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# A SOLAR COLLECTOR DESIGN PROCEDURE FOR CROP DRYING

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**Abstract -** A design procedure was proposed for sizing solar-assisted crop-drying systems and assessing the combination of solar collector area and auxiliary energy needs that meets the requirements of the load. Two empirical correlations were compared for use with high thermal inertia solar collectors that are cheap and appropriate for rural areas. A case study as performed in the city of Campinas in southeastern Brazil. Grain drying with partial air heating by solar energy can provide an annual savings of 30% in fuel consumption for 1.80m$^2$ collector area during the drying of 1.2t of corn at 50ºC at a daily air rate of 1526.8 m$^3$/day.

*Keywords*: Solar crop drying; Solar collectors; Solar air heating; Design procedure; Appropriate technologies.

## INTRODUCTION

The use of solar energy in grain drying can great reduce the use of fossil fuels, consequently reducing pollutant emission. However, there is no simple design tool for sizing solar-assisted crop dryers based on drying load, climate and economic data. This lack affects rural producers, who prefer to continue using traditional sources of energy. It also affects the small producer, who is deprived of technologies appropriate to the socioeconomic realities of rural areas in developing countries.

In the 1970's, Klein, Beckmann and Duffie (1975, 1976) developed the *f-Chart* methodology based on TRNSYS software simulations. They established correlations between dimensionless design parameters and the solar fraction (ratio of the energy supplied by the solar system to the energy demand of the process). This methodology was developed for water and air heating systems; however the focus was not on the drying of agricultural products. The main characteristic of the *f-Chart* is its simple operation and accessibility to people not skilled in solar energy engineering.

The first Brazilian studies on application of solar energy in drying processes were done at UNICAMP by a drying research group in association with the Solar Energy Group at the end of the 1970's and beginning of the 1980's. Santos (1980) studied the use of collectors with beds made of pebbles in in-bin soy drying. The advantages over flat-plate collectors were the lower cost per unit of area, the smaller collector area and the capacity to store energy and to avoid temperature peaks.

Studying the rubber-drying process with flat-plate solar collectors in Indonesia, Pratoto et al. (1997, 1998) proposed an empirical correlation similar to the *f-Chart*, but based on only one dimensionless design parameter.

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## LITERATURE REVIEW

### Flat-Plate Solar Collector

A grain-drying solar-assisted system is composed of a solar collector, a fan, an additional energy source for air heating, a plenum (for air distribution) and a bin batch drying system. Flat-plate collectors are used in air and water heating systems. The incident solar energy is partially absorbed by a dark and opaque surface, part of this energy is transferred to the fluid and the remainder is lost to the enviroment. The collector plate is covered with a glass in order to minimize convective losses and create a "green house" effect. Figure 1 shows the outline of a flat-plate collector for air heating and the main parameters involved in heat transfers: incident solar radiation (I), cover heat loss coefficient ($U_c$), coefficient of convective heat transfer between cover and air ($h_{c,c\text{-}a}$), coefficient of convective heat transfer between plate and air ($h_{c,p\text{-}a}$), coefficient of radiation heat transfer between plate and cover ($h_{r,p\text{-}c}$), bottom heat loss coefficient ($U_b$), ambient temperature ($T_{amb}$), cover temperature ($T_c$), air temperature ($T_a$) and mean plate temperature ($T_{pm}$).

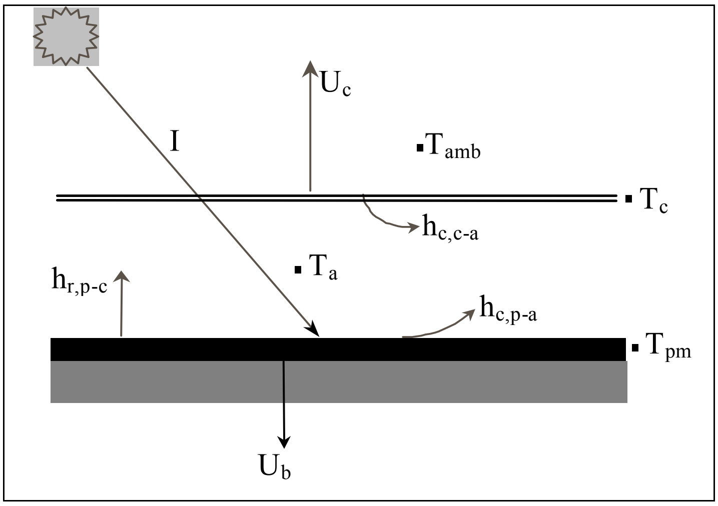

**Figure 1:** Flat-plate solar collector heat transfer parameters.

Bliss (1959) presented an expression (equation (1)) to describe the performance of a solar collector by an energy balance involving energy gain and thermal and optic losses. Since this equation assumes the mean plate temperature to be equal to the collector inlet air temperature ($T_i$), a heat removal factor ($F_R$) is introduced:

