DESIGN, CONSTRUCTION AND PERFORMANCE EVALUATION OF SOLAR WATER HEATER

BY

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CERTIFICATION

I hereby certify that this work was carried out by Mr. Orimogunje Bukola Adetunji of the Department of Physics, Federal University of Technology, Akure, Ondo State. And that he has under taken this dissertation to the best of my knowledge for the award of Master of Technology in Physics.

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DEDICATION

This Project is dedicated to the Glory of God and benefit of mankind, and to my loving wife Mrs. Orimogunje Folake Wonuola, who stood by me during the course of this project.

ACKNOWLEDGEMENTS

Glory and adoration be unto the almighty god for the successful completion of this project.

I wish to express my profound gratitude to Dr. Rabiu A.B., who supervised this project and offered useful suggestions and assistance during the course of this project. I also acknowledge with thanks, the Head of Department, my lecturers and all other members of staff of the Department of Physics.

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ABSTRACT

A solar water heater was designed and constructed using locally available materials. The components of the system are flat plate collector and storage tank. A method of estimating the performance of solar water heater circulating to a storage tank by thermosyphon is presented. Ideal condition of no draw off during the day and clear sunshine are assumed. An experimental study performed on the system shows that the system perform well with approximately 50.1% collector efficiency using Hottel – whiller equation (ASHARE 93-97 standard test method) and producing hot water at average temperature of 55^{0}C. The results were compared with those estimated from theoretical method. The results show very good agreement.

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CHAPTER ONE

INTRODUCTION

1.0 NEED TO DEVELOP INDIGENOUS SOURCES OF ENERGY

The worldwide energy crisis, which started in 1973 (Babatunde, 1985), has the possibility of getting worse as oil becomes depleted and the oil-rich countries cut down production. The developing countries are the hardest hit by this, and they need to address themselves to developing their indigenous resources of energy and adopting energy option to meet their immediate and long term energy demands.

Nigeria's demand for energy will increase enormously as her industrialization and her population growth are very rapid. The nation's population growth is enormous, about 1.8 million people every year (Fashola, 1983). Her conventional sources of energy, both developed and undeveloped are unlikely to be able to cope with this demand because of their rapid depletion. More importantly, they are not only sources of energy, but to a greater extent, the foreign exchange earners. It is neither wise nor affordable to import any form of energy as a way of conserving and increasing national foreign exchange.

At present, our electrical energy supply is inadequate and unsteady. It is distributed mainly to the urban areas and few rural areas. As at today the desire and yearning for rural electrification is very high, Fashola, (1983). It is therefore imperative for Nigeria to start developing her other sources of energy. It has been suggested that meeting Nigeria's energy need now and in future can be done through renewable sources and optional utilization of the energy now available to her.

When estimating the share which renewable energy may sustain in meeting the future energy demand of the developing nations, Khan, (1983) assumed that electricity supply to cities will be met solely through centralized supply, while the supply to the village will partially be met by soft decentralized renewable energy sources, so as to cut down on the high cost in transmission networks and the associated maintenance and distribution expenses.

Soft decentralized technologies based on renewable energy sources will be a wise and compatible option for Nigeria's rural distributed population. By "soft decentralized" we mean simple technology, based on small scale, and locally distributed e.g. for individual homes or as a unit to a small community.

1.1 POSSIBLE SOLAR ENERGY APPLICATIONS IN NIGERIA.

Solar energy is providing by far the most attractive source of renewable energy for mankind. Many experimental and developmental solar energy utilization systems have long been pursued vigorously in several industrialized countries of the world Experiments that have been piloted cover a broad range of potential uses of solar energy, including thermal electric power generation on a small scale, heating and cooling of buildings, water heating, water de-salting by evaporation, cooking, food refrigeration, high-temperature materials processing, specialized solar drying, electricity generation by using photovoltaic cells etc. Some of these experiments have yielded very promising results and the devices thus provided have been put to some successful applications, while others are yet to be commercialized. Those that are already commercialized may take a long time to surface in the markets of the developing countries. However, developing countries have joined the race for solar energy application. In Sudan for example, a solar power project for drinking water and alkaline salt has been set up to produce 2m^3 of drinkable water daily. Similarly, a solar desalination water-pumping project has been undertaken in the Namibia (Garg and Prakash, 1997). Also, solar water heating is practiced in the republic of Niger (Adegoke and Bolaji, 1999). Flat-plate collectors have been used widely for utilizing solar energy for heating houses and for heating water for domestic hot-water supply in countries such as the U.S.A. and Japan. Many research workers have considered their performance both analytically and experimentally, and sufficient information and data are available so that a heating system can be designed to perform satisfactorily.

So far, the only activities of solar energy research utilization in Nigeria are in the area of thermal application - solar drying and solar radiation studies. Measurement of the global radiation is going on in most of the meteorological stations where synoptic records are taken. There are a few other places making similar measurement for academic purposes. Promising areas of solar energy utilization in Nigeria are many, but there are some, which are more viable and very relevant to Nigerian economic growth than the others.

Examples of these are:

1 Solar drying

2 Electricity generation using photovoltaic cells

3 Solar cooling and refrigeration

4 Solar still or solar distillation

5 Solar heater for domestic hot water services

This project focuses mainly on the solar heater for domestic hot water services (solar water heater).

1.2 SOLAR WATER HEATER

Solar water heater is a device, which is used to meet a significant proportion of hot water demand in the homes and in hotels. The main components in the construction consist of a flat plate collector and a large insulated storage tank with pipes to convey the hot water. By mounting the collector on the roof with storage tank located above the collector, the hot water is supplied to the storage tank by the principle of thermosyphon.

1.3 OBJECTIVES

The objective of this project is to design and construct a solar water heater for domestic hot water services. This project seeks to enhance solar energy utilization in Nigeria, by concentrating on heating as one of the applications of solar energy. The locally constructed solar water heater will surely conserve and increase our foreign exchange. The solar water heater to be constructed would be designed so as to ensure that it

- is efficient
- needs no maintenance and running cost
- saves time and energy
- is simple to construct and install
- can be fitted to existing houses.
- is economically and operationally competitive with electric water heaters.
- is able to achieve the required temperature easily.

1.3.1 JUSTIFICATION OF OBJECTIVES

Solar water heaters have a high utility value. They find wide application in large establishment like hotels, hospitals, and industries such as textile, paper and food processing, domestic uses and in heating swimming pools.

Among the different sources of renewable energy in Nigeria, only hydropower has been significantly applied on a commercial basis. This project is a way of utilizing solar energy on a commercial basis also. The design and construction of the solar water heater from locally available materials is to conserve and increase our foreign exchange, hence boosting economic value.

The soft decentralization option of applying renewable energy should be practiced in Nigeria because of her pattern of life style and the distribution of her population. Solar water heating is one of the possible ways of achieving the soft decentralization of energy option since the devices can be provided in the rural areas, on individual basis or on a community basis.

This project is a way of considering the solar energy applications, to meet the present and long-term energy demand in Nigeria. Although figures are not provided to give information on the cost and on the share of the total energy they will sustain, the array of installation of soft decentralized renewable sources of energy will certainly relieve pressure on the other energy sources. Consequently, this option will provide a desirable long-term cumulative effect on our national economy.

In Nigeria, where there is acute energy shortage, and abundant sunshine, solar water heating offers a big relieve pressure on the other alternative energy sources.

CHAPTER TWO

2.0 SOLAR RADIATION AND ENERGY

2.1 Solar Radiation

Solar radiation is the radiation from the sun. Most solar and terrestrial radiations falls between 0.5 and 120µm (micronmeter), and the radiation of practical importance to the solar energy users falls between 0.15 and 3.0µm. Wavelengths of the visible radiation lie between 0.38 and 72µm (Garg and Prakash, 1997).

Table1: Electromagnetic spectrum according to wavelength

Wavelength (µm)	E.M Radiation
$<10^{-6}$	Cosmic rays
$10^{-6} - 10^{-3}$	X-rays and γ rays
$10^{-3} - 0.2$	Far ultraviolet
0.2 – 0.315	Middle ultraviolet
0.315 – 0.38	Near Ultraviolet
0.38 – 0.72	Visible
0.72 – 1.5	Near Infrared
1.5 – 5.6	Middle infrared
6.5 – 1000	For infrared
>1000	Micro and radio waves

(Source: Garg and Prakash, 1997)

2.2 SOLAR ENERGY

Solar Energy is the radiant energy produced in the sun as a result of nuclear fusion reaction. It is transmitted to the earth through space in quanta of energy called photons, which interact with the earth's atmosphere and surface. The earth receives only about one-billionth of the total energy radiated by the sun which is enough to sustain the entire biosphere (Garg and Prakash, 1997). At the periphery, that is the outer edge of the earth's atmosphere, the strength of solar radiation is $1.35kWm^{-2}$ or about 2 calories/min/cm^2; this is called the solar constant. The intensity is not constant; however, it appears to vary by about 0.2 percent in 30 years. The intensity of energy actually available at the earth's surface is less than the solar constant because of absorption and scattering of radiant energy as photons interact with the atmospheric particles.

2.3 SOLAR ENERGY COLLECTION

The strength of the solar energy available at any point on the earth depends, in a complicated but predictable way, on the day of the year, the time of day, and the latitude of the collection point. The solar energy is abundant in the tropics because of the geographical location of the orientation of the collecting object.

There are three types of solar collector system, which convert solar energy to other forms of energy.

1 Flat plate collector
2 Solar concentrating collectors
3 Solar photovoltaic

2.3.1 FLAT PLATE COLLECTORS

The flat plate collector is basically a heat exchanger, which transfers the radiant energy of the incident sunlight to the sensible heat of a working fluid-liquid or air.

Flat plate collectors have the following advantages over other types of solar energy collectors.

i. Absorb direct, diffuse and reflected components of solar radiation.
ii. Are fixed in tilt and orientation and, thus there is no need of tracking the sun.
iii. Are easy to make and are low in cost.
iv. Have comparatively low maintenance cost and long life.
v. Operate at comparatively high efficiency.

2.3.1.1 THE WORKING PRINCIPLE OF FLAT PLATE COLLECTORS.

The principle behind a flat plate collector is simple. If a metal sheet is exposed to the solar radiation, the temperature will rise until the rate at which energy is received is equal to the rate at which heat is lost from the plate; this temperature is known as the "equilibrium temperature". If the back of the plate is protected by a heat insulating material and the exposed surface of the plate is painted black and is covered by one or two glass sheets, then the equilibrium temperature will be much higher than the simple exposed sheet. This plate may be converted into heat collector by adding a water circulating system; either by making it hollow or by soldering metal pipes to the surface and transferring the heated liquid to a tank for storage. For heat withdrawal from the system, the equilibrium temperature must decrease, since no useful heat can be extracted at the maximum equilibrium temperature at which collection efficiency is zero.

The other extreme condition is when the flow of fluid is so fast that the collection approaches 100 percent, yet no useful heat can be extracted. The optimum condition is approximately midway between the atmospheric temperature and the maximum equilibrium temperature, whereby an output of liquid at a useful temperature is obtained.

2.3.1.2 THE LIQUID FLAT PLATE COLLECTOR

Flat plate collectors consist of several basic elements as shown in fig.1.1. These are as follows.

(i) A flat absorbing plate, normally metallic, upon which the short wave solar radiation falls and is absorbed.

(ii) Tubes, channels or passages attached to the absorbed plate to circulate the liquid required to remove the thermal energy from the plate.

(iii) Thermal insulation, provided at the back and sides of the absorber plate to minimize the heat losses.

(iv) A transparent cover (one or two sheets) of glass or transparent plastic to reduce the upward heat loss from the absorber plate, and

(v) A weather-tight container to enclose the above components

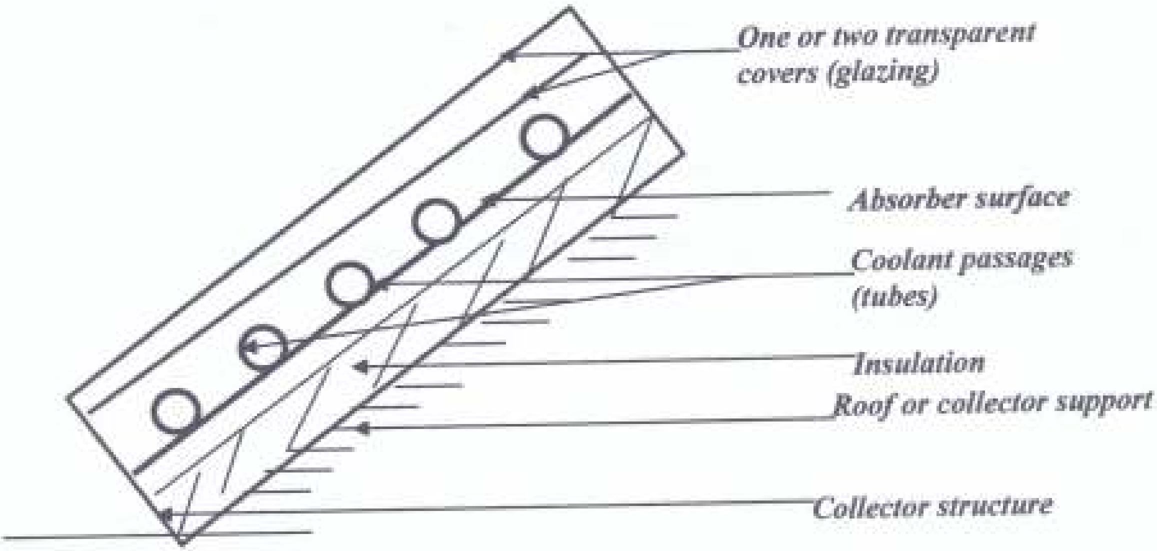


Fig. 1.1 Schematic cross-section of a typical flat plate solar collector illustrating the major functional parts

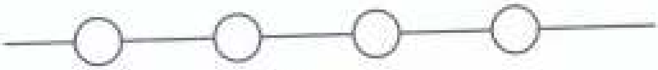
These liquid flat plate collectors are potentially useful in supplying low-grade thermal energy at temperature generally less than 100°C and may be used in systems to supply heated water for domestic, agricultural and industrial application. Flat plate collectors are classified into three groups depending on the application. These are as follows:

(i) Simple and low cost collectors with no cover and insulation; can be used for heating swimming pool, where the required rise in temperature is very small.

(ii) Flat plate collectors with applications in areas requiring medium temperature as for domestic water heating, where the maximum temperature required may be around 60°C; need some lower cost insulation and at least one transparent cover.

(iii) Well engineered and sophisticated flat plate collectors with application in process heating or small-power production, which requires temperature in the range 80 – 95°C.

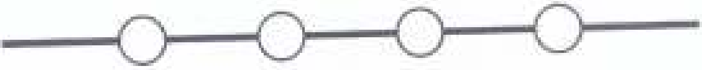
There is a great variety of successful solar collector-absorber plate for liquid heating as shown in fig. 1.2



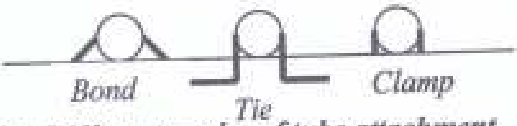
(a) Tube in black plate

(b) Tubes bonded to upper surface of black plate

(c) Tubes fastened to lower surface of plate



(d) Tubes fitted in grooved plate

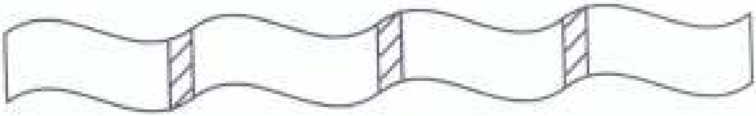


(e) Different modes of tube attachment

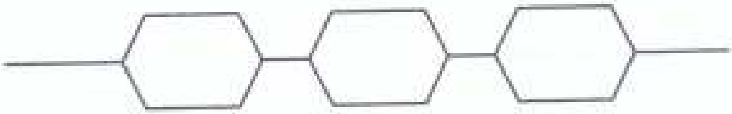
(f) Rectangular tubes bonded to plate

(g) Corrugated sheet on a flat plate

(h) Corrugated sheets wetted together



(i) Corrugated sheets fastened together



(j) Roll bond aluminum collector

(k) Thomson system

(l) Roll bond aluminum collector

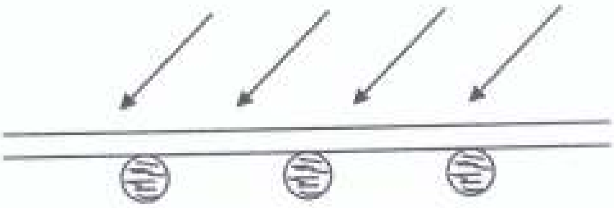
Fig. 1.2 Cross section through collector plate

These absorber plates can be broadly divided into three types as shown in fig. 1.3 depending on the extent of wetted surface area relative to the absorbing surface area.

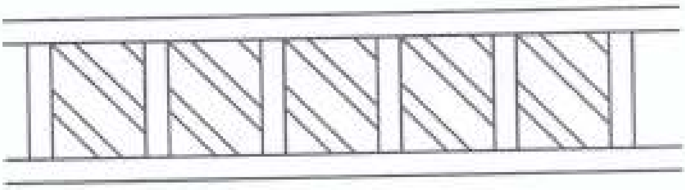
Type I: Pipe and fin type in which the liquid flows only in the pipe and hence has comparatively low wetted area and liquid capacity.

Type II: Rectangular or Cylindrical full sandwich type in which both the wetted area and the water capacity are high.

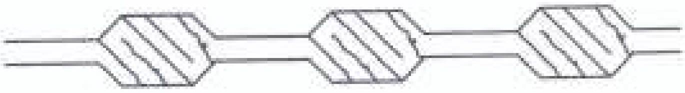
Type III: Row bond type or semi-sandwich type intermediate between type I and II.



Types I: Pipe and fin



Type II : Water sandwich



Type III : Semi water sandwich

Fig. 1.3 Basic collector-absorber plate types

For domestic and industrial application where higher temperatures, high efficiency, reliability and long life are required; pipe and fin type panel may be more suitable.

2.3.2 SOLAR CONCENTRATING COLLECTORS

Solar concentrators increase the amount of incident energy on the absorber surface as compared to that on the concentrator aperture. The increase is achieved by the use of reflecting or refracting surfaces, which concentrate the incident radiation onto a suitable absorber-receiver. Due to the apparent motion of the sun, the concentrating surface is unable to redirect the sunrays on the absorber throughout the day if both the concentrating surface and the absorber surface are stationary. Ideally, the concentrating system should follow the sun so that the sunrays are always focused on the absorber. Therefore, a solar concentrator generally consists mainly of:

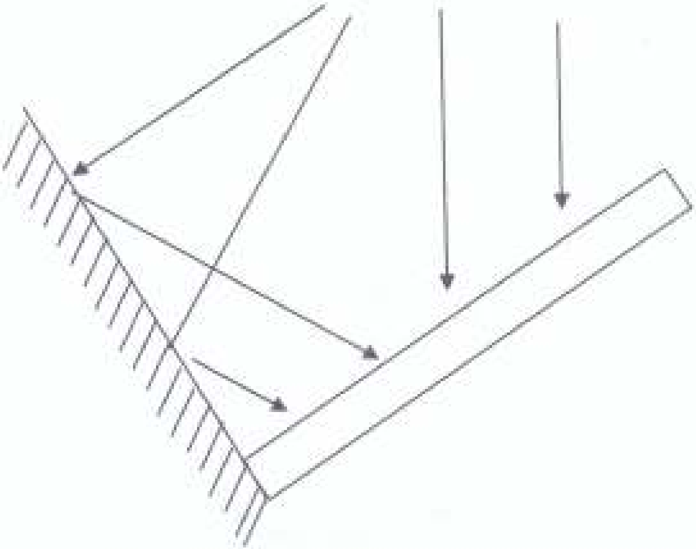
(i) A focusing device, (ii) an absorber/receiver provided with or without transparent cover, and (iii) a tracking device for continuous location of the sun. Temperature as high as 3,500^{0}C have been achieved with such devices. Solar concentrations are used for thermal as well as photovoltaic conversion of solar energy. Solar concentrators have the following advantages.

(i) Higher delivery temperature resulting in better thermodynamic efficiency.

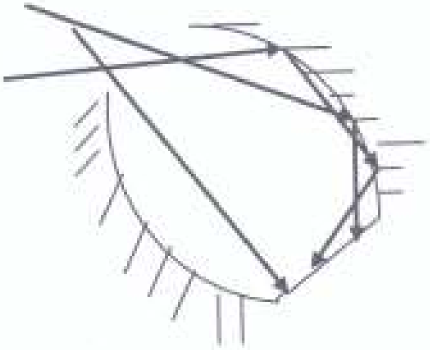
(ii) Reduced losses due to reduced heat loss area.

(iii) Reduced cost due to less material requirements compared to flat plate solar collector system. Storing heat at higher temperature results in reducing the storage.

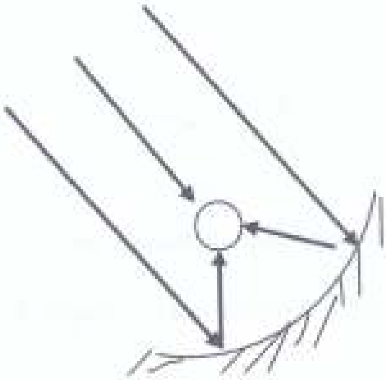
Types of concentrating Collectors are shown in fig.1.4.



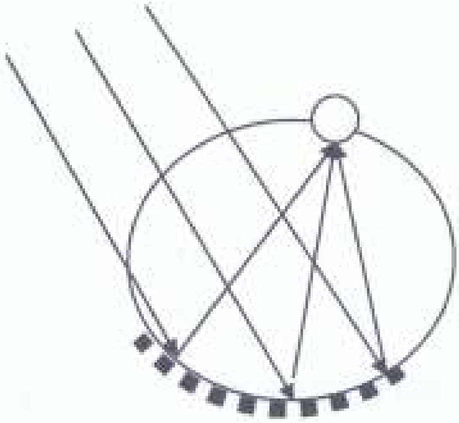
(a) Flat Plate collector with plane reflectors



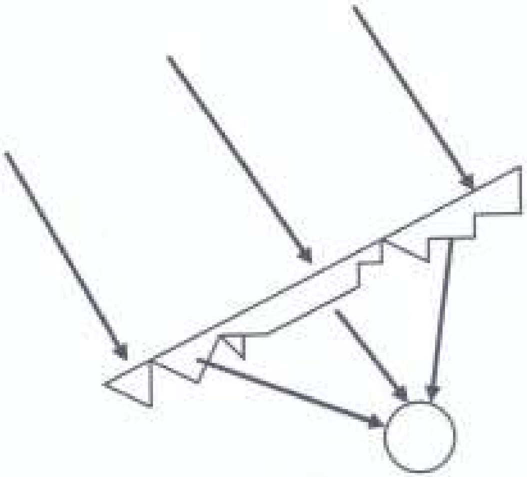
(b) Compound parabolic collector



(c) Cylindrical parabolic collector



(d) Collector with fixed circular concentrator and moving receiver



(e) Fresnel lens concentrating collector

Fig. 1.4 Types of concentrating collectors

2.3.3 SOLAR PHOTOVOLTAIC

Photovoltaic cells or the so-called solar cells generate electromotive force as a result of absorption or ionizing radiation. Solar cells directly convert the solar radiation into electricity using photovoltaic effect without going through a thermal process. Such solar cells are reliable, modular durable and generally maintenance free and therefore suitable even in isolated and remote areas.

2.4 SOLAR WATER HEATING

For water heating it is not economical to concentrate the radiation because tracking the sun throughout the year is both costly and complex. Developmental work on solar water heating has therefore mainly been done flat-plate solar collectors. Almost all solar water heaters are based on the principle of flat plate collector. Over the past 60 years pioneering work has been done mainly in the U.S.A, the UK, Australia, South Africa, Israel and India and many different types of solar water heaters have been designed and built (Garg and Prakash, 1997). The main objectives of these studies have been, to convert as much solar radiation as possible into heat at the highest attainable temperatures and for the lowest possible investment in material and labour.

2.4.1 CLASSIFICATION OF SOLAR WATER HEATERS

Solar water heaters employing flat-plate collectors can be divided into the following four types according to their applications, temperature of operation and capabilities.

(i) Swimming pool water heating: Where a cheap plastic collector can be used without any cover and insulation. A high flow rate is maintained to limit rise to less than 20^{0}C.

(ii) Built-in-storage type solar water heater: Where all the three functions/components i.e. collection, storage and control are combined in into a single unit. Hot water (up to 60^{0}C only) from such water heater has to be used during the day; otherwise the heat stored would be lost during the night.

(iii) Domestic Solar water heater: Where the maximum temperature required is not more than 70^{0}C. Here the collector and storage function are separate. The control function is still accomplished through the use of natural principles and this technology is frequently employed for domestic systems in the form of rather well known "***thermosyphon systems.***"

(iv) Large size solar water heaters designed for community and industrial use. Since, here the quantity of hot is large; a large number of collectors are employed with a storage tank along with a control system, which is to be built as required.

For the purpose of this project, separate collector and storage type solar water heater will be employed.

2.4.2 SEPARATE COLLECTOR AND STORAGE TYPE SOLAR WATER HEATER

The combined collector and storage type solar water heaters are generally not preferred and more than 90 percent of solar water heater installed in USA, Israel, Australia, India and other counties have the collectors and storage tanks as separate units (Garg and Prakash, 1997). A basic domestic conventional water heater is shown in fig 1.5.

