Solar Energy 160 (2018) 103–116

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

Analog model of dynamics of a flat-plate solar collector

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ARTICLE INFO

Keywords:
Solar collector
Transfer function
Hybrid system supply
Control system

ABSTRACT

The flat-plate solar collector has been treated as a regulation object. An analog model of dynamics of the collector, based on the equivalent thermal network (ETN) method, has been proposed. The solar collector has been presented as an electrical circuit and has been calculated as a four-terminal network. Model was based on the construction and operating parameters of the collector, which allowed to shape the dynamics of work already at the stage of its design. An innovative solution has been proposed that has not yet appeared in the subject. The analog model has been verified on the digital model determined by experiment with using the parametric identification method. The models are to be used in designing of systems and algorithms for controlling of operation of hybrid supply systems. Transfer functions and step responses for both collector models (analog and digital) has been analyzed.

1. Introduction

Investment decisions associated with building or development of a company are always made taking into account the available power engineering infrastructure, existing or planned. The investor analyzes the future costs of energy consumption, considers the possibility of their reduction, taking into account the potential use of renewable energy sources. When the investment is planned in less urbanized areas, where electricity is accessible to a limited extent, worth considering is the possibility of construction of a Hybrid System Supply (HSS). HSS is based on cooperation of traditional and non-conventional energy sources, which complement one another and work for a shared grid. Renewable energy (solar, geothermal, wind energy) in such systems is of priority significance. It should be used in the first place, and any surplus should be accumulated for further use. Such solution requires management of energy flows through proper control of operation of the HSS segments, including the energy accumulators. Without engaging broadly understood automation in the process of obtaining, processing and accumulating of energy, such undertaking will be of low efficiency.

The automation systems used in this case include high-tech equipment and software to implement the intelligent control algorithms. They must be based on ongoing analysis of HSS operation, with the possibility of prediction of future states in intervals of 2, 4 and even 24 h. Construction of a hybrid system supply and a control system is expensive. Therefore, it is necessary to identify the potential problem at the design stage. Such identification should be based on earlier simulation tests using models that reproduce the dynamics of operation of individual system components.

Solar collectors for heating of tap water are a component of solar heating installations, which usually constitute the basic segment of the HSS. Determination of dynamics of operation of the collector, as the object of regulation, requires, in the first place, isolation of input and output signals. In this study, the output signal is the temperature of the medium at the collector outlet. There are two input signals: solar radiation intensity and temperature of the medium at the collector inlet. There are other physical quantities present in the analysis of the collector dynamics, which may be treated as forcing signals. However, the potential changes in their value have a much lesser impact on the collector operation in comparison with those listed earlier. Such quantities include, for instance, ambient temperature, wind speed, humidity etc., which in this analysis will be treated as operating parameters.

The collector dynamics are determined if: equations describing correlations between input/output signals are known, or the form of transfer function binding the input/output signals is known, or step response courses are known for certain standard forced generations of input signals (in this case, for the step function). Therefore, in analyses of operation of solar heating installation, a lot of attention is paid to modeling of thermally transient states. The collector models built are analog or digital.

The objective of this study is to develop an analog model, which reproduces the dynamics of work of a solar collector, based on its structural and operating parameters and to compare it with a digital model determined on the basis of an experiment (model verification:

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https://doi.org/10.1016/j.solener.2017.11.079
Received 12 October 2017; Received in revised form 23 November 2017; Accepted 30 November 2017
0038-092X/

Nomenclature

Basics

I	solar radiation intensity, W/m^2
P	solar radiation, W
T	temperature, K
Q	volumetric flow rate, m^3/s
$R_{i\text{-}j}$	thermal resistance between the node i–j, K/W
C_i	heat capacity of the node i = 1–3, J/K
P_i	heat flux generated in the node i = 1–2, W
v	flow rate (in Fig. 1)
$P_{i\text{-}j}$	heat flux between the node i–j, W
G(s)	transfer function
a	absorptivity (in Eqs. (2) and (4)) or transfer function coefficient (in Eqs. (6) and (7))
b	transfer function coefficient (in Eqs. (6) and (7))
s	Laplace operator
τ	transmittance

Indexes

fin, i	inlet
fout	outlet
o	outside
he	heat exchanger – environment (Fig. 2)
hh	hot side of the heat exchanger (Fig. 2)
hc	cold side of the heat exchanger (Fig. 2)
c	collector
f	working medium (fluid)
a	absorber
g	glass cover

when analog model corresponds to a digital model – which is developed from real measurement data – it means that also analog one corresponds to reality). Both models are to be presented in a transfer function format.

