Renewable Energy 89 (2016) 108–124

Contents lists available at ScienceDirect

Renewable Energy

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

Optimal flow control of a forced circulation solar water heating system with energy storage units and connecting pipes

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ARTICLE INFO

Article history:
Received 23 June 2015
Received in revised form
8 November 2015
Accepted 17 November 2015
Available online xxx

Keywords:
Flat plate solar collector
Flow rate optimization
Maximum energy extraction
System thermal losses
Thermal comfort

ABSTRACT

This paper focuses on pump flow rate optimization for forced circulation solar water heating systems with pipes. The system consists of: an array of flat plate solar collectors, two storage tanks for the circulation fluid and water, a heat exchanger, two pumps, and connecting pipes. The storage tanks operate in the fully mixed regime to avoid thermal stratification. The pipes are considered as separated components in the system so as to account for their thermal effects. The objective is to determine optimal flow rates in the primary and secondary loops in order to maximize energy transfer to the circulation fluid storage tank, while reaching user defined temperatures in the water storage tank to increase thermal comfort. A model is developed using mainly the first and second laws of thermodynamics. The model is used to maximize the difference between the energy extracted from the solar collector and the combined sum of the energy extracted by the heat exchanger and corresponding energies used by the pumps in the primary and secondary loops. The objective function maximizes the overall system energy gain whilst minimizing the sum of the energy extracted by the heat exchanger and corresponding pump energy in the secondary loop to conserve stored energy and meet the user requirement of water tank temperatures. A case study is shown to illustrate the effects of the model. When compared to other flow control techniques, in particular the most suitable energy efficient control strategy, the results of this study show a 7.82% increase in the amount of energy extracted. The results also show system thermal losses ranging between 5.54% and 7.34% for the different control strategies due to connecting pipe losses.

1. Introduction

Recently, intensive efforts have been made in attempt to either integrate or replace conventional energy sources with renewable energy sources (RES) in order to meet power demands [1]. This is due to the fact that RES are non-polluting and non-depletable whilst they also have low operation and maintenance costs thus making them potential sources of alternative energy [1–3]. Solar water heating systems (SWHS) are among the most common and favourable renewable energy systems as the use of these systems can result in significant energy savings. However, there are limiting factors to be considered when utilizing SWHS. These include:

a) Unpredictable behaviour (energy produced from RES may not always meet the demand)
b) Economic viability
c) Thermal performance

It is therefore essential to investigate ways to overcome these limitations so as to increase the viability of SWHS. A common solution to a) and b) is the use of an effective thermal energy storage system (one that is able to store thermal energy at the highest possible temperature whilst exhibiting minimal thermal losses). The main thermal energy storage techniques include: thermally stratified storage[1] and reversible chemical heat storage.[2] A second method involves integrating SWHS with a flow control device (pump) in order to increase the rate of energy transfer thereby maximizing energy transfer from the solar collector to the energy storage units (tanks) [4,6]. Optimal flow control is therefore an

[1] Thermal stratified storage is a technique that is widely used in energy conservation and load management applications. Stratification describes the temperature difference that can exist between different levels inside a tank. A multinode approach (the tank is typically divided into N nodes) is used to characterize the energy in the tank [4,5].

[2] Reversible chemical heat storage is a technique that is based on the conversion of solar radiation into high-temperature heat. This technique utilizes a system of reactants that either transfer energy to the storage tank or extract energy from the tank. The system is connected in an open loop or closed-loop configuration [4].

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http://dx.doi.org/10.1016/j.renene.2015.11.047
0960-1481/

important factor that can be used to increase the performance of SWHS.

