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A dynamic thermal performance model for flat-plate solar collectors based on the thermal inertia correction of the steady-state test method

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ABSTRACT

In determining the dynamic thermal performance of a flat-plate solar collector, when the instantaneous solar irradiance changes sharply at one moment, most of the existing models cannot accurately predict the momentary thermal characteristics of outlet temperature and useful heat gain. In the present study, an analytical model in the form of series expansion is put forward to depict the momentary thermal characteristics of flat-plate solar collectors. The analytical model reveals that, instantaneous useful heat gain of a solar collector at one moment consists of the steady-state useful heat gain and corresponding thermal inertia correction. The model is then validated by the experimental data. It indicates that the analytical model can properly predict the dynamic thermal performance of the solar air collector. Besides, the model pertains to other types of solar thermal collectors, if they can be tested by the steady-state test method.

1. Introduction

Flat-plate solar collectors are popularly used for providing domestic hot water or space heating. In the practical applications, solar collectors usually work under dynamic weather conditions. So the thermal performances of the solar collectors are dynamic and the steady-state model derived from steady-state test (SST) method [1] does not pertain to the dynamic conditions. Hence, dynamic model is needed to predict the thermal performances of flat-plate solar collectors under realistic weather conditions. Researchers have developed dynamic test methods for flat-plate solar collectors. Amer et al. [2] and Nayak and Amer [3] gave a detailed review of transient methods, such as one-node method [4–10], multi-node method [11,12], response function method [13–16], etc. The disadvantages of most of the one-node method are described by Amer [2]. Nayak and Amer [3] carried out sensitivity study to examine the effect of uncertainties in measurements on the values of the estimated parameters using different methods. They found that the new dynamic method (NDM) [2,16] seems to be quite reliable and the quick dynamic test (QDT) [4,17] method is the simplest for the purpose of product's quality control. However, the NDM requires familiarity with digital signal analysis and filtering [3]. Thus the calculation by NDM is very complex. When it comes to QDT, the model is just a simplified quasi-dynamic model of a flat-plate solar collector with a correction term of thermal capacitance, which is inferior to the quasi-dynamic test method (QTM) by Perers [7–10] from the view point of theoretical completeness. Furthermore, Kong et al. [18] verified that the transfer function method (TFM) [19,20] is more accurate than the QTM by Perers. It seems the TFM has a good accuracy than the QDT and QTM methods. However, dynamic thermal performance predictions done by Kong et al. [18,21] with flat-plate solar collectors suggest that, the TFM cannot accurately predict the momentary thermal characteristics of outlet temperature and useful heat gain when the instantaneous solar irradiance changes sharply at one moment.

In order to accurately predict the dynamic thermal performance of a flat-plate solar collector when the instantaneous solar irradiance changes sharply, the present study puts forward an analytical model in the form of series expansion, starting from the simplified model of QDT [4,17] of a flat-plate solar collector. Based on the analytical model deduced in the condition of a small time interval, the physical explanation of the model is presented and the solving method is elaborated. Moreover, experiments are conducted to validate the accuracy of the analytical model. And the dynamic

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Nomenclature

A_a	transparent frontal area or the aperture area of a collector, m^2
A_g	gross collector area, m^2
b_0	constant used in incident angle modifier equation, dimensionless
C_f	specific heat of the working fluid, J/(kg °C)
F_R	solar collector heat removal factor, dimensionless
$f(n)$	useful heat gain of the collector in the steady-state test method, W
G_b	beam irradiance of inclined surface, W/m^2
G_d	diffuse solar irradiance of inclined surface, W/m^2
G_g	global solar irradiance of inclined surface, W/m^2
j	a forced integer number in Equations (16) and (17), dimensionless
$K_{\theta b}(\theta)$	collector incidence angle modifier for beam irradiance, dimensionless
$K_{\theta d}(\theta)$	collector incidence angle modifier for diffuse irradiance, dimensionless
m	mass, kg
$(mC)_e$	effective thermal capacitance of solar collector, J/°C
$\dot{m}_f$	mass flow rate of flowing air, kg/s
N	number of time step, dimensionless
NDM	new dynamic method
QDT	quick dynamic test
QTM	quasi-dynamic test method
Q_u	instantaneous useful heat gain of the collector dynamic test, W
S	absorbed solar radiation per unit area, W/m^2
SST	steady-state test
T	response time constant, s
TFM	transfer function method
$TICM$	thermal inertial correction model
T_a	ambient temperature, °C
T_f	characteristic temperature of the working fluid, °C
T_{fi}	collector inlet temperature, °C
T_{fo}	collector outlet temperature, °C
$T_{fo,initial}$	initial collector outlet temperature in the test of time constant, °C
U_L	overall heat loss coefficient of a solar collector, W/(m^2 °C)
Greek symbols	
α	absorptance, dimensionless
β	collector slope angle, °
η_g	collector thermal efficiency based on the gross area, %
θ	incidence angle on the tilted surface of a collector, °
ρ	density, kg/m^3;
τ	time, s; transmittance of glass cover, dimensionless
$(\tau\alpha)_{en}$	effective transmittance-absorptance product at normal incidence, dimensionless
$\Delta\tau$	small time interval, s
Subscripts	
a	ambient
f	working fluid
i	inlet air
o	outlet air

