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Transfer functions of solar collectors for dynamical analysis and control design

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ABSTRACT

In view of system efficiency and environmental protection, it is of primary importance to harvest solar energy better and better for example by means of developing solar collectors. Mathematical modelling is the theoretically established tool for it, for example with using the collector transfer functions. Knowing the transfer functions, the collector outlet temperature can be predicted as a function of the input variables (solar irradiance, inlet temperature, environment temperature), furthermore, collector control can be effectively designed based on the well-tried methods of control engineering.

In this study, new, validated collector transfer functions are proposed based on a mathematical model that can be found in the literature and has been applied successfully in the field. The transfer functions are used for dynamical analysis of collectors and for collector control design based on the methods of control engineering. The dynamical analysis is shown and the efficiency of the worked out control is demonstrated with regard to a real collector field.

1. Introduction

In view of system efficiency and environmental protection, it is of primary importance to harvest solar energy better and better for example by means of developing solar collectors. Mathematical modelling is the theoretically established tool for it.

Several physically-based collector models can be found in the literature. Among the most important and current ones, the Hottel–Whillier–Bliss model [1] may be the earliest one, which is frequently used to date [2]. This model determines the collector temperature as a function of not only the time but a space coordinate, so the model is distributed, the same as the system of partial differential equations proposed by Hilmer et al. [3] corresponding to unglazed collectors. This latter model divides the collector into three main parts.

Nayak and Amer [4] introduced ten different methods (e.g. the method of the standard ASHRAE 93-86 [5]) along with the used collector models for the determination of the characteristic collector parameters.

Among the recent and current collector models, the nonlinear one proposed by Perers and Bales [6] may be the most widely used one. This model, which is the improved version of the quasi-dynamical one from the standard EN 12975 [7], takes into account several environmental circumstances, for example the radiant heat loss to the environment, the wind speed and the inclination angle of the solar irradiance. The model (denoted with "type 832" in TRNSYS [8]) and its former version ("type 132") are widely used in the large No. 26 project of the IEA (International Energy Agency), which aims at the development of combined solar heating systems [9].

Amrizal et al. [10] developed a dynamical collector model applying the piston flow concept as a simplification of a linear ordinary differential equation model similar to the one used in the present paper. Namely, the collector model proposed by Buzás et al. [11] is linear with respect to the outlet temperature, validated [11–13] and accurate enough for different successful applications [12–14]. The simple applicability is an advantage of the linear model. It should be mentioned that the nonlinear improvement of this model [15] is not much more accurate but generally much more complicated to apply (cf. [12,15]).

From the model of Buzás et al. [11], the collector transfer functions have been determined in a recent conference paper [16] and a doctoral dissertation and thesis [17,18], and have been applied for the dynamical analysis of a solar collector. It can be said generally that the transfer function based modelling is a relatively new and not frequent approach in the analysis of solar collectors, especially in case of domestic purposes. Some further

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examples in this subject are the following: Amer et al. [19] solved the basic collector model with time and one space dimension for the collector fluid temperature using Laplace transformation. The result is used in a dynamical test method for identifying the characteristic parameter values of flat-plate collectors. Huang and Wang [20] simplified a nonlinear two-node (fluid and solid nodes) collector model and wrote it into the Laplace transformed form then the gained transfer function was used to describe the dynamical behaviour of the system. Also a two-node model is used by Bettayeb et al. [21] to determine the transfer function corresponding to the fluid temperature and the absorbed solar energy, which was considered as a function of time (in time domain). The resultant high-order rational transfer function is reduced in different ways. The efficiency of the reduced order models is compared in simulations.

The most prevalent and simple control strategy is the differential (or on/off) control for solar collectors in domestic hot water (DHW) production. In this control strategy, the pump is switched on and off according to prefixed values of the difference between the collector outlet and inlet temperatures. This control is customarily used in solar heating systems without heat exchanger, where the solar storage (outlet) temperature can be considered directly as the collector inlet temperature. Such systems are often applied for swimming pool heating (see e.g. Ref. [22]) or DHW heating (see e.g. Refs. [23,24]) primarily in climates, where freezing temperatures do not occur. The detailed analysis of the differential control can be found in the literature (see e.g. Ref. [25]).

