# 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 to 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 can be drawn for use at night and on cloudy days.

A precise and detailed 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.

## NOMENCLATURE

$A$      collector area, m$^2$

$F_R$      collector heat removal factor

$I$      intensity of solar radiation, W/m$^2$

$T_c$      collector average temperature, $^\circ$C

$T_i$      inlet fluid temperature, $^\circ$C

$T_a$      ambient temperature, $^\circ$C

$U_L$      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

### Greek Symbols

$\eta$      collector efficiency

$\tau$      transmission coefficient of glazing

$\alpha$      absorption coefficient of plate

### Subscripts

$m$      mass flow rate of fluid through the collector, kg/s

## INTRODUCTION

### Solar Collectors

Solar collectors are the key component of active solar-heating systems. They gather the sun's energy, transform its radiation into heat, 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 in two general types of solar collectors:

- **Flat-plate collectors** – the absorbing surface is approximately as large as the overall collector area that intercepts the sun's rays.
- **Concentrating collectors** – large areas of mirrors or lenses focus the sunlight onto a smaller absorber.

### 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.
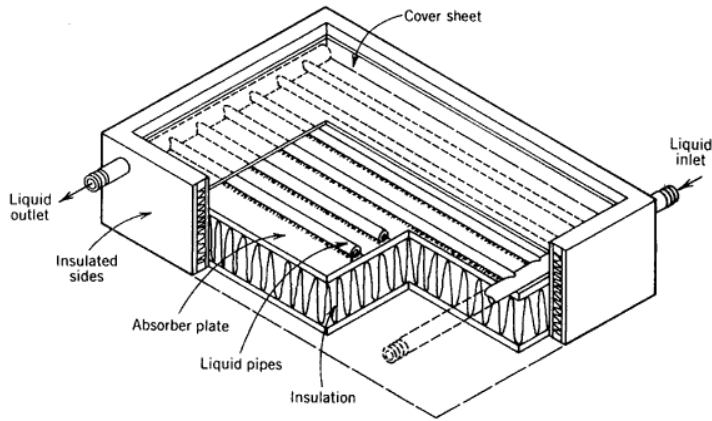
Fig. 1 A typical liquid Flat Plate Collector

Flat-plate collectors are used for residential water heating and hydronic space-heating installations.

## PROBLEM STATEMENT

Figure 2 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.
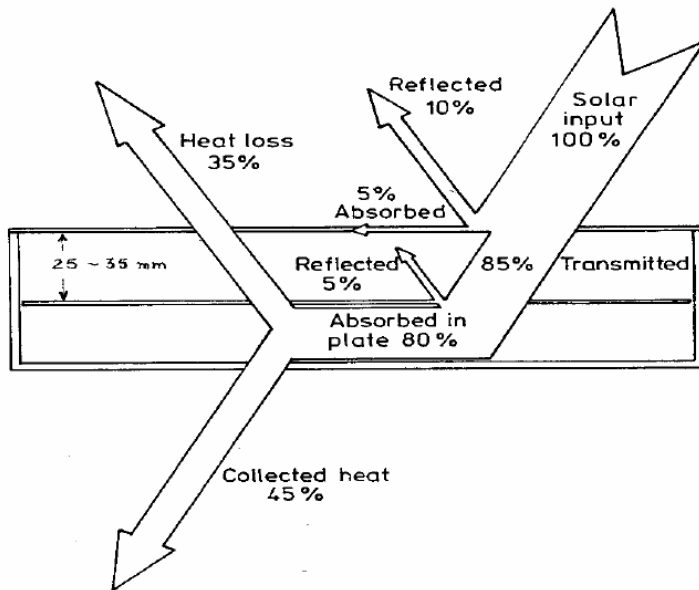


Fig. 2 Heat flow through a Flat Plate solar collector

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.

