International Journal of Engineering Applied Sciences and Technology, 2022
Vol. 7, Issue 6, ISSN No. 2455-2143, Pages 117-121

ANALYSIS OF A FLAT PLATE SOLAR COLLECTOR

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Abstract— **In the solar-energy industry great emphasis has been placed on the development of "active" solar energy systems which involve the integration of several subsystems: solar energy collectors, heat-storage containers, heat exchangers, fluid transport and distribution systems, and control systems. The major component unique in active systems is the solar collector.**

This device absorbs the incoming solar radiation, converting it into heat at the absorbing surface, and transfers this heat to a fluid (usually air or water) flowing through the collector. The warmed fluid carries the heat either directly to the hot water or space conditioning equipment or to a storage subsystem from which it can be drawn for use at night and on cloudy days.

The thermal analysis of a solar flat plate collector is quite complicated because of the many factors involved. Efforts have been made to combine a number of the most important factors into a single equation and thus formulate a mathematical model which will describe the thermal performance of the collector in a computationally efficient manner.

Keywords— **solar, flat collector, problem statement, literature survey, mathematical modelling**

Notations and Greek Symbols

A	Collector area, m^2
F_R	Collector heat removal factor
I	Intensity of solar radiation, W/m^2
T_C	Collector average temperature, ^OC
T_i	Inlet fluid temperature, ^OC
T_a	Ambient temperature, ^OC
U_L	Collector overall heat loss coefficient, W/m^2
Q_i	Collector heat input, W
Q_U	Useful energy gain, W
Q_O	Heat loss, W
m^o	Mass flow rate of fluid through the collector, kg/s
η	Collector efficiency
τ	Transmission coefficient of glazing
α	Absorption coefficient of plate

I. INTRODUCTION

Renewable energy has always played a great deal in our human existence. The earliest form of renewable energy was wood; this is because it was the easiest to manipulate to produce thermal energy. Burning wood was important in preparing food and keeping warm. Eventually, it was found that by relative combustion without the presence of oxygen charcoal could produce; which burns longer and hotter.

Methods such as wind, hydraulic, solar, and nuclear power generation continue to advance in technology and as a result have experienced increases in production efficiency. Also, technologies such as fuel cells and wind turbines are presenting themselves as viable options to traditional methods with the promise of advanced efficiency in the future.

One of most important sources of renewable energy; is solar energy. Clearly, the sun provides a huge amount of energy for the earth that is distributed across the earth's surface. However, the intensity of solar rays, and therefore the amount of energy, can change significantly across different regions, seasons, and time of day. The practical amount of energy that can be utilized is also significantly affected by other factors, such as the amount of cloud cover. In some regions, this energy can be more than one kilowatt hour per square meter of area (one kwh/m^2) or less than 0.1 kwh/m^2 (kilowatt hour per square meter). Solar energy can be utilized by one of the following to methods: conversion of solar radiation to electrical energy, using photovoltaic cells, and conversion of solar radiation to direct heat energy using solar collectors.

Solar collectors are the key component of active solar-heating systems. They gather the sun's energy, transform its radiation into heat, and then transfer that heat to a fluid (usually water or air). The solar thermal energy can be used in solar water-heating systems, solar pool heaters, and solar space-heating systems.

There are a large number of solar collector designs that have shown to be functional. These designs are classified into two general types of solar collectors:

flat-plate collectors in which the absorbing surface is approximately as large as the overall collector area that intercepts the sun's rays, and concentrating collectors in which large areas of mirrors or lenses focus the sunlight onto a smaller absorber.

A. Flat-Plate Collectors

Flat-plate collectors are the most common solar collector for solar water-heating systems in homes and solar space heating. A typical flat-plate collector is an insulated metal box with a glass or plastic cover (called the glazing) and a dark-colored absorber plate. These collectors heat liquid or air at temperatures less than 80°C. Flat-plate collectors are used for residential water heating and hydronic space-heating installations. Fig. 1 below shows a typical liquid flat plate collector.