Maximal exergy gain from solar collectors has been realized with flow rate modulation [26,27]. The maximization of the time integral of the exergy flow takes place numerically with special mathematical programming using realistic (METEORAR) meteorological data in Ref. [26]. Similarly (with flow rate modulation), Badescu [24] maximized the time integral of the output heat from the collector (transferred into the storage) based on the Pontryagin maximum principle and again on the a priori knowledge of weather data. Based on the mathematical exergy and energy analysis of flat plate solar collectors, Jafarkazemi and Ahmadifard [28] gave formulae of exergy and energy efficiencies, which can be used to optimize working conditions of collectors.

Tóth et al. [29] used a partial differential equation model to describe the physical processes in a solar collector-like water heating equipment. The outlet temperature is controlled to maintain a reference value by model-based controls corresponding to the proposed model and its mathematical inversion. The manipulated variable is the flow rate in the equipment.

Based on our studies in the literature, not many improvements on control for collectors used in domestic applications have been established in the recent few decades, furthermore, the transfer function based control design can be said to be rather rare in case of such systems. Two examples in this subject are the following: Candanedo and Athienitis [30] controlled solar buildings (which meet a considerable fraction of their energy needs directly from solar irradiation and active solar heating systems) with PID and predictive control methods based on the transfer function model of the buildings. Pasamontes et al. [31] dealt with the temperature control of the collector field of a solar air cooling system. The used simplified model is of first-order with time delay, from which the transfer function is determined. The parameter values in the transfer function are being varied during operation according to the proposed switching control strategy. (This strategy type chooses from among several linear models of different operating points according to the current operating state of the system.)

Transfer function based control design is much more prevalent for industrial processes, as is the case for solar power plants and solar desalination plants. A basic collector model for such systems is a system of partial differential equations [32], with the linearization of which relevant PID [33] or model predictive controls [34] can be given. The general control purpose in such systems is the output temperature control to follow some reference signal in time (see e.g. Ref. [35] regarding a molten-salt solar thermal central receiver [32], for solar power plants generally and [36] for seawater desalination) by means of flow rate modulation. Meaburn and Hughes [37] dealt with the control of a collector field of a solar power plant using oil as heat transfer fluid. From the discretized version of the collector model, which contains two nodes (oil and metal nodes), the collector transfer function is determined and used in the prediction of a feedback control scheme with parallel predictor (or compensator). A special power plant type employing molten salt as a heat transfer fluid is investigated in Ref. [38]. From the simplified version of the governing two-node (salt and metal nodes) model, the collector transfer function is determined. Then the transfer function is used to parameterize dynamical model uncertainties and, by this, to work out a predictive controller for the collectors. Based on models for solar desalination plants, collector transfer functions are determined and used for the prediction process of different predictive controllers in Refs. [36,39,40].

In this study, new, validated transfer functions for solar collectors used primarily for domestic purposes are proposed and a control for collectors is designed based on the transfer functions. These are the unique transfer functions concerning the linear mathematical model validated in Refs. [11–13], so the transfer functions are also validated, since they are an alternative representation of the same model. (In other words, the validation corresponding to the solar collector in Refs. [11–13] is the validation of the transfer functions proposed in this paper.)

The advantages of the transfer functions are considerable: Knowing them, dynamical analysis of the collectors can be carried out and collector control can be effectively designed based on the well-tried methods of control engineering. The simple applicability is a further advantage of the linear mathematical approach in connection with the transfer functions.

The contributions of our work in details are the following:

1. Based on a validated collector model [11], collector transfer functions are determined and used for the dynamical analysis of a real collector field. It should be noted that the most of these theoretical and practical results can be found in the recent conference paper [16] and doctoral dissertation with its thesis [17,18], although with respect to another real collector. Nevertheless, it is the first time that these results are published in the international literature.
2. As a further important and new application of the transfer functions, a closed-loop (PI) control for solar collectors is worked out by the methods of control engineering. The efficiency of the proposed control is demonstrated based on simulation results.

The paper is organized in the following way: Section 2 describes the basic collector model, based on which the collector transfer functions are determined in Section 3 and applied for the dynamical analysis of a real collector field. The transfer functions are used for collector control design in Section 4, where the worked out control is applied and evaluated in relation to the mentioned real collector field. Final conclusions and future research proposals are given in Section 5.

The main concepts and methods of control engineering (Laplace transform, transfer function, step response, P, PI controls, stability, static error, etc.) underlying our work can be found e.g. in Ref. [41].