The innovation of the proposed model solution is based on the technology of its creation. This technology combines heat transfer issues with the theory of electrical circuits and – most of all – automation issues. The result is a model, described by a transfer function, that is part of a block diagram of a control system, e.g. in a hybrid system supply (HSS). The layout of the control system contains a number of elements (blocks), which represent the dynamics of the cooperating devices. In general, these devices operate with different forms of energy, such as thermal, electrical, mechanical. Their analysis – without a certain reference to common analogy, such as for electrical phenomena – would be difficult to carry out. A simpler way is to develop a control algorithm, select the kind and type of the controller, with an outlined block diagram of the system with indicated signals (physical quantities) flowing between individual elements of the scheme. Thermoelectric analogy allows to interpret the heat flux flow and thermal process as a flow analysis of the current and related voltage drops on the passive elements of the electric circuit. The analogy to electrical phenomena is also used in other areas of science, e.g. in pneumatics. Significant methods for electrotechnics can solve problems in different disciplines. Circuit theory has extensive methods and numerical tools, which greatly simplifies a solution seeking.

2. Solar collector dynamics models

Solar collector dynamics models are usually developed in the context of research objectives. They may differ due to simplifying assumptions, which may be acceptable in one case and unacceptable in another. It means that use of the models proposed may be limited only to the same or similar problems analyzed (Szargut and Stanek, 2007; Liang et al., 2015; Luminosu and Fara, 2005).

The analog model is most often based on differential equations describing heat exchange in transient states (Beckman and Duffie, 1974; Tsilingiris, 2000). For this purpose, it is possible to use the traditional energy balance methods, such as (Beckman and Duffie, 1974; Zima and Dziewa, 2010a, 2010b), as well as other methods, such as the equivalent thermal network (ETN) method based on a thermoelectric analogy (Chochowski, 1991; Chochowski and Obstawski, 2017; Chochowski and Piotrowska, 2013; Farkas, 1991). This method, or rather a technique of building of heating models, fits well the application in automation. A weakness of analog models is caused by assumptions made upon their development, which sometimes to oversimplify the phenomena analyzed. On the other hand, the possibility of conducting simulation research at the design stage is a strength. They do not require an experiment using the ready device.

Development of digital models requires a database from operating measurements. This is associated with the necessity to conduct the experiment using real models. First, an object is built, a long-term experiment is conducted, and then the model is developed. This is a flaw of the modeling, which makes it expensive. Thanks to measurements, however, it is possible to adapt the model with a single, required level of accuracy on the basis of parametric identification (Chochowski and Piotrowska, 2013; Aleksiejuk, 2016; Piotrowska and Chochowski, 2012) or the method of artificial neural networks (ANN; Kalogirou, 2000). It may sometimes be more accurate than the analog model, as it is not necessary to introduce additional simplifying assumptions.

In literature, modeling is most often connected with analysis of collector performance, determination of heat losses, forecasting of temperature of the medium at the collector outlet (Deng et al., 2015a, 2015b, 2017, 2016a, 2016b; Amrizal et al., 2012). Some publications have emerged, in which modeling has been studied more broadly in the context of optimization, e.g. in terms of the economic effects achieved, (Kalogirou, 2004; Szargut and Stanek, 2007), in particular, in relation to solar power systems as a whole.

In Prapas et al. (1988) the authors analyze the work and performance of the solar collector in transition states. By investigating the collector's response to the change in solar radiation, they propose a method for short-term forecasting of the collector's heat output (taking into account transient states). The collector is treated as a homogeneous body, described by one equation. As a forced variable, solar radiation was assumed. The influence of the working medium inlet temperature change on the dynamics of its heating has not been analyzed.

The same authors have worked on the variability of effective heat capacity in steady and transition states of different heat systems (Prapas et al., 1987), including the solar collector. The results of the analytical work may be useful for modeling and evaluating the dynamics of the collector and for the development of control algorithms.

There are not many publications focusing on issues of automation, selection of controllers, control algorithms and management of energy flows in hybrid systems.

A large number of studies use the equivalent thermal network (ETN) method based on a thermoelectric analogy, to design and analyze the collector thermal states (Chochowski, 1991; Kamminga, 1985a, 1985b; Farkas and Geczy-Vig, 2003; Bosanac et al., 1994; Henning and Sasse, 1955; Cristofari et al., 2002; Fraisee et al., 2003). As thermal phenomena are reproduced using electrical circuits, the method enables a transparent analysis of heat flows in extended power supply systems (Chochowski and Obstawski, 2017). It is used to study heat exchange not only in solar collectors (Chochowski and Piotrowska, 2013; Capizzi et al., 2017; Zhao et al., 2016; Cascellaa et al., 2017; Chen et al., 2015). However, these works do not indicate directly the possibility of