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Dynamic thermal performance prediction model for the flat-plate solar collectors based on the two-node lumped heat capacitance method

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ABSTRACT

Two-node lumped heat capacitance model of the flat-plate solar collectors is derived strictly based on the concept of the collector flow efficiency factor F'. It is found that the obtained first-order differential model turns out to be the amended ***quasi-dynamic test*** (QDT) model. The collector dynamic response time constant τ_d is identified referring to the first-order response system in automatic control theory. Then the dynamic thermal performance prediction model for the flat-plate solar collectors on the basis of the amended QDT model is deduced using integral treatment within a small time interval in order to extend the ***thermal inertia correction model*** (TICM) to be fit for different conditions, such as moderate or intensive change rates of the collector inlet temperature, wide-range ratios of the diffuse radiation to global radiation, different incidence angles, etc. Correlation between the presented prediction model and the TICM base on the ***steady-state test*** (SST) for the flat-plate solar collectors is elucidated and the relation between the collector dynamic response time constant τ_d and the static time constant τ_C is elaborated. Finally, experimental tests of both the steady-state tests and dynamic tests with a specific flat-plate solar air collector are conducted to verify the performance of the proposed dynamic prediction model and corresponding parameters. It is verified that the presented prediction model in terms of the collector dynamic response time constant τ_d can accurately predict the dynamic thermal performances of the flat-plate solar air collector under different conditions.

1. Introduction

As a kind of clean, renewable energy, solar energy is widely used instead of a part of fossil energy due to energy depletion and environment protection on the earth. As the core components of solar thermal harvesting systems, solar collectors usually work under variable whether conditions consequently performing dynamic thermal characteristics. In fact, the so-called instantaneous thermal efficiency curve obtained by the ***steady-state test*** (SST) method as shown in Eq. (1) (ANSI/ASHRAE Standard 93-2003, 2003), performs poorly in the predictions of collector dynamic thermal performances due to no consideration of solar collectors' thermal capacitances. Moreover, only the incidence angle modified coefficient $K_{\theta b}(\theta)$ for solar beam radiation is considered in the SST model, which ignores the effect of solar diffuse radiation. Therefore, researchers have been focusing on the collector dynamic thermal performance test methods for identifying collector thermal performance characterization parameters, as well as prediction models in the purpose of accurately predicting the collector thermal performances under dynamic weather conditions.

$$\eta_g=\frac{Q_u}{A_gG_g}=\frac{\dot{m}_fc_f(T_{fo}-T_{fi})}{A_gG_g}=(A_a/A_g)\left[F_R(\tau\alpha)_{en}\cdot K_{\theta b}(\theta)-F_RU_L\frac{(T_{fi}-T_a)}{G_g}\right]$$
$$=(A_a/A_g)\left[F'(\tau\alpha)_{en}\cdot K_{\theta b}(\theta)-F'U_L\frac{(T_f-T_a)}{G_g}\right] \quad (1)$$

and

$$K_{\theta b}(\theta)=1-b_0\cdot\left(\frac{1}{\cos\theta}-1\right) \quad (2)$$

where η_g represents the collector thermal efficiency based on the collector gross area A_g, rather than the aperture area A_a.

In the aspect of the collector dynamic thermal performance test methods, Kong et al. (2012a,b) and Deng et al. (2015a) reviewed the previously extensive work concerning on different kinds of

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Nomenclature

List of symbols

A_a	collector aperture area, m^2
A_g	gross collector area, m^2
A_t	heat transfer area from collector absorber to working fluid, m^2
b_0	a constant in the incident angle modifier equation, dimensionless
c	specific heat, J/(kg °C)
F'	solar collector flow efficiency factor, dimensionless
F_R	solar collector heat removal factor, dimensionless
G_b	solar beam radiation on the collector surface, W/m^2
G_d	solar diffuse radiation on the collector surface, W/m^2
G_g	global solar irradiance on the collector surface, W/m^2
$K_{\theta b}(\theta)$	collector incidence angle modifier for beam radiation, dimensionless
$K_{\theta d}(\theta)$	collector incidence angle modifier for diffuse radiation, dimensionless
m	mass, kg
$\dot{m}_f$	mass flow rate of the working fluid, kg/s
$(mc)_e$	solar collector effective thermal capacitance, J/°C
n	time step number (integer), dimensionless
Q_u	useful heat gain power of the collector, W
S	absorbed solar radiation per m^2, W/m^2
T_a	ambient temperature, °C
T_b	lumped mean temperature of the absorber plate, °C
T_f	characteristic temperature of the collector working fluid, °C
T_{fi}	collector inlet temperature, °C
T_{fo}	collector outlet temperature, °C
$U_{b,f}$	convective heat transfer coefficient between the absorber plate and the working fluid, W/(m^2 °C)
U_L	total heat loss coefficient of a solar collector in SST, W/(m^2 °C)
U'_L	total heat loss coefficient of a solar collector in dynamic test, W/(m^2 °C)
U_w	wind heat loss coefficient, J/(m^3 °C)
U_1	temperature dependence heat loss coefficient, W/(m^2 °C^2)
w	outdoor wind velocity, m/s

