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Short-term efficiency test procedure for solar thermal collectors based on heat loss measurements without insolation and a novel conversion towards daytime conditions

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Abstract

In order to determine the usual thermal efficiency parameters $\eta_{0,hem}$, a_1 and a_2 of solar collectors according to the current international standard ISO 9806:2013, a new and simple short-term test procedure has been developed. It bases upon the experimental determination of the fluid-temperature dependent loss coefficient $F'U_L$ without insolation using stationary heat loss measurements during night. To account for the fact neglected so far, that without insolation the mean absorber temperature is lower than the mean fluid temperature, a conversion to daytime conditions has been evolved: depending on hemispherical irradiance G, transmittance–absorptance product $(\alpha\tau)$ and absorber efficiency factor F', the new conversion formula calculates the (lower) mean fluid temperature during daytime operation, for which the absorber has the same temperature as during the nightly heat loss measurements. The thermal efficiency η_{hem} during daytime operation for arbitrary G then is obtained from the Hottel–Whillier–Bliss equation using $F'U_L$ from nightly heat loss measurements and the recalculated mean fluid temperatures. The new procedure allows the determination of η_{hem} with only a few hours nighttime measurements, provided the peak collector efficiency $\eta_{0,hem}$ and $(\alpha\tau)$ is known. Otherwise, only one additional bright day is needed to perform a standard efficiency measurement at mean fluid temperature equal to ambient temperature. This effort has to be compared to typically one week of clear weather conditions necessary in today's standard steady state tests. The test procedure was successfully validated for two completely different flat plate collectors, a modified standard collector with backside aluminium-film insulation instead of mineral wool ($F'U_L \approx 4,4\frac{W}{m^2K}$ at 70 K over ambient) and an ultra-flat prototype collector with only 40 mm height and no insulation on the backside ($F'U_L \approx 7,0\frac{W}{m^2K}$ at 70 K over ambient). The results of nightly cooling measurements with subsequent conversion by the developed formula show full agreement to the results of η_{hem}-measurements according to ISO 9806:2013 within the common error bars. The new procedure yields an experimental error in daytime-efficiency of 3–4% and can help research institutes or R&D-departments of collector producers to shorten testing time to determine the thermal efficiencies of solar collectors. A broader application and test of the new method for further types of solar collectors by independent researchers is desirable.

Keywords: Short-term collector efficiency test; Nightly heat loss measurement; Conversion formula to daytime efficiency; Heat transfer absorber-fluid

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1. Introduction

The heat losses of a solar collector physically occur from its hottest part, the absorber, which is warmed up by

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Nomenclature

a_1	collector heat loss coefficient, W/(m^2 K)
a_2	temperature dependence of collector heat loss coefficient, W/(m^2 K^2)
c_p	specific fluid heat capacity, kJ/(kg K)
F'	collector efficiency factor, –
F_R	collector heat removal factor, –
G	hemispherical vertical solar irradiance, W/m^2
$\dot{q}$	useful collector heat flux, W/m^2
$T_m{}^*$	reduced (fluid) temperature during daytime operation, m^{2}K/W
U_L	overall heat loss coefficient of the absorber, W/(m^{2*}K)
$\dot{V}$	volumetric flow rate per aperture area, m^3/(s*m^2)

Greek

α	solar absorptance of absorber, –
$(\alpha\tau)$	effective transmittance–absorptance product, –
η_{hem}	collector efficiency, with reference to $T_m{}^*$, based on hemispherical vertical irradiance G, –
$\eta_{0,hem}$	maximum collector efficiency, with reference to $T_m{}^*$, based on hemispherical vertical irradiance G, –
ρ	density of heat transfer fluid, kg/m^3
τ	transmittance of cover, –
ϑ_a	temperature of collector ambient or surrounding, °C
ϑ_{abs}	temperature of absorber, °C
ϑ_e	temperature of fluid exit (=outlet), °C
ϑ_{in}	temperature of fluid inlet, °C
ϑ_m	mean temperature of heat transfer fluid, °C
$\vartheta_{m,day}$	ϑ_m as determined during day at $G > 0$ W/m^2, °C
$\vartheta_{m,night}$	ϑ_m as determined during night at $G = 0$ W/m^2, °C