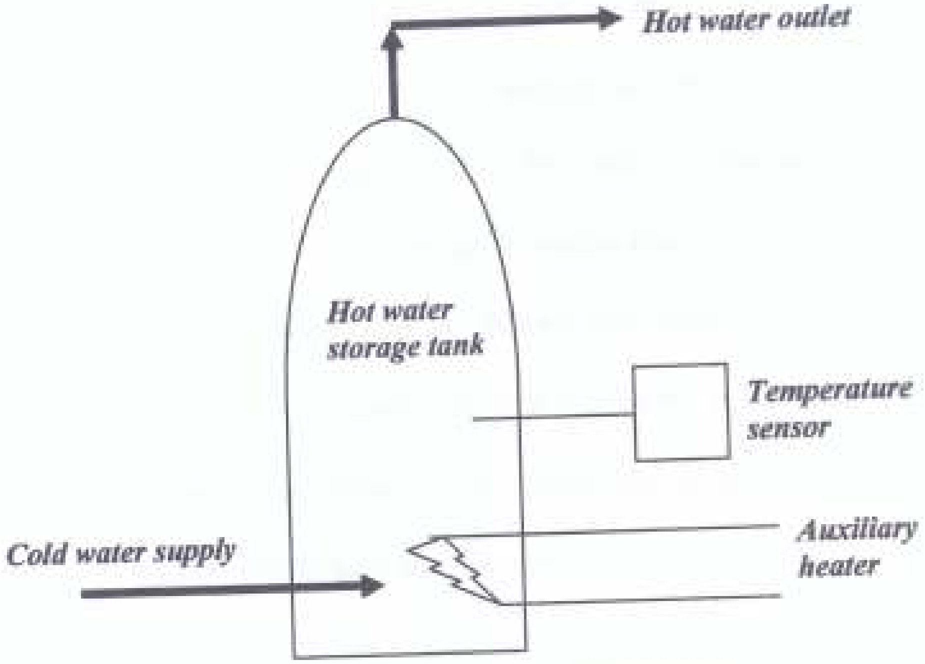


Fig. 1.5 Conventional hot water system for domestic use

The cold water enters the bottom of the tank through a cold water feed cistern. A heater is also fitted near the bottom of the hot water tank, a sensor monitors the temperature on the wall at the middle of the tank, and when the hot water temperature in the tank drops below a preset value, a Thermostat turns on the gas jets or electrical heater automatically. When the desired temperature is reached, the thermostat turns off the heaters. Hot water is drawn from the top of the tank when a hot water tap is opened.

Solar water heating can be accomplished in several ways. The working principle of solar hot water system is shown schematically in fig. 1.6.

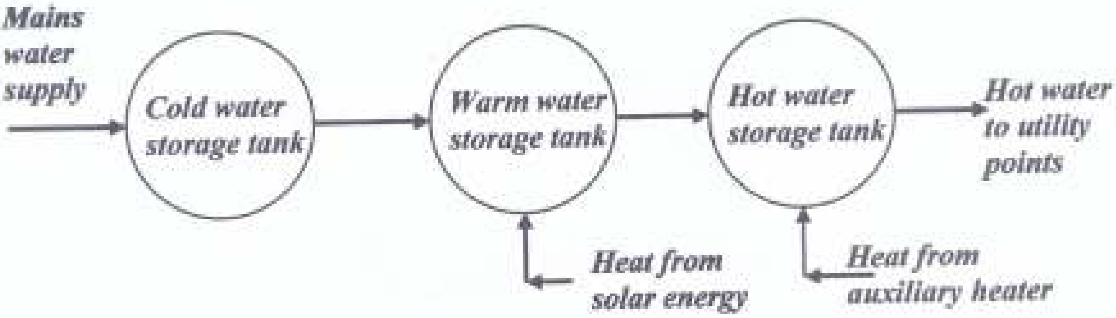


Fig. 1.6 Principle of solar water heating system

Water flows from the mains supply to the "cold store" (the feed cistern) then it passes into the preheat vessel, forming the "warm store" where the cold water is heated by solar energy up to a certain temperature. From the warm store the water is transferred to the hot water storage where it (the hot water cylinder) is further heated by a boiler or electric heater. Sometimes the auxiliary heater is fitted in the warm water store itself, thus saving one cylinder. In hot weather or in tropical countries, the auxiliary heating arrangement is not required, and solar energy alone may be sufficient to heat the water to the desired draw-off temperature. In cold climates or in countries where the solar radiation is low, water cannot be heated to the required draw-off temperature at all times of the year by solar energy alone, and therefore, arrangement for providing heat by other means such as solid fuel, gas, oil fired or an electric immersion heater are made.

2.4.3 Solar Water Heating Configuration

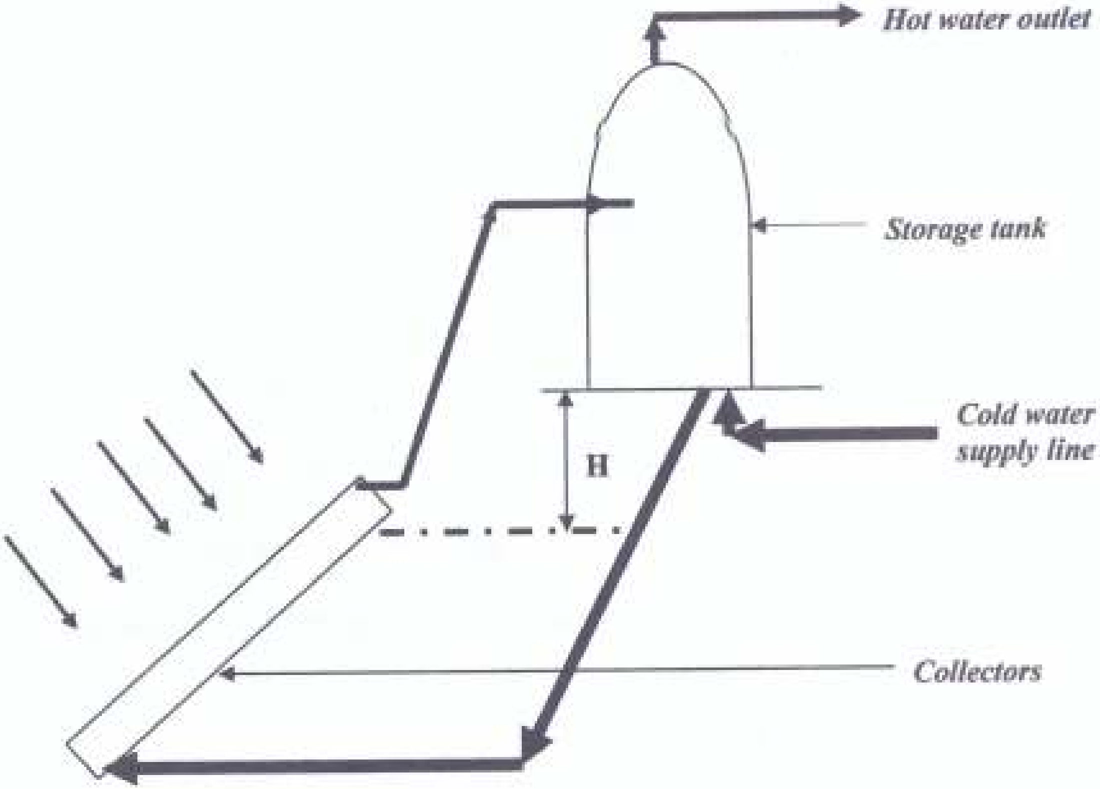
Many different designs of solar water heating system are possible and they may be classified in several ways. Each type has its own advantages and disadvantages, and at the present stage one common design cannot be recommended for use in all the situations. Some of the solar water heating configurations are:

-Natural circulation type systems

- Forced circulation or pumped systems

2.4.3.1 Natural Circulation Type Systems

A natural circulation type water heater consists of a separate collector and storage tank. The latter is placed at a certain height (30 – 60cm) relative to the top of the collector to prevent reverse circulation during off – sunshine hours. In this system, as shown in fig. 1.7, the hot water storage tank can be either under city water ***pressure*** or under a cold-water storage tank ***(pressure type)*** or it can be ***non-pressure type*** in which water leaves at the bottom of the tank. In the morning as the sun heats the collectors the hot water inside rises by natural convection and the cold tank water leaves from its bottom and flows into the collector by ***gravity***. Thus the circulation loop is automatically established whenever there is sufficient sunshine and circulation automatically stops during insufficient insolation when the upward buoyant force is unable to overcome the fluid friction losses inside the pipe. In well-designed solar water heater, the natural circulation flow rate is between 40-60 μm^2hr during sunshine hours. All the pipes and bends should be smooth and should slope upward to avoid air pockets and hence stoppages of water flow.



Fig, 1.7. Direct natural circulation solar water heaters

Generally, the hot water pipe from the collector enters the upper section of the storage tank at a level lying between the two – third and three-quarter of the height of the tank. In cold climates, auxiliary heating arrangement is provided with the solar heater. This arrangement can either be directly fitted in the solar hot water storage tank (simple and cheap) or in the hot water supply line or in a separate hot water tank. Separate hot water storage has the additional advantage of avoiding the mixing of hot water with the inlet cold water, which generally happens in single tank type solar water heaters.

In freezing weather, this thermosyphon type solar water heater cannot be used as such. Two alternatives are suggested to protect the system; the collector is drained manually in the evening through a gate valve provided at the bottom of the collector, by closing the collector isolation valve provided in the flow line, which connects to the tank bottom to the collector bottom. In the second system as shown in fig. 1.8, a heat exchanger is provided in the storage tank and an anti freeze mixture is used in the collector to permanently freeze proof the system. In such sealed heat exchanger system a sealed expansion tank or a separate coldwater "topping-up" tank and an overflow pipe is also provided.

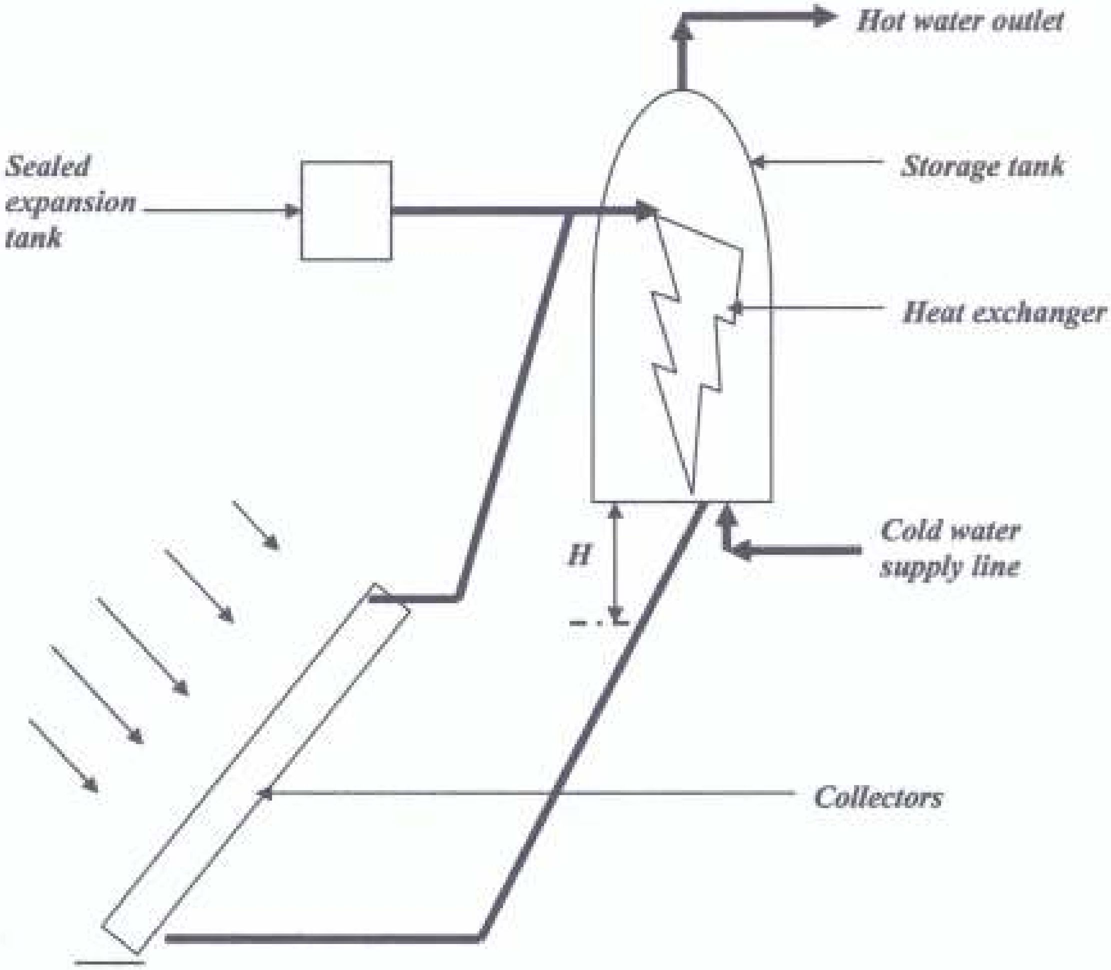


Fig. 1.8 Indirect natural circulation solar water heater

Apart from protecting damage due to freezing in this indirect (heater exchanger) natural circulation system, cheap but efficient collector such as roll bond type of aluminum collector can be used, which otherwise cannot be used, due to corrosion with ordinary tap water. Moreover, in this system better heat transfer fluid can also be used. The only precaution in such a system is that the heat exchanger should be completely sealed and the anti-freeze mixture or heat transfer fluid should not leak into the hot water storage tank. The disadvantage of this heat exchanger system is that it reduces the overall efficiency of the domestic solar water heater.

2.4.3.2 Forced-Circulation or Pumped Systems

A forced-circulation or pumped system may be either direct or indirect type. In a direct system the portable or service water is directly between the solar hot water storage tank and solar collector.

In indirect system, a fluid such as anti freeze, air distilled water, or an organic heat transfer fluid is circulated in the solar collectors. In indirect systems some kind of heat exchangers are used in or outside the hot water storage tanks. Direct systems are useful in milder climates where damage due to freezing is not a problem, although methods to protect the direct system from damage due to freezing are available such as draining collectors at nigh trickle circulation, flexible collector waterways etc. All pumped systems have at least four basic solar components, the collectors, the storage tank, the circulation pump, and the control system. The pumps are generally controlled by electronic differential controller which operates by turning on and turning off the pump at a predetermined temperature difference between the solar hot water tank and collector outlet temperature. Recently, proportional flow controllers have been developed which vary the pump speed to collect a greater amount of energy.

2.5 History of Solar Water Heater

Solar energy to heat water has been in use for many years, and the design requirements of solar water heating equipment have been studied for more than 100 years. Solar water heaters were not widely used, not due to lack of understanding, but because the other sources of energy were more economical. Interest in solar water heating was limited to those with the understanding and enthusiasm necessary to build their own equipment. A solar water heater industry in South Florida was started in 1950. It is estimated that about 30,000 to 50,000 units were installed by 1950, but around that time their popularity began to decline due to readily available cheap energy from fossil fuels, (Garg and prakash, 1997).

Technical advances in solar water heating have been very rapid in the last 40 years. The obvious benefits to the house holders can no longer be overlooked, where the climate is ideally suited for the application of solar energy for water heating, particularly, in the present situation of acute energy shortage. Solar water heater find wide application in the large establishment like hostels, hotel, hospitals, industries such as textile, paper, and food processing, domestic uses and in heating swimming pools.

2.6 Previous Studies on Flat Plate Collector

Quick glance at the available literature on the flat plate collector gives an idea of the work done so far in this field. The invention of the liquid heating flat plate solar water heater is credited to H.B. Saussure, a Swiss scientist, during the second half of the seventeenth century as reported by Ackermann in the year 1915. However, the use of flat plate collector on a fairly large scale in the United States – in Illinois it was resumed in the early 1905 and later in Needles, California. Water was heated in relatively shallow horizontal troughs made of asphalts, usually double glazed, with desert sand as an insulator, and the heat thus collected was used to generate sulphur dioxide or ammonia for operating pumps. The most impressive array of the near -1900 eras was that of Frank Shuman of Philadelphia, who, in 1907, built a flat plate collector to produce hot water, which in turn, evaporated ether, and thus, powered a vertical single cylinder engine. During the last fifty years scientists all over the world have been trying to build and test different types of liquid flat plate collectors. This work has been carried out mainly in the United States, United Kingdom, Australia, South Africa, Israel and India (Garg and Parkash, 1997)

Therefore developmental work on solar water heating has mainly been done on flat-plate solar collectors

It should be remembered that one of the objectives of most research works has been to develop a collector with improved performance and insignificant increase in cost compared to a flat plate collector. It is therefore necessary to briefly review previous studies, which are related to this objective. Several investigations have been carried out in this area and it is impossible to mention all of them. So only a few are referred to in the following paragraphs.

It is possible to imagine perfect solar flat-plate collector whose transparent cover transmits all incident solar radiation, which is totally absorbed by an insulator that does not emit thermal radiation. The objective of many research workers has been to get as close as possible to this ideal collector using simple methods and cheap materials. Several authors, among them Tabor (1958), Rankine and Charter (1969), and Tan and Charters (1970) have dealt with specific problems in heat transfer characteristics of collectors. Others have looked at practical problems e.g. dirt on covers, effects of air leak, effect of inclination and use of plastics in collector construction (Garg, 1974, Close and Yusoff, 1981, copper, 1981 and Blaga, 1978). In general, attention has been focused on two major areas: Type and number of transparent cover plates; and materials and geometry of the absorber plate (selective or non-selective) but the common goals are the reduction of heat losses and improvement of heat transfer from the collector to the carrier fluid. Investigations have been made either theoretically or experimentally. Hottel and Woertz (1942) and Hottel (1950) suggested the quantitative relations for theoretical prediction of the effect of the many factors, which contribute to the overall performance of a flat-plate collector. Similar analytical methods used by Buelow and Boyd (1957) and Close (1963), and derived theoretically by Bliss and Whillier (1964), lead to the well known Hottel - Whiller - Bliss (HWB) equation which described collector efficiency in term of collector parameters. Gupta and Garg (1976) and Smith and Weiss (1977), evaluated these parameters experimentally. Klein, et al (1976) has suggested a very descriptive computer model known as the f-chart design method. Duffie and Beckman (1980) gave a simple and generalized explanation of this method.

In an attempt to improve the performance of a flat plate collector, Lof (1971) investigated experimentally a solar collector, which consisted of a sheet metal trough about 0.07123m deep, 2 feet wide and 4 feet long containing glass plates arranged in stair-step fashion and separated by 0.00625m spaces. Each glass pane was partly blackened with black paint and arranged so that each black surface was beneath two clear surfaces. One or more cover glasses were used to form a nearly air tight enclosure conditioning the overlapped plates. By means of this arrangement, solar energy is transmitted through the transparent surface and absorbed by the black areas. It was found that under winter conditions with ordinary glass, the trough with one cover plate showed the highest efficiency. But under other conditions and with surface-treated glass, two and even three cover systems yielded higher efficiencies than a glass cover system. Selcuk (1971) outlined a theoretical analysis of this type of air heater and verified his analysis experimentally. Other air heaters with porous and non-porous absorbers have also been reported by Selcuk (1971).

Buelow and Boyd (1957) studied another type of air heater consisting of a painted metal absorber plate with air to be heated passing both above and below the absorbing plate. The collector was mounted so that it could be rotated to keep it at a fixed angle with respect to the sun. The mathematical analysis showed that efficiency varies significantly at low airflow rates but not at high flow rates. It was noted that if only a small temperature rise is required, then the overall heat loss coefficient, U_2, of the collector is not important in determining the temperature rise of the air. Therefore in many applications with small temperature rises, it may be most economical to use only one cover. Close (1963) also studied the performance of this type of air heater mathematically and compared it with other types single plate (flat, vee-corrugated and finned) with air duct between the cover and the absorber plate, and flat plate with air duct under the absorber plate. Both selective and non-selective surfaces on the absorber plates were used. It was found that these heaters could be built to provide air at 55°C above ambient at collection efficiencies of 50% or more. Selective surface, vee-corrugated and finned absorber plates produced good air-heater performance, but improvements were enhanced when convective heat transfer to the cover was suppressed by the use of a stagnant air gap between the cover and the absorber plate. This means that collector heat loss by convection is significant-more so where a selective surface is used to produce higher air temperatures. A study of this type of air heater is reported by Wijeysundera et al (1982).

2.7 Efficiency of Collector

The concept of efficiency is generally simple. It is the ratio of useful energy (or output energy) to input energy. When studying solar collectors, one needs to understand the concept of collector efficiency factor, which is a measure of the effectiveness of the collector absorber plate in transferring heat to the working (or transport) fluid. Another parameter, which must be clearly defined and understood, is the heat loss factor. These two factors, together with the effective absorptance-transmittance product, enable one to write the general performance equation.

The following nomenclature is used in the discussion below:

F' – Collector factor = Actual heat collection rate/useful heat collection rate attainable with entire collector surface at average fluid temperature

I – Incident solar radiation on collector cover (Wm^{-2}).

T_P – Absorber plate temperature (^0C);

Ta- ambient air temperature (^0C);

T_F – Fluid temperature (^0C);

q_u – Useful energy collected, (Wm^{-2});

$(\tau_\alpha)_e$ – Effective transmittance-absorptance product

U_L – Overall heat loss coefficient, ($Wm^{-2}K^{-1}$);

η – Collector efficiency

A generalized performance equation for a solar collector is

$q_u = (\tau\alpha)_e I - U_L\ (T\rho\text{-}Ta)$ ....(2.1)

Fluid temperature and collector efficiency factor can be introduced into this equation so that it becomes:

$q_u = F'\ (\tau\alpha)_e I - U_L\ T\rho\text{-}Ta)$ ....(2.2)

And collector efficiency is:

$$\eta = F' (\tau\alpha)_e - U_L (T\rho\text{-}Ta) \quad \ldots\ldots (2.3)$$

From equation 2.3 it is clear that the use of a selective surface which has high absorptance in the range of solar spectrum and low emittance of infra-red radiation will significantly improves the collector efficiency, since α will increase while U_L is decreased. It is also obvious that the collector efficiency will be highest when

$T_f = T_P - T_a$.

2.8 Advances in Solar Water Heater

Numerous studies have been performed on thermosyphon solar water heating systems since they have the advantage of avoiding a water pump for circulating water in the collector. Such systems can be designed to operate either at full line pressure or at a reduced pressure; the former is usually termed as a pressurized system and the latter a non – pressurized system.

Close (1962) studied the performance of solar water heaters circulating to a storage tank by thermosyphon. He assumed the ideal condition of no draw off during the day and clear sunshine. Two absorber and tank systems were tested and the results compared with those estimated from the theoretical method. The result showed very good agreement. For a specific thermosyphon configuration, Close (1962) observed experimentally that the average collector temperature was only slightly higher than the average temperature of water in the tank. Based on this experimental fact, he developed a simple mathematical model for predicting the daytime performance of such a system.

Chimnery (1971) through his mathematical model explained the reverse flow under certain specific conditions, but he did not make any prediction of the magnitude of the effect on the system performance. Uhlemann and Bansal (1985) also studied the side-by-side comparison of a pressurized and non-pressurized solar water heating themosyphon. Two, commercially available domestic size hot water heating systems, in which the natural convection maintained the flow of water from the collector to the tank, were studied experimentally under identical meteorological conditions. One of the systems a pressurized type of system and the other was a non-pressurized type. They proved and shown by measurements, the effect of reverse flow from the storage tank side through the collector (during the night). An explicit expression has been derived for the mass flow rate of water due to thermosyphon effect in term of known physical parameters.

Desa (1964) generated a lumped parameter heat balance equation which was solved numerically using actual solar radiation and an half – hour time step.

The analysis of Close (1962) has been improved by Gupta and Garg (1968), Ong (1974), and Sodha and Tiwari (1981) in the system modeling.

Morrison and Braun (1985) worked on the system modeling and operation characteristics of thermosyphon solar water heaters. They developed an efficient numerical simulation model for thermoysphon solar water heaters and compared it with test data from two locations. The model was used to study the characteristic of vertical and horizontal tank themosyphon systems. The result indicate that thermosyphon have optimum performance when the daily collectors volumes flow is approximately equal to the daily load volume. Heat conduction in one tank horizontal system was found to significantly reduce solar contribution.

Here in Nigeria, some scholars have made notable efforts in this area of research. Many solar water heaters have been constructed and tested at the Centre for Energy Research and Development, University of Nigeria, Nsukka. Adegoke and Bolaji (1999) also made notable efforts on Exergetic Analysis of thermosyphon solar water heating systems. Exergetic analysis was carried out on two thermosyphon solar water heating system to evaluate their thermal performances. The two systems are of similar design but system B with the storage tank insulated is an improvement on system A with an uninsulated storage tank. In comparison with system A, system B, absorbed more energy with about 62.4% of the absorbed energy available as useful energy. On the other hand, system A absorbed less energy and only about 31.1% of the absorbed energy is available as useful energy.

2.9 System Models

Models may be based on the fundamental equation describing the behaviour of the equipment and may also be expressed as empirical or stochastic representations of operating data from particular items of equipment. These empirical relations may be in the form of equations, graphs or tabular data. In whatever form the models are expressed, they must represent component performance over the full range of operating condition to be encountered in the solar operation. System models are the assemblies of appropriate component models. The net effect of this assembly is to produce a set of coupled algebraic and differential equations, having time as the independent variable. These equations include meteorological data as forcing functions that operate on the collector, and possibly also on the load, depending on the application. These equations can be manipulated and combined algebraically or they can be solved simultaneously without formal combinations, (Garg and Parkarsh, 1997).

CHAPTER THREE

DESIGN CONSIDERATION AND CONSTRUCTION

3.0 CONCEPTUAL DESIGN

The conceptual design is a solar water heater consisting of a separate flat plate collector and a large insulated storage tank with pipes to convey the hot water. The control function is accomplished through the use of natural principle known as thermosyphon. The model is illustrated in Fig. 3.1. The model consists of a flat plate solar collector which made up of galvanized iron upon which the short wave solar radiation falls and is absorbed.

