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Analysis of dynamic properties of flat plate and heat pipe solar collectors

Abstract

The paper presents an analysis of dynamic properties of two flat plate solar collectors differing in the design of coil and vacuum tube liquid-vapour (heat-pipe) collector. The collector identification experiment was carried out under field conditions based on the methodology described in PN-EN ISO 9806: 2014-2 standard. The results of the field experiment were compared with those obtained under laboratory conditions.

Keywords: solar collector, step response, time constant.

1. Introduction

The operational parameters of a solar collector are defined on the basis of the analysis of static and dynamic characteristics, which are determined experimentally based on the methodology described in PN-EN ISO 9806:2014-2 standard [1]. Static properties of the collector are represented by the efficiency characteristic which expresses collector efficiency as a function of reduced temperature. The dynamic properties are characterized by a step response. Analysis of the collector step response enables estimation of the value of steady-state gain factor, time delay and equivalent time constant, which determine the collector response time to stochastic changes in the value of solar irradiance.

In most cases, the so-called differential controller is applied to control a solar heating system. The controller switches a solar pump on or off depending on the preset gradient between the working medium temperature and the temperature of the heated utility water storage tank. Conducted field tests show that the achieved performance of the solar heating system is significantly affected by the performance of the solar pump, which should be selected depending on operating conditions [2, 3, 4]. Commonly used differential controllers performing on-off control algorithm should be replaced by continuous control devices. For correct design of continuous control system, it is essential to know the dynamic properties of a controlled object, at least the solar collector, for which the thermal load is a heated utility water storage tank. In practice, in order to meet the power demand of the system, collectors are usually arranged in series more often than in parallel forming the so-called batteries. Knowing the dynamic properties of a single collector, and the connection method it is possible to estimate the dynamic properties of the entire battery.

The dynamic properties of the collector are usually omitted in certificates prepared during normative investigations. This is probably due to the fact, that according to the standard the determination of a step response is not mandatory. Furthermore, the standard only provides a methodology for determining the equivalent time constant T_z leaving out the time delay T_0 and gain factor k_p, as highlighted in [5]. The main problem is to determine the dynamic properties of the collector at the design stage of the installation based only on catalog data. One of the key collector operating parameters provided in manufacturers technical documentation is the effective thermal capacity of the collector. As pointed in [6, 7], the equivalent time constant, determined from the experimentally defined step response, is independent relation (1) with the effective thermal capacity of the collector, specific heat and mass flow rate of working medium (refrigerant) through the collector.

$$T_z = \frac{(mc)_k}{\dot{m} * c_p} \tag{1}$$

where:

T_z – equivalent time constant, s
$(mc)_k$ – thermal capacity of the collector, J/kgK
$\dot{m}$ – mass flow rate, kg/s
c_p – specific heat of working medium, J/K

The equivalent time constant can be calculated from equation (1) based on the catalog data. The aim of this study was to compare the value of the equivalent time constant determined from the experimentally defined step response with a time constant based on the collector catalog data via equation (1).

2. Methodology of determining the effective thermal capacity of a solar collector during standard tests

The effective thermal capacity is an important performance parameter affecting the dynamic characteristic of the collector, (see equation (1)). There are three methods [1] to determine effective thermal capacity during normative investigations.

The recommended method of calculating the effective thermal capacity is summing the product of mass, specific heat and weighting factor for all components of the collector. The value of weighting factor ranging from 0 to 1 is determined for all components respectively and equals, e.g.: 1 for the absorber and a working medium, 0.5 for the insulation and the product of 0.01 and heat loss coefficient.

$$(mc)_k = \sum_i p_i m_i c_{p_i} \tag{2}$$

where:

p – weighting factor
m – component mass, kg

The standard also allows the determination of the effective thermal capacity of the collector based on the data recorded during the experiment performed either in a room or in the field or a laboratory [1].