absorption of solar radiation. They depend on the temperature difference between absorber temperature ϑ_{abs} and ambient temperature ϑ_a. From energy conservation, for the usable heat flux $\dot{q}$ and the daytime efficiency η_{hem} of the collector, respectively, under steady state conditions with hemispherical vertical irradiance G, absorber loss coefficient U_L to ambient, effective product of absorptance α of the absorber and transmittance τ of the cover, $(\alpha\tau)$, is obtained (Duffie and Beckman, 2006):

$$\dot{q} = (\alpha\tau)G - U_L(\vartheta_{abs} - \vartheta_a) \tag{1a}$$

and

$$\eta_{hem} = (\alpha\tau) - \frac{U_L}{G}(\vartheta_{abs} - \vartheta_a) \tag{1b}$$

To account for the fact, that the absorber temperature of solar collectors is not easily accessible for a direct temperature measurement and to facilitate the determination of the collector thermal efficiency via the fluid temperature, the concept of the absorber efficiency factor F' or, alternatively, of the heat removal factor F_R, has been introduced in the 1950s (Hottel and Bliss, 1955; Bliss, 1959). Since then, the following (Hottel–Whillier–Bliss) equations have been used with ϑ_{in} as collector inlet temperature and ϑ_m *as* mean fluid temperature, respectively:

$$\eta_{hem} = F_R\left\{(\alpha\tau) - \frac{U_L}{G}(\vartheta_{in} - \vartheta_a)\right\} \tag{2a}$$

$$= F'\left\{\alpha\tau - \frac{U_L}{G}(\vartheta_m - \vartheta_a)\right\} \tag{2b}$$

The additionally introduced factors F' and F_R balance the fact that the losses, instead to absorber temperature like in Eq. (1), now are referred to fluid mean and inlet temperature, respectively.

While in North America Eq. (2a) so far has been predominantly used, in European standards Eq. (2b) is preferred. With the publication of the joined Standard EN ISO 9806:2014 (ISO, 2014), Eq. (2b) will be used worldwide and is therefore further followed in this article.

Expanding Eq. (2b), the effective loss coefficient becomes $F'U_L$, simultaneously, the maximum efficiency $(\alpha\tau)$ from Eq. (1b) is multiplied by F', the product usually being designated by $\eta_{0,hem}$. Then for η_{hem} is obtained:

$$\eta_{hem} = \eta_{0,hem} - \frac{F'U_L}{G}(\vartheta_m - \vartheta_a), \quad \text{where} \quad F'U_L = a_1 + a_2(\vartheta_m - \vartheta_a) \tag{3}$$

$(\vartheta_m - \vartheta_a)/G$ under daytime conditions usually is designated as reduced fluid temperature $T_m{}^*$, while $\eta_{0,hem}$, a_1 and a_2 are the usual thermal efficiency parameters of solar collectors. In order to determine them from Eq. (3), under steady-state conditions according to ISO 9806:2013 (ISO, 2013), the thermal efficiency has to be measured for at least 4 different ϑ_m evenly spread up to the maximum operating temperature as specified by the manufacturer. This has to be accomplished at clear weather conditions for vertical or at least nearly vertical solar incidence. Due to natural weather variations, this procedure normally takes several days to weeks. Somewhat shorter durations can be realized by sumptuous solar tracking devices or by a relatively sophisticated analysis, if the quasi-dynamic approach is used.

On the other hand, steady-state heat loss measurements without insolation, e.g. during night-time with hot water reversely circulated through the collector, to determine $F'U_L$, are quite simple and of short duration. Typically 1–2 h per operation temperature, characterized by the temperature difference $(\vartheta_{m,night} - \vartheta_a)$, are sufficient. Here,