The absorbing plate is painted matt-black with tubes clamped to it to circulate the water required to remove the thermal energy from the plate. The collector is covered with transparent plastic to reduce the upward heat loss from the absorber plate. Thermal insulation, made of plywood, is provided at the back and sides of the absorber plate to minimize the heat losses. A weather tight container made of galvanized iron sheet is used to enclose all the basic elements of the flat plate collector.

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The storage tank consists of inner cylindrical vessel made of galvanized iron. This inner tank is insulated properly with sawdust from the outer cylindrical vessel, which serves as container for the tank. Because of the intermittent nature of solar energy, the storage tank serves the purpose of storing the hot water produced during the sunshine hours. The flat plate collector and the storage tank are interconnected by means of pipes made of galvanized iron to convey the preheated and the heated water into and from the collector to the storage tank.

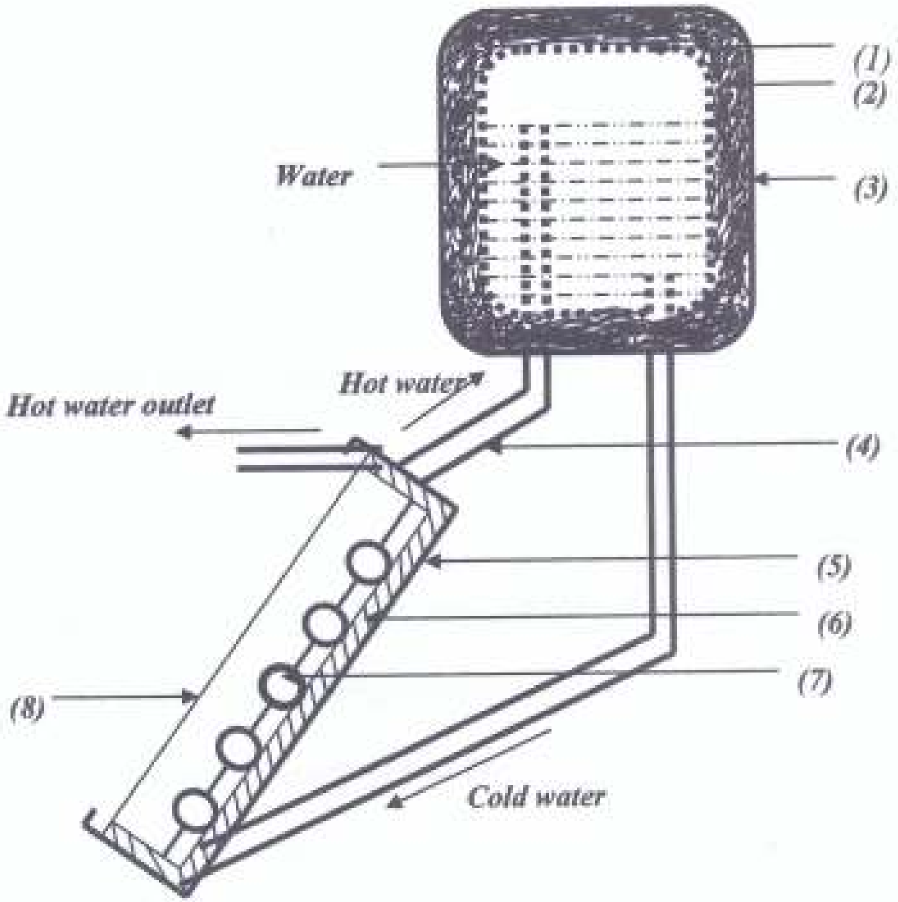

Fig. 3.1: Schematic diagram of natural circulation type solar water heater.

(1). Inner storage tank

(2). Sawdust

(3). Storage tank containers

(4). Connecting pipe

(5). A weather tight container

(6). Insulation (plywood box

(7) Tubes

(8) Transparent plastic cover

3.1 Design Consideration

In designing systems, there are certain factors that must be considered to have good performance of the systems. To design solar heating systems, knowledge of the properties of the materials and characteristics of the various components is necessary to predict the performance and durability of the systems. Solar systems respond to the environment and to certain characteristics of system components. For example, the location of a solar system, the imposed heat load, ambient solar intensity levels, and ambient temperature all determine the response of the system to its load. Identical solar systems will function entirely differently in different locations.

For the purpose of designing, it will be highly necessary to consider the complex nature of the photo-thermal conversion solar energy that takes place in solar water heating systems.

Because of the low densities of solar fluxes and only carefully designed collectors where heat losses are minimized will lead to acceptable performances.

3.1.1 Heat Transfer Processes in solar collectors.

The useful extracted energy will be the difference between the absorbed energy and the energy losses.

Useful Energy = (Absorbed Energy) – (Energy losses)

The solar collector has two distinct processes to deal with:

(1). The absorption of radiant energy, which requires the highest possible transmission coefficient,τ, for the transparent cover and the highest possible absorption coefficient,α, for the absorber plate, the effective parameter will be the product ($\alpha\ \tau$).

(2). The loss of energy in the infra-red spectrum due to:

a. Radiation losses between the absorber plate and the transparent cover;

b. Natural convection losses between the absorber plate and the transparent cover;

c. Conduction losses through the back-insulation and the edges.

It can be seen that the three modes of heat transfer: radiation, natural convection and conduction are involved in flat plate collector. The green house effect is very important for the efficiency of the system.

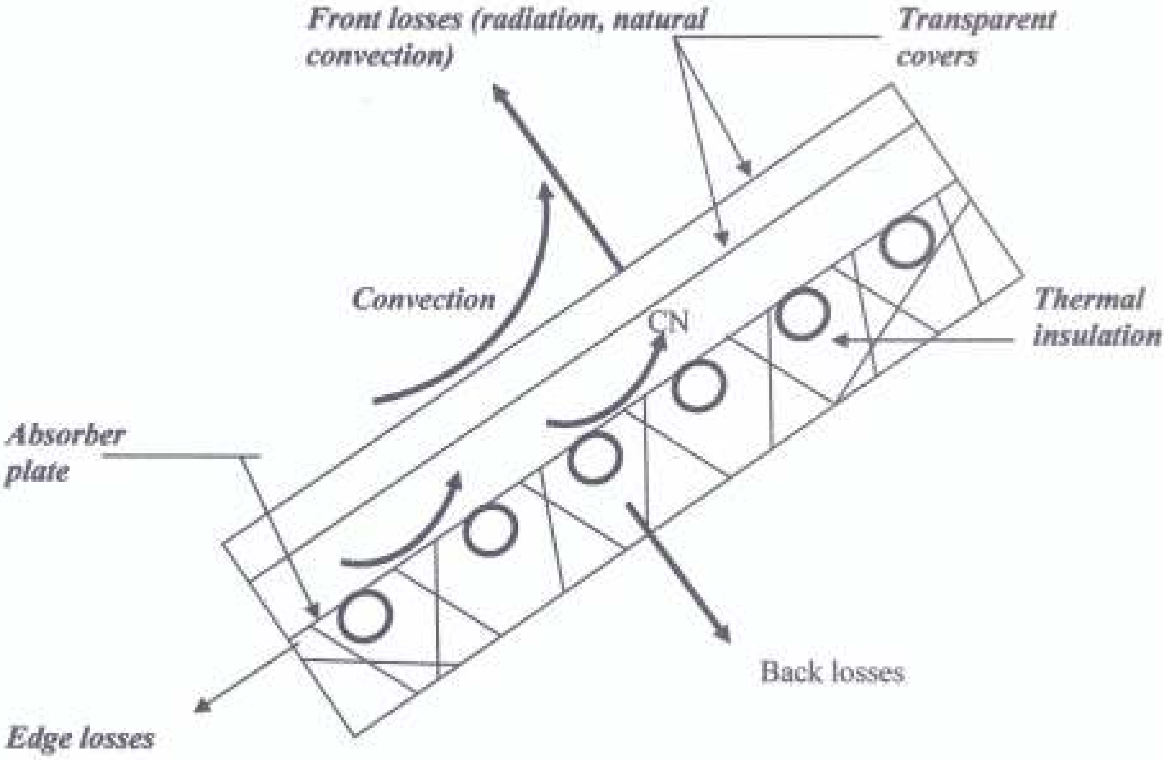

Fig. 3.2: Heat loss scheme of a flat – plate collector

3.1.2 Heat losses due to Radiation

The heat transfer between the absorber plate and the transparent cover can be represented with an acceptable approximation of equation (3.1)

$$q_r = \frac{\sigma(T_2^4 - T^4)}{{}^1\!/_{\varepsilon_1} + {}^1\!/_{\varepsilon_2} - 1} \tag{3.1}$$

Where ε_1 and ε_2 are emittances of the 1st plane (cover) and the 2nd plane (absorbing plate) respectively. T_1 and T_2 are temperature of the (1st plane) cover and the 2nd plane (absorbing plate)

The Global emittance, ε_g, between the two planes is

$$\varepsilon_g n = \frac{1}{\varepsilon_1 + \varepsilon_2 - 1} \tag{3.2}$$

For the purpose of this design, ε_g was taken to be order of 0.85. To obtain maximum temperature of water required; the plate temperature was target at 120°C and the cover temperature targeted at 40°C.

Therefore, $T_p = 273 + 120 = 393K$

$T_c = 273 + 40 = 313K$

$q_r = 0.85 \ (5.67 \times 10^{-8}) \ [(393)^4 - (313)^4)$

= 687W/m²

3.1.3 Heat losses by natural Convection

A Nusselt number, Nu, characterizes heat losses by natural convection from the absorber plate to the transparent cover:

$$N_u = \frac{U_{cn} d}{\lambda_{air}} \tag{3.3}$$

Where

U_{cn} = heat transfer coefficient between absorber plate and cover.

d = Plate spacing

λ_{air}= thermal conductivity of air

The Nusselt number can be expressed as a function of the Grashof number, Gr, and of the slope S:

$$G_r = \frac{g\beta d^3 \Delta T}{\upsilon^2} = \frac{g d^3 \Delta T}{\upsilon^2 T} \tag{3.4}$$

Where g = gravitational constant

β = expansion coefficient, $\beta = 1/T$

ΔT = temperature difference between plates

υ = Kinematics viscosity of air

T = average absolute temperature of air between plates, K.

The heat transfer coefficient U_{cn} between the absorber plate and the cover can be calculated if the function that relates the Nusselt number, N_u, to the Grashof number G_r, and the slope, S is known. A great number of experimental correlations have been proposed for the calculation of heat transfer by natural convection in closed inclined cells. Dropkin – Somerscales formula has a great merit for simplicity and can easily be used in design applications.

$$N_u = [0.078 - 0.026(s/90)](G_r)^{1/3} \qquad (3.5)$$

With $10^4 < G_r < 10^5$

Therefore, the heat transfer coefficient between the two planes is represented by

$$U_{cn} = [1 - 0.33(s/90)]\ (\Delta T^{1/3}) \qquad (3.6)$$

Where U_{cn} is expressed in W/m² °C

The heat transfer per unit surface area is then

$$q_{cn} = U_{cn}\Delta T = [1 - 0.33(s/90)]\Delta T^{4/3} \qquad (3.7)$$

For the purpose of this design, a slope of 8° was assumed because the location (Akure) is on the latitude of 7.25° N and longitude of 5.08° E of the equator.

$q_{cn} = [1\text{-}0.33(8/90)][120\text{-}40]^{4/3}$

$= 287.83\text{W/m}^2$

This shows that for non-selective surface heat losses by radiation are predominant over heat losses by natural convection.

3.1.3.1 Determination of the Spacing between the Absorber Plate and the Plastic Cover

From a fabrication point of view, the manufacturer will be interested in reducing the spacing, d, between the cover and the absorber plate.

For G_r<2000 that is

$$d < \left(\frac{2000T^2}{g\Delta T}\right)^{1/3} \qquad (3.8a)$$

Then it is assumed that air remains stagnant and the heat losses are due only to conduction through the air. The heat losses, expressed as a function of the spacing, will be

$$q = \frac{(\lambda_{air})\Delta T}{e} \qquad (3.8b)$$

Where e = thickness of the stagnant air.

For G_r>10,000 that is

$$d > \left(\frac{10{,}000T^2}{g\Delta T}\right)^{1/3}$$

Then, the heat losses, expressed as a function of the spacing, d will be equation (3.7)

For the purpose of designing, value of d equal to 2.5 cm seems reasonable.

3.1.4 Back Losses and Edge Losses

For convenience, back losses and edge losses are generally characterized by a single heat transfer coefficient, U_b, can be represented with an acceptable approximation by

$$U_b = \frac{\lambda_b}{e_b} \tag{3.9}$$

Where

λb = thermal conductivity of the insulating material.

ε_b = thickness of the insulating material.

For the purpose of this design, the thermal conductivity of sawdust at 200^0C is assumed to be equivalent to one-tenth of the thermal conductivity of crown white wool, which is 0.034 W/m^0C

$\lambda b = 0.0034\ W/m^0C$

Also, the heat transfer coefficient for back and edges is assumed to be equal or greater than 0.18 $W/m^2\ {}^0C$.

Therefore, the thickness of the insulating material e_b will be equal or greater than

$$\frac{0.0034 W m^0 C}{0.18 W/m^{2}\,{}^0C}$$

$e_b \geq 0.0188$ m

≤ 1.88 cm

It takes a wall of an infinite thickness to achieve zero heat loss, in which case, the equipment will be too bulky for handling. To reach a compromise between portability and heat loss, 1.5cm plywood is chosen for the construction of insulating box.

3.1.5 Heat Losses from the Transparent Cover to the Ambient Air.

The heat losses from the transparent cover to the ambient air are due to radiative and convective exchanges that are affected by the wind velocity. Radiation exchanges are not only influenced by the ground ad surrounding conditions (snow, reflective windows, etc), but also by long wave radiation from the sky; especially in the case of a very clear sky when the "sky temperature" can be significantly lower the ambient air temperature.

Swinbank relate sky temperature to the local air temperature by

$T_{sky} = 0.0552T_{air}$ (K)

Whillier recommends a simpler formula

$T_{sky} = T_{air} - 6$

For the purpose of this design, two correlations proposed by Tabor and Mac Adams are used, (Aranovitch, 1957).

The linear equation for Mac Adams;

$$Ua = 5.7 + 3.8V \qquad (3.10)$$

Where U_a = heat transfer coefficient from cover to the ambient air ($W/m^2 {}^0C$).

V = wind velocity (m/s)

Fit well with the values recommended by Tabor, when the wind velocity is in the range of 2 – 5m/s.

3.1.6 Transmission of radiation through Transparent Covers.

The transparent cover plays an important role in the solar collector because of the so called "greenhouse effect". Because of its selective properties, it transmits the solar radiation in the spectrum of sunlight and acts as a grey or blackbody in the infrared spectrum, for the re-emitted radiation from the absorber plate thereby "trapping" sunlight. Not all the incident radiation reaches the absorber plate. Due to the Fresnel reflections and the absorption within the cover material, only a portion of the incident energy is transmitted.

Fresnel Reflection at Interface

The Fresnel transmission coefficients, at normal incidence, (Aranovitch 1957), are:

$$\tau_r(0) = \frac{2n}{n^2+1} \quad (3.11)$$

$$\tau_r \tau_{r,N}(0) = \frac{2n}{2n+N(n-1)^2} \quad (3.12)$$

Where n = refractive index of transparent cover.

N = no of transparent cover

Absorption of Radiation

The coefficient of transmission, τ_a, within the material is represented by Bougler's law

$$\tau_a = e^{-KL} \quad (3.13)$$

Where k is the extinction coefficient that can vary from 0.04/cm for an excellent glass to 0.32/cm for a poor glass; L is the normal path of radiation through the medium.

Combined Transmission due to Reflection and Absorption.

The combined transmission coefficient, τ taking into account both reflection and absorption, is given by

$$\tau = \tau_a . \tau_r \quad (3.14)$$

For this design, one (N=1) plate cover of polyethylene (Martex) with refractive index n = 1.50 is considered. The thickness of the cover is 4mm (4 x 10^{-3}m), this is equal to the normal path of radiation through the medium L. the extinction coefficient K is assumed to be around 0.205/cm at normal incidence.

$n = 1.50$

$L = 4 \times 10^{-3}\text{m}$

$K = 0.205/\text{cm} = 20.5/\text{m}$

From (A)

$$\tau_r = \frac{2n}{n^2+1} = \frac{2(1.5)}{(1.5)^2+1}$$

$$= 0.923$$

$$\tau_a = e^{-KL}$$
$$= e^{-(20.5)(4x10^{-3})}$$
$$= 0.921$$

Therefore the transmittance of the cover used is

$\tau = \tau_a \cdot \tau_r$

$= 0.923 \times 0.921$

$= 0.85$

Absorptance of the Absorber Plate

Galvanized iron sheet is used for absorber plate. To have high absorptance it is painted matt black very well. The plate absorptivity α is 0.94.

The Transmittance – Absorptions Product.

The transmittance-absorptance product of the system represented by the transparent cover and absorber plate determines the effective energy absorbed.

The energy ultimately absorbed is defined by effective transmittance-absorptance coefficient $(\tau\alpha)_e$, (Aranovitch, 1957).

Useful Energy Absorbed and Instantaneous Efficiency of a solar Collector.

If I is the incident energy on the cover, the useful energy, q_u, absorbed per unit surface, will be different between the absorbed energy $(\tau\alpha)_e.I$ and the heat losses $U_L(T_p - T_a)$:

$$q_u = (\tau\alpha)_e I - U_l(T_p - T_a) \tag{3.15}$$

If A is the surface of the collector exposed to the incident radiation, the useful energy becomes (assuming steady state conditions):

$$q_u = AI(\tau\alpha)_e - AU_L(T_p - T_a) \tag{3.16}$$

The instantaneous efficiency, η is defined as the section of the useful energy, q_u, over the incident energy AI:

$$\eta = \frac{q_u}{AI} = (\tau\alpha)_e - U_L \frac{(T_p - T_a)}{I} \tag{3.17}$$

The equation, which defines the instantaneous efficiency, is known as the Hottel Whilier equation, (Aranovitch, 1957).

The first coefficient $(\tau\alpha)_e$ relates to the process of absorption of energy and the second coefficient to the thermal loss. It is the basic equation that is used in collector testing for the determination of the thermal performance of a collector.

3.1.7 Material Selection

To design and construct solar collector for heating and cooling purposes, knowledge of the properties of the materials and characteristics of the various components is necessary to predict the performance and durability of the collector. Durability is the criterion most often overlooked by the novice in constructing collectors.

3.1.7.1 Covers

The uppermost component of a flat-plate collector is the transparent cover of glass or plastic. One or two sheets are used in commercial units. The purpose of the cover(s) is to trap a layer of air 1.3 cm to 2.6 cm thick, providing thermal resistance to heat loss from the absorber plate. Glazing must have a high transmission coefficient, (Garg and Parkash 1997).

The decision whether to use a plastic or a glass cover depends on cost and durability. Transparent plastic cover is used because of its resistance to breakage, reduction in weight and more importantly reduction in cost. Although transparent glass performs better than plastic because it reduces radiation loss from the absorber plate but it is easily breakable.

The plastic cover was attached to the collector housing by means of silicon materials as a seal. The silicon material was used because of its ability to withstand very high temperature, very low temperature the differential expansion and contraction of both the cover and the housing.

3.1.7.2 Absorbers

The most desirable characteristics of the absorber plate are thermal conductivity and high resistance to corrosion. Three metals are commonly used – aluminum, copper and steel.

Aluminum is light and has high thermal conductivity but it is very difficult to repair in the field; if a leak develops, the collector must be removed and delivered to the factory or service shop for repair. Therefore, aluminum is not chosen for this design.

Copper has a very high thermal conductivity and corrosion resistance. It is easy to repair in the field but is very expensive.

Steel sheet of gauge 18 is chosen for the absorber plate in this design because of the lower price of steel relative to copper and aluminum. Since the thermal conductivity of steel is relatively low, a large amount of steel of surface area $1.5m^2$ is used as compared to either aluminum or copper absorber that requires less.

3.1.7.3 Absorber Surface

The surface of an effective solar absorber must convert at least 90 percent of the incident solar flux to heat, (Garg and Prakash, 1997).

The surface of the absorber is painted matt black to enhance its absorptivity and prevent corrosion. The entire absorber plate is left for at least 30minutes at temperature of about 200^0C to dry off all solvents and other materials that could later vaporize to prevent outgassing. Outgassing is a process by which solvent and other components of paints and materials in solar collectors vaporize or pyrolyze at high temperature. The gases condense on the inner glazing surface. Many of these condensates are not entirely transparent and can reduce the cover transmittance.

See Fig 3.3.

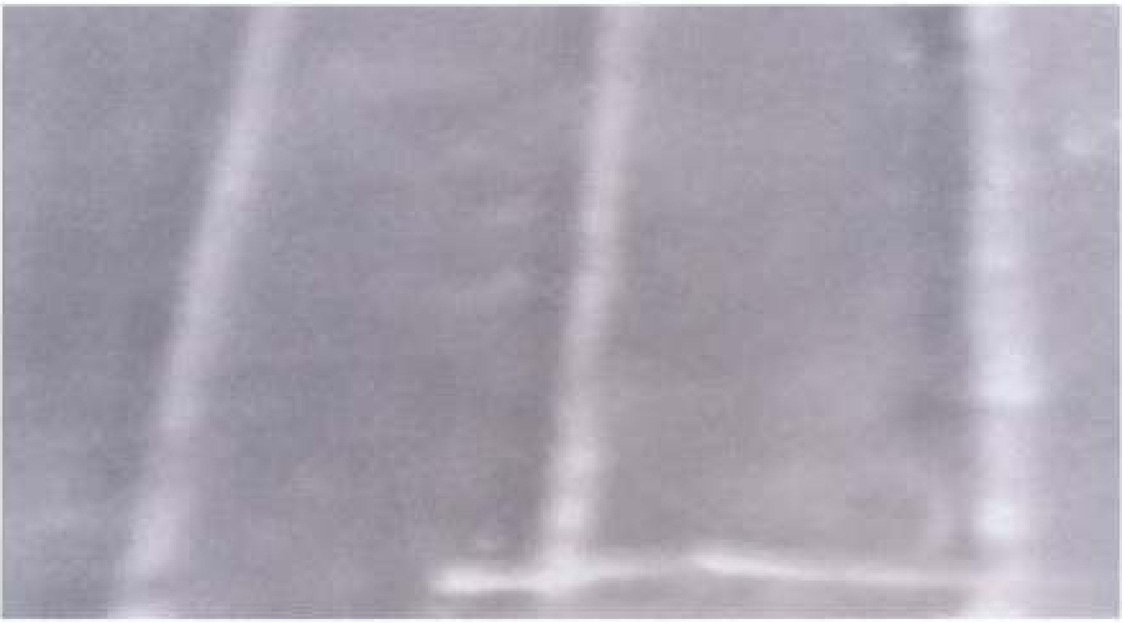

Fig.3.3 Absorbing plate painted matt-black

3.1.7.4 Insulation

Plywood is chosen for the insulation of the flat-plate collector and foam is chosen for the pipe sections. Plywood is chosen because of its low thermal conductivity, stability at high temperature (up to 200°C), no degassing up to around 200°C, and self-supporting feature without tendency to settle, ease of application and no contribution in corrosion.

Losses through the insulation depend on the conductivity and thickness. The thickness of the plywood used is 1.88 cm and the collector will be too thick if higher values of thickness are used. Too much insulation is not cost effective since the majority of the heat loss occurs via the "front" (glazed side) of the collector.

3.1.7.5 Housing

The collector housing is used to protect the insulation and the absorber plate from the environment. It also provides collector mounting.

Materials that can be used for the housing are various metal (aluminum, galvanized steel), wood, and fiberglass or high-temperature thermal plastics.

For this design the housing is steel, and it is protected by galvanizing and coated with paint to prevent corrosion.

Aluminum is not chosen because the difference in the electrochemical potential between the aluminum housing and the steel support structure will cause the aluminum to corrode and leak within a few years. Fiberglass is not chosen even though it is light and easy to attach to any structure but it will deteriorate at high temperature. Wood will outgas under high-temperature conditions, depositing tars, and other components on the inner surface of the glazing. Wood also presents a fire hazard. The normal ignition temperature of wood is 392^{0}F but it can self-ignite below 250°F after long exposure to heat, according to International Association of Arson Investigators.

3.1.7.6 Seals

At least two pipes or ducts pass through opening in the housing. It is essential that these opening be sealed to prevent dust from entering the collector. Any dust in the collector will partially deposit on the absorber surface and reduce its absorptions. The seals must also block rain or snow, both of which can deteriorate the insulation, the absorber plate and even the collector housing.

For this design, a silicon seal is considered for the sealing because of its resistance to ultraviolet light, ozone, and high temperatures. Pipes and duct are sealed with silicon seals because of its flexibility to accommodate expansion and contraction of the absorber plate and the repeated motion of pipe and duct connections.

3.1.7.7 Pipe and Ducts

The major design parameters that must be specified for fluid conduits are materials and size.

For this design, ducts of galvanized iron are used, even though it is very expensive as compared to steel in purchasing cost, but less expensive in maintenance cost since steel requires proper water treatment and dielectric protection from copper components.

An economic trade off determines pipe and duct sizes. For large ducts, the pressure drop is relatively smaller. As a result, pump may be required for water circulation. For this design, which makes use of Themosyphon principle ducts of smaller size are considered for the construction. The diameter 15 mm is chosen since the mass flow rate is chosen to be less than or equal to 5 g/s and flow velocity is 2.85×10^{-2} m/s.

3.2 Major Characteristics of Solar Water

As it was stated earlier that the performance of a solar system depends on the knowledge of properties of the materials and characteristics of the various components. The major characteristics of solar systems that need to be considered in designing the system are:

- Collector size
- Collector tilt angle
- Collector flow rate
- Storage size
- Heat exchanger size.