According to the procedure of determining the thermal capacity of the collector carried out in a room, working medium flows down from the top of the collector with a constant mass flow and the inlet temperature is constant and equal to the outlet temperature of the medium. The inlet temperature is then increased by steps of 10 K and the transition state of the working medium outlet temperature, mass flow of the working medium and the ambient temperature is recorded until the working medium outlet temperature and thus the collector itself reaches a steady state. The transition state of the collector can be described by equation (3).

$$(mc)_k \frac{dt_m}{dt} = -\dot{m} c_p \Delta T - AU(t_m - t_a) \tag{3}$$

where:

ΔT – gradient between the inlet and outlet temperature of the working medium, K
A – area of the absorber, m^2]
U – coefficient of total heat loss of the collector in relation to the reduced temperature, W/m^2K^2
t_m – average temperature of the working medium, °C
t_a – ambient temperature, °C

Assuming that in steady state $(mc)_k \frac{dt_m}{dt} = 0$ equation (3) can be converted to (4), which allows determining the product of the AU based on the measured values taken in both steady states.

$$AU = \frac{\dot{m}c_p\Delta T}{(t_m - t_a)} \tag{4}$$

By substituting the equation (4) into (3) and converting the equation (3) into (5) it is possible to determine the thermal capacity of the collector.

$$(mc)_k = \frac{-\dot{m}c_p \int_{t1}^{t2} \Delta T dt - \frac{\dot{m}c_p\Delta T}{(t_m - t_a)}\left[\int_{t1}^{t2}(t_{in} - t_a)dt + \frac{1}{2}\int_{t1}^{t2}\Delta T dt\right]}{t_{m2} - t_{m1}} \tag{5}$$

where: t_{in} – inlet temperature of the working medium, °C.

The procedure of determining the thermal capacity of the collector in the field or using a solar radiation simulator implies that the collector aperture is shielded by a transparent cover reflecting solar radiation and the working medium flow through the collector is constant. When the collector reaches the steady state the aperture must be uncovered, and the transition state of the outlet temperature of the working medium, inlet temperature, ambient temperature, solar irradiance and mass flow rate of the working medium must be recorded. The transition state of the collector can be represented by equation (6).

$$(mc)_k \frac{dt_m}{dt} = A\eta_0 G - \dot{m}c_p\Delta T - AU(t_m - t_a) \tag{6}$$

where:

η_0 – optical efficiency of the collector, %,
G – solar irradiance, W/m^2.

By substituting equation (4) into (6), and integrating them, equation (7) is obtained which allows determining the thermal capacity of the collector.

$$(mc)_k = \frac{A\eta_0 \int_{t1}^{t2} G dt - \dot{m}c_p \int_{t1}^{t2} \Delta T dt - \frac{\dot{m}c_p\Delta T}{(t_m - t_a)}\left[\int_{t1}^{t2}(t_{in} - t_a)dt + \frac{1}{2}\int_{t1}^{t2}\Delta T dt\right]}{t_{m2} - t_{m1}} \tag{7}$$

Both experimental methods differ in methodology. In the first method, the transition state of the outlet temperature of the working medium is a result of a step change in the inlet temperature, while in the second method it is a result of a step change in solar radiation. It should be noted that both experimental methods are more labor-intensive than the gravimetric method. It was not specified in technical documentation which method was applied to determine the thermal capacity of the collector.

Fig. 1. The test set-up at WULS-SGGW

3. The test set-up

The Faculty of Production Engineering of WULS-SGGW has a scientific-educational site (Fig. 1), the precise description of which was given in [8] and which allows the experimental determination of the step response of the solar collector in field conditions. The study was conducted according to the methodology presented in [1, 6].

4. Analysis of dynamic properties of flat plate solar collectors

There were performed three studies of flat plate solar collectors: two flat-plate collectors varied in terms of the coil construction (harp and meandering arrangement) and heat pipe solar collector. In order to make a comparative analysis of the collectors dynamic properties, their step responses were set in similar operating points determined by the operating parameters (Table 1). The following operating parameters were considered: solar irradiance, ambient temperature, inlet temperature of the working medium and its volumetric flow. The experiment was repeated four times at the inlet temperature of the working medium of (32 ± 1)°C and the constant mass flow rate. Figures 2, 3, 4 display the experimentally determined characteristics of the selected collector types which will be analyzed later.

