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Pump Speed Optimisation for Solar Thermal System

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ABSTRACT

Photovoltaic as well as solar thermal systems have been particularly useful for harvesting the inexhaustible energy from the sun and to reduce the carbon emissions normally produced by burning fossil fuels. In either of these cases, reaching a higher efficiency obviously brings substantial benefits, and while much research has been performed on PV efficiency, most research has focused on the solar thermal collectors themselves, while our approach considers the system's perspective by optimizing the pump speed based on the performance of the various heat exchangers within the full system. In order to test the theory, a prototype solar thermal system was built, in which the pump speed was adjusted by considering: the water demand, the input and output temperatures of the solar panel and the output temperature of the produced hot water. By combining the solar thermal system with an existing gas boiler and continuously adjusting the pump speed, a reduction of between 10% and 30% in gas consumption and 5–10% in electricity consumption was observed.

1. Introduction

Due to the ever-increasing global population and an increased integration of technology, as demonstrated by the link between growth of the GNP per capita (The Chartered Institution of Building Services Engineers, 2016), the world's energy demand will most likely continue to grow and so the use of renewable energy sources is of significant importance. Normally, renewable energy is generated from either hydro, wind or solar sources.

Out of these three sources, solar energy is used within this study. Solar energy harvesting can be achieved by using Photo-Voltaic (PV) electrical systems or Solar Thermal systems. While the latter have been designed to gather the sun's radiation energy and use it to heat water or any other liquid, for industrial, commercial and/or domestic use. Either of these systems can be hugely profitable, depending on the user demands and installation, and their installation helps to gradually decrease the quantity of site-related greenhouse gases like: Carbon dioxide (CO_2), Methane (CH4), Nitrous Oxide (N_2O), Ozone (O3) and water vapour that are all associated with the use of conventional, fossil-based sources (World Energy Council, 2013).

While solar thermal systems were invented in the early 1890s in California and commercially approved in the late 1970s, it took until the 1980s for these systems to commercialise. As the current technology is quite mature (Cervantes and Torres-Reyes, 2002) and therefore overall cost-effective, efficient and well regulated (Kuang et al., 2003), it has been adopted in many infrastructures to aid with the need for hot water. However, limited work has been performed on efficiently integrating and combining these systems with existing installations, which is the focus of Yergin and Gross (2012).

This paper starts of by looking at the theoretical aspects of such an integration, which is then followed by representing an extensive set of data gathered on the real system, after which the paper concludes.

2. Theoretical study

For a solar thermal collector, the heat exchange within the panel is essential to its efficiency and has been studied for various designs (Aye et al., 2002; Mathioulakis and Belessiotis, 2002).

However, the overall system has a second heat exchanger, within the storage tank, which could have a quite different characteristic from the collector itself. This implies that the pump speed, as optimal for the collector, may be different from that for the storage tank, which means that compromises may need to be made in reaching an optimal overall efficiency. In order to achieve such optimization, a variety of points within the system need to be measured and a suitable controlling algorithm derived that combines the information of these sensors into an optimised pump speed. This research project involves designing such a controller for use on a domestic hot water system which was adapted for this study. In order to better appreciate the complexity of combining different heat exchangers and their characteristic, rather than obtaining an off the shelf solar thermal panel, a collector was built from scratch following the guidelines presented in Duffie and Beckman (1991) and Deutsche Gesellshaft für Sonnenenergie (2010).

The fully installed system, as shown in Fig. 1, consists of two

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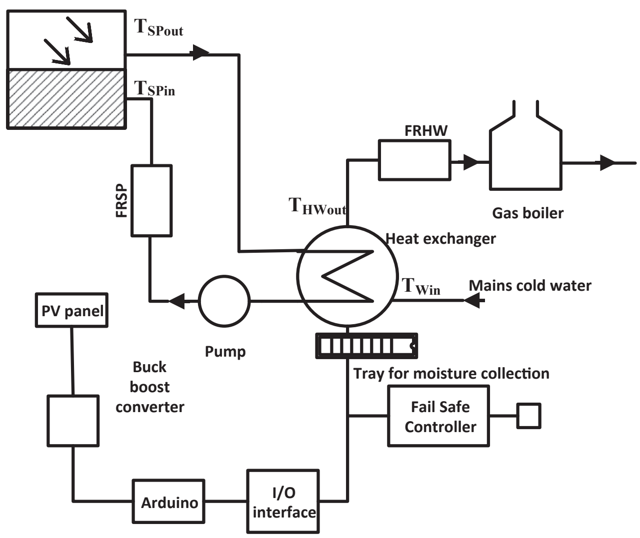

Fig. 1. Block diagram of the solar hot water system.

circuits. The first circuit, is a closed circuit and comprises of the solar thermal panel, a circulating pump, a flow meter (FRSP), an expansion vessel and a heat exchanger as part of the heat storage vessel. The second system, is an open circuit and consists of the same heat exchanger/storage vessel, a flow meter (FRHW), and an expansion vessel. Normally Open/Normally Closed (NO/NC) electro valves are fitted on both circuits to allow the normal operation of the system and to control the safety system of the circuit. If in normal operation a valve has to stay open, a NO valve was chosen and vice versa. In this way, the valves will need to be powered up only for emergency. The closed circuit uses antifreeze fluid, because the pipe work goes through the solar thermal panel located on a roof in the UK, and could therefore experience freezing temperatures. Using antifreeze liquid also aids with the heat conduction and exchange as well as helping to prevent pipe oxidation. As the antifreeze fluid is heated up by the sun and gains thermal energy, this energy is transferred to the water in the storage's heat exchanger. To minimise heat losses, this heat exchanger is positioned within the loft, immediately under the solar panel, while all pipes are insulated.