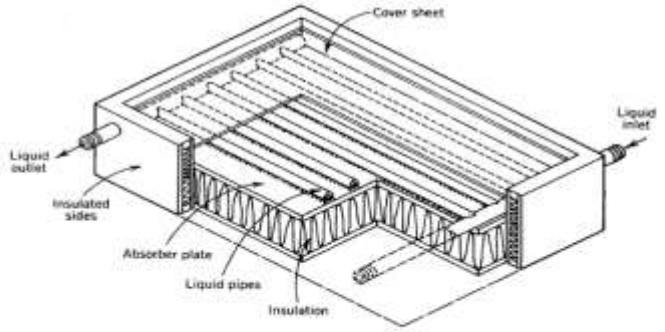

Fig. 1 A Typical Liquid Flat Plate Collector

II. PROBLEM STATEMENT

Fig. 2 below shows a schematic drawing of the heat flow through a collector. The question is, how to measure its thermal performance, i.e. the useful energy gain or the collector efficiency. Thus, it is necessary to define step by step the singular heat flow equations in order to find the governing equations of the collector system.

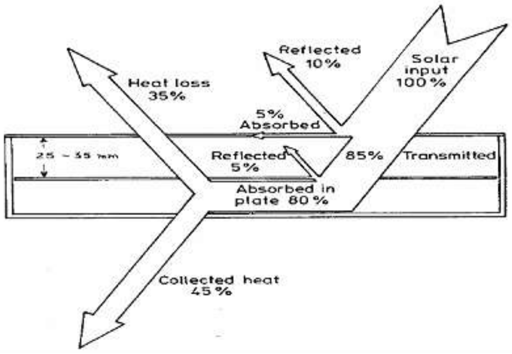

Fig. 2 Heat Flow through a Flat Plate Solar Collector

III. LITERATURE SURVEY

The idea of using solar energy collectors to harness the sun’s power is recorded from the prehistoric times when at 212 BC the Greek scientist/physician Archimedes devised a method to burn the Roman fleet.

Archimedes reputedly set the attacking Roman fleet afire by means of concave metallic mirror in the form of hundreds of polished shields; all reflecting on the same ship. Malik MAS, Tiwari GN, Kumar A, Sodha MS. [1].

The Greek historian Plutarch (AD 46–120) referred to the incident saying that the Romans, seeing that indefinite mischief overwhelmed them from no visible means, began to think they were fighting with the gods. The basic question was whether or not Archimedes knew enough about the science of optics to device a simple way to concentrate sunlight to a point where ships could be burned from a distance. Archimedes had written a book “On burning Mirrors” but no copy has survived to give evidence. Soteris Kalogirou [2].

Eighteen hundred years after Archimedes, Athanasius Kircher (1601–1680) carried out some experiments to set fire to a woodpile at a distance in order to see whether the story of Archimedes had any scientific validity but no report of his findings survived as stated in Soteris Kalogirou [2] and J.A. Duffie and W. A. Beckman [3].

Amazingly, the very first applications of solar energy refer to the use of concentrating collectors, which are by their nature (accurate shape construction) and the requirement to follow the sun, more ‘difficult’ to apply. During the 18th century, solar furnaces capable of melting iron, copper and other metals were being constructed of polished-iron, glass lenses and mirrors. The furnaces were in use throughout Europe and the Middle East. One furnace designed by the French scientist Antoine Lavoisier, attained the remarkable temperature of 1750 ^{O}C. The furnace used a 1.32 m lens plus a secondary 0.2 m lens to obtain such temperature which turned out to be the maximum achieved by man for one hundred years.

During the 19th century the attempts to convert solar energy into other forms based upon the generation of low pressure steam to operate steam engines. August Monchot pioneered this field by constructing and operating several solar powered steam engines between the years 1864 and 1878 as reported by J.A. Duffie and W. A. Beckman [3] and Meinel AB, Meinel

MP. [4]. Evaluation of one built at Tours by the French government showed that it was too expensive to be considered feasible. Another one was set up in Algeria. In 1875, Mouchot made a notable advance in solar collector design by making one in the form of a truncated cone reflector.