Tab. 1. Design parameters and parameters determining the operating points of the collectors during the experiment

		A m^2	G W/m^2	T_a °C	T_{in} °C	$\dot{m}$ dm^3/min	$(mc)_k$ kJ/m^{2}K
Flat plate collector	Harp coil	1.73	995±15	33.3	31.6	2.1	5.67
	Meandering coil	2.00	992±2	29.5	32.3	2.5	5.85
Heat pipe collector		2.11	960±20	29.7	32.9	2.6	4.74

Figure 2 shows the experimentally determined step response of the flat plate solar collector with harp coil arrangement.

The step response was determined in field conditions at the working medium inlet temperature of 31.6°C, the average ambient temperature of 33.3°C, and solar irradiance (995 ± 15) W/m^2. The steady-state gain factor determined by the step response equals $k = 0.0064$, the time delay is 16 s, and the equivalent time constant is 40 s. The test collector has a relatively large ratio of the equivalent time constant to the time delay of 2.5.

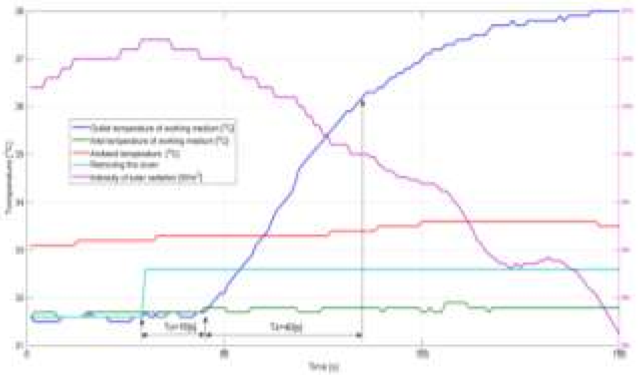

Fig. 2. Step response of the flat plate solar collector with harp coil arrangement

Figure 3 presents the step response of the flat plate solar collector with meandering coil arrangement. The experiment was performed at a slightly lower ambient temperature (29.5 C) compared to the conditions during the tests of the collector with harp coil arrangement. The inlet temperature of the working medium during the experiment was 32.3°C, and the value of solar irradiance varied within the range of (992 ± 2) W/m^2. The steady-state gain factor determined by the step response is of greater value than for the collector with harp coil arrangement and amounts to 0.0066. In both analyzed cases, the analyzed time delay is identical and amounts to 16 s, while the equivalent time constant for the collector with meandering coil arrangement is greater and amounts to 55 s, which means that the collector with meandering coil arrangement is more thermally inert.

Figure 4 shows the experimentally determined step response of the heat pipe collector. The step response was determined in field conditions at the working medium inlet temperature of 32.9°C, the average ambient temperature of 29.7°C and solar irradiance of (960 ± 20) W/m^2. The steady-state gain factor determined by the step response is similar in value to the factors determined for flat plate collectors, and equals k = 0.0056. As compared to the flat plate collectors, the time delay of the heat pipe collector is almost twice as long and amounts to 30 s and the equivalent time constant is almost five times as long (247 s).

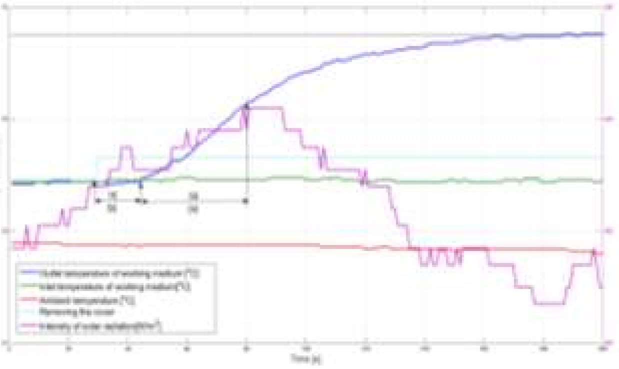

Fig. 3. Step response of the flat plate solar collector with meandering coil arrangement