Throughout the system there are various points of data collection, which are: the temperatures at the solar panel inlet (T_{SPin}), the solar panel outlet (T_{SPout}), the hot water circuit inlet (T_{HWin}), and the heat exchanger outlet (T_{HWout}), while the flow rates in the closed (Flow Rate Solar Panel, FRSP) and open circuit (Flow Rate Hot Water, FRHW) are measured as well as the solar Illumination (Ill). The latter is measured through a small PV panel, which also powers the electrical part of the installation.

All of these measured parameters form the input to the controller, which uses them to continuously adjust the optimal pump speed. In order to determine this pump speed, each measured parameter is multiplied by a specific value, which allows one to optimise the pump speed for a variety of different usage and other environmental conditions, resulting in the following formula:

$$pumpspeed = FRHW*K_f - \Delta T_{HW}*K_{HW} + \Delta T_{SP}*K_{SP} + \Delta T*K_{\Delta T}\ (\%) \quad (1)$$

The four 'K' values are the respective "multipliers" to adjust the influence of that respective factor. By changing these values, the pump speed and the circulating fluid flow vary, based on the efficiency of the heat transfer. The 'K'-values have the following meaning and are calculated as follows:

- K_f – is calculated by considering the maximum PWM output for a 10-bit micro-controller, divided by the maximum flow rate of the system's pump.

$$K_f = X\frac{PWM_{max}}{flowrate_{max}} = X\frac{1023}{20} \quad (2)$$

- K_{HW} – is determined by considering the maximum and minimum temperatures of the heated water.

$$K_{HW} = Y\frac{PWM_{max}}{T_{HWmax} - T_{HWmin}} = Y\frac{1023}{65-12} \quad (3)$$

- K_{SP} – is calculated by using the maximum and minimum temperatures of the fluid at the in- and outlet of the solar panel.

$$K_{SP} = Y\frac{PWM_{max}}{T_{SPmax} - T_{SPmin}} = Y\frac{1023}{80-12} \quad (4)$$

- $K_{\Delta T}$ – considers the maximum values of the outlet temperatures of the solar panel and the hot water system.

$$K_{\Delta T} = Y\frac{PWM_{max}}{T_{SPmax} - T_{HWmax}} = Y\frac{1023}{80-65} \quad (5)$$

Within the above formula, the values 'X' and 'Y' dictate how much the constant 'K' weighs within the whole formula. X as well as Y can have a value between 0 and 100, and affect the pump speed and consequently influence the heat exchanger efficiency. For the purpose of this work, two different values were chosen, namely X = 80 & Y = 20 and X = 60 & Y = 40. This results in the following respective 'K'-values: $K_f = 40.92$, $K_{HW} = 3.86$, $K_{SP} = 3.00$ and $K_{\Delta T} = 29.23$ or $K_f = 30.69$, $K_{HW} = 7.72$, $K_{SP} = 6.02$ and $K_{\Delta T} = 27.28$.

When the house needs no hot water, then the circulation of the water in the close circuit only aids when it can increase the temperature of the storage tank. However, when hot water is demanded, then there will be cold water flowing into the storage/heat-exchanger tank, which needs to be heated up, and this requires the liquid in the closed circuit to start circulating more regularly, which is the main reason for the fact that the X-value is much higher than the Y-value.

With the calculated 'K' coefficients, the first parameter of the equation has an influence of 80% or 60% of the total speed adjustment while the second, the third and the forth parameters were set at 20% or 40% in Eq. (1). It is worth nothing that since one of the factors is negative, the total reaches 100% in either case.

The equation's second parameter slows down the pump based on the fact that if the temperature of the storage's heat exchanger has reached its optimal (65 °C) then the only purpose is to keep the water at this temperature, while preventing the heat to escape to the outside (when the outside temperature could be lower), that is why it is subtracted in the formula.

When the solar panel temperature is higher, then there is also a higher benefit in increasing the pump speed as influenced by the third parameter, which checks the temperature difference on the solar panel ΔT_{SP}. Finally, the last parameter considers the difference in temperature between the fluid coming out of the solar panel and the hot water coming out of the heat exchanger. The larger this temperature differential, the higher the pump speed should be in order to heat up the water in the storage tank. When the temperature difference is negative, then the pump stops working because that means that the storage tank's water is at a higher temperature than the solar panel's fluid.

In practice, the sensors were all linked up to an Arduino board that drives the pump by adjusting its PWM continuously. Fig. 2 shows this process of using a closed control loop to control the system. Additionally, interrupts were added to read the flow values in both circuits and to record all measured data onto an SD card.

The controller and other electronic components are all fed of a small photovoltaic panel that is combined with a backup battery. This panel is also used to measure the solar illumination information, which is an input to the system, available for future optimisations.