3.2.1 Collector Size

To obtain total useful energy of about 4.6 kWh with average global insolation of 750 W/m^2, the total collector area of about 1.5 m^2 is considered for the design.

3.2.2 Collector Tilt Angle

Collector tilt angle for solar water heater should be such that the amount of radiation intercepted by the collector is a maximum on a year round basis, not during the winter only. The collector should be tilted up from the horizontal at angle equal to the latitude.

To obtain maximum absorptivity of solar radiation, the solar collector of the water heater was inclined at angle of 8^0. It was designed for use in Akure at the Federal University of Technology, Akure in latitude of 7.25^0N and longitude of 5.08^0E of the equator.

3.2.3 Collector Orientation

One major decision that must be made regarding the installation of a solar collector is its orientation relative to the sun. The orientation of the collector must be related to the position of the sun at the time of year during which solar collection is to be maximized.

To obtain good annual performance of the system, the collector was installed facing south roughly because the orientation will give the best performance over the course of a year.

3.2.4 Collector Flow Rate

For most water heating collectors the collection efficiency is not significantly affected by the flow rate used, but for the purpose of calculating collector performance, the flow rate must be known to at least the same accuracy as that required for the efficiencies deduced. Typically the flow rates selected are into the region of 0.02 $kgS^{-1}m^{-2}$ and the accuracy required is about ±1%, (Aranovitch, 1957).

For this design, mass flow of value less than 0.005 kg/s and flow velocity of 2.85×10^{-2} m/s are selected.

3.2.5 Storage Size

The amount of storage used is determined by economic and not by technical criteria (Baum, 1955).

Since this project deals with construction of solar water heater for domestic purpose, a storage size of 55 liters was considered.

3.2.6 Heat Exchangers

Heat exchangers are devices that ideally execute a no-loss heat transfer between two fluid streams that must not be mixed (Baum, 1955). For this design, no heat exchangers are used because water is the only heat-removal fluid used.

3.3 Construction Plan

A description of the solar water heater has been given under conceptual design in section 3.0. A procedure for the construction of the equipment is presented under this section. Although figures are included here for easy comprehension of job description, they do not bear complete dimensional details. Such details have been given in the construction drawings. Precautions are stated wherever necessary.

The works was organized in components and were constructed separately. The components include: flat Plate collector and storage tank. Assembly was done when two components had been constructed.

3.3.1 Construction of Flat-Plate solar collector

This involves the construction and assembling of the basic elements of the flat-plate solar collector. The basic elements are a flat absorbing plate, tubes, thermal insulation, transparent cover of plastic and a weather tight container.

3.3.1.1 Alignment of Tubes

Five pieces of lengths 150cm each of galvanized iron pipe of diameter 0.0015m were cut from a long pipe. Six pieces of length 12cm were also cut from the same pipe. Both ends of all these pieces of pipes were threaded properly. These pieces were aligned on a horizontal plane and screwed together with the help of 10 galvanized angle corner fittings to form the channels shown in fig. 3.4, which are equally spaced.

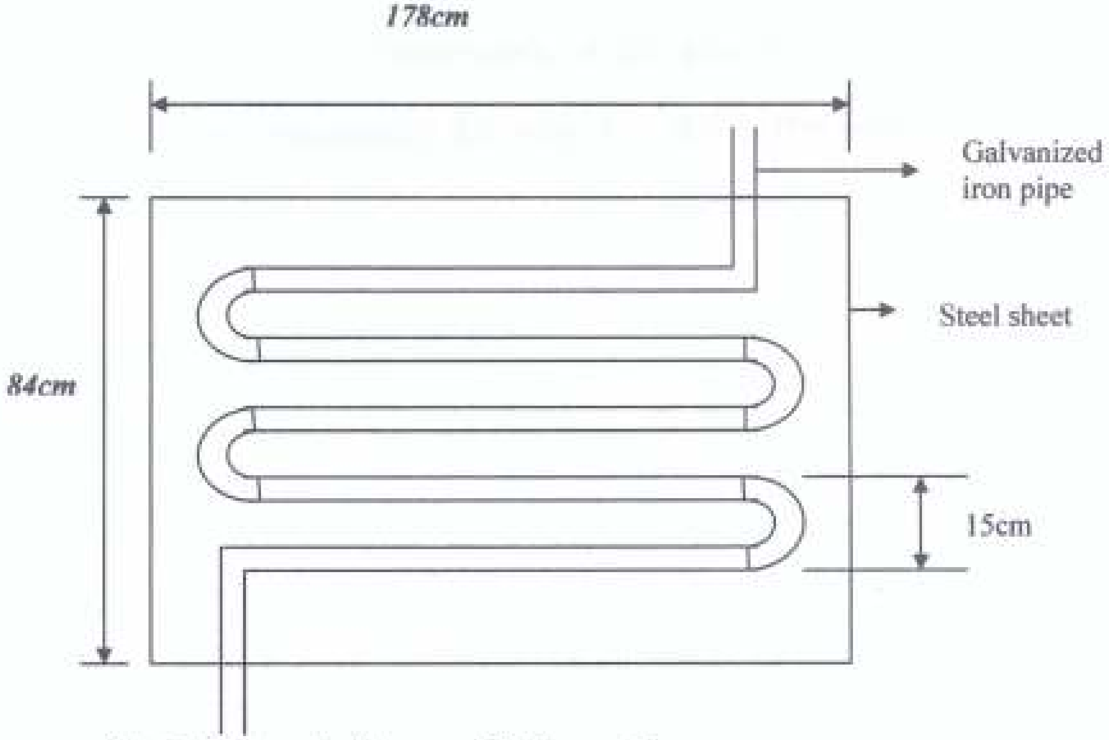

Fig. 3.4 Schematic diagram of the inner tubes

3.3.1.2 Formation of Absorbing Plate

A sheet of galvanized iron of size 178cm x 84cm was cut from 244cm x 122cm galvanize iron plate. The tubes constructed in section 3.3.1.1 were later clamped with the plate to form the Absorbing plate.

3.3.1.3 Building of Plywood Insulation

The details of the dimensions of the plywood box insulation were given in the engineering drawing. Fig. 3.5 is the isometric view

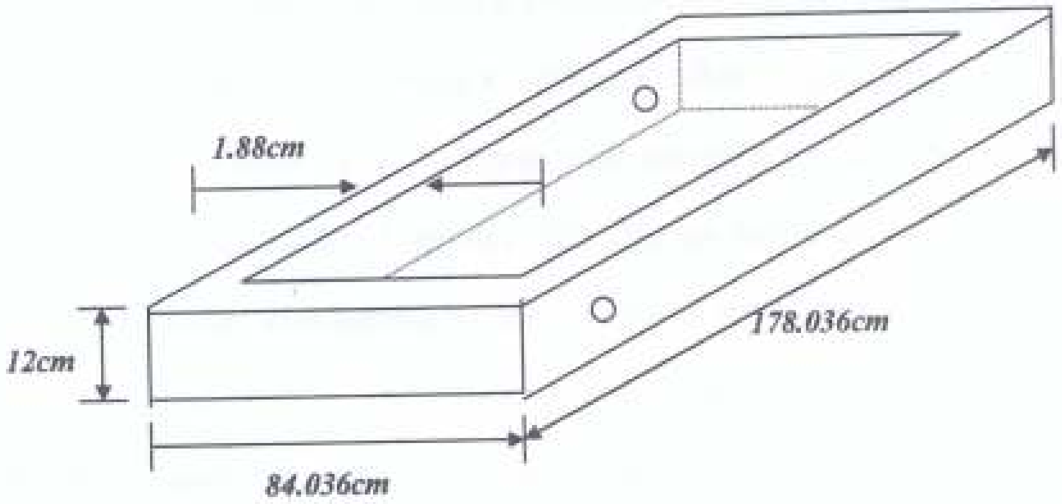

Fig. 3.5 isometric view of insulation box

The following dimensions of plywood were cut for making of the open-end box.

(a) Two pieces of 12cm x 178.036cm x 1.88cm plywood.

(b) Two pieces of 12cm x 84.036cm x 1.88cm plywood

(c) One piece of 84cm x 178cm x 1.88cm plywood.

Item (a) and (b) were set on a horizontal plane, forming the sides of the box and were nailed together with 26mm nails. Item (c), which formed the base, was joined to the sidewalls with 26mm nails. The groove for glass was on the inner surface of these pieces.

3.3.1.4 Insertion of Absorbing Plate into the Insulation Box

The absorbing plate was properly inserted into the insulation box by drilling two holes of size 15mm (0.015m) at the sides of insulation box through which inlet and outlet pipes can be inserted and screwed with the main channel.

3.3.1.5 Placing of the Plastic Cover

The plastic cover of size 84cm x 178cm and thickness 4mm is used to cover the absorbing plate. The groves for the plastic cover were fitted at height of 1in or 2.5cm (0.025m) away from the absorbing plate. The plastic cover was placed on a horizontal plane with a separation gap of 2.5cm between the plastic cover and absorbing plate. The plastic cover was properly sealed with the insulation box.

3.3.1.6 Building of Housing/Casing

The details of the dimension of the iron box casing were given in the engineering drawing. Figure 3.6 is the isometric view

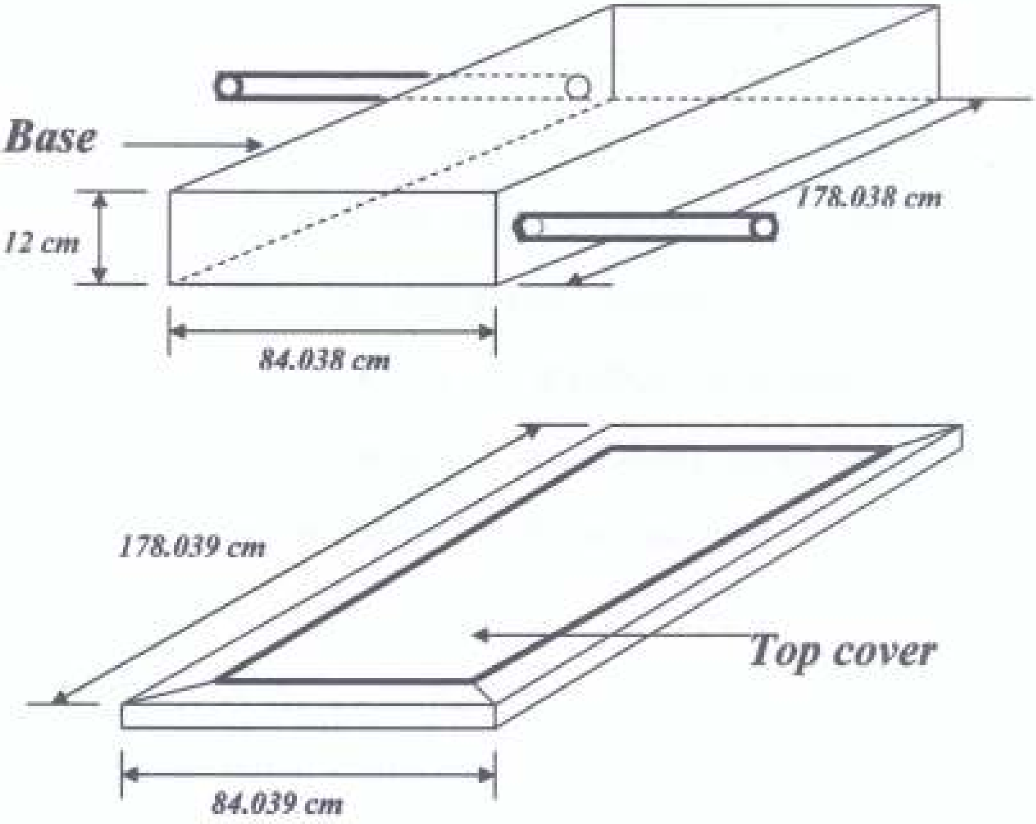

Fig. 3.6 Isometric view of iron casing.

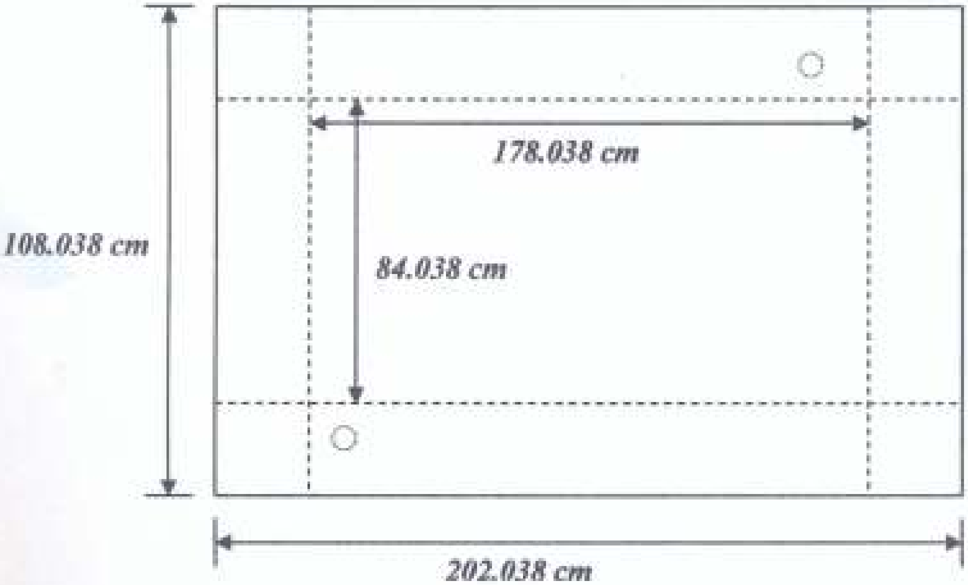

Fig. 3.7. The iron sheet for casing showing the folding lines

Galvanized iron sheet gauge 18 of size 108.038cm x 202.038cm was cut from 244cm x 122cm sheet and folded into the shape shown in Fig. 3.6 using folding lines indicated in Fig 3.7.

The top cover for the iron casing is made of 2.6cm angle bar iron with dimension 84.039cm x 178.039cm to properly cover the iron casing. Holes are drilled at interval along this iron top cover, through which it can be screwed with the base iron casing.

Note that the iron casing was framed up with the plywood insulation box that contains the absorbing plate and the plastic cover. Hence, the flat plate collector is constructed. See fig.3.8.

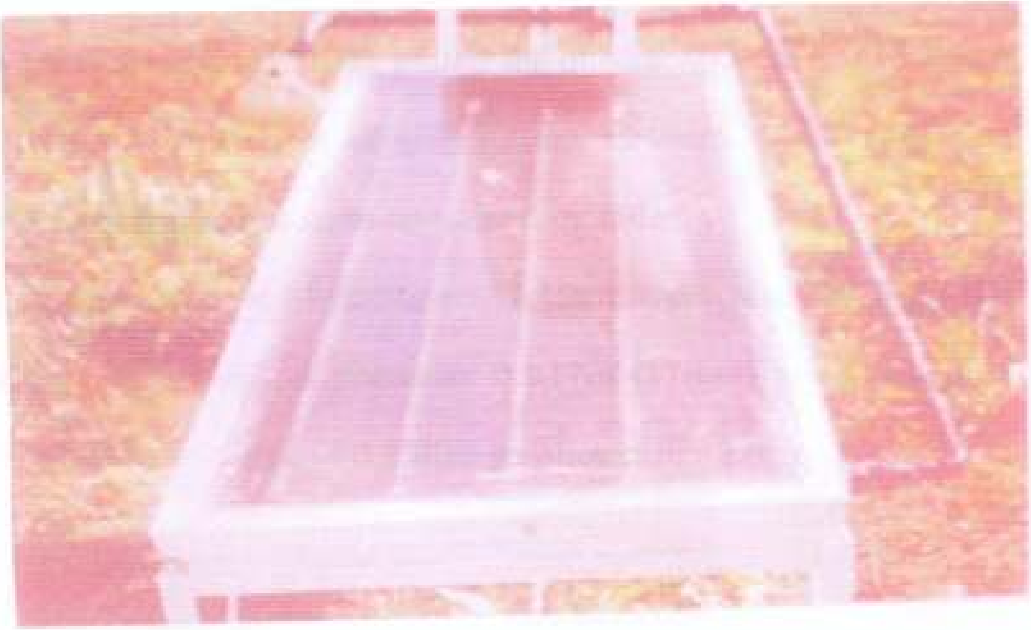

Fig.3.8 Constructed Flat Plate Solar Collector

3.3.2 Construction of Storage Tank

The storage tank consists of the inner tank that is the actual tank and outer cylindrical container.

3.3.2.1 Construction of Inner Tank

A galvanized iron sheet gauge 24 of size 50.8cm x 116.66cm was cut from a full sheet of size 122cm x244cm. This sheet was rolled and arc welded to form open-end cylinder.

Two circular disc of diameter 37.12cm were also cut from the main sheet. Two holes of diameter 0.017m (17mm) were drilled at the first quadrant of one of the disc as shown fig. 3.9.

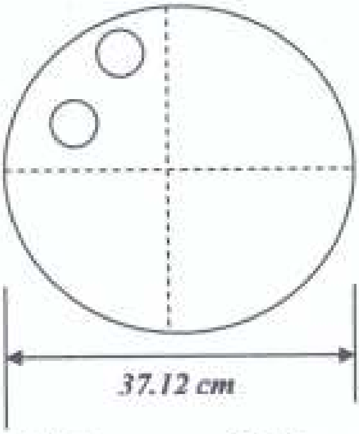

Fig. 3.9. Base cover of the inner tank

This formed base cover of the inner tank while the other disc formed the top cover. Two galvanized iron pipe (diameter 15mm) of length 70.30cm and 14.50cm were cut to form the tank inlet pipe and tank outlet pipe. These pipes were arc-welded to the base cover with 12.00cm length outside the tank as shown in fig.3.10.

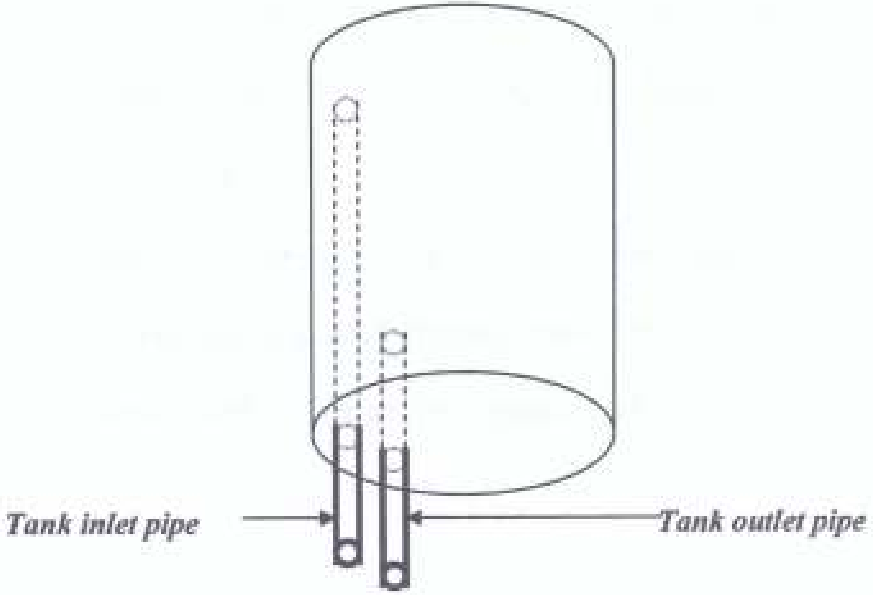

Fig. 3.10. Schematic diagram of inner tank showing the inlet and outlet pipe

3.3.2.2 Construction of tank container.

This is constructed from galvanized iron sheet of gauge 18. A rectangular sheet of size 55.8cm x 132.38cm was cut and folded into open-end cylinder.

Two circular discs of diameter 21.06cm were also cut from the main sheet to form the top and bottom cover for the container. The bottom cover were perforated at two points coincide with two holes in the first quadrant of the inner tank while top cover was perforated at center for ventilation.

3.3.2.3 Coupling of the Inner tank and the container

The inner tank was placed inside constructed container. Sawdust was used to insulate the inner tank from the container to prevent heat loss. This is shown in Fig.3.11.

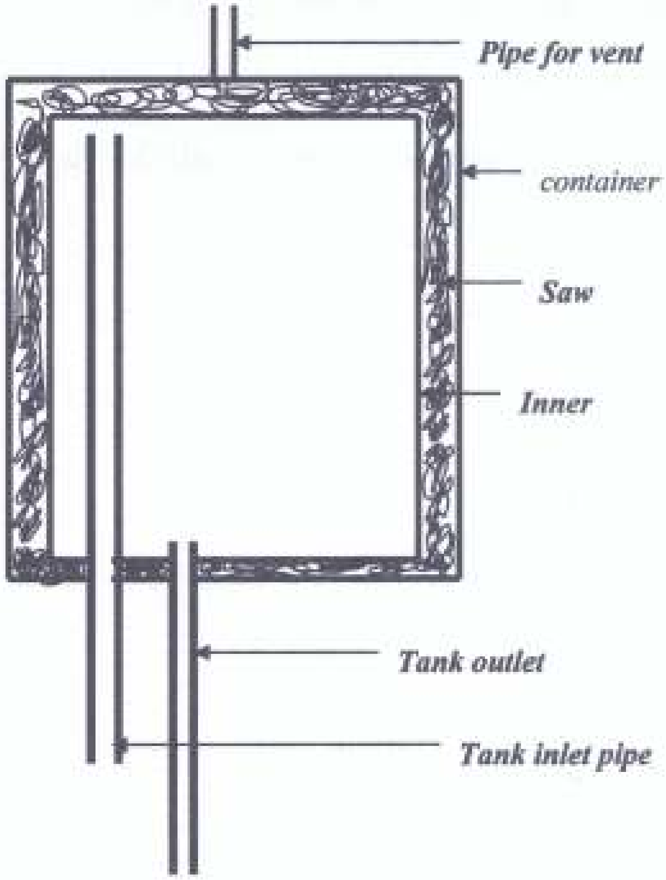

Fig. 3.11 Schematic diagram of the storage tank

3.4 Interconnection and Control of various components of the Solar water Heater.

The flat plate collector and the storage tank are interconnected together by using a galvanized iron pipe of diameter 15 mm. The geometrical tube length to and from tank is 370 cm. Fig.3.12 is a photograph of the locally constructed solar water heater.

Fig.3.12. Photograph of the locally constructed solar water heater.

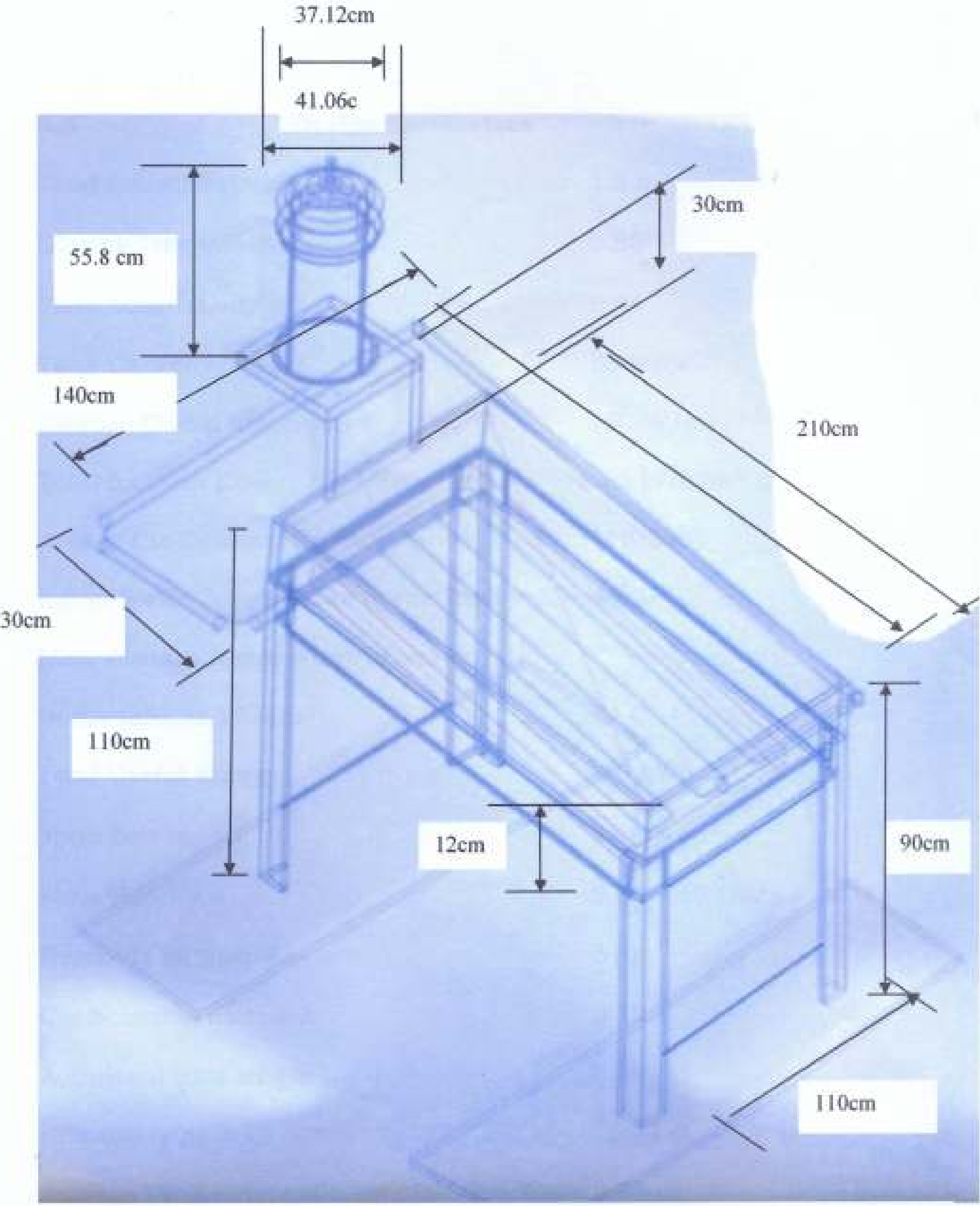

Fig. 3.13(a) AutoCAD Engineering drawing of the system.

