Solar Energy 150 (2017) 596–607

Contents lists available at ScienceDirect

Solar Energy

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

Transfer functions of solar heating systems with pipes for dynamic analysis and control design

Richárd Kicsiny

Department of Mathematics, Institute of Environmental Systems, Szent István University, Páter K. u. 1., 2100 Gödöllő, Hungary

ARTICLE INFO

Article history:
Received 6 October 2016
Received in revised form 8 April 2017
Accepted 2 May 2017
Available online 11 May 2017

Keywords:
Solar heating systems
Pipes
Transfer functions
Control design

ABSTRACT

In view of system efficiency and environmental protection, it is important to harvest solar energy better e.g. by improving solar heating systems. A theoretically founded tool for it is mathematical modelling with the use of system transfer functions. Knowing the transfer functions, the outlet temperature of the system can be determined as a function of the system inputs (solar irradiance, inlet and environment temperatures), the dynamic analysis of the system can be carried out, furthermore, stable feedback control can be designed effectively based on the mathematical methods of control engineering. The designed control can be used e.g. to provide just the minimal required outlet temperature for the consumer and, therefore, to maximize the produced heat with minimal or without any auxiliary heating cost.

Although, pipes can affect the operation of solar heating systems considerably, this effect has not been built in the transfer functions of such systems worked out already in the literature. In this study, new transfer functions for solar heating systems with pipes are proposed based on a validated mathematical model. Transfer function based control design is also given generally. As particular applications, the dynamic analysis and the design of a stable P control are presented on a real solar heating system. It is also presented quantitatively that the designed P control is faster and more precise than the most conventional on/off control. Furthermore, the presented methods can be easily adapted for any solar heating system with long pipes equipped with an external heat exchanger.

1. Introduction

In view of system efficiency and environmental protection, it is important to harvest solar energy better e.g. by developing solar heating systems (see e.g. (Bíró-Szigeti, 2014)). The theoretically founded tool for it is mathematical modelling.

Various ordinary differential equation (ODE) models are used in the field. In (Buzás and Farkas, 2000), systems with collector, heat exchanger and storage are modelled with a (multidimensional) ODE, which is linear as well as its improved version in (Kicsiny et al., 2014), where system pipes are also modelled with ODEs. The latter linear model, which is used with slight modification in the present paper, is validated and accurate enough for general engineering purposes on modelling and developing solar heating systems. The simple usability is a great advantage of linear models. Furthermore, the nonlinear version of the linear model of (Kicsiny et al., 2014) (proposed there as well) is not much more accurate but much more complicated to apply.

From the mathematical model of Buzás et al. (1998), transfer functions for collectors (Buzás and Kicsiny, 2014) and for simplified solar heating systems without pipe effects (Kicsiny, 2015) have been worked out and used for dynamic analysis. These research results are extended in the present paper by the determination of transfer functions for solar heating systems with pipes and the application of the transfer functions in the dynamic analysis of a particular real system. It can be stated generally that the transfer function based modelling is a relatively new and not frequent approach in the analysis of solar heating systems, especially, in the domestic case. Further examples in this subject are the following: Bettayeb et al. (2011) and Huang and Wang (1994) used two-node models to propose collector transfer functions.

Several control strategies with pump flow rate modulation have been applied in solar heating systems: in (Löf, 1993), differential, P (proportional), I (integral), PID (proportional integral differential), adaptive and certain kinds of optimal controls are discussed. Generally, the useful heat gain is to be maximized, in some sense, with optimal controls, by flow rate modulation. The Pontryagin maximum principle (Pontryagin et al., 1962) is used to work out such controls in the field of solar heating systems in (Badescu, 2008; Kovarik and Lesse, 1976; Orbach et al., 1981; Winn and Hull, 1979). For the application of the controls of (Badescu, 2008; Kovarik and Lesse, 1976; Orbach et al., 1981), the knowledge of

---

E-mail address: Kicsiny.Richard@gek.szie.hu

http://dx.doi.org/10.1016/j.solener.2017.05.006
0038-092X/

Nomenclature

t	time (s)
L^{-1}	symbol for inverse Laplace transformation
Time-dependent variables	
I_c	solar irradiance (global) on the collector surface (W/m^2)
T_c	collector (fluid) temperature (°C)
T_{pc1}	pipe temperature between the collector outlet and the heat exchanger (°C)
T_{pc2}	pipe temperature between the heat exchanger and the collector inlet (°C)
T_{pi1}	pipe temperature before the heat exchanger in the inlet loop (°C)
T_{pi2}	pipe temperature after the heat exchanger in the inlet loop (°C)
T_{out}	outlet temperature of the heat exchanger in the inlet loop (°C)
$T_{out,r}$	reference (outlet) temperature of the heat exchanger in the inlet loop (°C)
T_{ce}	temperature of the collector environment (°C)
T_{pce}	environment temperature of the pipes in the collector loop (°C)
T_{pie}	environment temperature of the pipes in the inlet loop (°C)
T_i	temperature of the inlet (fluid) to the system (°C)
v_c	flow rate in the collector loop (m^3/s)

