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Testing of solar thermal collectors under transient conditions

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Abstract

The most important standard for collector testing in Europe is the EN 12975:2006 which is applied in all the major laboratories and is the reference for the Solar Keymark certification. Besides the steady-state method, the EN 12975 allows the application of the quasi-dynamic method performed outdoors in natural conditions with variable radiation and ambient temperature. The available number of days for each test was investigated by analyzing meteorological data series acquired in the Solar Energy Laboratory (LES) in Lisbon since 2008 showing the advantage of the quasi-dynamic test. Both the steady-state and the quasi-dynamic methods were applied to five collectors of different types (two flat plate collectors, one evacuated tube collector with a back reflector and direct flow circulation, one evacuated tube collector with heat pipes, and a CPC collector). The results were compared and a good agreement between the steady-state and the quasi-dynamic test results was observed. Issues concerning the incidence angle modifiers and the effective thermal capacity of the collectors were analyzed in detail, which resulted in the identification of model and test limitations. Suggestions are given to improve the test methodology and the data analysis of quasi-dynamic test.

Keywords: Solar collector testing; Quasi-dynamic model; Steady-state model; EN 12975

1. Introduction

Tests on performance and quality of solar collectors have a fairly long history. The current European standards were developed on the basis of the ISO and ASHRAE standards created before 1990. In the most common test methods recommended by ISO 9806-1,3 (ISO, 1994), EN 12975-2 (CEN, 2006) and ASHRAE 93 (ANSI/ASHRAE, 2003) the collector thermal performance is determined under stationary and clear-sky conditions, i.e. steady-state test (SST). The EN 12975-2 also allows testing according to the quasi-dynamic test (QDT) method (clause 6.3), performed under natural conditions (outdoors) with variable radiation and ambient temperature (Fischer et al., 2004). In the past years, this method has been applied to several types of solar collectors, namely, flat plate, CPCs (compound parabolic concentrators) and ETCs (evacuated tubular collectors) (Perers, 1997; Horta et al., 2008; Zambolin and Del Col, 2010). The concentrating collectors are also mentioned in the ASHRAE 93-77, ISO 9806-1 and EN 12975-2 but no specific test methods have been developed within these standards. However the QDT was applied to a parabolic trough with good results (Fischer et al., 2006).

The understanding of the transient behavior of a solar collector is important to know how it will perform during the initial phase of heating, how temperature will vary in days with intermittent clouds, when auxiliary heaters will be needed and is also important to study complex systems that have solar collectors as components, such as solar

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Nomenclature

a_1	heat loss coefficient at $(t_m - t_a) = 0$ ($Wm^{-2} K^{-1}$)
a_2	temperature dependent heat loss coefficient ($Wm^{-2} K^{-2}$)
A_a	aperture area of collector (m^2)
b_0	constant for the calculation of the incidence angle modifier
c_1	heat loss coefficient at $(t_m - t_a) = 0$ ($Wm^{-2} K^{-1}$)
c_2	temperature dependent heat loss coefficient ($Wm^{-2} K^{-2}$)
c_3	wind speed dependent heat loss coefficient ($Jm^{-3} K^{-1}$)
c_4	sky temperature dependent heat loss coefficient ($Wm^{-2} K^{-1}$)
c_5	effective thermal capacity ($Jm^{-2} K^{-1}$)
c_6	wind dependent zero loss efficiency (sm^{-1})
c_{eff}	effective thermal capacity of collector ($JK^{-1} m^{-2}$)
E_L	longwave irradiance ($\lambda > 3$ μm) (Wm^{-2})
E_{horiz}	average daily energy on the horizontal plane (MJm^{-2})
F'	collector efficiency factor
G	hemispherical solar irradiance (Wm^{-2})
G_b	direct solar irradiance (Wm^{-2})
G_d	diffuse solar irradiance (Wm^{-2})
K_θ	incidence angle modifier
$K_{\theta b}$	incidence angle modifier for direct radiation
$K_{\theta d}$	incidence angle modifier for diffuse radiation
$K_{\theta T}$	transversal incidence angle modifier
$K_{\theta L}$	longitudinal incidence angle
MLR	multiple linear regression
$\dot{m}$	mass flowrate of heat transfer fluid (kgs^{-1})
QDT	quasi-dynamic test
$\dot{Q}$	useful power extracted from collector (W)
SST	steady-state test
t	time
t_a	ambient air temperature (°C)
t_{in}	collector inlet temperature (°C)
t_m	mean temperature of heat transfer fluid (°C)
T^*	reduced temperature difference $(t_m - t_a)/G$ ($m^2 KW^{-1}$)
u	surrounding air speed (ms^{-1})
u_{ss}	average air speed during the steady-state test (ms^{-1})
θ	angle of incidence – angle between the direction of sunlight and the normal direction of the collector (°)
θ_T	incidence angle projection in the transversal plane (°)
θ_L	incidence angle projection in the longitudinal plane (°)
η_0	zero-loss collector efficiency
σ	Stefan–Boltzman constant ($Wm^{-2} K^{-4}$)
σ_q	power standard deviation (Wm^{-2})
$(\tau\alpha)_{en}$	effective transmittance–absorptance product for direct solar radiation at normal incidence

cooling systems. These concerns have led to the development of many models since the late 70s until now.

Some of these models aim to simulate the behavior of a specific collector and are usually based on the thermophysical properties of materials that constitute the collector and on energy transfer phenomena, such as radiation, convection and conduction, using heat transmission coefficients and correlations available in the literature. These models give good insight into the constructive aspects that have impact on the performance of the collector (Cadafalch, 2009; Rodríguez-Hidalgo et al., 2011; de Ron, 1980; Saito et al., 1984; Zhao et al., 1988; etc).

Other models are intended to serve as a basis for developing experimental test methods for identification of the characteristic parameters of the collector through non-intrusive means, i. e., no instrumentation is placed inside the collector like measuring the temperature of the absorber plate, the glazing or the isolation (Emery and Rogers, 1984; Fischer and Müller-Steinhagen, 2009; Isakson and Eriksson, 1994; Kamminga, 1985; Muschaweck and Spirkl, 1993; Perers, 1993, 1997; Wang et al., 1987; Kong et al., 2012; etc). The Perers model is the basis of the quasi-dynamic model owing to its completeness and ease of use.

1.1. Available testing days

By using the QDT, a testing laboratory will need less intervention from the operator and will have potentially more test days available. This was checked for LES (Solar Energy Laboratory – LNEG – Portugal) (38°46′N, 9°11′W) based on records of all the major meteorological variables (radiation, ambient temperature, etc.) and daily precipitation. These data are available, with few flaws, since the year 2008 with acquisition times ranging from 1 to 5 min. With these data the potential impact that testing with the QDT method would have on the number of collectors tested annually was analyzed. The methodology used in this analysis differs from others (Emery and Rogers, 1984; Kratzenberg et al., 2002; Rojas et al., 2008) and applies specifically to the particularities of thermal performance tests in the LES. In this laboratory, for each test performed with the SST method it takes about 3 h to reach the desired temperature, stabilize the circuit and perform the test. In a clear-sky day only two temperature levels are usually tested. When analyzing the data, each day was identified as having: (a) zero (b) one (1/2 SST day) or (c) two (SST day) 3 h periods in which radiation was stable.