$$q = AF_R \left[ I(\tau\alpha) - U_L (T_i - T_{amb}) \right] \qquad (1)$$

($U_L$ is the collector heat loss coefficient)

The instantaneous efficiency of the flat-plate solar collector ($\eta$) is defined as the ratio of the rate of useful energy supplied by the collector (q) to the rate of incident solar energy in its area A:

$$\eta = \frac{q}{IA} = F_R (\tau\alpha) - F_R U_L \frac{(T_i - T_{amb})}{I} \qquad (2)$$

($\tau\alpha$ is the absorptance-transmittance product).

The products $F_R(\tau\alpha)$ and $F_R U_L$ are assumed to be constant terms. They can be experimentally determined by plotting $\eta$ versus $(T_i\text{-}T_{amb})/I$ as a independent variable and applying a linear regression to the set of experimental points. Two characteristic parameters of solar collectors are obtained: one is related to thermal losses and gains ($F_R\,(\tau\alpha)$) and the other is related to thermal losses ($F_R U_L$). The ASHRAE 93-77 standard gives the procedures to characterize a flat-plate collector and to calculate its characteristic parameters.

### Energy Storage Collectors

The main characteristic of energy storage collectors is the high thermal inertia, represented by a high value for the collector time constant (Duffie and Beckman, 1991). The advantage of this unit in the drying process is the capacity to avoid temperature peaks during the day and to continue transferring heat even when the incidence of solar radiation ends. However, due to their nature, characterization of these collectors based on ASHRAE 93-77 standard Equation (2) does not supply appropriate information about operation of this equipment. An alternative is to consider the storage collector as a flat plate and to use the daily efficiency $\bar{\eta}$ (ratio of the heat supplied by the solar collector to the total incident radiation in a whole day of sun exposure) in the performance analysis:

$$\bar{\eta} = \frac{\int q \; dt}{A \int I \, dt} \tag{3}$$

Nayak et al. (1989) and Boppshetty et al. (1992) observed that despite their high thermal inertia, concrete collectors have linear behavior similar to that in the instantaneous efficiency model:

$$\bar{\eta} = a - b \left[ \frac{\bar{T}_i - \bar{T}_{amb}}{H_T} \right] \tag{4}$$

where $\bar{T}_i$ is the mean inlet air temperature, $\bar{T}_{amb}$ is the mean ambient temperature, $H_T$ is the daily incident radiation on a tilted surface and a and b are the daily characteristic parameters.

## Empirical Correlations

Klein et al. (1976) determined a correlation between the solar fraction f (ratio of the heat supplied by a solar system $Q_s$ to the energy demand of the process $Q_p$) and two dimensionless design parameters (X and Y) for an air heating solar system:

$$f = \frac{Q_s}{Q_p} \tag{5}$$

$$X = \frac{A F_R U_L (100 - \bar{T}_{amb})}{Q} \tag{6}$$

$$Y = \frac{A F_R (\tau\alpha)_m H_T}{Q} \tag{7}$$

$$f = 1.040\,Y - 0.065\,X - 0.159\,Y^2 + 0.00187\,X^2 - 0.0095\,Y^3 \tag{8}$$

The above correlation assumes a system with an air flow rate between 5 and 20 l/s.m$^2$, a slope equal to the local latitude plus or minus 15° and thermal storage pebble diameters between 1 and 3 cm.