thermal performance predictions by different models are compared with the experimental data. In addition, the applicable condition of the analytical model is discussed.

2. Analytical model

2.1. Transformation of simplified quasi-dynamic model

The simplified model of QDT [4,17] for a flat-plate solar collector is given in Equation (1). It is a first-order differential model based on Hottel-Whillier-Bliss equation [17] with a correction term of effective collector thermal capacitance [22].

$$(mC)_e\frac{dT_f}{d\tau} = F_R A_a\left[S - U_L\left(T_{fi} - T_a\right)\right] - \dot{m}_f C_f\left(T_{fo} - T_{fi}\right) \quad (1)$$

where the term on the left of the equation represents the effective internal energy variation. The first term on the right indicates the effective absorbed radiation subtracting the total heat loss in terms of the heat removal factor F_R. The second term on the right denotes the thermal enthalpy increment between the collector out and inlet. $(mC)_e$ is the effective heat capacity of the solar collector, J/°C. The absorbed radiation per unit area (S) consists of beam radiation and diffuse radiation [7–10], as given in Equation (2). The incidence angle modifier $K_{\theta b}(\theta)$ for beam radiation is given by Equation (3). With regard to the incidence angle modifier $K_{\theta d}(\theta)$ for diffuse radiation, an equivalent angle of incidence can be considered according to Duffie and Beckman [17]. And $K_{\theta d}(\theta)$ is the cosine value of the equivalent angle, ranging from 55° to 60° for solar collectors with inclined angles of 0–90°. The calculation method of the equivalent angle of incidence can be found in Ref. [17].

$$S = (\tau\alpha)_{en}K_{\theta b}(\theta)G_b + (\tau\alpha)_{en}K_{\theta d}(\theta)G_d \quad (2)$$

$$K_{\theta b}(\theta) = 1 - b_0\left(\frac{1}{\cos\theta} - 1\right) \quad (3)$$

The model of QDT by Equation (1) represents a simplified first-order differential system, which has a mathematical form of Equation (4), as verified by Ref. [22].

$$T\frac{dy}{d\tau} + y = Ax \quad (4)$$

where y is the system output, x is the system input, T is the time constant of the object, A is the system amplification coefficient.

Similar to the form of Equation (4), taking the collector outlet temperature T_{fo} as the system output of the solar thermal collector and substituting the characteristic fluid temperature T_f with $(T_{fi} + T_{fo})/2$, Equation (1) can be rearranged to Equation (5).

$$\frac{dT_{fo}}{d\tau} + \frac{2\dot{m}_f C_f}{(mC)_e}\left(T_{fo} - T_{fi}\right) = -\frac{dT_{fi}}{d\tau} + \frac{2F_R A_a}{(mC)_e}\cdot\left[S - U_L\left(T_{fi} - T_a\right)\right] \quad (5)$$

In the test process of response time constant T of a solar collector, the temperatures T_{fi},T_a, outdoor wind speed, and the mass flow rate $\dot{m}_f$ of the working fluid are kept to be constant. The term $\frac{dT_{fi}}{d\tau}$ is zero in this case. Then Equation (5) is reduced to Equation (6)