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Study on the second-order transfer function models for dynamic tests of flat-plate solar collectors Part I: A proposed new model and a fitting methodology

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Abstract

The existing second-order transfer function models (TFMs) for solar collector dynamic tests are reviewed in light of the heat transfer principles, their inherent relationship, and limitations. Then, another form of TFM in terms of the collector heat removal factor F_R is put forward in this study. And the equivalent relationships among different forms of TFMs are elucidated. Strict error analysis and the weighed least square (WLS) method are used to construct model coefficients in the TFMs due to random measurement errors of data points in dynamic tests. Accuracy levels of the three TFMs will be validated with experimental data in the companion paper (Deng et al., 2015).

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

1. Introduction

Thermal performance tests of solar thermal collectors are important for guiding collector design or engineering applications. There are mainly two categories of collector test methods, i.e., the steady-state test (SST) method and the dynamic test (DT) method. Albeit the SST method is easy to use for determining the thermal performances of solar collectors, it usually requires strict test conditions that are difficult to meet. Moreover, the thermal capacitance of a solar collector is not considered in the SST method. And thus the mathematical model obtained by the SST method usually fails to catch the dynamic feature of a solar thermal collector under variable meteorological conditions. In view of the limitations of test conditions and dynamic thermal performance prediction by the SST method, researchers have developed quasi-dynamic or dynamic test methods of solar collectors.

According to the review by Amer et al. (1997) and Nayak and Amer (2000), dynamic test methods for flat-plate solar collectors can be classified into three broad categories based on their similarities in approach: (a) One-node methods (Cooper and Dunkle, 1981; Perers, 1993, 1997; Fischer et al., 2004; EN 12975-2, 2006); (b) Multi-node methods (Frid, 1990; Wijeysundera et al., 1996); (c) Response function methods (Emery and Rogers, 1984; Wang et al., 1987; Prapas et al., 1988; Amer et al., 1999).

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Nomenclature

A	design matrix in WLS method
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 part, m^2
a_j	model coefficient of the corresponding related parameter X_j, different units
b_0	constant used in incident angle modifier equation, dimensionless
c	specific heat, J/(kg °C)
C	covariance matrix in WLS method
DT	dynamic test
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
$K_{\alpha\tau}$	collector incidence angle modifier in steady state method
$K_{\theta b}(\theta)$	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	number of related parameters or model coefficients
MLR	multiple linear regression
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
N	number of testing data points
Q_u	useful heat gain of the collector, W
QDT	quasi-dynamic test
R^2	statistical variance
S	absorbed solar radiation per unit area, W/m^2
SST	steady-state test
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
$U_{b,a}$	heat transfer coefficient of the absorber to ambient, W/(m^2 °C)
$U_{b,f}$	heat transfer coefficient of the absorber to the working fluid, W/(m^2 °C)
U_L	overall heat loss coefficient of a solar collector, W/(m^2 °C)
U_w	wind heat loss coefficient, J/(m^3 °C)
u	uncertainty or error, unit is the same as specific measured parameter
$\dot{V}_f$	volume flow rate of the working fluid, m^3/h
WLS	weighed least square
W	outdoor wind velocity, m/s
X	related parameter
x	measured quantity
y	indirectly obtained parameter

Greek symbols

α	absorptance, dimensionless
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
σ	standard deviation of testing data point
χ^2	merit function value of the WLS method

Subscript

A	type A uncertainties
a	ambient
B	type B uncertainties
b	collector absorber plate
C	combined standard uncertainty
exp	experimental value
f	working fluid
fi	working fluid inlet; independent quantities in error analysis
fo	working fluid outlet
$pred$	model prediction value

Although Nayak and Amer (2000) argued that the response function method seems to be quite reliable among the methods they evaluated, it requires familiarity with digital signal analysis and filtering theory, or many tests and complex calculations (Kong et al., 2012a). Thus it is not convenient to use. When it comes to the multi-node methods, test procedures may not be implemented accurately in experimentation, as presented by Amer et al. (1997). It is