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A dynamic model based on the piston flow concept for the thermal characterization of solar collectors

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ABSTRACT

A simple, transient model for the characterization of the dynamic thermal performance of solar thermal collectors was developed and experimentally validated. The proposed model equation is linear with respect to the input parameters and does not require any treatment for ordinary differential equations (ODEs). The temperature distribution in the fluid flowing inside the collector is described by means of the piston flow and finite increment concepts. The dynamic effect, for a given flow rate, is expressed by the heat transport time and is based on the effective thermal capacity of the collector. The results reveal that the characteristic parameters involved in the model agree reasonably well with the experimental variables obtained from standard steady-state measurements. After a calibration process the model can well predict the thermal performance of a solar thermal collector, for a specific weather data set.

1. Introduction

Solar collectors thermal performance can be characterized by a steady-state or a dynamic model. Research concerning dynamic modelling is essential to adequately characterize the transient behavior of solar thermal collectors. At this point it should be mentioned that a dynamic model can be very useful because it provides information about the collector behavior and facilitates experimental tests in comparison with the steady-state and the quasi-dynamic standard tests. In the literature there are several studies about these types of models, however only a few of them regard the dynamic performance of solar thermal collectors.

In terms of the steady-state testing, the EN 12975 standard, the ISO 9806-1 and the ANSI/ASHRAE 93-2003 are available for characterizing and rating a collector under outdoor testing conditions [1–3]. These standards have been adopted worldwide as reference methodologies for solar thermal collectors testing. Nevertheless, steady-state outdoor testing includes several difficulties associated with the weather conditions. In many places in the world and over many periods through the year, the weather conditions do not fulfil the requirements for the steady-state testing standards defined in EN 12975 [2].

Thus, in order to overcome the difficulties associated with the steady-state testing, transient testing methods have been developed and reported in the literature [1,4–8]. The EN 12975 standard includes a procedure for partially transient testing. This standard is based on the so called one-node, one-segment model [4] and takes into account effects such as the second-order processes, wind speed and long-wave irradiance dependence of heat losses. However, there are restrictive requirements associated with the constant inlet fluid temperature and predominant weather conditions; experimental testing difficulties arise from both. Furthermore, it is essential to have large enough variability of solar radiation during the test in order to increase the thermal capacitance effects. In addition, if some conditions are not fulfilled during the testing period, then an extra testing day is required.

On the other hand, Muschaweck and Spirkl [6] proposed a dynamic solar collector (DSC) performance testing and developed the model and the computation procedure. The model is an extension of the Hottel-Whillier-Bliss equation to a dynamic model with simple collector parameters: zero loss efficiency, slope of the characteristic curve and thermal mass. The collector is considered as split into N-segments connected in series and by connecting them the overall behavior is then determined. The method allows arbitrary variations of irradiance, ambient temperature, inlet temperature and fluid flow rate during the test. Although the model should be simple and practical for rating the collector under outdoor conditions, the authors reported that there are difficulties in determining the heat thermal capacity parameter. This is presumably because results are obtained from a large time step in the experimental data (5 min) and from the crude way of modelling the collector thermal capacity. Moreover, the method requires the use of a specific ODE solver such as Lavenberg-Marquardt.

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Nomenclature

A_c	absorber plate area of the collector (m^2)
A_s	absorber plate area of the collector segment (m^2)
c_f	specific heat capacity of the fluid (J/kg K)
c_1, c_2, c_3	model parameters: c_1 (Km^2/W), c_2 and c_3 (–)
F'	collector efficiency factor (–)
G	solar radiation (W/m^2)
$K_\theta(\theta)$	incidence angle modifier (–)
$\dot{m}_f$	mass flow rate of the fluid (kg/s)
$m_e c_e$	effective thermal capacity of a segment (J/K)
$M_e c_e$	effective thermal capacity of the collector (J/K)
nt	number of time steps
N	number of segments
t	time (s)
T	outlet temperature (K)
T_a	ambient temperature (K)
T_0	inlet temperature (K)
T_{ix}^{it}	fluid temperature at segment *ix* and time interval *it* (K)
U_L	overall convective heat loss coefficient of the collector ($W/(m^2K)$)
U_1	convective heat loss coefficient at $(T_m - T_a) = 0$ ($W/(m^2K)$)
U_2	wind-induced convective heat loss coefficient ($J/(m^3K)$)

Greek symbols

Δt	time step, time interval (s)
θ	incidence angle (°)
v	wind velocity (m/s)
$(\tau\alpha)_{en}$	normal incidence transmittance-absorbance product (–)
τ_c	collector time constant (s)
τ_t	heat transport time (s)

Nayak et al. [7] studied three transient methods for testing solar flat-plate thermal collectors: Perers, DSC and Wijeysundera. The main conclusions revealed are: Perers method generates simulated results close to the steady state value (within 4%), whereas DSC and Wijeysundera methods underpredict it (maximum deviation ≈ 10%). In addition, DSC model shows large variation in the values of the heat thermal capacity parameter. Test set-up and procedures for both Perers and DSC methods are simpler in comparison to Wijeysundera method. Perers method requires control of the inlet fluid temperature while DSC method does not require flow rate and fluid inlet temperature control.