v_i	flow rate in the inlet loop (m^3/s)
Constant parameters	
A_c	area of collector surface (m^2)
A_P	control (tuning) parameter for the proportional control (–)
c_c	specific heat capacity of the fluid in the collector (J/(kg K))
c_i	specific heat capacity of the fluid in the inlet loop (J/(kg K))
k_{pc}	heat loss coefficient of the collector pipes to the environment (W/(mK))
k_{pi}	heat loss coefficient of the storage pipes to the environment (W/(mK))
L_{pc}	length of the collector pipe in one direction (m)
L_{pi}	length of the storage pipe in one direction (m)
T_I	control (tuning) parameter for the integral control (–)
U_{Le}	(overall) heat loss coefficient of the collector (W/(m^2 K))
V_c	volume of the collector (m^3)
V_{pc}	volume of the collector pipe in one direction (m^3)
V_{pi}	volume of the storage pipe in one direction (m^3)
η_0	optical efficiency of the collector (–)
Φ	effectiveness of the heat exchanger (–)
ρ_c	mass density of the fluid in the collector (kg/m^3)
ρ_i	mass density of the fluid in the inlet loop (kg/m^3)

future meteorological data is needed. This is also the case in (Ntsaluba et al., 2016), where the objective is to maximize the overall gained solar energy of the system while minimize the losses but still meet the heat requirements of the consumer. Clearly, such controls cannot be put directly into practice because the weather is not known in advance. The problem is partially but not fully resolved if it is assumed a priori that only one on and off switches will occur during the considered time interval. In this case a feedback control stands for the optimal one, which, theoretically, can be used in the practice (Orbach et al., 1981), but, the mentioned assumption seems rather speculative.

So-called (often nonlinear) model based controls also exist but they are generally complicated to apply because of the need to predict system output at future time instants and (similarly to the optimal controls) the use of objective functions (Camacho et al., 2007a).

P and PI (proportional integral) controls for collectors (Buzás and Kicsiny, 2014) and for simplified solar heating systems without pipes (Kicsiny, 2015) have been proposed recently. The present work extends these results by means of control design for solar heating systems considering pipe effects according to a future research task set in the Conclusion of (Kicsiny, 2015). Based on studying the literature, not many developments have been carried out on controls (particularly, on transfer function based controls) for domestic type solar heating systems in the recent few decades. Controls based on transfer functions occur in industrial processes, e.g. for solar power plants (Camacho et al., 2007b) and solar desalination plants (Ayala et al., 2011; Fontalvo et al., 2014). The general purpose in such control schemes, as in the present work as well, is that the output temperature follows some reference signal in time by means of the flow rate modulation.

Although, pipes can affect the operation of solar heating systems considerably (Kicsiny et al., 2014; Ntsaluba et al., 2016), this important effect has not been built in the transfer functions of such systems worked out already in the literature. The significant delaying and heat loss effects of pipes in hydraulic systems are studied and modelled generally in (Kicsiny, 2017). The contributions of the present paper are the following in details: by means of the mathematical methods of control engineering, new transfer functions for solar heating systems with pipes are proposed and used for dynamic analysis and control design. According to a there appointed future research task, the present study extends the research results of (Buzás and Kicsiny, 2014 and Kicsiny, 2015), where transfer functions, dynamic analysis and corresponding control have been proposed for solar collectors and simplified solar heating systems (without considering pipe effects). The here worked out transfer functions are based on the slightly modified version of the linear ODE model proposed and validated in (Kicsiny et al., 2014). The main novelty and advantage of this model, in contrast to former ones used to work out transfer functions, is that it takes into account the effects of the pipes in the system, so the worked out transfer functions, as their novelty and advantage as well, also consider pipe effects. This modified model is detailed and validated in the present paper based on measured data. Both the dynamic analysis and the control design are interpreted with respect to a real solar heating system, where the pipe effects are significant and important to model, see (Kicsiny et al., 2014; Kicsiny, 2017). Stability criterion is also given for the designed closed-loop proportional (P) control. The efficiency of the proposed control design is shown by means of simulations. The advantages of the transfer functions are considerable: by knowing them, dynamic analysis can be made and feedback control can be designed based on the standard methods of control engineering. Such a control is generally much simpler than optimal and (nonlinear) model based controls but it can follow the reference signal more precisely and rapidly than the on/off control working with constant flow rate (Duffie and Beckman, 2006), which can be called the most conventional control method, even, it is not out of date and still worth researching (Araújo and Pereira, 2017). The simple usability may be the main advantage of the linear approach in connection with the transfer functions.