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Study on the second-order transfer function models for dynamic tests of flat-plate solar collectors Part II: Experimental validation

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Abstract

In order to validate the accuracy levels of three forms of transfer function models (TFMs), dynamic thermal performance tests of a flat-plate solar air collector with louvered fin structure are conducted. Model coefficients in the TFMs are constructed by strict error analysis and the weighed least square (WLS) method. Comparing with the experimental data, it is verified that the three forms of TFMs perform well and have the similar level of accuracy. It is further demonstrated that, the second-order differential TFMs have the same accuracy as the reduced first-order differential models with the present temperature measurement accuracy using thermocouples. Whilst the collector thermal storage quantities of the second-order differential terms in the TFMs are very small. In order for the second-order TFMs to perform better in the dynamic tests, the measured accuracy of temperatures should be improved. 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 the second-order terms in the three forms of TFMs would become meaningless.

Keywords: Flat plate solar collector; Dynamic thermal performance; Transfer function model

1. Introduction

In the companion paper, the second-order transfer function model (TFM) in terms of the collector heat removal factor F_R is presented for dynamic tests of flat-plate solar collectors (Deng et al., 2015). The equivalent relationships among the three different forms of TFMs (TFM by Hou, 2005; ITFM by Kong et al., 2012b, TFM based on F_R) are elucidated. The ITFM by Kong et al. (2012b) is expressed as Eq. (1) below (Eq. (7) in the companion paper). Eq. (2) (Eq. (16) in the companion paper) shows the TFM based on F_R. And Eq. (3) gives the equivalent form of the TFM developed by Hou (2005). The TFM by Eq. (2) based on F_R is equivalent to the ITFM by Eq. (1) according to energy balance. The TFM by Hou (2005) is equivalent to the ITFM by Kong et al. (2012b) as well as the TFM based on F_R when the working fluid inlet temperature rate of change is small enough. Furthermore, the methodology of constructing the model coefficients in the TFMs is elucidated, based on error analysis and the weighed least square (WLS) method.

$$\begin{aligned} Q_u = \dot{m}_f c_f (T_{fo} - T_{fi}) = F'(\tau\alpha)_{en} K_{\theta b}(\theta) A_a G_b \\ + F'(\tau\alpha)_{en} K_{\theta d}(\theta) A_a G_d + \tau_{cu} \cdot (m_f c_f) \frac{d^2 T_f}{d\tau^2} - (mc)_e \frac{dT_f}{d\tau} \\ - \tau_{cu} \cdot \dot{m}_f c_f \cdot \left(\frac{dT_{fo}}{d\tau} - \frac{dT_{fi}}{d\tau} \right) - F' A_l (U_L + wU_w)(T_f - T_a) \quad (1) \end{aligned}$$

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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
A_l	total heat dissipating surface area of solar collector, m^2
A_t	heat transfer area from collector absorber to fluid, m^2
b_0	a constant used in incident angle modifier equation, dimensionless
c	specific heat, J/(kg °C)
D	diameter, m
F'	solar collector flow efficiency factor, dimensionless
F_R	solar collector heat removal factor, dimensionless
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
$ITFM$	improved transfer function model
$K_{\theta b}(\theta)$	collector incidence angle modifier for beam irradiance, dimensionless
$K_{\theta d}(\theta)$	collector incidence angle modifier for diffuse irradiance, dimensionless
L	length of collector, m
LS	least square
m	mass, kg
$\dot{m}_f$	mass flow rate of the working fluid, kg/s
$(mc)_e$	effective thermal capacitance of a solar collector, J/°C
Q_u	useful heat gain of the collector, W
QDT	quasi-dynamic test
R^2	statistical variance
t	student-t value of statistics, dimensionless
T_a	ambient temperature, °C
T_b	lumped mean temperature of the absorber plate, °C
T_f	characteristic temperature of working fluid, °C
T_{fi}	collector inlet temperature, °C
T_{fo}	collector outlet temperature, °C
TFM	transfer function model
$u_C(X)$	combined standard uncertainty of the quantity$X$, unit is the same as X
U_L	overall heat loss coefficient of a solar collector, W/(m^2 °C)
U_w	wind heat loss coefficient, J/(m^3 °C)
$\dot{V}_f$	volume flow rate of the working fluid, m^3/h
WLS	weighed least square
w	outdoor wind velocity, m/s

Greek symbols

α	absorptance, dimensionless
β	collector slope angle, °
θ	incidence angle on the tilted surface of a collector, °
ρ	density, kg/m^3;
τ	time, s; transmittance of glass cover, dimensionless
τ_{cu}	time scale indicating solar collector heat transfer rapidity, s
$(\tau\alpha)_{en}$	effective transmittance-absorptance product at normal incidence, dimensionless

Subscript

a	ambient
b	collector absorber plate
DT	dynamic test
exp	experimental value
f	working fluid
fi	working fluid inlet
fo	working fluid outlet
$pred$	model prediction value

$$\begin{aligned} Q_u &= \dot{m}_f c_f (T_{fo} - T_{fi}) \\ &= F_R(\tau\alpha)_{en} K_{\theta b}(\theta) A_a G_b + F_R(\tau\alpha)_{en} K_{\theta d}(\theta) A_a G_d \\ &\quad - \frac{\tau_{cu}}{2} \cdot (m_f c_f) \left(\frac{d^2 T_{fo}}{d\tau^2} + \frac{d^2 T_{fi}}{d\tau^2} \right) \\ &\quad - \left[\frac{1}{2}(mc)_e + \tau_{cu} \cdot \dot{m}_f c_f \right] \frac{dT_{fo}}{d\tau} + \left[\tau_{cu} \cdot \dot{m}_f c_f - \frac{1}{2}(mc)_e \right] \\ &\quad \cdot \frac{dT_{fi}}{d\tau} - F_R A_l (U_L + wU_w)(T_{fi} - T_a) \end{aligned} \tag{2}$$

$$\begin{aligned} Q_u &= \dot{m}_f c_f (T_{fo} - T_{fi}) \\ &= \dot{m}_f c_f \left[-\frac{1}{B} \frac{d^2 T_{fo}}{d\tau^2} - \frac{A}{B} \frac{dT_{fo}}{d\tau} + \frac{C}{B} \frac{dT_{fi}}{d\tau} + \frac{E_1}{B} G_b \right. \\ &\quad \left. + \frac{E_2}{B} G_d + \frac{F}{B} (T_{fi} - T_a) \right] \end{aligned} \tag{3}$$

where the time scale τ_{cu}, effective collector thermal capacity $(mc)_e$ and the incidence angle modifier for solar beam radiation are respectively given as:

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