The correlation of Pratoto et al. (1997) (Equations 9 and 10) uses only one design parameter (Y) because when $T_i = T_{amb}$ the heat losses term in Equation (1) becomes negligible.

$$f = Y; \quad 0 < Y < 0.2 \tag{9}$$

$$f = -0.009 + 2.0251\;\; Y - 3.0482\;\; Y^2 + 1.5263\;\; Y^3; \quad 0.2 < Y < 0.554 \tag{10}$$

## CASE STUDY

A case study was conducted in the city of Campinas in Brazil (latitude 22º53'S) on an in-bin corn-drying system. Figure 2 shows the system comprises a bin full of grains, an energy storage solar collector (with 1.80m$^2$ of collector area), a fan for the drying air supply and a complemental conventional source of energy. The data on the in-bin corn drying and the solar air heating system are given in Table 1. The solar collector was built with cheap materials (concrete bricks, pebbles, wood and glass) and faced directly north with a slope approximately equal to the local latitude. The storage bed is made of pebbles and the air flows above the bed, as shown in Figure 3.

**Figure 2:** Solar air heating system for in-bin crop drying.

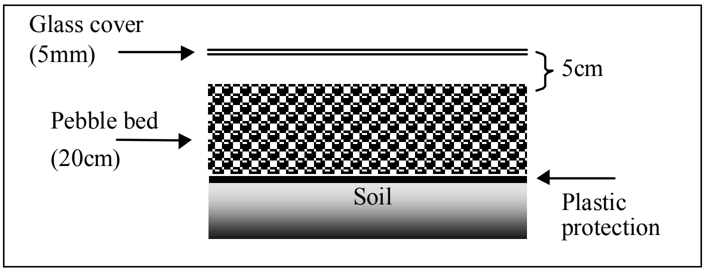

**Figure 3:** Pebble bed energy storage cross section.

**Table 1: In-bin corn drying and solar air heating system characteristics.**

| **Location** | **Campinas, SP, Brazil** |
|---|---|
| **Latitude:** | 22°53'S |
| **Collector tilt** | 23° |
| **Collector area** | 1.80 $m^2$ |
| **Recommended range for specific air flow rate (Brooker et al., 1992)** | 0.8 – 4.0 $m^3/m^3$.min |
| **Drying temperature (Brooker et al., 1992)** | 50°C |
| **Corn bulk density (Brooker et al., 1992)** | 721 $kg/m^3$ |
| **Bin volume** | 1.77 $m^3$ |
| **Corn mass** | 1276.17 kg |
| **Drying air flow rate used** | 2.10 $m^3$/min |

## MATERIALS AND METHODS

### Solar Collector Characterization

The solar collector was characterized according to the concrete plates methodology described by Nayak et al. (1989). The collector had been exposed to ambient conditions during the previous night. The next morning, the glass cover was cleaned and the Eppley pyranometer was set up on the collector plate. A digital data logger was used for measurements and storage of temperatures and incident solar radiation values. After the pyranometer started receiving direct solar radiation, the data on incident solar radiation, inlet and outlet collector air temperatures (dry and wet bulb) and ambient air temperature were stored at five-minute intervals. Type T thermocouples were used. Due to its high thermal inertia, in the early morning hours the air loses heat from the storage collector (negative instantaneous efficiency). Therefore, to construct the daily efficiency curve, Equation (4) was used with the data after the time at which the instantaneous efficiency became positive. On this curve each point represents a day of tests.

### Collector Incident Radiation and Energy Demand of the Corn-Drying Process

The monthly average of incident solar radiation on the tilted collector was calculated according to the methodology described by Beckmann et al. (1977) and Klein (1977), based on the Liu and Jordan (1961) model. Monthly average energy demand of the process was determined assuming the continuous drying of grains during all months of the year, twelve hours a day and using an air flow rate of 2.10$m^3$/min at 50°C. The solar and meteorological data used were supplied by IAC (1989) and CEPAGRI-UNICAMP (2004) and the psychrometric relations were obtained from Brooker et al. (1992).

The parameters involved in the design of solar crop-drying systems are shown in Figure 4.

