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A new Laplace transformation method for dynamic testing of solar collectors

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ABSTRACT

A new dynamic method for solar collector testing is developed. It is characterized by using the Laplace transformation technique to solve the differential governing equation. The new method was inspired by the so called New Dynamic Method (NDM) (Amer E. et al (1999) [1]) but totally different. By integration of the Laplace transformation technique with the Quasi Dynamic Test (QDT) model (Fischer S. et al (2004) [2]), the Laplace − QDT (L-QDT) model is derived. Two experimental methods are then introduced. One is the shielding method which needs to shield and un-shield solar collector continuously during test period. The other is the natural test method which doesn't need any intervention.

The new L-QDT model with the shielding method are tested by TRNSYS (Klein S. et al (1988) [3]) simulation. Experiments were carried out at Technical University of Denmark by using the L-QDT method and the natural experimental method. The identified collector parameters are then compared and analyzed with those obtained by the steady state test method and the QDT test method. The results comparison shows that the L-QDT method and the natural experimental method are also valid.

It can be concluded that the new Laplace test method can obtain reasonable and accurate collector parameters under transient weather condition.

1. Introduction

1.1. Background

The solar collector testing technology is mainly applied in the area of solar collector evaluation and thermal performance prediction. The definition and identification of solar collector parameters are the main tasks of solar collector testing. The collector parameters can have a variety forms by different test methods. The prevalent test method is the steady state test method which is adopted by most test standards around the world such as ISO 9806 [4], EN 12975-2 [5] and ASHRAE 93 [6]. The steady state test method is featured by its simple mathematical model and convenient data processing method. But the strict test conditions and high-precision data acquisition requirements limit its wide application in connection with outdoor testing. For example, in some regions, especially the north of Europe, it may take several months to acquire enough test data for one test. What's more, the cost of construction and maintenance of the high-precision data acquisition device and control instruments will be obviously high.

To overcome the drawbacks of the steady state test method mentioned above, different kinds of dynamic and quasi-dynamic test methods have been invented since 1980s [7]. Generally, the dynamic test method can be characterized by its relatively complicated mathematical model and data processing techniques but relatively loose test conditions, short test period and extensive adaptability. The Quasi- Dynamic Test (QDT) method [2] is the only dynamic test method adopted by the standard till now as an alternative method in EN 12975 [5] and ISO 9806 [4]. It is the representative of one node method which considers the solar collector and the fluid as a whole. The collector thermal capacity is lumped together and referenced by the mean fluid temperature. The transfer function method [8–11] and the improved transfer function (ITF) method [12] are typical multi-node test methods. The solar collector is divided into a solid part and a fluid part. Each part has its own thermal capacity which is referenced by each part's mean temperature. Other dynamic test methods are known as its unique mathematical model or data processing techniques such as

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Nomenclature

A_P	aperture area of solar collector (m^2)
c	specific heat capacity (J/(kg K))
F'	collector efficiency factor (−)
$F'U_L$	heat loss coefficient at $T_f - T_a = 0$ (W/(m^2 K))
$F'U_1$	temperature dependence of the heat loss coefficient (W/(m^2 K^2))
$F'U_w$	wind speed dependence of the heat loss coefficient (J/(m^3 K))
G_t	total solar irradiance (W/m^2)
G_b	beam irradiance (W/m^2)
G_d	diffuse solar irradiance (W/m^2)
K_b	incident angle modifier for beam irradiance (−)
K_d	incident angle modifier for diffuse irradiance (−)
L	length of collector absorber (m)
m	mass (kg)
$\dot{m}$	mass flow rate (kg/s)
$(mc)_e$	effective heat capacity of the collector per unit area (J/(m^2 K))
n	number of times
t	time (s)
q_u	heat flux per square meter (W/m^2)
T	temperature (K)
T_m^*	reduced temperature (K m^2/W)
U	heat loss coefficient (W/(m^2 K))
w	wind velocity (m/s)

Greek symbols

$\Delta\tau$	time interval (s)
τ	time (s)
$(\tau\alpha)_{en}$	transmittance-absorptance product at normal incidence (−)
θ	angle of incident (°)
ρ	fluid density (kg/m^3)

Subscripts

a	ambient
c	collector
f	fluid
fin	collector absorber fin
fo	fluid outlet
fi	fluid inlet
w	wind
0	beginning

response function method [13–16], the filter method [17], the Laplace transformation method [1], the thermal resistance method [18], the power correction method [19], etc.