3.5 Design Parameters

Total Collector Area Ac	1.5 m^2
Glazing Transmittivity τ	0.85
Plate Absorbitivity α	0.94
Tank Capacity	55 litres
Average Global Insolation S	750 W/m^2
Total Incident Energy per Unit	6.75 kWh/m^2
Area of the Collector Surface	1.495 m^2
Initial Water Temperature in the Tank	25°C
Max. Average temperature of water In the tank at 17.00h	51°C
Total Useful Energy	4.6 kWh
Mass flow m	$\leq$5 g/s
Flow Velocity υ	2.85 x 10^{-2} m/s
Reynolds number Re	540
Coefficient of friction λ	0.12
Additional tube length l_a	0.36 m
Effective Length l_{eff}	13.71 m
Average Tank Height H	0.58 m
Inner Diameter of the Tubing	15 x 10^{-3} m
Geometrical Tube length:	

Inside Collector	9.65 m
To and from Tank	3.70 m
Total geometrical tube length l	13.35 m

3.6 Construction cost analysis

The cost analysis was undertaken to ascertain the total materials and labour cost in the construction of this solar water heater for domestic purpose. The system is constructed using inexpensive local and readily available materials. All materials were purchased at Akure Township in Ondo state.

The construction costs for executing the solar water heater are as shown below:

Item	Description of materials	Quantity	Unit price #: K	Total #: K
1	4cm x 4cm with thickness 0.1cm full length; Angle iron bar	12	950:00	11400:00
2	Galvanized iron sheet gauge 18 of size 4fts x 8fts.	2	2500:00	5000:00
3	Galvanized iron sheet gauge 24 of size 4fts x 8fts.	1	3750:00	3750:00
4	High thermal insulated plywood of thickness 1.5cm.	1	4600:00	4600:00
5	One-half inches nail	1 pound	200:00	200:00
6	High thermal insulated foam 1cm thickness.	1	2500:00	2500:00
7	Black matt paint	1gallon	800:00	800:00
8	Transparent plastic (Perspex) cover with dimension 84cm x 178 cm and thickness 4mm.	1	9500:00	9500:00
9	Galvanized iron pipes and ducts	6	1800:00	10800:00
10	Galvanized angle corner fittings.	15	50:00	750:00
11	Control valve	3	100:00	300:00

12	Control tap	1	300:00	300:00
13	Bolt and nut with parking covering a diameter 0.013m.	20	17:50	350:00
14	Gallon of glossy paint	1	2400:00	2400:00
15	Paint brush	2	200:00	400:00
16	Screw	12	5:00	60:00
17	Packet of calcium carbide electrode	5	140:00	700:00
18	Iron cutter	1	400:00	400:00
19	Sawdust		Free	Free
20	Water pump		Free	Free
21	Silicon seals	3	2000:00	6000:00

Total transportation cost of materials	#2000:00
Labour cost for fabrication	#5000:00
Labour cost on carpentry	#1500:00
Grand total cost for constructing the water heater	#57310:00

The water pump is free because the heater makes use of thermosyphon principle for water circulation instead of pumb. sSawdust is also free because it is waste product of saw milling industries. This reduced the cost for constructing the water heater. Solar systems are generally characterized by high initial cost and low operational cost as compared with the relatively low initial costs and high operating costs of conventional systems. The comparison between these systems is based only on the direct monetary outlay of the user ignoring non –economic factors like social, environmental, status value, novelty value, and freedom from the utility grid. (Garg and Parkash, 1997).

CHAPTER FOUR

PERFORMANCE TESTS, RESULTS AND CONCLUSION

4.0 Introduction

Main quantities of interest in the thermal evaluation of water heating systems are the collector's parameters, viz: the plate efficiency factor, and the heat loss coefficient and the system's overall efficiency. The heat losses of the collector defined by the heat loss coefficient U_L and the plate efficiency factor $F^1$are related to the measurable parameters by the Hottel-Whillier – Bliss (HWB) equation, (Uhlemann and Bansal, 1985).

4.1 Measurable Parameters

4.1.1 Measurement of Solar Radiation

The two most widely used instruments for measuring solar radiation are the Kipp and Zonen pyranometer and the Eppley precision spectral pyranometer (PSP), (Garg and Parkash, 1997). For this performance test, Eppley precision spectral pyranometer (PSP) was used to measure solar radiation because it has a built in temperature compensation and its linearity is similar to that of the Kipp. It has an azimuthally symmetrical detector, which is less influenced by tilting, but the PSP also has an imperfect cosine response.

For this collector testing, both global and diffuse irradiance were measured in the plane of the collector. The pyranometer was placed at approximately the mid-height of the collector to measure the global irradiance, so that the sky and ground reflected irradiance entering the collector aperture is all included.

4.1.2 Measurements of Fluid Inlet Temperatures

Either thermocouples or platinum resistance thermometers can be used for the measurement of fluid inlet temperature. For this performance test, thermocouples thermometer was used because it is able to detect small drifts in the c collector inlet temperature.

The transducer was placed as close to the collector inlet as possible (<100mm away), and the inlet region was very well insulated. To avoid turbulence around the temperature probe, small diameter pipes (Ø 15mm) were used instead of large bore pipes for the fluid loop.

4.1.3 Measurement of the Temperature Difference Between the Collector Inlet and Outlet

As high accuracy as possible is required for the temperature difference measurements, because at high temperatures the collector may only achieve a temperature rise from 1 or 2K. The accuracy of the instrumentation determines the minimum temperature rise, which can be meaningfully used. For this measurements, a matched pair of platinum thermometers was used because it give a reasonable accuracy in collector efficiency measurements, even when using a temperature rise of only 1K.

The mounting of the transducers temperature difference measurement also needs to be in a well-stirred flow and as close to the collector as possible.

Note that different transducers were used to measure the temperature difference and the inlet temperature. This is to permit the inlet transducers to be compared from time to time, but still allows continuous recording of both experimental variable to be made simultaneously.

4.1.4 Measurement of Ambient Air Temperature

Ambient air temperature is usually measured by meteorologist in a 'Stephenson screen', which is a louvered white wooden box. However, discrepancies of between 1 and 2 Kelvin can be produced in such a box at low wind speeds, so a simple radiation shield consisting of a pair of concentric metal tubes, mounted vertical is recommended for collector testing. The outer tube is painted white, and either a platinum resistance thermometer or a weatherproof thermometer or a weatherproof thermocouple is placed inside the inner tube. For this test performance, a weatherproof thermocouple was used to measure the ambient air temperature and it is located near the collector, but away from the ground or any surface which might warm the air.

4.1.5 Measurements of Fluid Flow Rate.

For most water-heating collectors the collection efficiency is not significantly affected by the flow rate used, but for the purpose of calculating collector performance, the flow rate must be known to require for the efficiencies deduced. Typically the flow rates selected are in the region of $0.02 kgs^{-1}m^{-2}$ and the accuracy required is about ± 1 %', (Aranovitch, 1957). For this performance test, the flow rate selected is $\leq 0.005 kgs^{-1} m^{-2}$.

4.1.6 Measurement of Air Speed.

This parameter is called "air speed" because "wind speed" is a defined meteorological parameter which is measured at a height of approximately 10m in an open site. It is not yet clear how the local air speed over a collector can be correlated with that measured in a meteorological station, since air velocities change markedly around buildings, (Aranovitch, 1957).

4.2 Test Procedure

The most well established test procedure, which has been used by both the commission of the European communities (CEC) and the International Energy Agency (IEA) groups, is the steady-state outdoor test procedure published as ASHRAE 93-77 (Aranovitch, 1957) and this has been adopted as the basis for the development of national test procedures in many countries. For this performance test, the test procedure selected is the steady state outdoor efficiency test.

For the testing of solar collectors there are two basic procedures, the instantaneous procedure, and calorimetric procedure. Each of the procedures will allow determination of the fundamental characteristics of the collector. The most widely used procedure for testing collector is called instantaneous procedure.

For this performance test, the test procedure used is instantaneous procedure. The following relation can describe the performance of the flat plate collectors operating under steady state conditions:

From equation (2.1)

$$q_u = (\tau\alpha)_e I - U_L(T_p - T_a)$$

Introducing Collector Aperture Area A_C

$$q_u = I_{Tt} Ac(\tau\alpha)_e - U_L A_C (T_p - Ta) \tag{4.1}$$

Where Tp is the average temperature of the absorber surface of the solar collector.

Introducing the collector efficiency factor Fp of the collector heat removal efficiency factor, FR, then, equation (4.1) can be written as:

$$q_u = FpAc(\tau\alpha)_e - FpA_c UL(\frac{T_1+T_2}{2} - Ta) \tag{4.2}$$

or

$$q_u = FpAcI_{Tt}(\tau\alpha)_e - FpA_c UL(T_1 - Ta) \tag{4.3}$$

and

$$q_u = mAcCp(T_2 - T_1) \tag{4.4}$$

Equation (4.3) and (4.4) can be written in terms of instantaneous efficiency:

$$\eta_c = \frac{q_u}{AcI_{Tt}} = F_R(\tau\alpha)e - F_R U_L \frac{(T_1 - Ta)}{I_{Tt}} \tag{4.5}$$

and

$$\eta_c = \frac{mCp(T_2 - T_1)}{I_{Tt}} \qquad (4.6)$$

Where

η_c = Solar Collector Efficiency

q_u = Useful heat output, W

A_c = Collector Aperture Area, m^2

I_{Tt} = total solar energy incident upon the plane of the collector.

M = mass flow rate of the heat transfer fluid per unit area of collector, Kg/m^2S

Cp = Specific heat of the heat transfer fluid J/Kg^0K

T_2 = Temperature of heat transfer fluid leaving the collector K

T_1 = Temperature of the heat transfer fluid entering the collector, K

Equation (4.5) and (4.6) are used in the ASHARE 93-97 standard test method.

From equation (4.5), it is seen that if the efficiency is plotted against a parameter $(T_1 - T_a)/I_{Tt}$, a near straight line will result, where the slope is some function of U_L and y intercept is some function of $(\tau\alpha)_e$. In reality U_L is not a constant, but rather a function of the operating temperature of the collector and of the ambient weather conditions such as air temperature, sky temperature and wind velocity and its direction. In addition, $(\tau\alpha)_e$ varies with incident angle and to some extent, is a function of the spectral and spatial distribution of the incoming solar radiation.

4.3 Test, Results and Discussion

The solar water heater was monitored in the month of April, 2004, when its construction was completed. During the period of monitoring, the ideal conditions of no draw off during the day and clear sunshine are assumed. The temperature of the collector inlet and outlet T_1 and T_2 are taken simultaneously with two different thermocouples that are connected to a data logger. The absorber plate temperature Tp and plastics cover temperature T_c are also measured with different thermocouples connected to the data logger. The ambient air temperatures T_a were measured with weatherproof thermocouples placed under a shade in the vicinity of the heater. Temperature distributions of water inside the tank at three different points (top, middle and bottom) were also taken with thermocouples connected to the logger. These measurements were taken for a few days on hourly basis together with global insolation. Typical results obtained are in Table 4.1. Fig (4.1) and Fig (4.6) are displays of the temperatures variation at different points of the collector and the tank respectively for a typical day, 16th April, 2004. Vertical distances between curves in Fig. (4.6) show linearity or otherwise temperature distributions inside the tank. This indicates that water from the absorber rises to the top of the tank and that there are no losses or minute's losses in the connecting tubes. This linear temperature distribution inside the tank can be used to determine the thermosyphon head (flow) as generated by the differences in density of the fluid in the system.

The temperatures variation for the plate (Tp), cover (Tc), water at the inlet (T_1) and outlet (T_2) are at the highest at the 13:00 hours in Fig. (4.1), the temperatures were generally high when compared to the ambient temperature.

The highest temperature of the water obtained from the tap of the solar water heater was 69^0C, which is also obtained at the 13:00 hours when the sun is usually overhead and maximum insolation received.

In fig. 4.5, there are "drops" in curves for all temperature variations of the collector at the 14:00 hour local time because there was sudden change in climatic condition of the weather. The weather became cloudy; this has no effect in estimating the efficiency of the system because ideal condition of clear sunshine has been assumed.

From table 4.2, it can be seen that from 10:00 to 17:00 hours, positive values of (T_2-T_1) are due to the increasing insolation and due to thermosiphonic flow of water from the inlet of the collector to the outlet. Fig. (4.3) showing the histogram of useful heat Output of the same day (16:04:04), which is parabolic in nature with insolation curve for global and diffuse radiation measured on clear day (Garg and Parkash, 1997). This indicates that the performance of the system depends on the solar insolation.

Determination of Useful Heat Output

From design parameters

Mass flow m(Kg/s) = 0.005 kg/s

Specific heat capacity of water Cp (kJ/kgK) = 4, 182

Collector Area A_c (m^2) = 1.5

From equation (4.4)

Useful heat output $q_u = m\ A_cC_p(T_2\text{-}T_1)$

The result is analyzed in the table 4.2. The total useful heat output for day (16:04:04) is 3.04KW.

Determination of Collector Efficiency of the System

From the design parameters

Collector efficiency factor $F_p = 0.7$

Heat loss coefficient of the collector $U_l = 4.5W/m^2\ K$.

From equation (4.5)

$$\eta_c = Fp(\tau\alpha)e - FpU_l \frac{(T1 - Ta)}{I_B}$$

Equation (4.5) is straight-line equation of the form:

$$Y = C + mX \tag{4.7}$$

Compare equation (4.5) and (4.7)

$Y \Rightarrow \eta_c$

$C \Rightarrow \quad Fp(\tau\alpha)_e = 0.7x(0.85x0.94)$

$= 0.5593$

$m \Rightarrow \quad -FpU_L = -(0.7x4.5) = -3.15W/m^2K$

$X \Rightarrow \quad \frac{T_1 - T_a}{I_T}$

$$\eta_c = \frac{3.15(T_1 - T_a)}{I_T} + 0.5593$$

The results are analyzed in Table 4.3. The collector efficiency plot in Fig. (16) for day 1(16:04:04) is linear which correlated with efficiency curve of steady state outdoor test procedure published as ASHRAE 93-77(Aranovitch, 1957). The efficiency of the collector is averagely 50.1% by subjecting collector efficiencies of the system to statistical analysis.

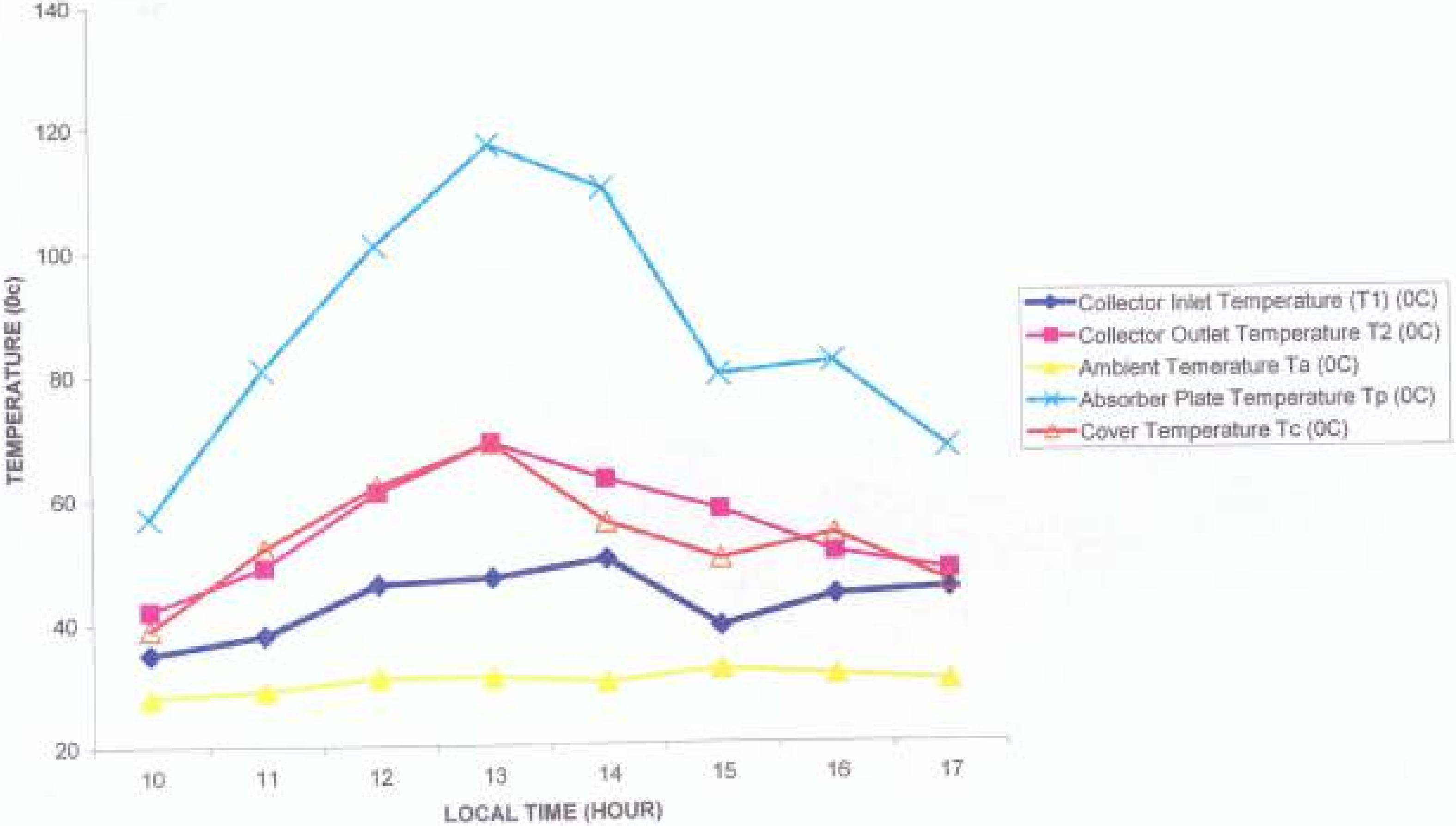

FIG. 4.1: GRAPH OF TEMPERATURE AT DIFFERENT POINTS OF THE COLLECTOR WITH LOCAL TIME FOR DAY 1 (16:04:04)

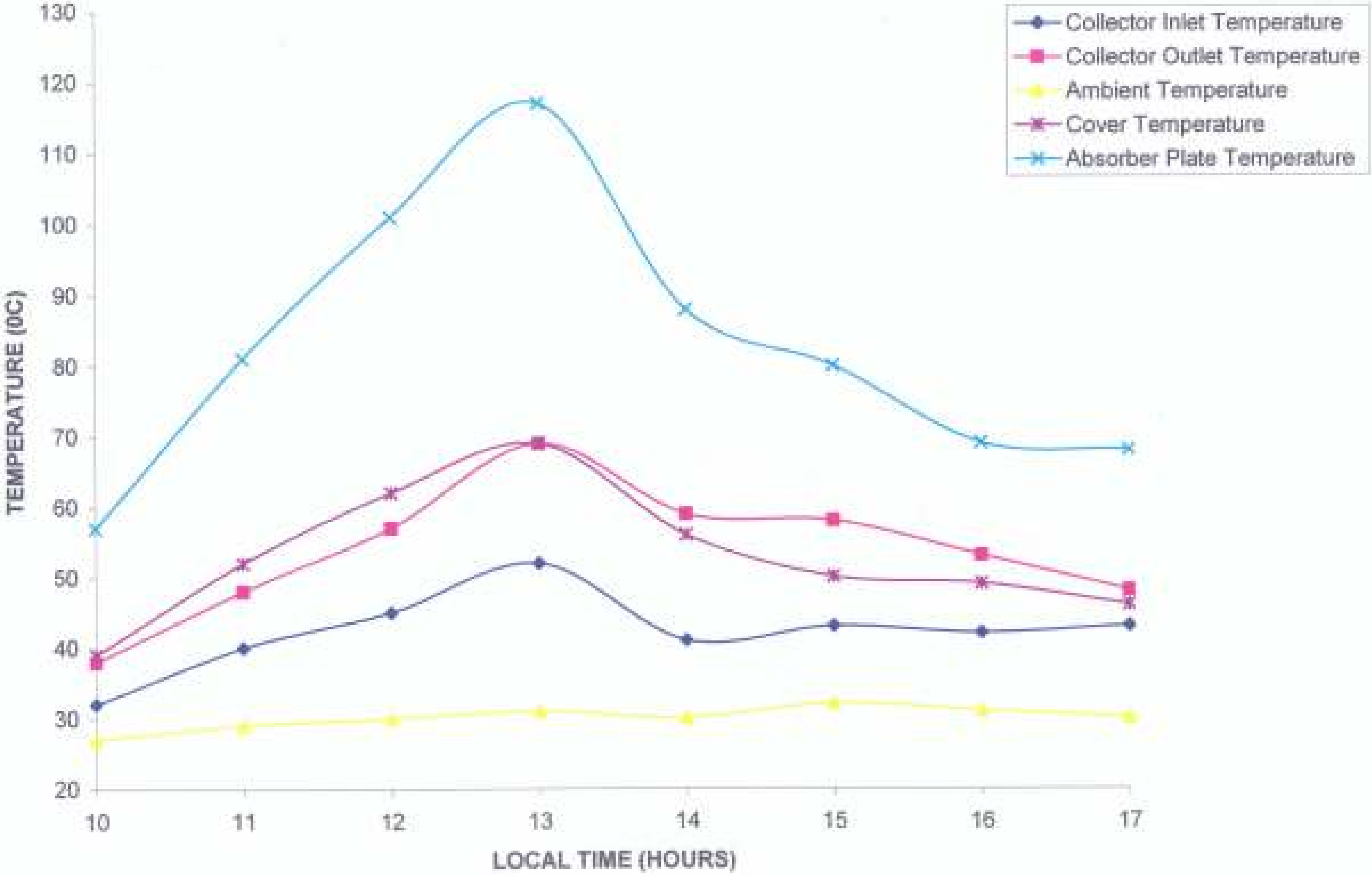

FIG. 4.2. THE GRAPH OF TEMERATURE AT DIFFERENT POINT OF THE COLLECTOR WITH LOCAL TIME FOR DAY 2 (17:04:04)

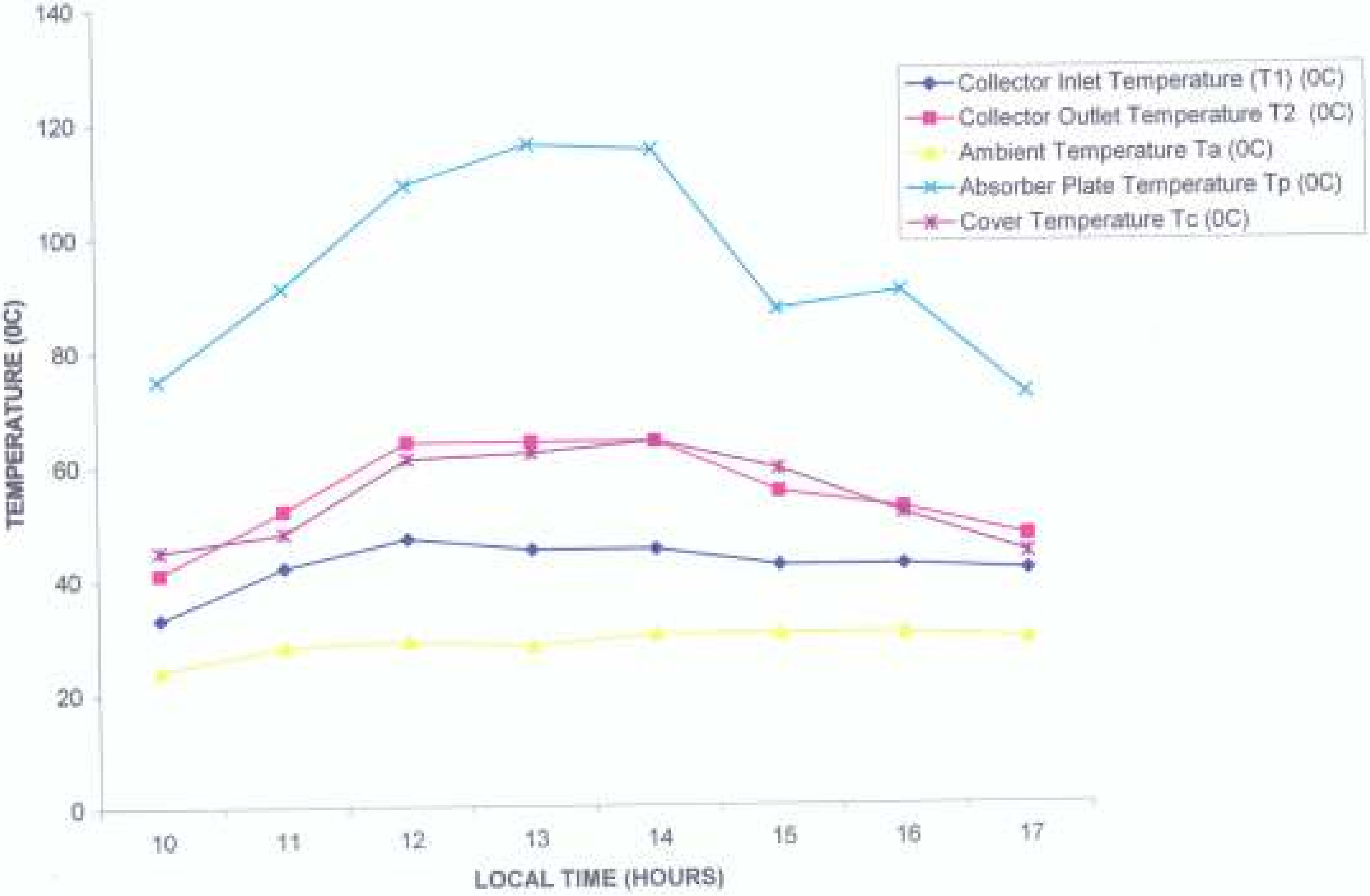

FIG. 4.3: THE GRAPH OF TEMPERATURE AT DIFFERENT POINTS OF THE COLLECTOR WITH LOCAL TIME FOR DAY 3 (18:04:04)

