thermal storage fluids

The theoretical instantaneous efficiency curves computed from the KOLEKTOR 2.2 model results are shown in **Figure 4.14.**

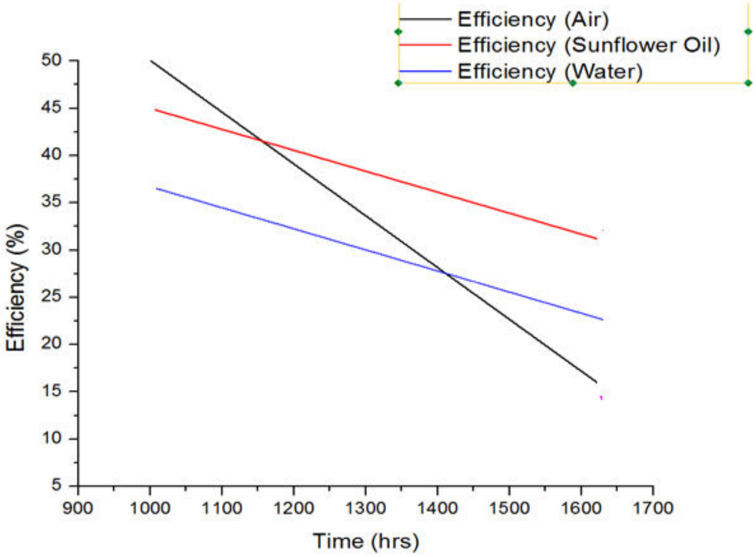


Figure 4. 14: Theoretical instantaneous efficiency curves for the thermal storage fluids

The experimental and theoretical efficiency trend curves show that in general, the system of flat plate solar water heating efficiency decreases during the morning and evening. Thermal storage fluid reduces the instantaneous decline in efficiency of the solar water heater. Thus sunflower oil has a higher efficiency than water in solar thermal storage in a flat plate solar water heating system. The overall system efficiency from the KOLEKTOR model due to sunflower oil and water were 75% and 68% respectively, while the solar collector without the storage medium had an efficiency of 54.4%, with a variation of ±2.5% from experimental results. These results are in agreement with earlier studies that sensible heat storage media reduce heat losses and increase efficiency, (Piyush *et al.*2022). Sunflower oil in particular under low and high power charging has energy storage efficiency of 85% and 78% respectively, Mawire *et al.*2014).

4.4 Comparison of Experimental Results against the KOLEKTOR 2.2 Simulation Results

Experimental results on solar receiver heat gain agree with the KOLECTOR 2.2 simulation results on the heat gained variation with the incident solar radiation intensity within the error of ± 4.5%. Further experimental investigations on output temperature, heat loss and heat exchange parameters as well as the overall system efficiency agreed with the KOLEKTOR 2.2 simulation results within the acceptable error limits discussed in this chapter.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATION

5.1 CONCLUSIONS

The heat gained by our prototype flat plate solar water whose absorber plate and tubes were made of mild steel, attained a peak output water temperature of 75℃. This temperature compares well with the commercial solar water heaters which have been reported by (Zarza, 2002) to heat water up to 80°C. The absorber plate and tubes of the commercial solar water heaters are made of aluminium and copper respectively. The heat gained by the solar collector is directly proportional to solar radiation intensity, aperture area, and absorption transmittance product.

From both experimental and theoretical results it was deduced that sunflower oil improved output temperature throughout while water initially reduced the outlet temperature until 1400hr, after which the temperature was improved. These results show that both water and sunflower oil are useful in thermal conservation within the solar collector since solar radiation intensity reduces from 1400 until sunset. For instance, at 1630 the output temperatures due to air, water and sunflower oil were 35.3℃, 48.5℃ and 57.2℃ respectively. Thus the thermal storage fluids increase the quantity of stored heat by the solar collector, hence increasing the temperature of the inlet fluids in to the solar collector.

Analysis of the impact of these thermal storage fluids on heat loss and heat exchange parameters showed that thermal loss from the collector receiver due to water was greater than sunflower oil. For instance thermal losses at 1630 due to air, water and sunflower were 345.5J, 330.2J and 295.6 respectively. From the results it was also noted that heat loss coefficient of the solar collector due to water was greater than sunflower oil as thermal storage media. This fact is attributed to higher thermal diffusivity and thermal conductivity of water than sunflower oil. These properties enable sunflower oil to retain heat for a longer period than water.

Further investigations on the thermal storage fluid effect on the solar collector's heat exchange characteristic revealed that sunflower oil has a higher heat removal factor than water. It is worth noting that both thermal fluids studied improved the heat removal factor of the flat plate solar collector. The efficiency factor of the solar collector also improved due to sunflower oil and water as the thermal storage media. Sunflower oil produced a greater positive impact on the efficiency factor.

The overall solar collector system efficiency was improved by these thermal storage media investigated in this study. Sunflower oil increased the solar collector efficiency than water. For instance, at 1430 the collector efficiency due to air, water and sunflower oil was 35.3%, 42.4% and 48.6% respectively, within experimental and theoretical variation of ± 8.5%. This shows that sunflower oil produces higher usable thermal power output than water from equal incident radiation on the solar collector surface.

However, despite its high cost, sunflower oil is a better thermal storage medium than water and also more suitable for higher temperature applications due to its high boiling point and flash points of 250℃ boiling temperature of 229-230℃ respectively. The research was successfully conducted since the set objectives were met.

5.2 RECOMMENDATIONS

Recommendations from this research are as follows:

- Coating the absorber plate and tubes in the solar water with a selective coating material like Indium Tin Oxide would have enhanced the instantaneous heat gained by the solar collector and outlet water temperature and reduced radiative thermal losses.
- Pre heating the thermal storage fluids using parabolic concentrators may greatly improve the instantaneous output temperatures of solar water heaters.
- More research should be conducted on the specific quantity of sunflower oil required for a given size of solar water heater for a specified thermal storage duration under various climatic conditions.
- Use of other vegetable oils as thermal storage media in solar water heaters should be investigated in further research. This should include blending such fluids with metallic nanoparticles in investigating their impact on the overall efficiency on the solar heating system.

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APPENDIX

MATLAB CODE

```
 q;double f1;double f2;double f3;double f4;double f5;double f6;double f7;double
f9;double f10;double f11;double eff;double kk;double k;double p;double z;double
y;double hrf;double hrf1;double n1;double frm;double f12;double n;double u;int8
to;double ti;double ta;

m=0.13;
c=4200;
ar=1.0266;
t=0.847;
ac=1.0266;

kk=input('Enter output incident solar radiation (i):');
to=input('Enter Output Temperature (to):');
ti=input('Enter The input temprature (ti:)');
ta=input('Enter Ambient Temprature (ta):');
frm=input('Enter Heat Removal factor (fr):');

 k=m*c;
 p=to-ti;
 f1=k*p;
 z=1;
 y=ti-ta;
 f2=z/y;

 f3=ac*frm;
 f4=f1/f3;
 f5=kkt;
 f6=f5-f4;
 f7=f2*f6;

f8=kk*ac;
eff=f1/f8;
f9=f5*ac;
f10=f9-f1;
fprintf('The instantaneous solar radiation=');disp(kk);
fprintf('The efficiency is=');disp(eff);
```

```
fprintf('The Heat loss Coefficient=');disp(f6);
fprintf('The output temperature');disp(to);
fprintf('The temperature rise=');disp(p);
fprintf('The heat loss=');disp(f10);
```