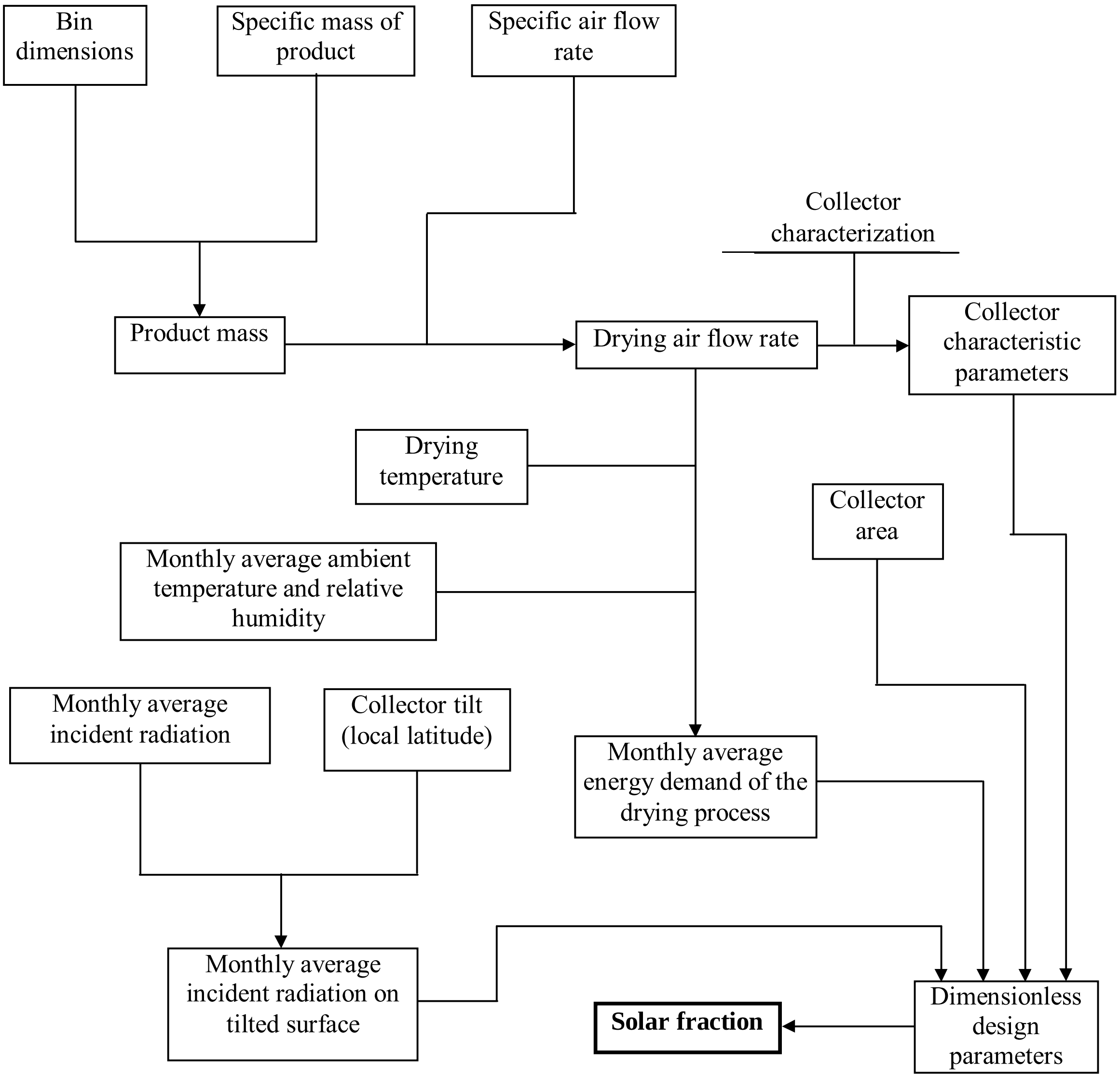

**Figure 4:** Parameters involved in the design of solar crop-drying systems.

## RESULTS

Figure 5 shows the characteristic curve of the energy storage solar collector. As for the flat-plate collectors, a linear relationship was observed. Equation (11) and the daily average characteristic parameters (a and b) were obtained by linear regression:

$$\overline{\eta} = 0.4332 - 0.1223 \left[ \frac{\overline{T}_i - \overline{T}_{amb}}{H_T} \right] \tag{11}$$

$$r^2 = 0.9398$$

Figure 6 presents the changes in the annual solar fraction as a function of solar collector area for the case studied. It was observed that the correlation of Pratoto et al. (1997) is limited to a small range of dimensionless Y parameter values. The monthly averages of energy demand, incident radiation in the collector and heat supplied by the system in the solar-assisted crop drying are shown in Figure 7. The monthly solar fractions are shown in Figure 8.

The correlation of Pratoto et al. (1997) gives higher solar fraction values than the f-Chart correlation (Klein et al., 1976). Similar behavior was observed in the two correlations for every month of the year. The annual solar fractions obtained were 0.38 and 0.30, assuming an energy demand of 16.85GJ.