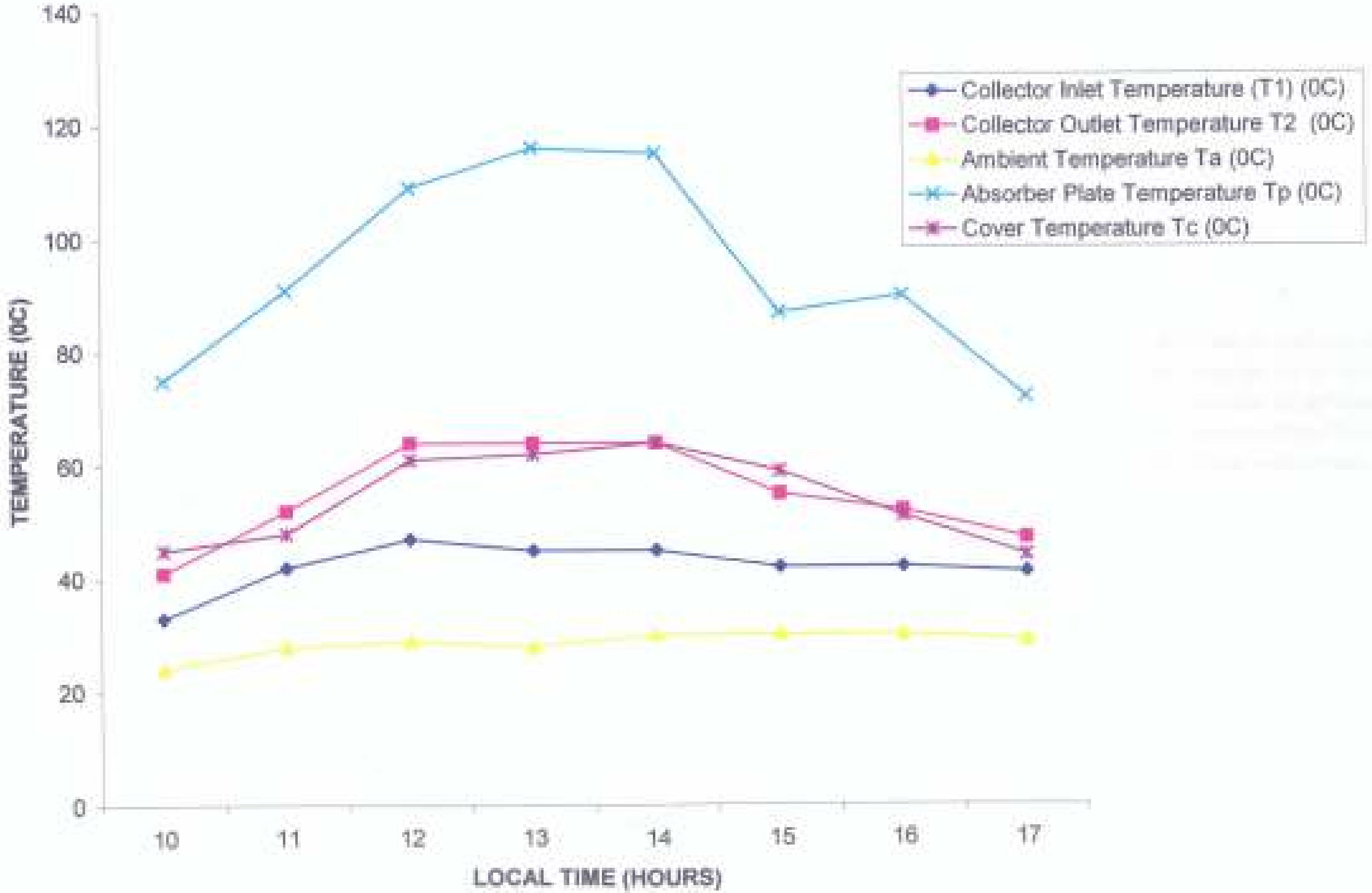

FIG. 44. THE GRAPH OF TEMERATURE AT DIFFERENT POINT OF THE COLLECTOR WITH LOCAL TIME FOR DAY 4 (18:04:04)

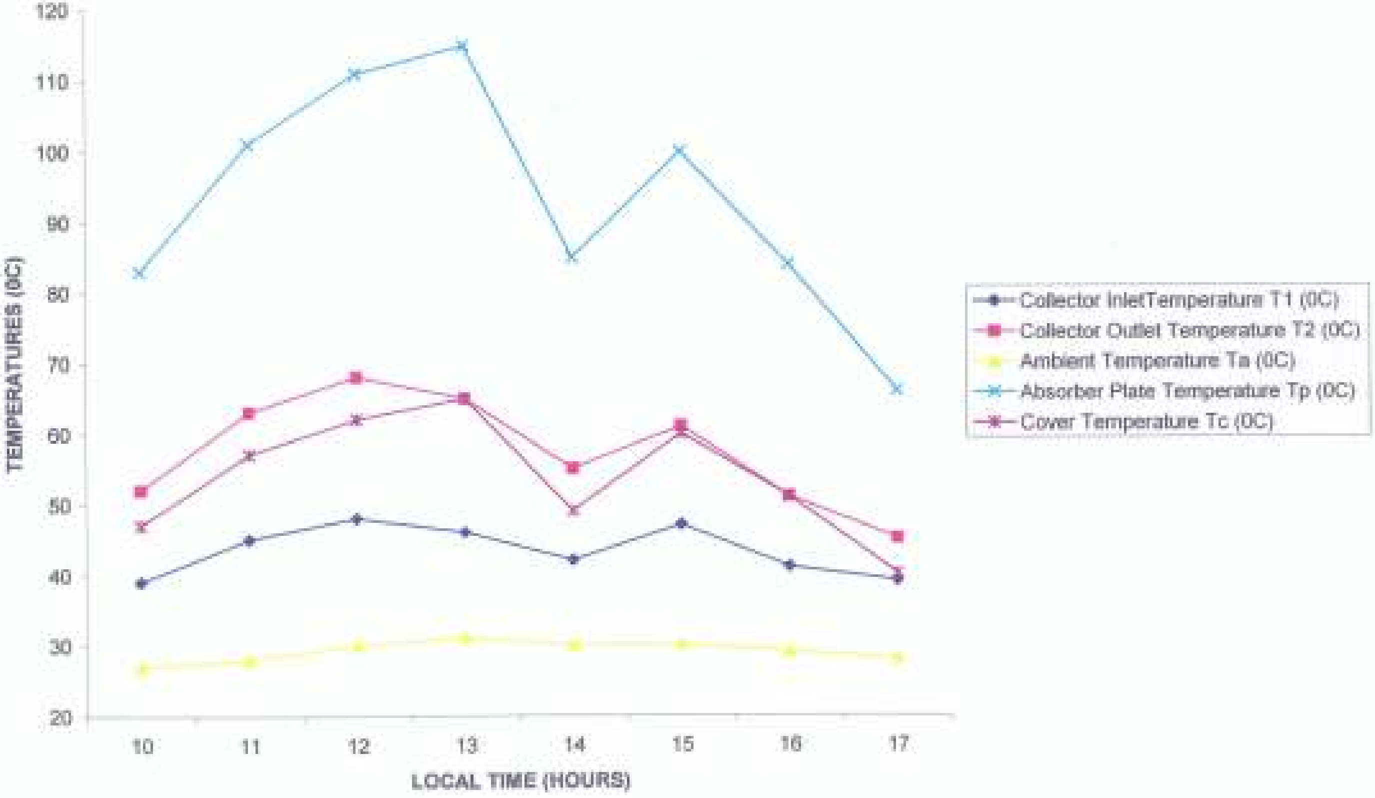

FIG. 4.5: THE GRAPH OF TEMPERATURE AT DIFFERENT POINTS OF THE COLLECTOR WITH LOCAL TIME FOR DAY 5 (20:04:04)

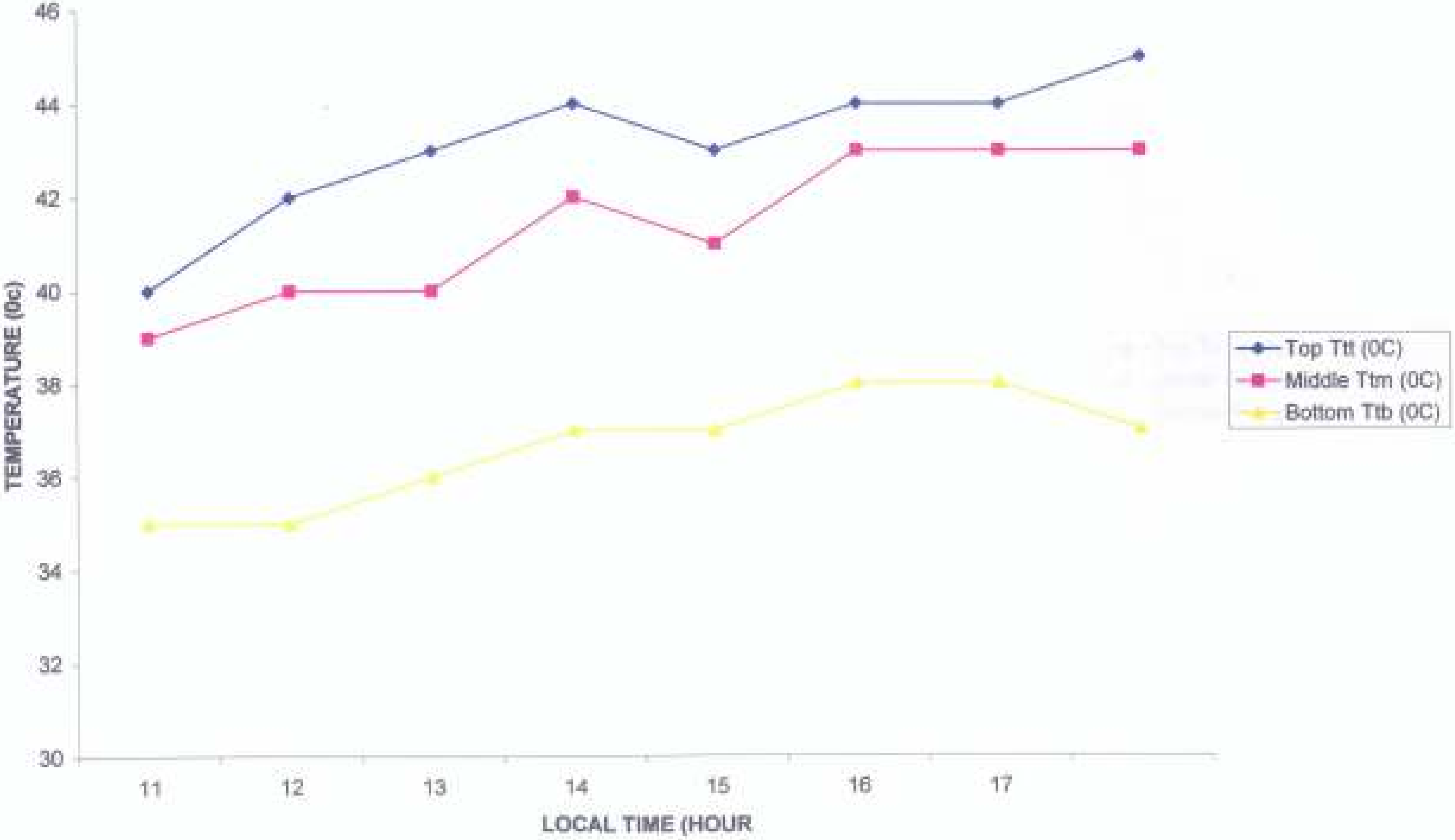

FIG. 4.6: THE GRAPH OF DAILY TEMPERATURE VARIATION OF WATER AT POINTS INSIDE THE TANK, FOR DAY 1 (16:04:04)

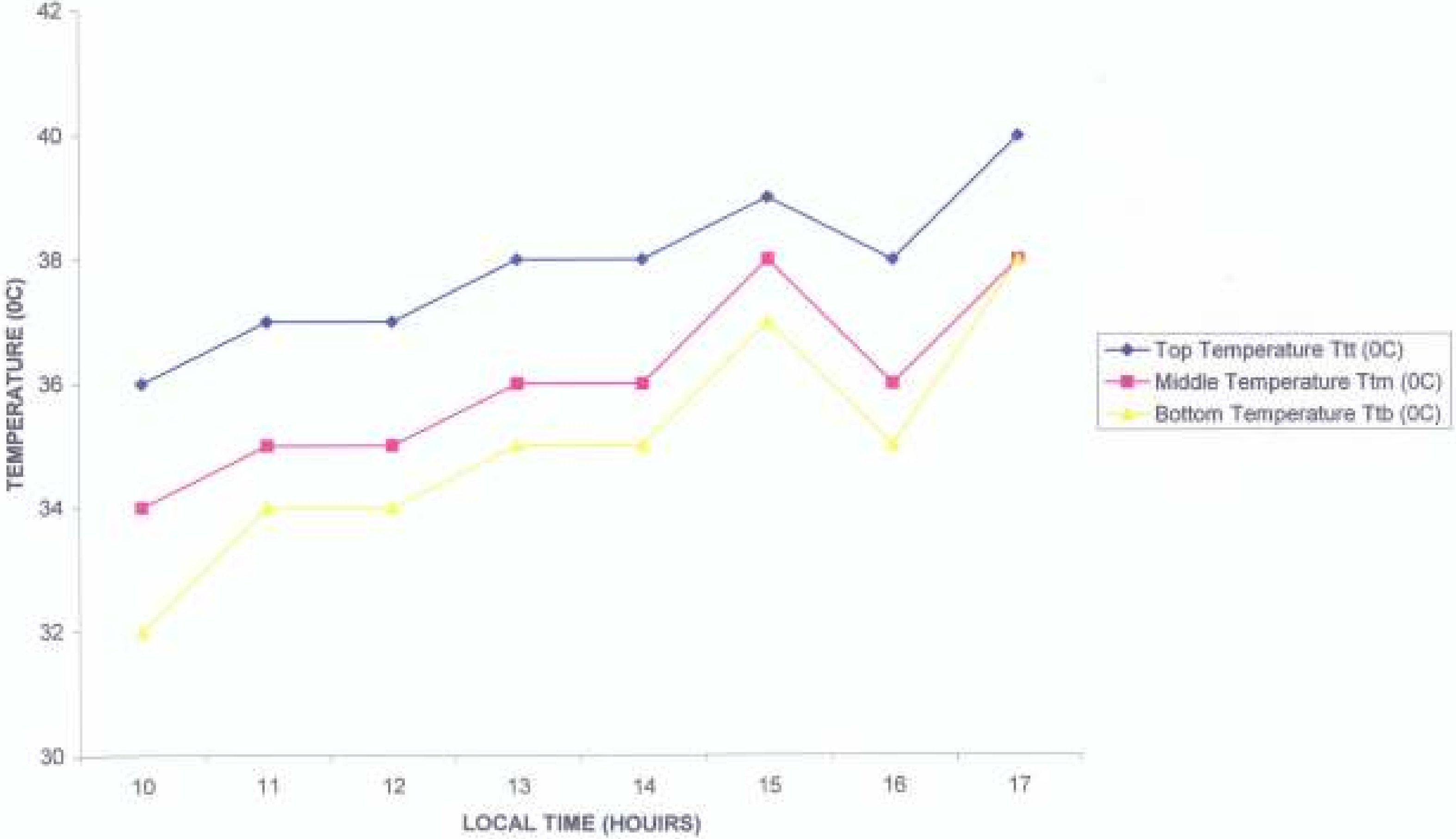

FIG. 4.7: THE GRAPH OF DAILY TEMPERATURE VARIATION OF WATER AT POINTS INSIDE THE TANK, FOR DAY 2 (17:04:04)

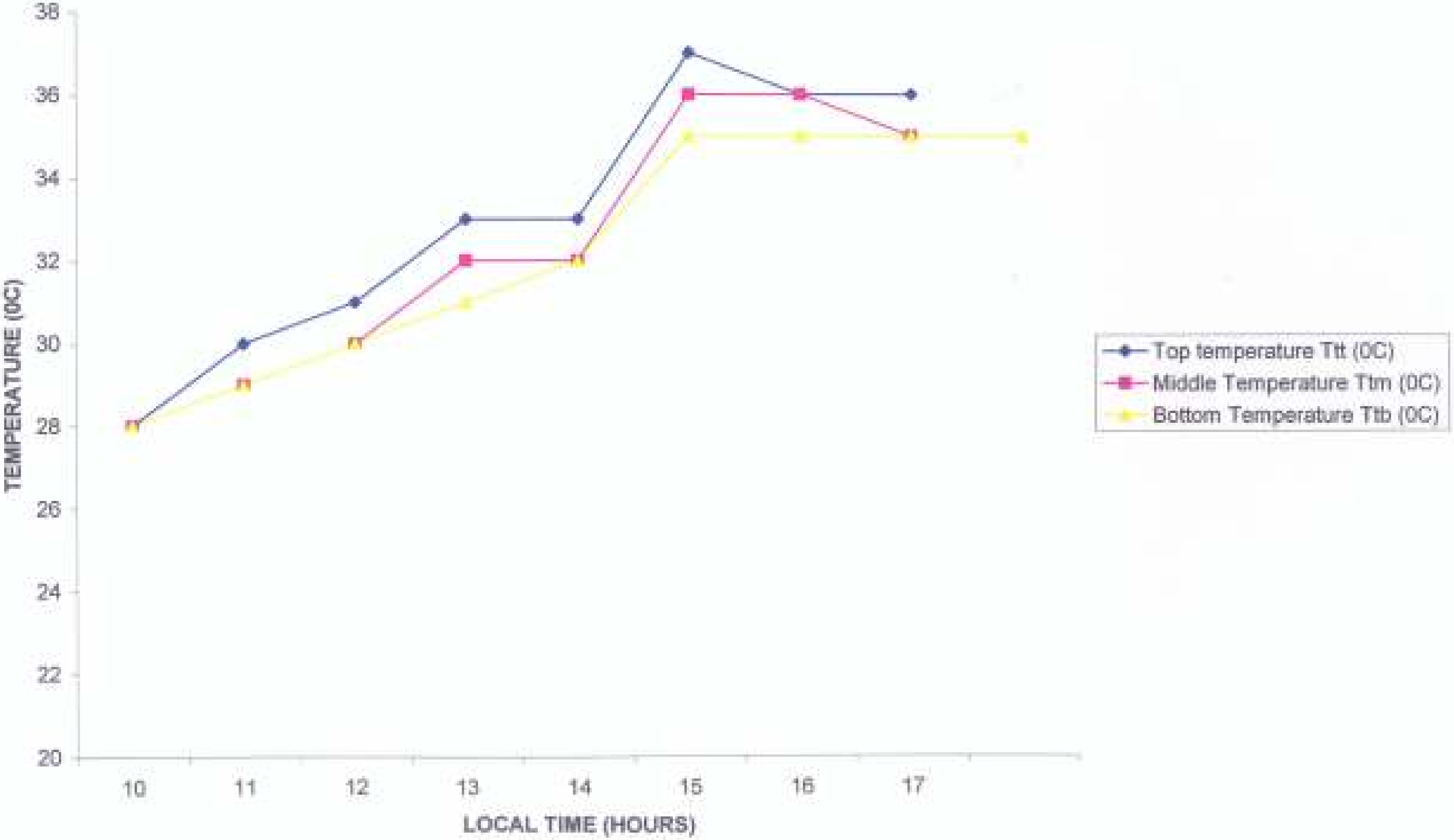

FIG. 4.8: THE GRAPH OF DAILY TEMPERATURE VARIATION OF WATER AT POINTS INSIDE THE TANK, FOR DAY 3 (18:04:04)

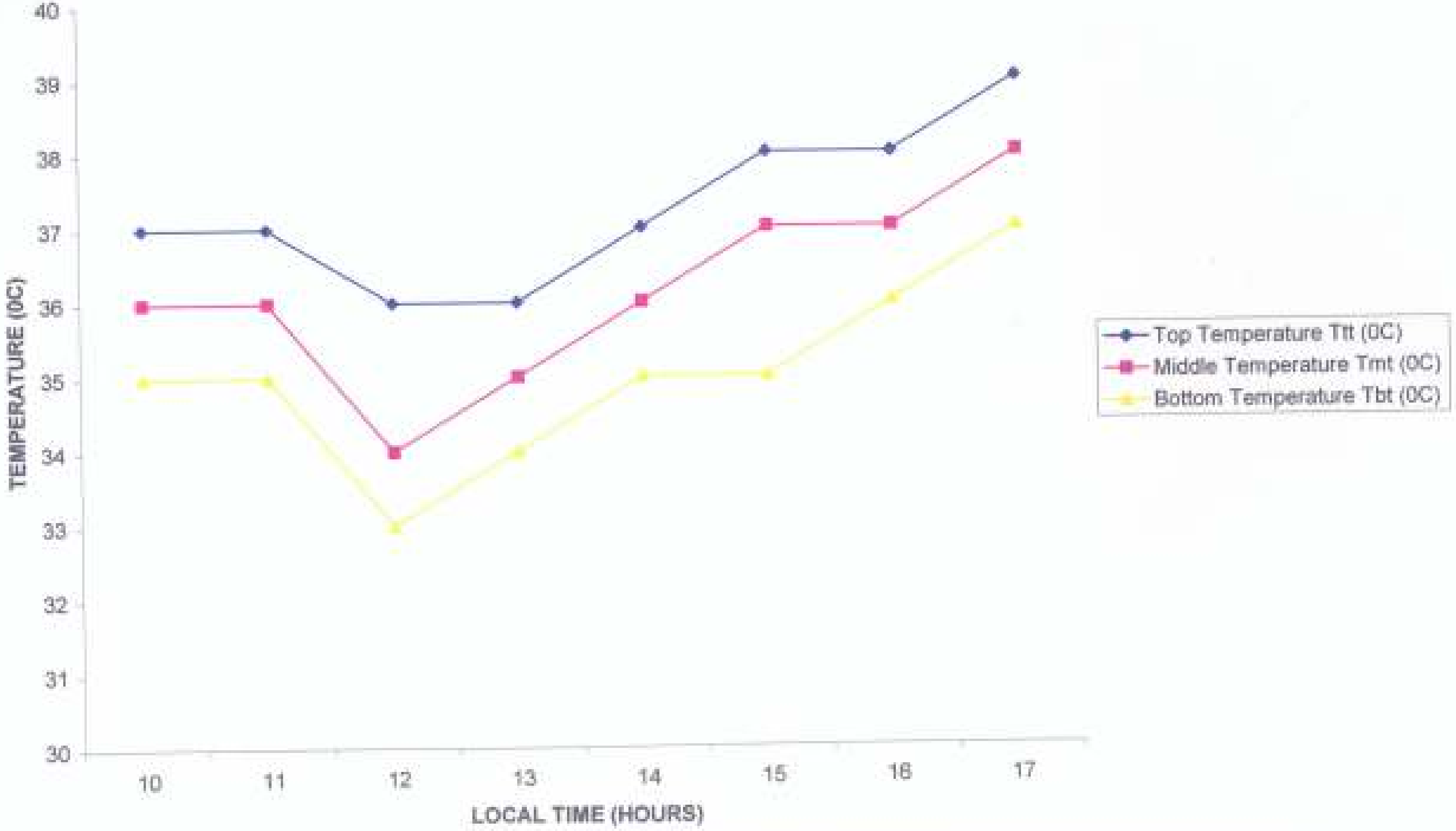

FIG. 4.9: THE GRAPH OF DAILY TEMPERATURE VARIATION OF WATER AT POINTS INSIDE THE TANK, FOR DAY 4 (19:04:04)