Mouchot's collector consisted of silver-plated metal plates and had a diameter of 5.4 m and a collecting area of 18.6 m^2. The moving parts weighed 1400 kg.

Abel Pifre was a contemporary of Mouchot who also made solar engines, see Meinel AB, Meinel MP. [4], and Kreider JF, Kreith F. [5]. Pifre's solar collectors were parabolic reflectors made of very small mirrors. In shape they looked rather similar to Mouchot's truncated cones.

In 1901 A.G. Eneas installed a 10 m diameter focusing collector which powered a water pumping apparatus at a California farm. The device consisted of a large umbrella-like structure open and inverted at an angle to receive the full effect of sun's rays on the 1788 mirrors which lined the inside surface. The sun's rays were concentrated at a focal point where the boiler was located. Water within the boiler was heated to produce steam which in turn powered a conventional compound engine and centrifugal pump, refer to Kreider JF, Kreith F. [5].

In 1904 a Portuguese priest, Father Himalaya, constructed a large solar furnace. This was exhibited at the St Louis World's fair. This furnace appeared quite modern in structure, being a large, off-axis, parabolic horn collector as illustrated in Kreider JF, Kreith F. [5].

In 1912 Shuman, in collaboration with C.V. Boys, undertook to build the world's largest pumping plant in Meadi, Egypt. The system was placed in operation in 1913 and it was using long parabolic cylinders to focus sunlight onto a long absorbing tube. Each cylinder was 62 m long, and the total area of the several banks of cylinders was 1200 m^2. The solar engine developed as much as 37–45 kW continuously for a 5 h period. Soteris Kalogirou [2], Meinel AB, Meinel MP. [4], and Kreider JF, Kreith F. [5]. Despite the plant's success, it was completely shut down in 1915 due to the onset of World War I and cheaper fuel prices.

During the last 50 years many variations were designed and constructed using focusing collectors as a means of heating the transfer or working fluid which powered mechanical equipment. The two primary solar technologies used are the central receivers and the distributed receivers employing various point and line-focus optics to concentrate sunlight. Central receiver systems use fields of heliostats (two-axis tracking mirrors) to focus the sun's radiant energy onto a single tower-mounted receiver as in SERI. [6]. Distributed receiver technology includes parabolic dishes, Fresnel lenses, parabolic troughs, and special bowls. Parabolic dishes track the sun in two axes and use mirrors to focus radiant energy onto a point-focus receiver. Troughs and bowls are line-focus tracking reflectors that concentrate sunlight onto receiver tubes along their focal lines. Receiver temperatures range from 100 C in low-temperature troughs to close 1500 C in dish and central receiver systems SERI. [6].

IV. MATHEMATICAL MODELLING OF SOLAR PLATES

Fig. 3 below shows the schematic of a typical solar system employing a flat plate solar collector and a storage tank. If I is the intensity of solar radiation, in W/m^2, incident on the aperture plane of the solar collector which is having a collector surface area of A then the amount of solar radiation received by the collector is:

$$Q_i = AI \qquad (1)$$

However, as it is shown Fig. 2, a part of this radiation is reflected back to the sky, another component is absorbed by the glazing and the rest is transmitted through the glazing and reaches the absorber plate as short wave radiation.

Therefore the conversion factor indicates the percentage of the solar rays penetrating the transparent cover of the collector (transmission) and the percentage being absorbed.

Basically, it is the product of the rate of transmission of the cover and the absorption rate of the absorber.