A comparison between stationary and dynamic solar collector models in terms of the energy yield, including DSC model, was conducted by Scnieders [8]. According to this study, 2-nodes model did show the best description of the actual collector behavior. Within 1-node methodologies, DSC model did show a better parameter identification of the collector than MFC (Matched Flow Collector) [5] and even better than 2-nodes model.

A dynamical simulation of a thermosyphonic flat-plate collector, using 3-nodes and 1-segment models, was developed and experimentally validated by Taherian et al. [9]. The governing differential equations were separately written for the absorber, the glass cover and the working fluid, and then solved as a system of equations. This model was capable of predicting system efficiency during sunny days, but on partially cloudy days, it only gave proper results for the glass cover temperature; however, it accurately predicted the mean collector fluid temperature. The authors attributed this behavior to the difference in the simulation time-step resolution and that of the climate data imported into the program.

In the present work, a dynamic model based on the piston flow concept was developed. This concept simplifies DSC model in terms of building an algebraic expression for describing the distribution of fluid temperature through the collector. The purpose of this simplification is to obtain a model that can be handled more easily with any spreadsheet programs using simple expressions. Furthermore, the method allows arbitrary variations of irradiance, ambient temperature and inlet temperature during the test. At this point it should be mentioned that the model has been validated in a Photovoltaic/Thermal (PV/T) flat-plate solar collector (Fig. 1a); however it can be applied to different collectors within the same range of the effective thermal capacity per collector aperture unit area. Although the model covers only the collectors which behave according the piston flow concept conditions, most of the commercial solar thermal collectors fulfils these requirements. The results revealed that the proposed model did show a good behavior, therefore can be used for the thermal performance characterization of solar thermal collectors.

2. The mathematical model

The dynamic model used in the present study is a simplification of the DSC model proposed by [6]. At the same time, the proposed model is an approximation of a Partial Differential Equation (PDE) which governs collector behavior by an Ordinary Differential Equation system (ODEs). In the DSC model the collector is divided into N equal parts and each segment is modelled by one ODE as given by:

$$(m_e c_e)\frac{dT}{dt} = A_s[F'(\tau\alpha)_{en}K_\theta(\theta)G - F'U_L(T - T_a)] - \dot{m}_f c_f(T - T_0) \qquad (1)$$

where $(m_e c_e)$ is the effective thermal capacity of the segment, $\dot{m}_f$ is the mass flow rate of the fluid, c_f is the specific heat capacity of the fluid, $F'(\tau\alpha)_{en}$ is the zero loss efficiency for global radiation at normal incidence, G is the solar radiation, F' is the collector absorber efficiency factor, U_L is the overall heat loss coefficient, T and T_0 are the fluid temperatures of the segment and at its entrance, T_a is the ambient temperature, A_s is the absorber plate area of the collector segment and $K_\theta(\theta)$ is the incident angle modifier.

In order to derive from Eq. (1) a simple algebraic expression, the piston flow concept is adopted. This concept is based on the fact that the fluid which enters in the first element displaces the fluid of the second element and so on. For the model development, the following assumptions have been adopted:

1. The fluid temperatures are considered to be constant at each segment.
2. Heat transfer processes are considered to be one dimensional.
3. The mass flow rate is considered constant in time.
4. The specific heat of the fluid and the overall heat loss coefficient are assumed to be constant with temperature.

DSC model equation can be simplified considering the outlet fluid temperature of the previous segment at the previous time interval, as the inlet fluid temperature. The derivative term is approximated through finite increments and the drag term is explicitly approached, considering the previous time step values. Thus, Eq. (1) can be expressed by:

$$(m_e c_e)\frac{(T_{ix}^{it} - T_{ix}^{it-1})}{\Delta t} = A_s\left[F'(\tau\alpha)_{en}K_\theta(\theta)G^{it} - F'U_L(T_{ix}^{it} - T_a^{it})\right] - \dot{m}_f c_f\left(T_{ix}^{it-1} - T_{ix-1}^{it-1}\right) \qquad (2)$$