## LITERATURE SURVEY

Figure 3 shows the schematic of a typical solar system employing a flat plate solar collector and a storage tank.
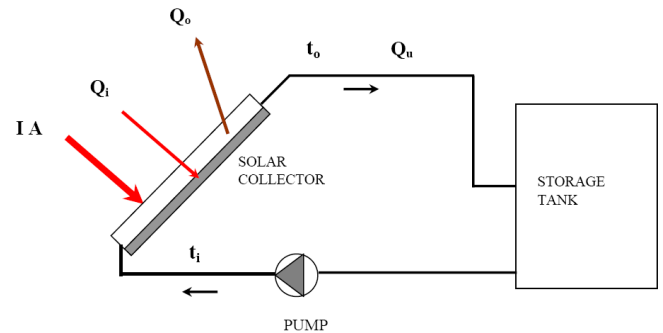


Fig. 3 Typical solar energy collection system

If **I** is the intensity of solar radiation, in W/m², incident on the aperture plane of the solar collector having a collector surface area of **A**, m², then the amount of solar radiation received by the collector is:

$$Q_i = I \cdot A \qquad (1)$$

However, as it is shown Figure 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,

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

As the collector absorbs heat its temperature is getting higher than that of the surrounding 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.

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

Thus, the rate of useful energy extracted by the collector ($Q_u$), expressed as a rate of extraction under steady state conditions, is proportional to the rate of useful energy absorbed by the

collector, less the amount lost by the collector to its surroundings.[1]

This is expressed as follows:

$$Q_u = Q_i - Q_o = I\tau\alpha \cdot A - U_L A(T_c - T_a) \quad (4)$$

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:

$$Q_u = mc_p(T_o - T_i) \quad (5)$$

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:

$$F_R = \frac{mc_p(T_o - T_i)}{A[I\tau\alpha - U_L(T_i - T_a)]} \quad (6)$$

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** ($Q_u$), is found by multiplying the collector heat removal factor ($F_R$) by the maximum possible useful energy gain. This allows the rewriting of equation (4):

$$\boxed{Q_u = F_R A[I\tau\alpha - U_L(T_i - T_a)]} \quad (7)$$

Equation (7) is a widely used 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:

$$\boxed{\eta = \frac{\int Q_u dt}{A \int I dt}} \quad (8)$$

The instantaneous thermal efficiency of the collector is:

$$\eta = \frac{Q_u}{AI} \quad (9)$$

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

$$\boxed{\eta = F_R\tau\alpha - F_R U_L\left(\frac{T_i - T_a}{I}\right)} \quad (11)$$

**PROJECT DESCRIPTION**

If it is assumed that $F_R$, τ, α, $U_L$ [2] 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 Figure 4. [3]

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[1] 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.

[2] 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).

[3] The resulting plot will be a straight line only if conditions are such that $F_R$, $U_L$ and (τ α) are constants.
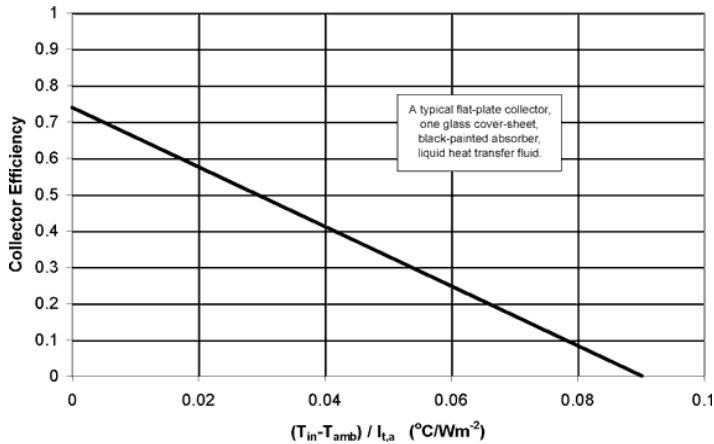
Fig. 4 Performance of a typical flat-plate thermal collector
(ambient temperature 25°C)

The collector efficiency η is plotted against $(T_i - T_a)/I$. 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 of a slope than those without cover sheets.

There are two interesting operating points on Figure 4.

1) The first is the maximum collection efficiency, called the optical efficiency. This occurs when the fluid inlet temperature equals ambient temperature ($T_i = T_a$). For this condition, the $\Delta T/I$ value is zero and the intercept is $F_R(\tau \alpha)$.

2) The other point of interest is the intercept with the $\Delta T/I$ 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.

## CONCLUSION

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.

**REFERENCES**

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

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

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

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