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Optimal Operating Temperature of Solar Collectors at Maximal Exergy Production

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Abstract: This paper aims to establish the optimal operating parameters of a solar collector in order to perform the maximum exergy production during the collection of solar energy. The optimal operating temperature and mass flow rate of the thermal fluid are investigated under given solar irradiation and for a given solar collector characterized according to EN 12975-2 standards.

Keywords: Solar collector, Optimal temperature, Exergy maximization.

1. Introduction

Solar collectors are now widely used for industry and domestic use. The use of solar energy is of considerable interest for two reasons: firstly, it leads to a diminution of fossil fuels consumption and secondly, solar energy is a non-polluting source of energy.

The fundamental operational problem with solar collectors is the collection and the delivery of solar energy to users with minimum losses. The optimum solar collector operating temperature has been studied by many researchers and can be investigated using different analysis approach. When a solar collector is used as a heat input source of a power generation process, one of the design objectives is to optimize the overall system performance. In general, the collector works best at low temperatures and its efficiency decreases with increasing temperature. On the other hand, the power generation process is more efficient with increasing temperatures. If the power generation process is considered as an idealized Carnot engine, then maximizing the exergy output of the solar collector leads to a maximization of the overall system performance.

In this paper, we develop a simple method to determine the optimal operating temperature that maximizes the exergy output of a real solar collector characterized according to the European standards..

2- Collector performance

Under steady-state conditions, the useful heat delivered by a solar collector is equal to the energy absorbed by a heat transfer fluid which is in direct contact with the absorber surface, reduced by the heat losses from the collector to the surroundings. The classical approach assumes the linearity of the overall heat loss term [1]. At low and intermediate temperatures, heat losses are dominated by convection and/or conduction. The radiation losses are generally linearized and included in the heat loss term [2]. Thus, the instantaneous thermal power provided by a solar collector depends on the global irradiance arriving to the absorber surface as well as on the collector thermal losses, which varies according to operating conditions (ambient temperature T_o , mean temperature of the thermal fluid T_f , wind speed,...). In such a case, the heat delivered by the solar collector may be given by [3, 4]:

$$Q_c = A_c F_R [\tau\alpha\Phi - K(T_f - T_o)] = q_m c_p (T_{fo} - T_{fi}) \quad (1)$$

Where K is the heat loss coefficient, F_R is a correction factor for heat transmission between the absorber surface and the heat transfer fluid circulating in the collector, T_f is the mean temperature of heat transfer fluid:

$$T_f = \frac{1}{2} (T_{fo} + T_{fi}) \quad (2)$$

In reality the heat losses from the solar collector that are a combination of convective and radiative heat losses are highly not linear. Thus, the heat loss coefficient K is not constant but varies in first approximation, linearly with the temperature difference of the collector with its surroundings:

$$F_R K = k_1 + k_2(T_f - T_o) \quad (3)$$

In this expression, k_1 is a coefficient for conductive and convective heat losses and k_2 a coefficient that takes into account the temperature dependence of radiative heat losses, that are linearized in this expression. All these parameters include the correction factor F_R for heat transmission between the absorber surface and the heat transfer fluid for a given solar collector.

The collector instantaneous efficiency is then defined as the ratio between the useful heat Q_c delivered per collector area A_c and the global irradiance Φ :

$$\eta = \frac{Q_c}{A_c \cdot \Phi} \quad (4)$$

According to the standard certification of solar collectors EN 12975-2, the efficiency curve is described by a second degree expression that fits the measured efficiency points obtained during stationary tests. This efficiency curve follows the relation:

$$\eta = \eta_o - k_1 \left(\frac{T_f - T_o}{\Phi} \right) - k_2 \cdot \Phi \cdot \left(\frac{T_f - T_o}{\Phi} \right)^2 \quad (5)$$

Where η_o is the optical efficiency (also known as the corrected absorbance-transmittance product ($F_R \tau \alpha$) for flate plate collectors), k_1 and k_2 are the negative heat loss coefficients of first and second order. Typical values for these coefficients are given in table 1 for different technologies of solar collectors and their impact on the collector efficiency is shown in Fig. 1.

Consequently, for any thermal solar collector, the efficiency η decreases as the collector operating temperature is increased. This efficiency equals zero for the maximum collector temperature T_{max} , also known as the stagnation temperature T_{st} of the collector. For this stagnation temperature obtained under no-flow conditions, the entire collected solar irradiation is lost to the ambient at T_o .