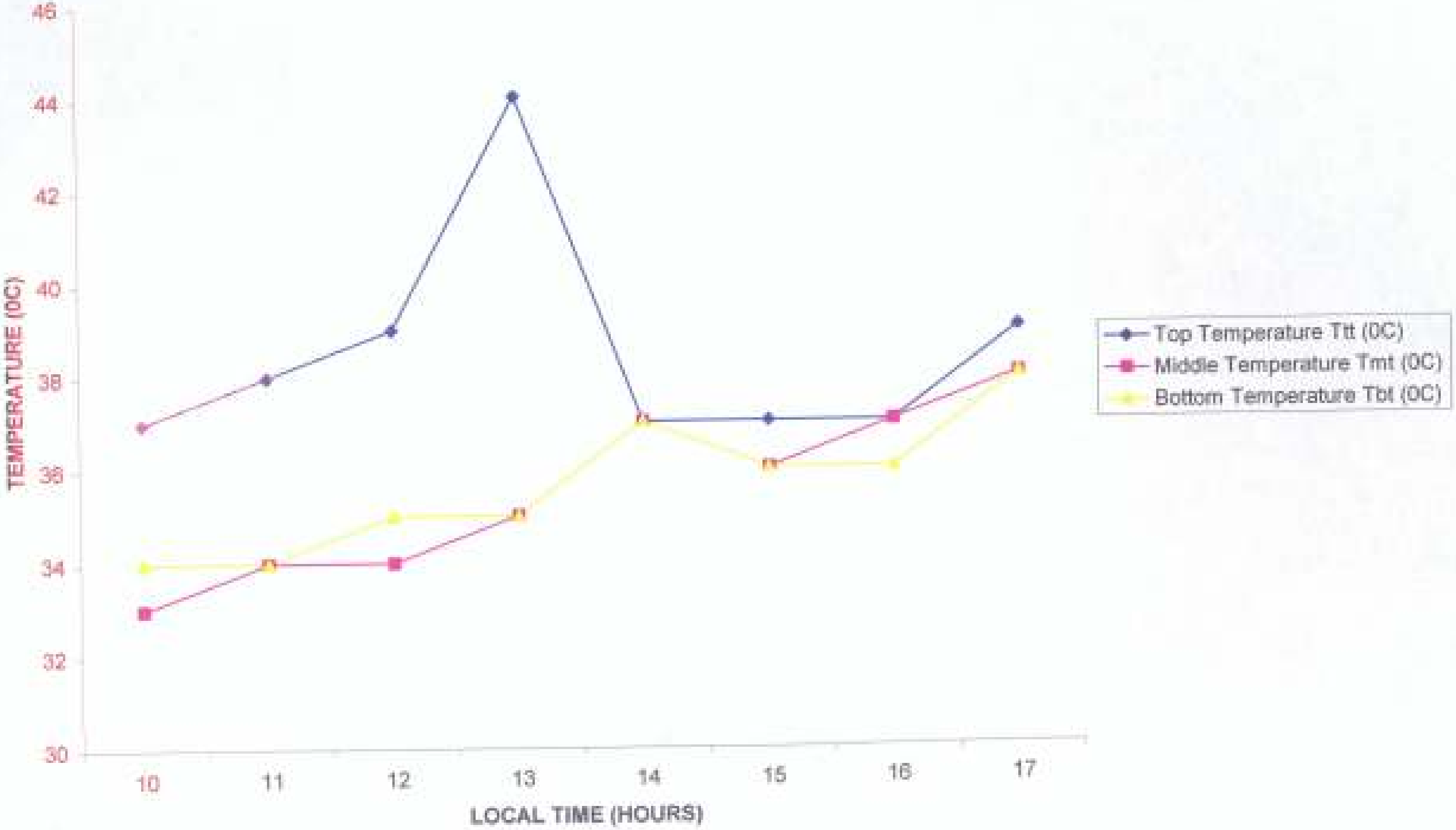

FIG. 4.10: THE GRAPH OF DAILY TEMPERATURE VARIATION OF WATER AT POINTS INSIDE THE TANK, FOR DAY 5 (16:04:04)

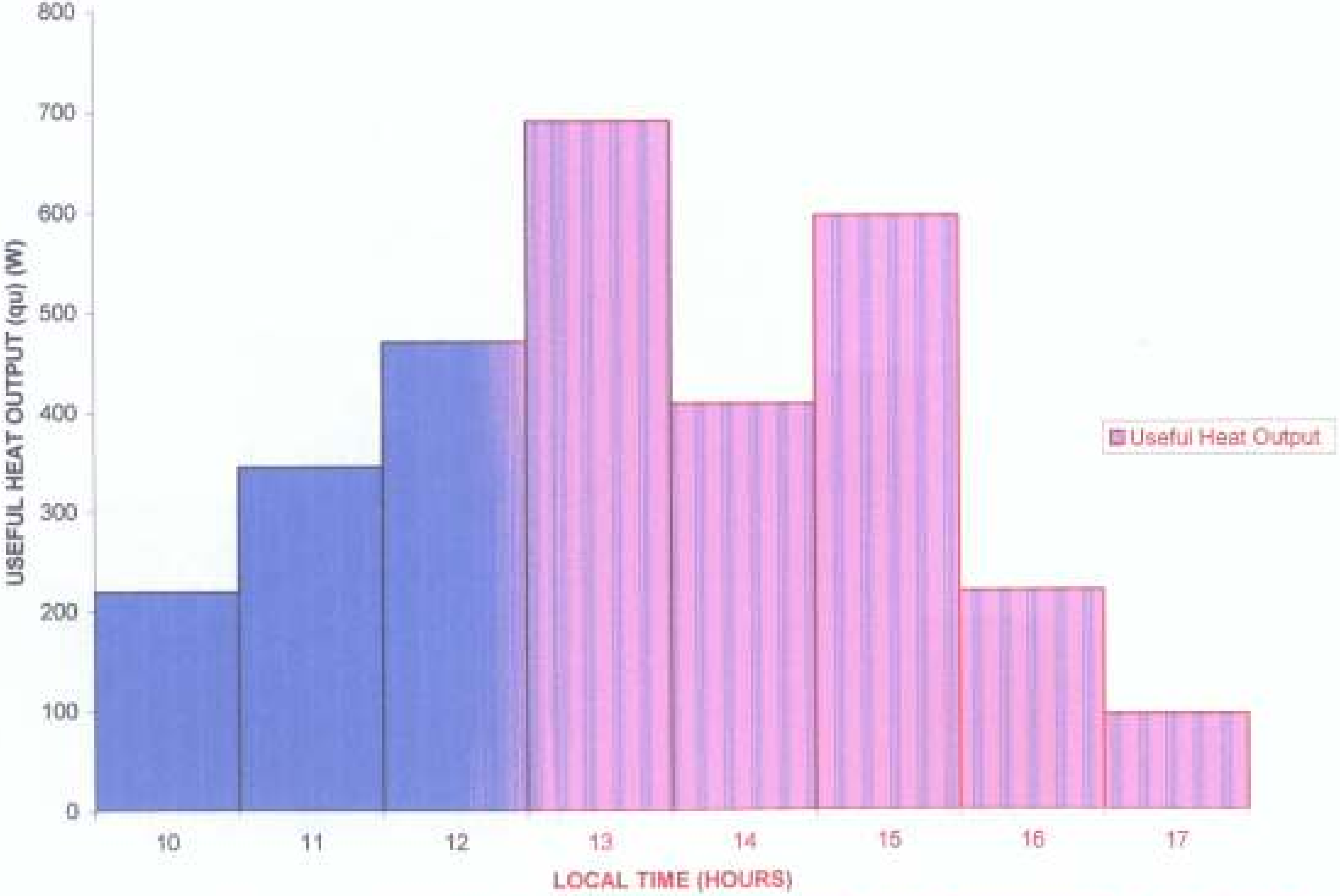

FIG. 4.11: THE HISTOGRAM OF USEFUL HEAT OUTPUT q_u FOR DAY 1 (16:04:04)

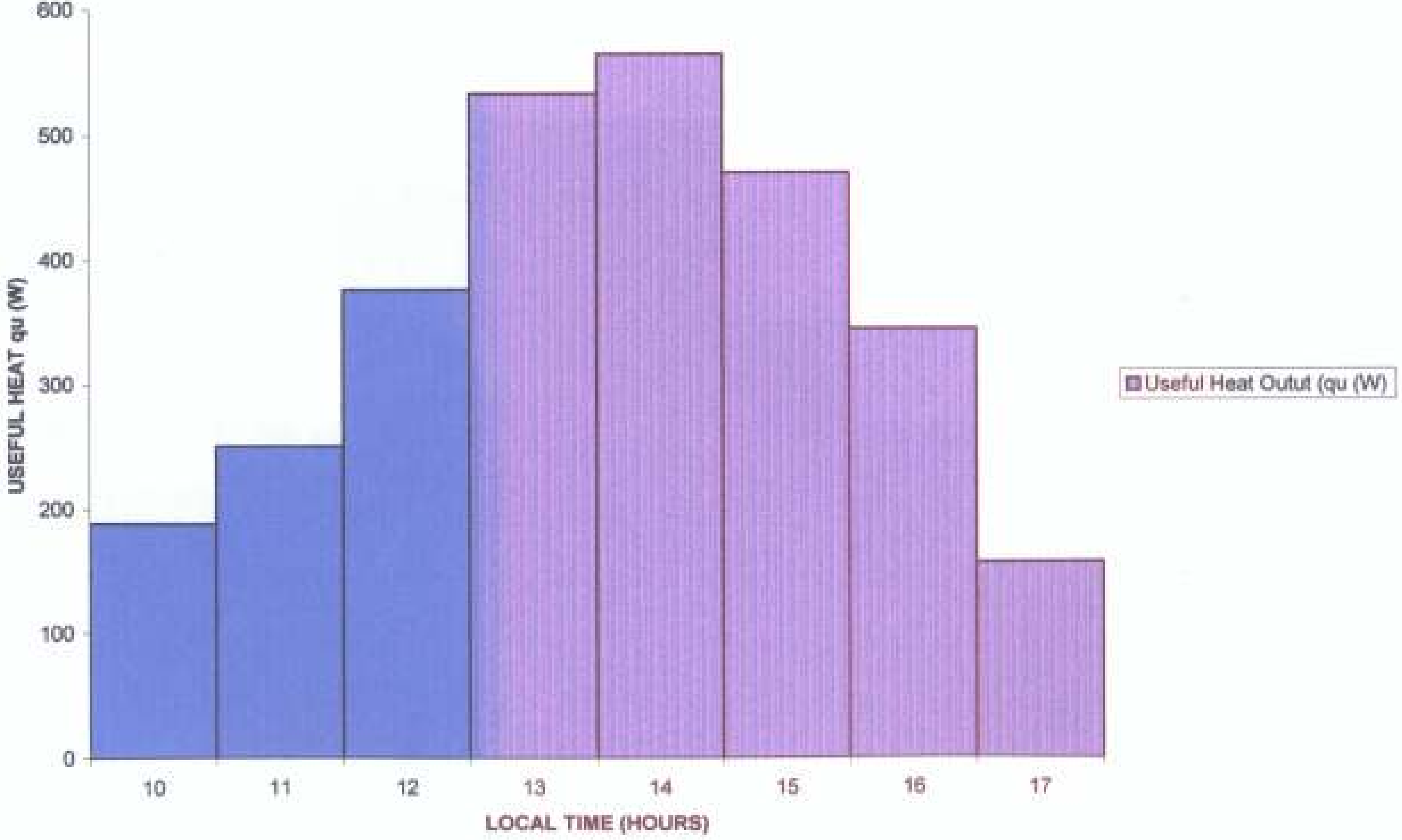

FIG. 4.12: THE HISTOGRAM OF USEFUL HEAT OUTPUT q_u FOR DAY 2 (17:04:04)

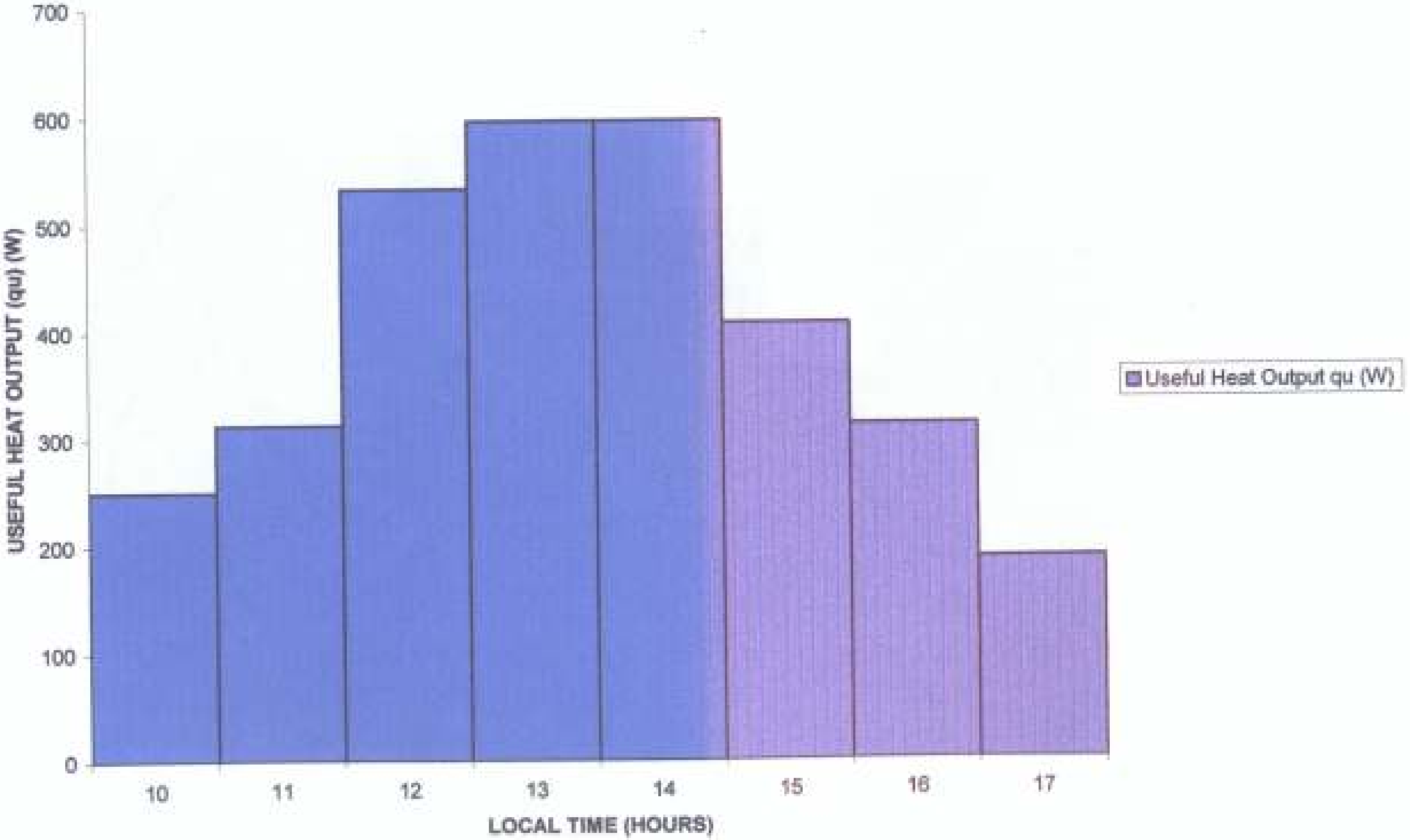

FIG. 4.13: THE HISTOGRAM OF USEFUL HEAT OUTPUT q_u FOR DAY 3 (18:04:04)

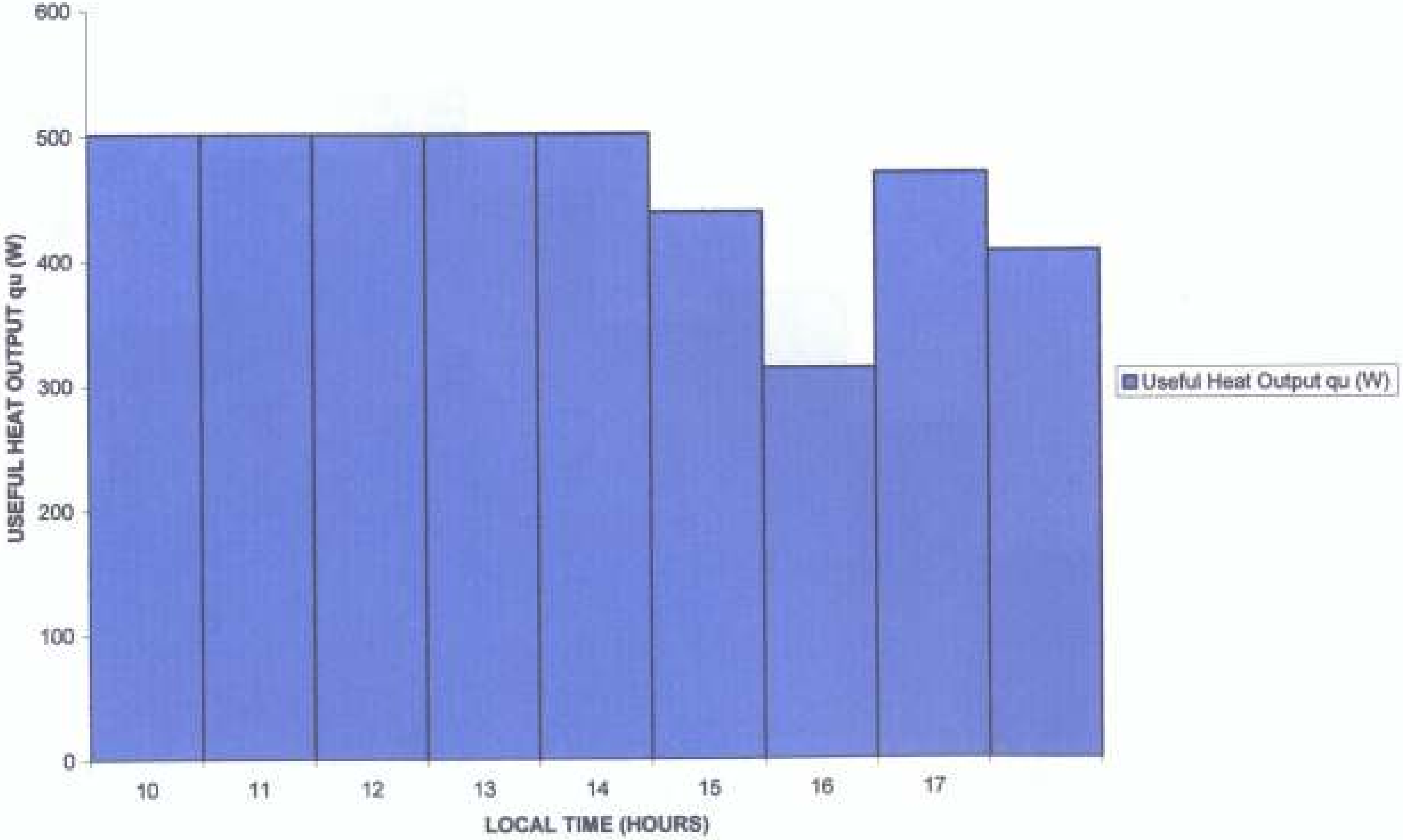

FIG. 4.14: THE HISTOGRAM OF USEFUL HEAT OUTPUT q_u FOR DAY 4 (19:04:04)

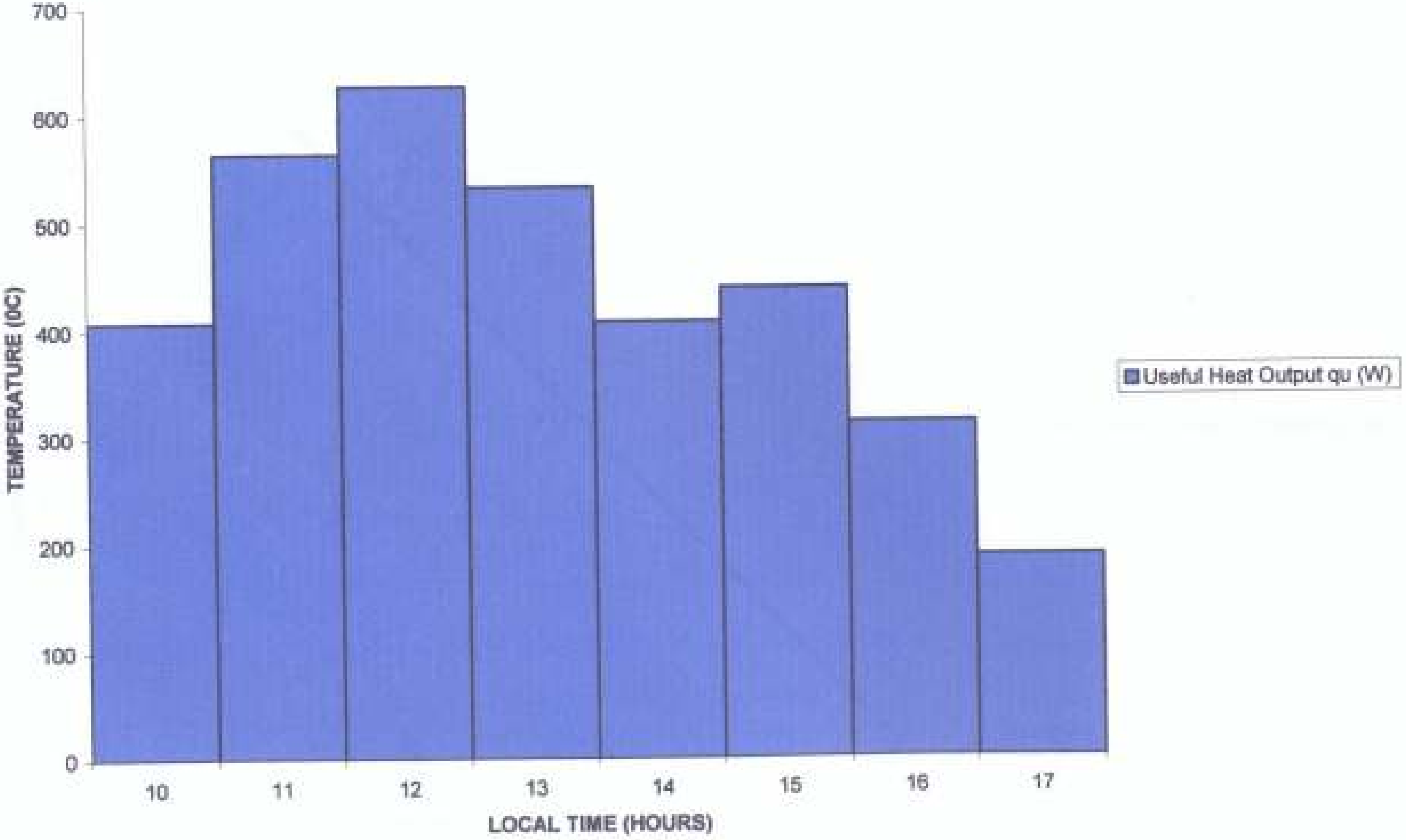

FIG. 4.15: THE HISTOGRAM OF USEFUL HEAT OUTPUT q_u FOR DAY 5 (20:04:04)

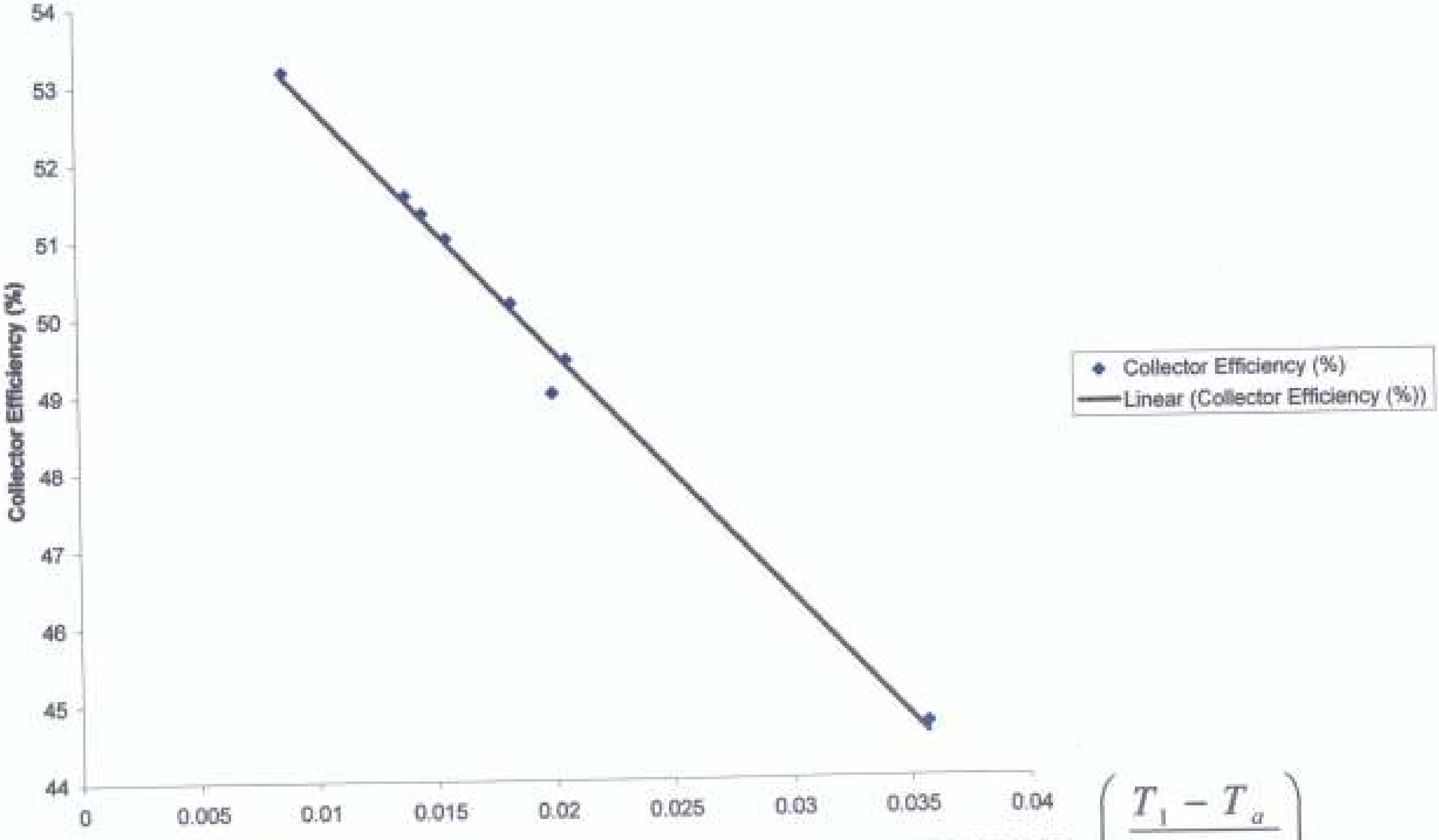

FIG. 4.16: THE GRAPH OF VARIATION OF COLLECTOR EFFICIENCY $\frac{T_1-Ta}{I_{Ti}}\left(\frac{m_2{}^0C}{W}\right)$ FOR DAY 1(16:04:04)