1.2. The Quasi-Dynamic Test (QDT) method

The QDT method [20–22] was first developed by Bengt Perers in 1990 and adopted by the European standard EN 12975 [5] in 2000 and by the international standard ISO 9806 [4] in 2013. The QDT mathematical model is well known as Eq. (1). The left hand side of Eq. (1) is solar collector's effective power gain. While at the right hand side, the irradiance is divided into the beam and the diffuse term each with its incident angle modifier and the rest are the detailed heat losses terms. The accuracy of the QDT method has been validated by different independent research, see Ref. [7].

$$\begin{aligned} qu &= \dot{m}c_f(T_{fo} - T_{fi})/A_P \\ &= F'(\tau\alpha)_{en}K_bG_b + F'(\tau\alpha)_{en}K_dG_d - F'U_L(T_f - T_a) \\ &\quad - F'U_1(T_f - T_a)^2 - F'U_w w(T_f - T)_a - (mc)_e\frac{dT_f}{dt} \end{aligned} \tag{1}$$

Compared with the steady state test method, most of the test conditions are loosened in the QDT method. But the allowed deviation of the inlet temperature is still strictly restricted within ±1 K during one test sequence and the flowrate should also be constant. The test duration is usually the same with the steady state test method and it was reported that the thermal capacity of solar collector may not always accurately be identified since the collector reacts under constant inlet temperature condition which could not supply enough collector dynamic response information [23].

1.3. The new dynamic method (NDM)

Amer and Nayak [1,24] developed a new dynamic method (NDM) which is characterized by using the Laplace transformation method for the mathematical model development.

The NDM method is summarized as follows [1]. Consider an element of length Δx along the flow direction of the collector. Its width w equals to the length between the axes of two adjacent riser tubes. The energy balance equation for the element at any time can be expressed as

$$\begin{aligned} \dot{m}c_f\left[T_f(x+\Delta x,\tau) - T_f(x,\tau)\right] &= F'(\tau\alpha)_{en}G_t(\tau)w\Delta x - F'U_L\Big[T_f(x,\tau) \\ &\quad - T_a(\tau)\Big]w\Delta x - (mc)_{\Delta x}\frac{dT_f(x,\tau)}{d\tau} \end{aligned} \tag{2}$$

The effective thermal capacitance of the collector is considered to be uniformly distributed over the area of the collector, then

$$\frac{(mc)_{\Delta x}}{w\Delta x} = \frac{(mc)_{fin}}{wL} = \frac{(mc)_e}{A_P} \tag{3}$$

Take limit of Eq. (2) can derive

$$\begin{aligned} \frac{\partial T_f(x,\tau)}{\partial x} + \frac{F'U_LA_P}{\dot{m}c_fL}T_f(x,\tau) &= \frac{F'(\tau\alpha)_{en}A_P}{\dot{m}c_fL}G_t(\tau) + \frac{F'U_LA_P}{\dot{m}c_fL}T_a(\tau) \\ &\quad - \frac{(mc)_e}{\dot{m}c_fL}\frac{\partial T_f(x,\tau)}{\partial\tau} \end{aligned} \tag{4}$$

The initial and boundary conditions are

$$T_f(x,0) = T_0 \tag{5}$$

$$T_f(0,t) = T_{fi}(t) \tag{6}$$

Eq. (4) is solved by using the Laplace transformation technique which gives the final expression of the fluid mean temperature