Table 1 : Typical values of efficiency parameters for different collector technologies

Type of solar collector	η_o	k_1	k_2
Uncovered collector (U.C)	0.85	15	0.05
Simple glazed collector (SGC)	0.78	3.5	0.01
Double glazed collector (DGC)	0.70	2.0	0.01
vacuum-tube collector (VTC)	0.65	1.3	0.005
Parabolic through collector (PTC)	0.63	0.1	0.0005

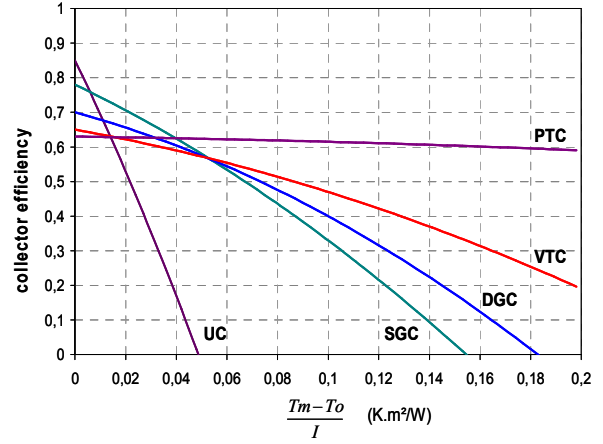


Fig. 1 : Solar collector efficiency according to their design and for a standard solar irradiation of 1000 W/m^2

The stagnation temperature T_{st} is given by solving the second order equation:

$$\eta \Phi = \eta_o \Phi - k_1 (T_{st} - T_o) - k_2 (T_{st} - T_o)^2 = 0 \quad (6)$$

One finally obtains:

$$T_{st} = T_{max} = T_o - \frac{k_1}{2k_2} + \sqrt{\left(\frac{k_1}{2k_2} \right)^2 + \frac{\eta_o \Phi}{k_2}} \quad (7)$$

This stagnation temperature is a function of the irradiation and is generally given by the constructor for the standard solar irradiation of 1000 W/m^2 and an ambient temperature of 30°C (EN 12975-2 standards).

The second solution T_{min} that cancels the solar collector efficiency is a virtual temperature, since it is negative:

$$T_{min} = T_o - \frac{k_1}{2k_2} - \sqrt{\left(\frac{k_1}{2k_2} \right)^2 + \frac{\eta_o \Phi}{k_2}} \quad (8)$$

Then, the heat collected per m^2 , Q_c , can be rewritten as a function of these two temperatures,

considering that the collector temperature is at the mean fluid temperature:

$$Q_c = \eta \Phi = k_2 \cdot (T_c - T_{\min}) \cdot (T_{\max} - T_c) \quad (9)$$

3. Exergy output of a solar collector

Exergy analysis is based on the second law of thermodynamics. The exergy characterises the maximum amount of work that can be produced by an ideal Carnot engine cycle from a given amount of heat Q_c available at a temperature level T_c . It is expressed as the product of amount of heat Q_c by the Carnot factor θ_c :

$$Ex = Q_c \cdot \left(1 - \frac{T_o}{T_c}\right) = Q_c \cdot \theta_c \quad (10)$$

Where T_o is the temperature of heat rejected by the Carnot cycle, which is generally the ambient temperature.

In this way, the exergy output of a 1 m² solar collector can be expressed as :

$$Ex = k_2 \cdot (T_c - T_{\min}) \cdot (T_{\max} - T_c) \cdot \left(1 - \frac{T_o}{T_c}\right) \quad (11)$$

Since the solar collector efficiency decreases and the Carnot factor increases with increasing collector temperature T_c , there is an optimum operating temperature T_{opt} that maximizes the exergy output of the solar collector (Fig 3).

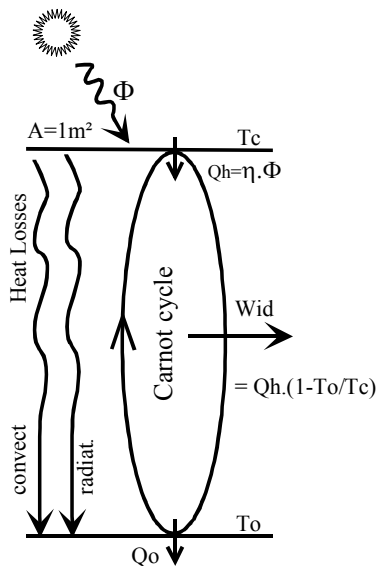


Fig 2 : Exergy analysis of a solar collector

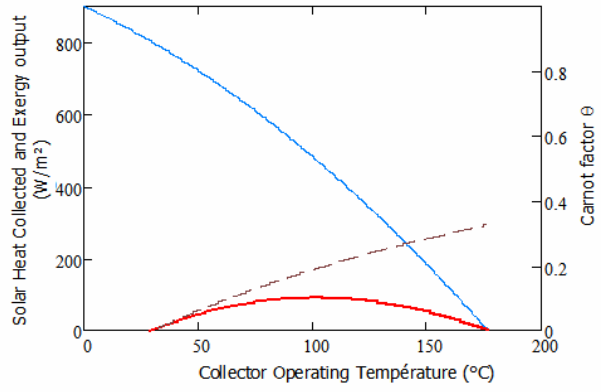


Fig. 3 : Temperature dependence of collector efficiency and collector exergy output