Greek symbols

α	absorptance, dimensionless
η_g	collector thermal efficiency based on the gross area, %
θ	incidence angle on the collector surface, °
ρ	density, kg/m^3
τ	time, s; transmittance of glass cover, dimensionless
τ_C	the static response time constant of the collector, s
τ_d	the dynamic response time constant of the collector, s
$(\tau\alpha)_{en}$	effective transmittance-absorptance product at normal incidence, dimensionless

Subscript

a	ambient
b	collector absorber plate
f	working fluid
fi	working fluid inlet
fo	working fluid outlet

Abbreviation

Dyn	dynamic
QDT	quasi-dynamic test
SST	steady-state test
TICM	thermal inertia correction model

methods which aimed at obtaining the solar collector characteristic parameters, such as the collector heat loss coefficient $F'U_L$, the effective transmittance-absorptance product $(\tau\alpha)_{en}$, the effective thermal capacitance $(mc)_e$, etc. It was worth mentioning that the ***quasi-dynamic test*** (QDT) method presented by Perers (1993, 1997) was the most complete one-node lumped thermal capacitance model among all the one-node collector dynamic test models as argued by Nayak and Amer (2000). It considered all the effects concerned such as both incidence angle modified coefficients of solar beam radiation and diffuse radiation, wind velocity effect, temperature dependence effect of the heat loss coefficient, sky background long-wave radiation effect and the collector effective thermal capacitance, etc. The first-order differential model for the dynamic thermal performance tests of solar collectors used in the QDT method was given in Eq. (3) (Fischer et al., 2004; EN 12975-2, 2006).

$$Q_u = \dot{m}_f c_f (T_{fo} - T_{fi}) = F'(\tau\alpha)_{en}\left[1 - b_0\left(\frac{1}{\cos\theta} - 1\right)\right] G_b A_a + F'(\tau\alpha)_{en} K_{\theta d}(\theta) G_d A_a - F' U_L A_a (T_f - T_a) - F' U_1 A_a (T_f - T_a)^2 - w F' U_w A_a (T_f - T_a) - (mc)_e \frac{dT_f}{d\tau} \quad (3)$$

Although the accuracy of the QDT method had been discussed by published work (Nayak and Amer, 2000; Kratzenberg et al., 2006; Kong et al., 2012a,b, 2015; Osório and Carvalho, 2014), the allowed deviation of the collector inlet temperature was still restricted within ±1 °C during one test sequence in EN12975-2 Standard (2006), which would result in inaccurate identification of the solar collector effective thermal capacitance $(mc)_e$ due to the fact that no sufficient collector dynamic response information was available for identifying $(mc)_e$ with the QDT under constant inlet temperature conditions (Kong et al., 2015). In order to improve the accuracy level of the dynamic test models, Kong et al. (2012a,b) studied the second-order transfer function models for flat-plate solar collectors based on two-node lumped thermal capacitance method. But the results provided by them did not show obvious superiority of the transfer function model to the QDT model. Furthermore, Deng et al. (2015a,b) validated that the second-order differential transfer function models had the same accuracy as the reduced first-order differential models with temperature measurements of the routine accuracy levels. In order for the second-order transfer function models to perform better in the dynamic tests, the measured accuracy of temperatures should be improved since the collector thermal storage quantities of the second-order differential terms in the models were very small. Otherwise, the combined standard uncertainties of the second-order differential terms of temperatures could be larger than the second-order differential terms of temperatures and thus the second-order terms in the transfer function models did not make sense. Besides, Kong et al. (2015) proposed a QDT-based Laplace transformation method for dynamic testing of solar collectors and verified it can accurately identify the collector characteristic parameters through natural meteorological conditions. But the model they used in the method was not convenient to predict the collector dynamic thermal performance.

With regard to the solar collector dynamic thermal performance prediction models, the updated solar system simulation