This can be achieved through the application of optimal flow rate strategies. Optimization will however result in different optimal strategies based on the objectives and constraints of the defined problem. For instance, different optimal flow control strategies may be obtained when considering cost minimization as oppose to energy maximization. Existing approaches to energy maximization through mass flow rate control are reported in [4,7–13]. In particular [7], investigates optimal flow control of a closed-loop SWHS with one and two serpentines used for heat exchange in the storage tank. The results show that optimal switching between the minimum and maximum flow rate (mainly known as bang–bang control) yield a greater energy gain, system efficiency and reduced system thermal losses when compared to traditional flow strategies such as constant flow rate, proportional and proportional integral derivative (PID) control. In Ref. [8], optimal operation strategies for SWHS connected in an open loop configuration are considered. The results suggest that a constant optimal mass flow rate (which can be obtained using the overall average of the optimal mass flow rates that are determined for each sample instance of the optimization interval) may be a good strategy during warmer seasons of the year as this can yield results that are very close to the optimum results. In Ref. [10], a low temperature solar water collector connected to a thermally stratified tank is considered with the objective of obtaining optimal mass flow rates required to maximize the net gained energy. The resulting mass flow rate values are close to the minimum and maximum limits which support the strategy of optimal switching between the minimum and maximum available flow rate. In Ref. [9], a co-generation system consisting of a solar collector, gas burner, thermal reservoir, hot water heat exchanger and absorption refrigerator connected in a two loop configuration with two pumps is devised for producing heating as well as cooling. The objective is to maximize the system performance (reduce exergy destruction) whilst also minimizing the system pull up and pull down times (time taken to reach a set point temperature). The results show two optimum constant pump flow rates values for the two pumps. In Ref. [11] an optimal control method for a solar collector loop in a closed-loop configuration is studied. The system is described by a bilinear lumped parameter model for the collector fluid temperature and a bilinear lumped parameter model for the storage fluid temperature. The objective is to obtain optimum values for the collector fluid velocity in order to maximize the net energy that is collected over a fixed time period. The results agree with [8] and [10] in that optimal switching will occur between the minimum and maxim flow limits. The results also show that in instances where only two switches occur during the period of operation, the optimal control is highly dependent on the temperature difference across the collector. In [12,13] the application of block orientated type mathematical modelling is applied to SWHS with pumps. In this paper two different types of bang–bang control are used. In the first type (referred to as ordinary control), the on-off status of the pump is temperature dependent, whilst in the second type (referred to as energy based control) the control action is dependent on the comparison of the available energy to extract and the pump power used to extract this energy. The results show that the energy based control method results in greater energy gain and a higher water tank temperature. In Ref. [14], an energetic optimization of flat plate solar collectors is developed in order to determine the optimal performance and design parameters of the system. The objective is to determine the optimum flow rate and collector aperture area combination that will result in a maximized exergy efficiency. The results illustrate the dependence of exergy on the aperture area and flow rate with maximized exergy outputs correlating to maximum flow rate and aperture area values. Thermal losses due to the pipes connecting the solar collector to the storage unit are assumed to negligible in all the papers discussed above.

In Ref. [15], extended differential equations are used to model a SWHS consisting of a solar collector, heat exchanger, energy storage tank and connecting pipes. The developed model considers pipe thermal losses and simply illustrates the temperature distribution over the components of the SWHS. When compared to measured results from a physical system, the results of this model show lower absolute error than those of other models that do not take system thermal losses into account. The results of Ref. [15] highlight the importance of considering system thermal losses in order to increase the accuracy of any model. In attempt to further the work that has been developed by the previous authors, this paper focusses on flow rate optimization of SWHS with two energy storage tanks and connecting pipes.

There are three novelties to our approach. Firstly, unlike other models that either aim to maximize the energy extracted from the solar collector or to maximize the difference between the energy collected and the energy used by the pumps, our model is developed with two objectives; in the primary loop, the flow rates are optimized for maximum energy transfer to the energy storage tank, whilst in the secondary loop, the flow rates are optimized for minimum energy extraction from the first energy storage tank to the water tank in order to conserve energy whilst meeting user requirement of water tank temperatures at different hours of the day so as to increase thermal comfort. Our objective function therefore aims to maximize the overall energy gain of the SWHS whilst taking into account the energy extracted from the solar collector, the energy used by the pumps as well as the energy transfer that occurs between the two tanks. Secondly, most existing models have optimized flow rates for the daytime period where there is an opportunity to extract energy. Due to the presence of the two energy storage tanks, our model aims to optimize the flow rates of two pumps over a 24 h period as oppose to only during the period when energy available from the collector. Lastly, our SWHS model takes into account pipe thermal losses as well as resulting power losses. Previous optimal flow control models for SWHS do not take these losses into account. In this model, the losses are characterized as a function of the pipe parameters (heat loss coefficients of the pipes) which are calculated for every sample instant as oppose assuming them to be constant, as well as dimensions of the connecting pipe (inner diameter, length, and surface area). This will result in a more realistic model of SWHS that produces optimized flow results that can resemble those of a physical SWHS to a greater degree than current existing models. the developed model aims to optimize the flow rates in the primary and secondary loops whilst meeting user defined water tank temperatures at different hours of the day so as to increase thermal comfort.

The layout of this paper is as follows: The problem formulation is discussed in Section 2. The formulation of the mathematical model is presented in Section 3. The model optimization procedure is presented in Section 4. In Section 5, a case study is presented together with a discussion and analysis of the corresponding results. This study is concluded in Section 6.

2. Problem formulation

The system considered in this paper is shown in Fig. 1. It consists of a flat plate solar collector with surface area A_{coll}, a storage tank (T_1) used to store circulation fluid with mass M_{cf}, and specific heat capacity C_{cf}, a storage tank (T_2) with water tank used to store water with mass M_w, and specific heat capacity C_w, connecting pipes cp_i of