Thus,

$$Q_i = A(\tau\alpha)I \qquad (2)$$

As the collector absorbs heat its temperature is getting higher than that of the surrounding environment and heat is lost to the atmosphere by convection and radiation. The rate of heat loss (Q_o) depends on the collector overall heat transfer coefficient (U_L) and the collector temperature. The useful energy gain depends strongly on the energy losses from the top surface of the collector both due to convective and radiative heat transfer processes. The losses from the bottom and from the edges of the collector do always exist. Their contribution, however, is not as significant as the losses from the top. Refer to [7] – [10].

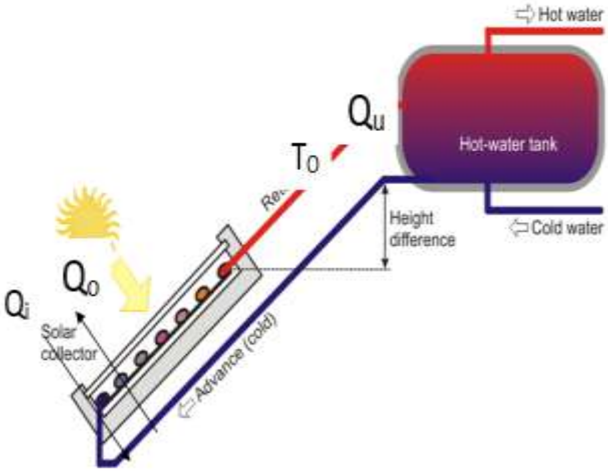

Fig. 3 Schematic Representation of a Typical Solar System

$$Q_o = U_L A(T_C - T_a) \qquad (3)$$

Thus, the rate of useful energy extracted by the collector (Q_u), expressed as a rate of extraction under steady state conditions, and is proportional to the rate of useful energy absorbed by the collector, less the amount lost by the collector to its surroundings.

$$Q_u = Q_I - Q_O$$
$$= A(\tau\alpha)I - U_L A(T_C - T_a) \qquad (4)$$

It is also known that the rate of extraction of heat from the collector may be measured by means of the amount of heat carried away in the fluid passed through it, that is:

$$Q_U = m^o C_P(T_O - T_i) \qquad (5)$$

Equation 4 proves to be somewhat inconvenient because of the difficulty in defining the collector average temperature. It is convenient to define a quantity that relates the actual useful energy gain of a collector to the useful gain if the whole collector surface were at the fluid inlet temperature. This quantity is known as "the collector heat removal factor (F_R)" and is expressed as:

$$F_R = \frac{m^o C_P(T_O - T_i)}{A(\tau\alpha)I - U_L A(T_i - T_a)} \qquad (6)$$

The maximum possible useful energy gain in a solar collector occurs when the whole collector is at the inlet fluid temperature. The actual useful energy gain (Qu), is found by multiplying the collector heat removal factor (FR) by the maximum possible useful energy gain. This allows the rewriting of equation (4):

$$Q_U = F_R \; A(\tau\alpha)I - U_L A(T_i - T_a) \qquad (7)$$

Equation (7) is a widely used as a relationship for measuring collector energy gain and is generally known as the "Hottel-Whillier-Bliss equation". A measure of a flat plate collector performance is the collector efficiency (η) defined as the ratio of the useful energy gain (Q_u) to the incident solar energy over a particular time period.

$$\eta = \frac{\int Q_U dt}{A\int I dt} \qquad (8)$$

The instantaneous thermal efficiency of the collector is:

$$\eta = \frac{\int Q_U}{AI} \qquad (9)$$

$$\eta = \frac{F_R \; A(\tau\alpha)I - U_L A(T_i - T_a)}{AI} \qquad (10)$$

$$\eta = F_R \, \tau\alpha - F_R U_L \frac{T_i - T_a}{I} \qquad (11)$$

V. CONCLUSIONS

If it is assumed that F_R, τ, α, U_L are constants for a given collector and flow rate, then the efficiency is a linear function of the three parameters defining the operating condition: Solar irradiance (I), Fluid inlet temperature (T_i) and Ambient air temperature (T_a).