4- Optimal operating temperature of a given collector

The optimal operating temperature of a given collector, which is characterized according to the EN 12975 standard, is obtained by taking the derivative of the exergy output and setting it equal to zero:

$$\frac{dEx}{dT_c} = 0 \quad (12)$$

This derivation leads to the resolution of a third order equation:

$$2 \cdot T_c^3 - S \cdot T_c^2 - P = 0 \quad (13)$$

Where the terms S and minus P are respectively the sum and the product of T_o , T_{\min} and T_{\max} :

$$S = T_o + T_{\max} + T_{\min}$$

$$P = -T_o \cdot T_{\max} \cdot T_{\min}$$

The resolution of this third order equation is carried out by the Cardan's method, which finally gives the optimal operating temperature T_c^* :

$$T_c^* = U + \frac{S}{6} \left(1 + \frac{S}{6 \cdot U}\right) \quad (14)$$

where :

$$U = \frac{1}{2} \left(\sqrt{P} + \sqrt{V}\right)^{\frac{2}{3}}$$

with $V = P + \left(\frac{S}{3}\right)^3$

As T_{\min} and T_{\max} are function of the irradiance, then the terms S, P, U and V are also function of the irradiance.

This optimal operation temperature T_c^* can be approximated with high accuracy as the mean temperature of the ambient temperature T_o and the stagnation temperature $T_{st}=T_{\max}$:

$$\tilde{T}_c^* = \frac{T_o + T_{st}}{2} \quad (15)$$

As it can be shown in Fig. 4, the difference between the exact solution of eq. 13 and the approximated solution defined by eq. 15 is lower than 3°C for a high irradiance of 1000 W/m².

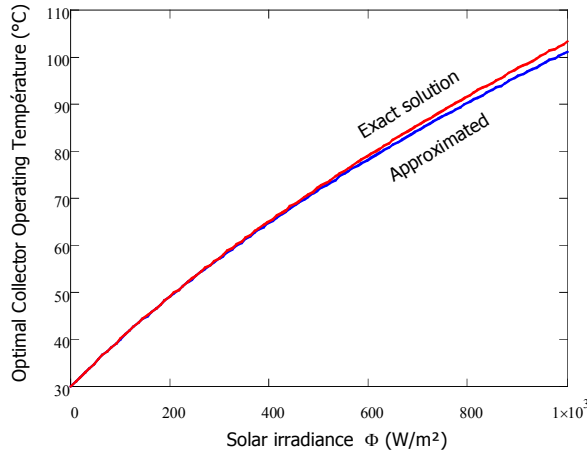


Fig 4: Comparison of the exact and approximated optimal operating temperature of a given collector ($\eta_o=0.8$; $k_1=3.7$ and $k_2=0.012$)

5- Mass flow optimization of a solar collector

The optimal mass flow rate (per m² of solar collector) of the heat transfer fluid circulating in the solar collector is then given by:

$$m_{opt} = \frac{(\eta \cdot \Phi)_{opt}}{c_p \cdot (T_{fo} - T_{fi})} \quad (16)$$

Where $(\eta \cdot \Phi)_{opt}$ is heat output from the solar collector operating at its optimal temperature T_c^* . Considering the relation the eq. (2), the optimal

temperature outlet of the heat transfer fluid is defined as :

$$T_{fo}^* = 2 \cdot T_c^* - T_{fi} \quad (17)$$

Then :

$$m_{opt} = \frac{(\eta \cdot \Phi)_{opt}}{2 \cdot c_p \cdot (T_c^* - T_{fi})} \quad (18)$$

As the optimal operating temperature is only function of the irradiance Φ , then it will be also the case for the optimal mass flow rate for a given inlet temperature T_{fi} of the heat transfer fluid Fig. 5:

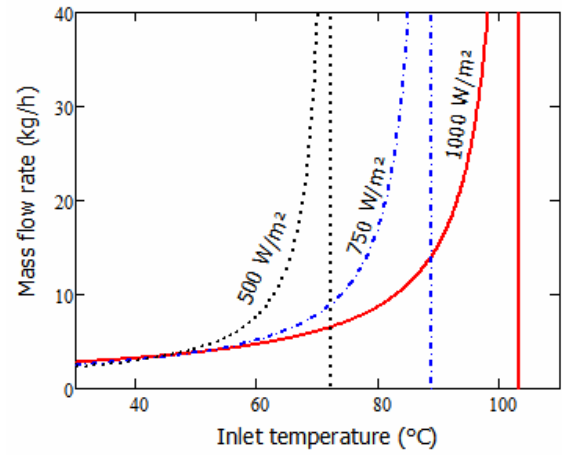


Fig. 5 : Evolution of the optimal mass flow of the heat transfer fluid as a function of the irradiance and the inlet temperature

One can notice that the mass flow rate increases with inlet temperature, and tends to an infinite value when the temperature becomes close the optimal operating temperature.

5- Conclusions

The determination of the optimal operating temperature and the corresponding efficiency is of considerable theoretical and practical interest. This optimal temperature can be easily calculated at a given irradiance for any solar collector from the stagnation temperature. This result provides a guideline for designing an optimal solar thermal system and for the performance comparison of existing solar systems.

Nomenclature

c specific heat, J/(kg K)

h heat transfer coefficient, W/(m² K)

\dot{m} mass flow rate, kg/h

T temperature, °C

Greek symbols

η efficiency

Φ solar irradiance (W/m²)

Subscripts and superscripts

opt,* optimal

st stagnation

fo fluid outlet

fi fluid inlet

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