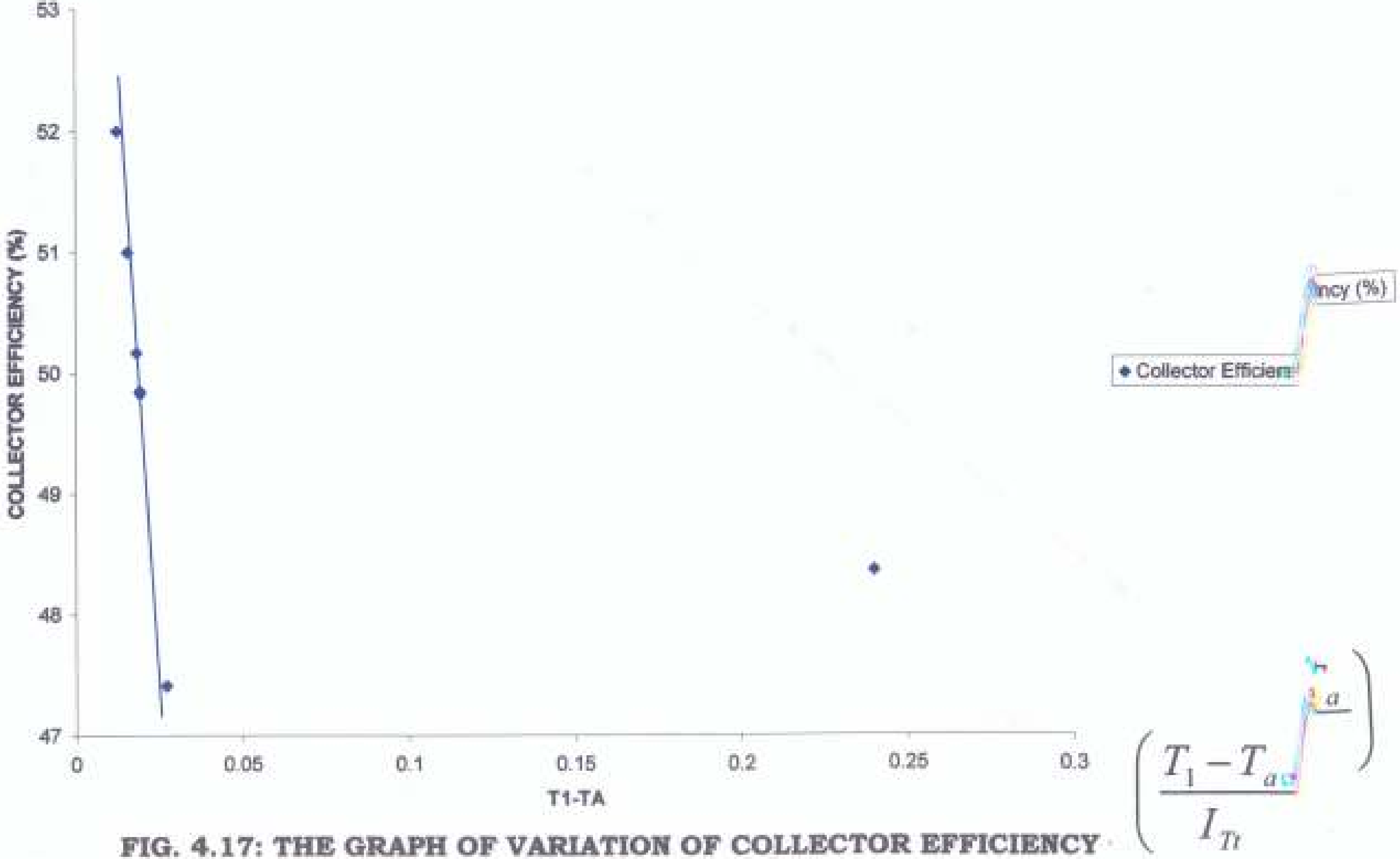

FIG. 4.17: THE GRAPH OF VARIATION OF COLLECTOR EFFICIENCY WITH $\frac{T_1 - Ta}{I_{Tt}}\left(\frac{m_2\,^0C}{W}\right)$ FOR DAY 2 (17:04:04)

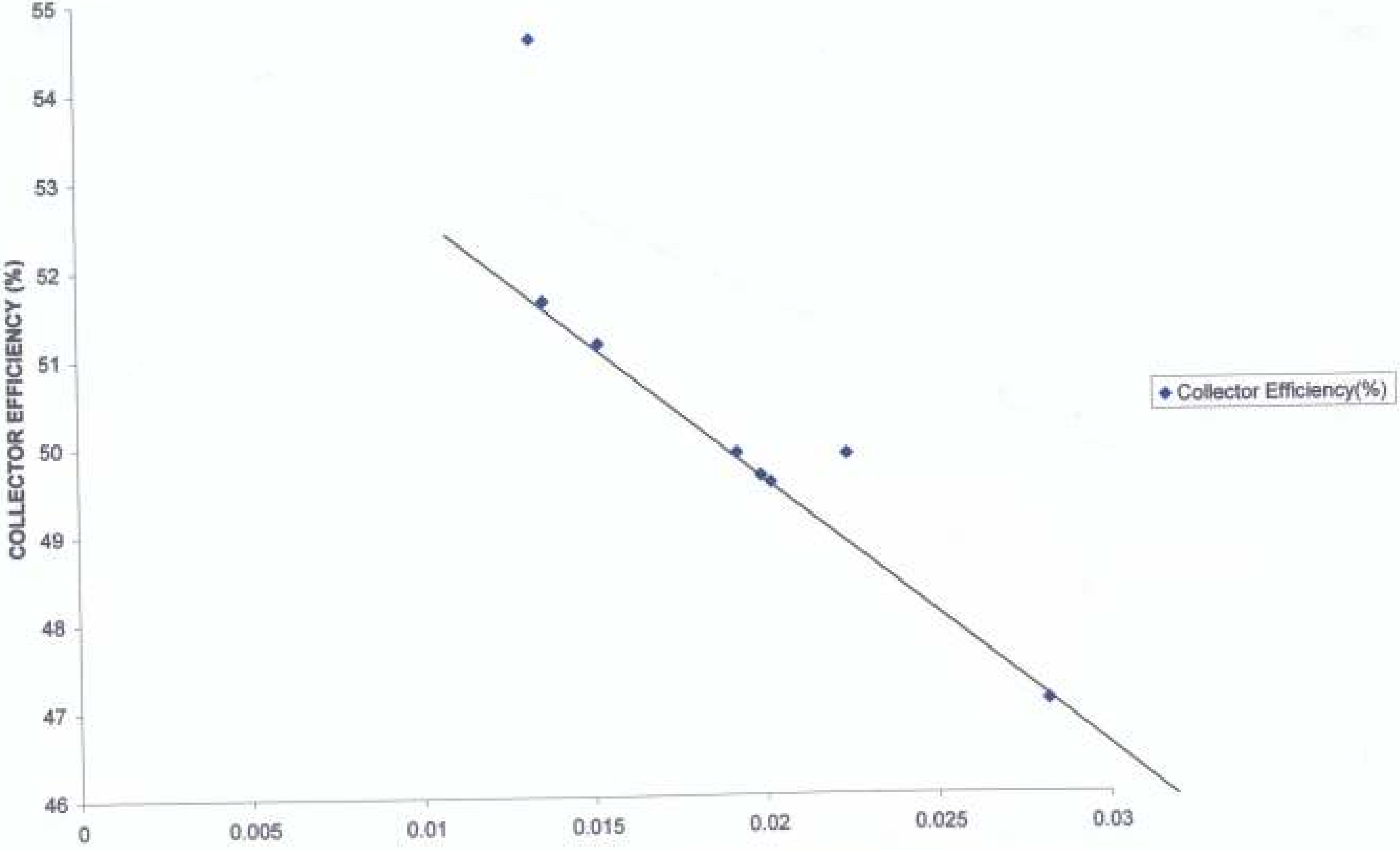

FIG. 4.18: THE GRAPH OF VARIATION OF COLLECTOR EFFICIENCY η WITH $\frac{T_1 - Ta}{I_{Tt}}\left(\frac{m_2{}^0C}{W}\right)$ FOR DAY 3(18:04:04)

$$\left(\frac{T_1 - T_a}{I_{Tt}}\right)$$

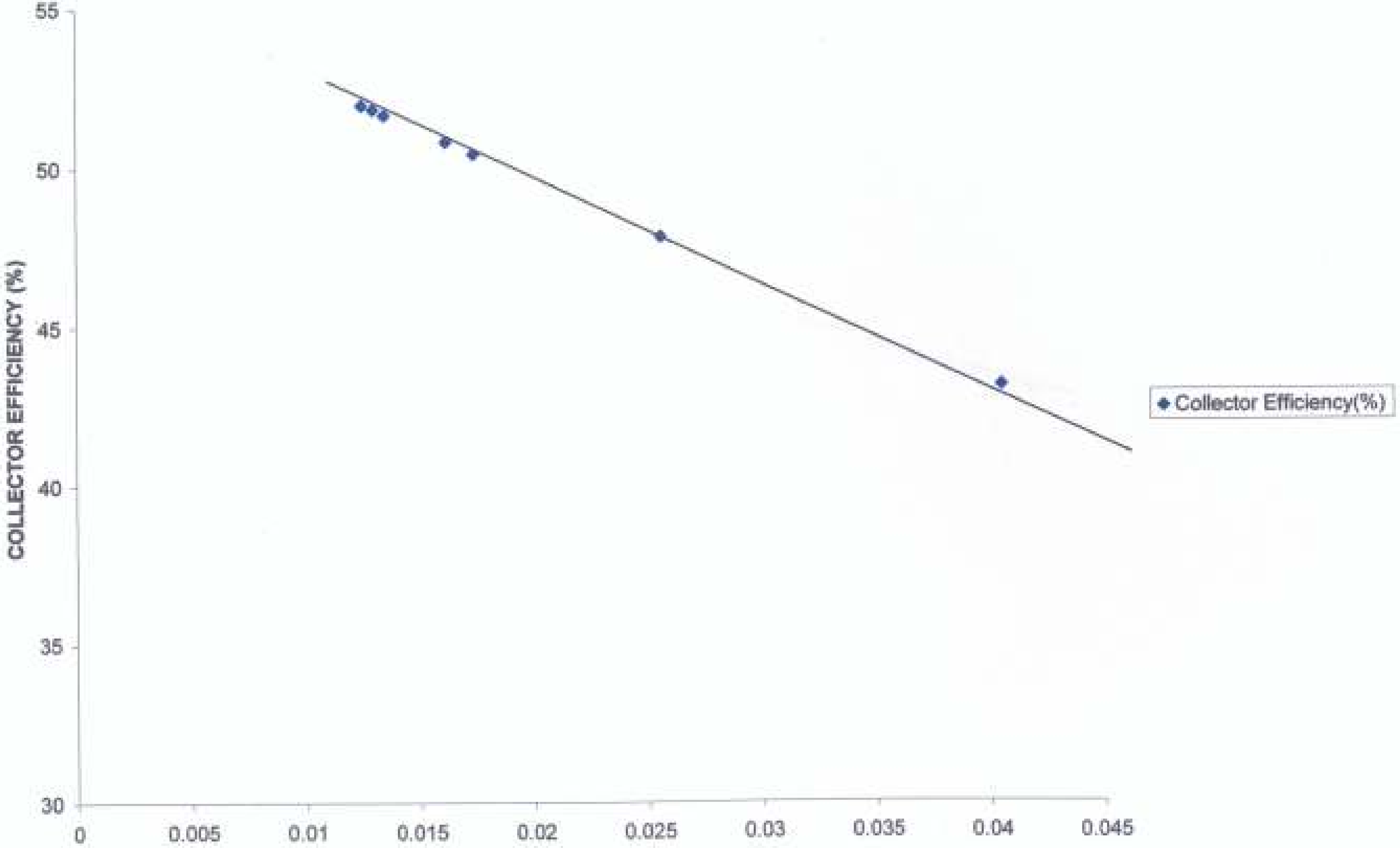

FIG. 4.19: THE GRAPH OF VARIATION OF COLLECTOR EFFICIENCY η WITH $\frac{T_1 - Ta}{I_{Tt}}\left(\frac{m_2\,^0C}{W}\right)$ FOR DAY 4(19:04:04)

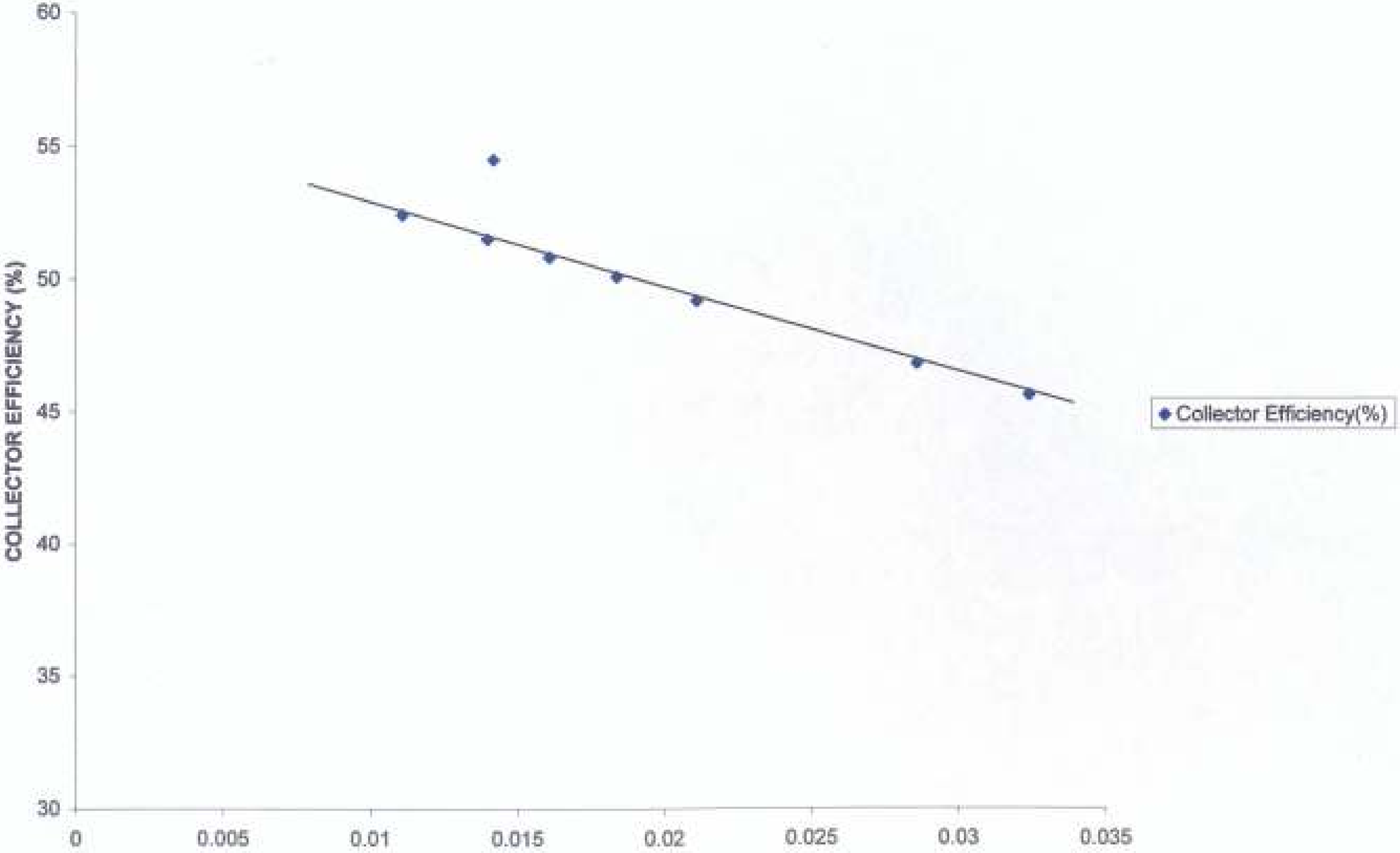

FIG. 4.20: THE GRAPH OF VARIATION OF COLLECTOR EFFICIENCY η WITH $\frac{T_1 - Ta}{I_T}\left(\frac{m_2\,^0C}{W}\right)$ FOR DAY 5(20:04:04)

$$\left(\frac{T_1 - T_a}{I_T}\right)$$

4.1 CONCLUSIONS

1. A simple and cheap solar water heater was constructed with materials that are readily available in the local market. It requires very simple technology and very little maintenance when installed. The device can be provided in the rural areas, on individual basis or on a community basis. Ready application of hot water from water heaters include: bath water, laundry, washing dishes and cooking utensils, pre-heated water for cooking, and hot water supply in health centre in rural areas.
2. The useful heat output per day is 3.04×10^4 KW and the power consumption of the solar heater is 4343KWh. If this power consumption of the solar heater is compared to that of electric water heater of the same power consumption, the bill that will be charged by Power Holdings Company of Nigeria (PHCN) is #212,800:00K (since the current charge rate is now #4:00K) for heating the same quantity of water to maximum average temperature of water in the for period of 7hours to 55 ^{0}C. This is highly expensive cost. Therefore, solar water heating and other solar energy applications will certainly relieve pressure on the other energy sources. Consequently,

this option will provide a desirable long-term cumulative effect on our national economy.

3. This project has not provided only technical but economic, environmental and other relevant information that will allow well-founded and well-timed decisions to be made in research and development of solar energy utilization systems.
4. An experimental study performed on domestic solar water heater using thermosyphon principle shows that the system perform well with approximately 50.1% collector efficiency, and producing hot water at average temperature of 55^{0}C.

RECOMMENDATION

Flat plate collectors should now be produced on commercial and competitive basis

A more detailed study of the performance of this hot-water system is anticipated, which will provide a more complete understanding of the mechanism of thermosyphon flow, and include the effect of tank size, pipe layout, draw off and intermittent sunshine. A critical examination of the design criteria used for solar hot-water can then be made.

There is need to develop solar water heating systems that can be easily moved from one place to another, hence, the collector can be constructed in such a way that the collector tilt angle can be varied.

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APPENDIX

Table 4.1: Temperature and Solar radiation measurements of the heater for five consecutive days (16-20 April, 2004).

Date	Local Time Hours	Collector inlet Temp. T_1 (^0C)	Collector outlet Temp. T_2 (^0C)	Ambient Temp. T_A (^0C)	Absorber Plate Temp T_P (^0C)	Cover Temp. T_C (^0C)	Tank Temperature			Solar Insolation I_T (W/m^2)
							T_H (^0C)	Middle T_2 (^0C)	Bottom T_{tB} (^0C)	
16:04:04	10:00	35	42	28	57	39	40	39	35	480
Day 1	11:00	38	49	29	81	52	42	40	35	650
	12:00	46	61	31	101	62	43	40	36	820
	13:00	47	69	31	117	69	44	42	37	1025
	14:00	50	63	30	110	56	43	41	37	1001
	15:00	39	58	32	80	50	44	43	38	800.01
	16:00	44	51	31	82	54	44	43	38	630.01
	17:00	45	48	30	68	46	45	43	37	420.5
17:04:04	10:00	32	38	27	57	39	36	34	32	400.57
Day 2	11:00	40	48	29	81	52	37	35	34	570.16
	12:00	45	57	30	101	62	37	35	34	774.87
	13:00	52	69	31	117	69	38	36	35	874.21
	14:00	41	59	30	88	56	38	36	35	702.31
	15:00	43	58	32	80	50	39	38	37	602.08
	16:00	42	53	31	69	49	38	36	35	406.65

	17:00	43	48	30	68	46	40	38	38	344.04
18:04:04	10:00	33	41	24	75	45	28	28	28	402
Day 3	11:00	42	52	28	91		30	29	29	731
	12:00	47	64	29	109	61	31	30	30	890
	13:00	45	64	28	116	62	33	32	31	1120
	14:00	45	64	30	115	64	33	32	32	1101.9
	15:00	42	55	30	87	59	37	36	35	905
	16:00	42	52	30	90	51	36	36	35	600.5
	17:00	41	47	29	72	44	36	35	35	425.5
19:04:04	10:00	41	57	27	93	54	37	36	35	346.04
Day 4	11:00	43	59	28	94	55	37	36	35	926.51
	12:00	42	58	29	86	55	36	34	33	1037.28
	13:00	42	58	29	82	54	36	35	34	747.72
	14:00	41	55	31	77	53	37	36	35	738.86
	15:00	43	53	30	75	50	38	37	35	747.28
	16:00	42	57	30	77	52	38	37	36	922.41
	17:00	41	54	30	68	47	39	38	37	430.0

20:04:04	10:00	39	52	27	83	47	37	33	34	844.6
Day 5	11:00	45	63	28	101	57	38	34	34	926.7
	12:00	48	68	30	111	62	39	34	35	1290
	13:00	46	65	31	115	65	44	35	35	1350
	14:00	42	55	30	85	49	37	37	37	745
	15:00	47	61	30	100	60	37	36	36	804
	16:00	41	51	29	84	51	37	37	36	420
	17:00	39	45	28	66	40	39	38	38	340

Table 4.2: Determination of useful heat output

Date	Local time (Hours)	Collector inlet Temp. T_1(ºC)	Collector outlet Temp. T_2 (ºC)	T_2-T_1	Useful heat output
14:04:04	10:00	35	42	7	219.56
Day 1	11:00	38	49	11	345.02
	12:00	46	61	15	470.48
	13:00	47	69	22	690.03
	14:00	50	63	13	407.75
	15:00	39	58	19	595.94
	16:00	44	51	7	219.56
	17:00	45	48	3	94.10
					3042.44
17:04:04	10:00	32	38	6	188.19
Day 2	11:00	40	48	8	250.92
	12:00	45	57	12	376.38
	13:00	52	69	17	533.21
	14:00	41	59	18	564.57
	15:00	43	58	15	470.48
	16:00	42	53	11	345.02
	17:00	43	48	5	156.83

18:04:04	10:00	33	41	8	250.92
Day 3	11:00	42	52	10	313.65
	12:00	47	64	17	533.205
	13:00	45	64	19	595.935
	14:00	45	64	19	595.935
	15:00	42	55	13	407.745
	16:00	42	52	10	313.65
	17:00	41	47	6	188.19

Date	Local time (Hours)	Collector inlet Temp. T_1(°C)	Collector outlet Temp. T_2 (°C)	T_2-T_1	Useful heat output
19:04:04	10:00	41	57	16	501.84
Day 4	11:00	43	59	16	501.84
	12:00	42	58	16	501.84
	13:00	42	58	16	501.84
	14:00	41	55	14	439.11
	15:00	43	53	10	313.65
	16:00	42	57	15	470.475
	17:00	41	54	13	407.745
20:04:04	10:00	39	52	13	407.745
Day 5	11:00	45	63	18	564.570
	12:00	48	68	20	627.300
	13:00	46	65	17	533.205
	14:00	42	55	13	407.745
	15:00	47	61	14	439.110
	16:00	41	51	10	313.650
	17:00	39	45	6	188.190

Table 4.3: Determination of collector efficiency of the system

Date	Local Time Hours	Collector inlet Temp. T_1 (^0C)	Ambient Temp. T_A (^0C)	(T_1-T_a) (^0C)	Solar insolation I_{Tt} (W/m^2)	$\frac{(T_1-T_a)}{I_{Tt}}$	Mx	Y = Mx + C = η_c(Col. Eff.) (%)
16:04:04	10:00	35	28	7	480	0.0146	0.0459	51.34
Day 1	11:00	38	29	9	650	0.0139	0.0436	51.57
	12:00	46	31	15	820	0.0183	0.0576	50.17
	13:00	47	31	16	1025	0.0156	0.04917	51.01
	14:00	50	30	20	1001	0.0200	0.0629	49.00
	15:00	39	32	7	800.01	0.0088	0.0276	53.17
	16:00	44	31	13	630.01	0.206	0.0650	49.43
	17:00	45	30	15	420.5	0.0357	0.1124	44.69
								400.38/ 8 = 50.1%
17:04:04	10:00	32	27	5	400.57	0.0125	0.0393	52.00
Day 2	11:00	40	29	11	570.16	0.0193	0.0608	49.85
	12:00	45	30	15	774.87	0.0194	0.0610	49.83
	13:00	52	31	21	874.21	0.0240	0.0757	48.36
	14:00	41	30	11	702.31	0.0157	0.0493	51.00
	15:00	43	32	11	602.08	0.0183	0.0576	50.17
	16:00	42	31	11	406.65	0.0271	0.0852	47.41
	17:00	43	30	13	344.04			

:04	10:00	33	24	9	402	00224	0.0705	49.88
	11:00	42	28	14	731	0.0192	0.0603	49.9
	12:00	47	29	18	890	0.0202	0.0637	49.56
	13:00	45	28	17	1120	0.0152	0.0478	51.15
3	14:00	45	30	15	1101.9	0.0136	0.0429	51.64
	15:00	42	30	12	905	0.0133	0.0418	54.60
	16:00	42	30	12	600.5	0.0199	0.0629	49.64
	17:00	41	29	12	425.5	0.0282	0.0888	47.05
4:04	10:00	41	27	14	346.04	0.0405	0.1274	43.19
	11:00	43	28	15	926.51	0.0162	0.05100	50.83
	12:00	42	29	13	1037.28	0.0125	0.0395	51.98
	13:00	42	29	13	747.72	0.0174	0.0548	50.45
y 4	14:00	41	31	10	738.86	0.0135	0.0426	51.67
	15:00	43	30	13	747.28	0.0174	0.0548	50.45
	16:00	42	30	12	922.41	0.0130	0.0409	51.84
	17:00	41	30	11	430.0	0.0256	0.0806	47.87

20:04:04	10:00	39	27	12	844.6	0.0142	0.0448	54.51
Day 5	11:00	45	28	17	926.7	0.0184	0.0578	50.15
	12:00	48	30	18	1290	0.0140	0.0440	51.53
	13:00	46	31	15	1350	0.0111	0.0350	52.43
	14:00	42	30	12	745	0.0161	0.0507	50.86
	15:00	47	30	17	804	0.0211	0.0666	49.27
	16:00	41	29	12	420	0.0286	0.0900	46.93
	17:00	39	28	11	340	0.0324	0.1090	45.74