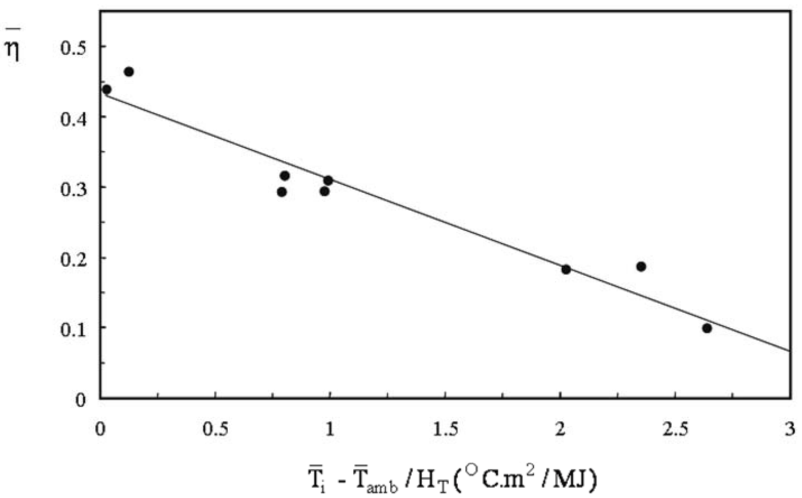

**Figure 5:** Characteristic curve for the energy storage solar collector.

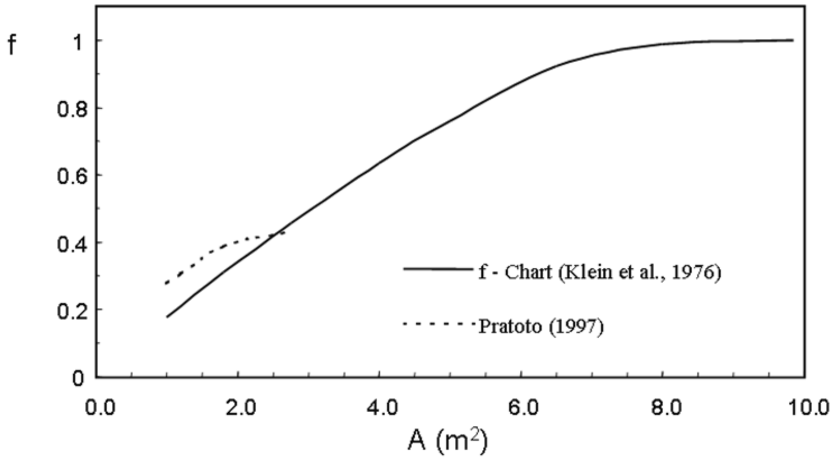

**Figure 6:** Annual solar fractions as a function of the collector area for an in-bin solar-assisted corn-drying system.

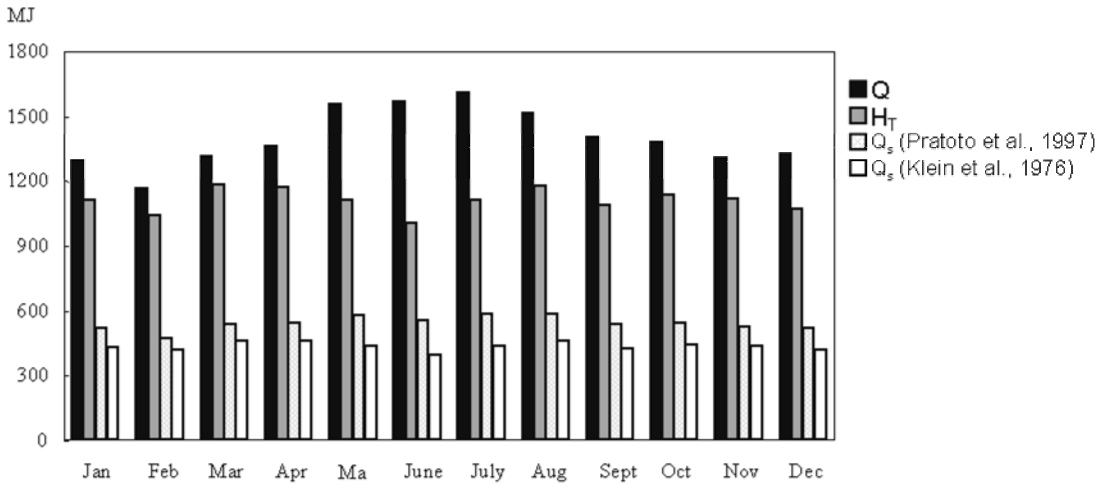

**Figure 7:** Monthly averages of energy demand, incident radiation on the collector and heat supplied by the system in the solar-assisted crop drying (A = 1.80m$^2$)