Thus, the performance of a Flat-Plate Collector can be approximated by measuring these three parameters in experiments. The result is a single line (ΔT/I – Curve) shown in Fig. 4.

In practice, U_L is not a constant as heat losses will increase as the temperature of the collector rises further above ambient temperature (thermal conductivity of materials varies with temperature).

The resulting plot will be a straight line only if conditions are such that F_R, U_L and (τ α) are constants. Fig. 4 below shows the collector efficiency plotted against $\frac{T_i - T_a}{I}$.

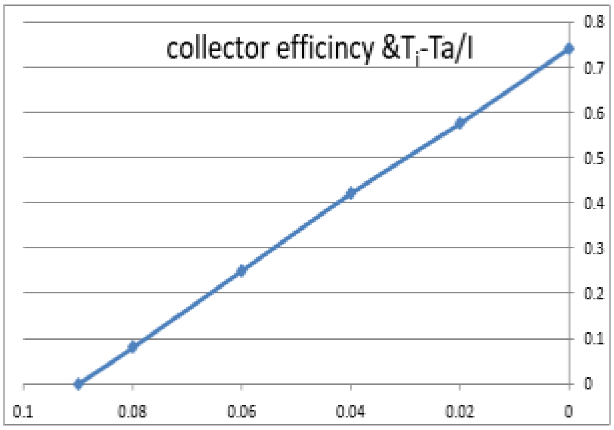

Fig. 4 The Collector Efficiency Plotted against $\frac{T_i - T_a}{I}$

The collector efficiency η is plotted against (Ti – Ta)/I. The slope of this line (- F_R U_L) represents the rate of heat loss from the collector. For example, collectors with cover sheets will have less slope than those without cover sheets.

There are two interesting operating points on Fig. 4. The first is the maximum collection efficiency, called the optical efficiency. This occurs when the fluid inlet temperature equals ambient temperature (Ti = Ta). For this condition, the ΔT/I value is zero and the intercept is F_R(τ α). The other point of interest is the intercept with the ΔT/I axis. This point of operation can be reached when useful energy is no longer removed from the collector, a condition that can happen if fluid flow through the collector stops (power failure). In this case, the optical energy coming in must equal the heat loss, requiring that the temperature of the absorber increase until this balance occurs. This maximum temperature difference or "stagnation temperature" is defined by this point. For well-insulated collectors or concentrating collectors the stagnation temperature can reach very high levels causing fluid boiling and, in the case of concentrating collectors, the absorber surface can melt.

A way to describe the thermal performance of a Flat Plate Solar collector has been shown. The most important measure is the collector efficiency. A more precise and detailed analysis should include the fact, that the overall heat loss coefficient (U_L) and other factors as the heat removal factor (F_R) are not constant values.

VI. REFERENCES

[1]. Malik MAS, Tiwari GN, Kumar A, Sodha MS. Solar distillation. New York: Pergamon Press; 1985.

[2]. Soteris Kalogirou. Solar energy engineering: processes and systems.1st edition. Printed in the United States of America, 2009.

[3]. J.A. Duffie and W. A. Beckman, Solar Engineering of Thermal Processes, 2nd edition, Wiley.

[4]. Meinel AB, Meinel MP. Applied solar energy: an introduction. Reading, MA: Addison-Wesley; 1976.

[5]. Kreider JF, Kreith F. Solar heating and cooling. New York:McGraw-Hill; 1977.

[6]. SERI. Power from the Sun: principles of high temperature solar thermal technology; 1987

[7]. Shepherd, D.W., 2003, Energy Studies (2nd edition), Imperial College, London, UK.

[8]. Cooper, P.I.; Dunkle, R.V., 1981, “A non-linear flat-plate collector model”, Solar Energy Vol. 26, Issue 2 pp. 133-140.

[9]. http://www.builditsolar.com/References/Measurements/CollectorPerformance.htm# Efficiency.

[10]. http://www.powerfromthesun.net/ .