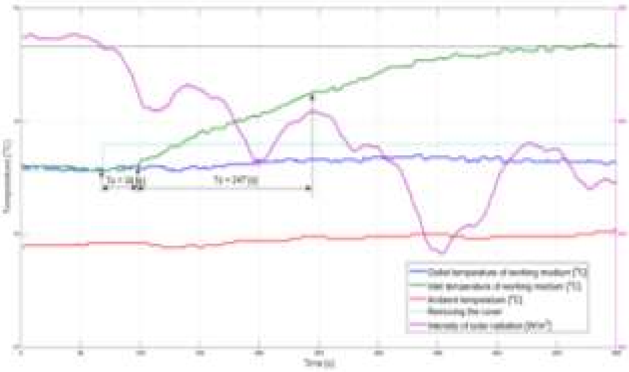

Fig. 4. Step response of the heat pipe collector

5. Analysis of the results

When analyzing the obtained results (Table 2), it should be noted that the flat plate collector with harp coil arrangement had the shortest time constant, and the heat pipe collector had the longest one. The time delay was identical for both types of the flat plate collector, but in the case of the heat pipe collector it was twice as long. The greatest steady-state gain factor value characterized the flat plate collector with meandering coil arrangement. Table 2 also features a comparison of the equivalent time constants of all the collectors, determined during field tests (Fig. 2, 3, 4) and the time constants determined from relation (1) based on the value of thermal capacity included in technical documentation of each collector type. The obtained results were mixed. This means that calculating the equivalent time constant based on relation (1) may result in an error in assessing the dynamic properties of the collector.

Tab. 2. The dynamic properties of tested collectors determined in field conditions

		k_p	T_0, s	T_z, s	T_z determined in relation (1), s
Flat plate collector	Harp coil	0.0064	16	40	67.6
	Meandring coil	0.0066	16	55	69.8
Heat pipe collector		0.0056	30	247	56.6

The step response was determined four times for each collector. For the flat collectors, there was a high repeatability of the results. In the case of the collector with harp coil arrangement the value of the equivalent time constant varied within the range of (40 ± 3) s, and in the case of the collector with meandering coil arrangement – within the range of (55 ± 3) s. The equivalent time constant determined by the step response obtained in field conditions was smaller than that determined by relation (1) in each of the repetitions (Table 2). The value of the gain factor for both flat plate collectors varied within the range of k_p ±0.0005 and the time delay T_0 within the range T_0 ±2 s.

For the heat pipe collector slightly larger discrepancies were obtained. In the analyzed case (Fig. 4), the equivalent time constant determined from relation (1) is five times shorter than that determined from the experimentally obtained step response. In four iterations, the equivalent time constant varied within the range of 180 to 250 s. Such a large difference in the value means significant difficulties in developing and implementing a continuous control algorithm for the solar pump performance. The steady-state gain factor for the heat pipe collector varied within the range of k_p ±0.005 and the time delay – within the range of T_0 ±2 s.

6. Conclusions

Knowledge of the dynamic properties of solar collectors is essential not only for the correct design of a continuous control system but also – right at the design stage – for preliminary assessment of the collector sensitivity to the variability of solar irradiance, which is a stochastic function. From the point of utilization the collectors of high inertia are preferable. They are less sensitive to frequent, short-term changes in solar irradiance - possible during a sunny day - which may destabilize an operating system (through turning a solar pump on and off). As the presented analysis shows, the value of the equivalent time constant determined from the experimentally obtained step response differs from the value determined from relation (1). However, it should be noted that both flat plate and heat pipe collectors are non-stationary objects. The lack of data on the steady-state gain and time delay as well as the fact that the collector is not thermally loaded during normative investigations pose an additional difficulty in the design of a continuous control system. Under operating conditions, the collector is thermally loaded by a heated utility water storage tank which may affect its dynamic properties.

7. References

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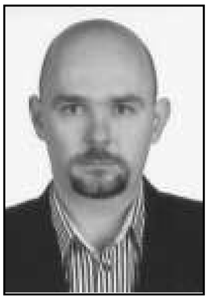

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