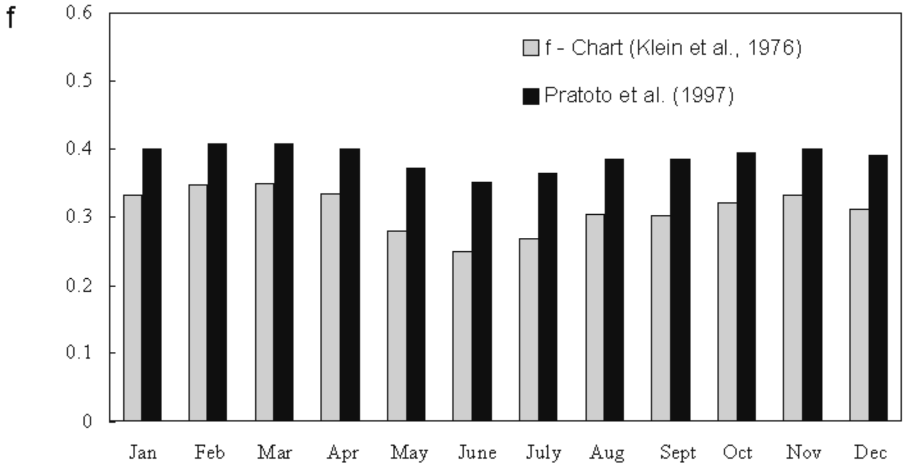

**Figure 8:** Monthly solar fractions for the solar air heating system ($A = 1.80 m^2$).

## CONCLUSIONS

The air heating solar collector with storage bed can be characterized by means of its daily efficiency, determining its daily average characteristic parameters. Empirical correlations developed for other collector plate types can be used to estimate solar fractions for solar-assisted grain drying. The f-Chart correlation gives a conservative result and should be used rather than the Pratoto et al. (1997) correlation, wich was shown to be limited to a small range of dimensionless design parameters (Y). A solar-assisted grain-drying system with a 1.80 $m^2$ collector area can provide an annual savings of 30% in fuel consumption, which was enough to dry 1.28t of corn at 50ºC, using a daily air flow rate of 1526.80 $m^3$ per day.

## NOMENCLATURE

| | | |
|---|---|---|
| a | Collector characteristic parameter (daily) | Dimensionless |
| b | Collector characteristic parameter (daily) | $MJ/m^2$ °C |
| $h_c$ | Convective heat transfer coefficient | $W/m^2$ °C |
| $h_r$ | Radiation heat transfer coefficient | $W/m^2$ °C |
| q | Useful solar heat delivered by the collector | W |
| A | Collector area | $m^2$ |
| $F_R$ | Collector heat removal factor | Dimensionless |
| H | Daily incident radiation | $MJ/m^2$ |
| I | Incident solar radiation flux | $W/m^2$ |
| Q | Drying heat requirement | MJ |
| $Q_s$ | Energy supplied by the solar system | MJ |
| $Q_p$ | Process energy demand | MJ |
| T | Temperature | °C |
| $\bar{T}$ | Daily mean temperature | °C |
| U | Heat loss coefficient | $W/m^2 K$ |
| $U_L$ | Collector loss heat coefficient | |
| X | Collector characteristic parameter (instantaneous) | Dimensionless |
| Y | Collector characteristic parameter (instantaneous) | Dimensionless |

### *Greek Symbols*

| | | |
|---|---|---|
| $\tau$ | Transmittance | Dimensionless |
| $\alpha$ | Absorptance | Dimensionless |
| $\bar{\eta}$ | Collector daily efficiency | Dimensionless |

### *Subscripts*

| | | |
|---|---|---|
| a | Air | (-) |
| amb | Ambient | (-) |
| b | Bottom | (-) |
| c | Cover | (-) |
| i | Inlet | (-) |
| m | Mean | (-) |
| p | Plate | (-) |
| T | Tilted surface | (-) |

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