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Experimental study of a solar pool heating system under lower flow and low pump speed conditions

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ABSTRACT

The operation of an unglazed, open-loop, solar-collector for residential pool heating was investigated experimentally under various flow conditions. The objective was to examine if solar pool collectors can be operated at lower flow conditions to minimize the pump energy while still providing sufficient thermal energy output to heat the pool. The system consists of a 20.5 m^2 plastic tube, solar collector and a 36 m^2 in-ground open-air pool. Key parameters were monitored over 38 days to validate a steady state model. The model achieved a good fit against the measured data and was used to simulate the system performance under various scenarios. Operating the system at low pump speed with a mass flow rate per unit collector area ($\dot{m}/A_C$) of 0.016 $kgs^{-1}m^{-2}$ was found to be optimal and achieved 60% pump energy savings. The coefficient of performance was increased by 2.5 times without compromising the thermal performance of the system in comparison to the Business as Usual (BAU) case. The optimal $\dot{m}/A_C$ is approximately 50% of the lower limit specified by International and Australian Standards. Assuming all systems in Australia were operated under optimal conditions, annually 180 GWh of electricity consumption and 150 kilotonnes of CO_2 emissions could be avoided.

1. Introduction

Approximately 15% of Australian households have a swimming pool and the associated pumping system is usually the largest energy user in these households [1]. For typical Australian households with pools, a pool pump consumes over 1500 kWh per year and comprises around 18% of the total electricity consumption [2]. Additionally, numerous studies have shown that households with a swimming pool have higher energy demand than households without a pool. For example, Elnakat et al. [3] reported households with pools in the U.S. use 40% more energy, while Fan et al. [4] also found that households with a pool have significantly higher daily electricity demand than those without one in the greater Sydney region, Australia. As a result, the operation of swimming pools increases a household's electricity costs significantly, and it also has significant impacts on the peak electricity demand and the environment. Seebacher [5] addressed the contributions of swimming pools to peak demand, and found that on average each pool added an additional load of around 1.2 kW. Further, Ergon Energy, one of the major electricity suppliers in Australia, also reported an average load of 1.1 kW is due to a swimming pool that is normally operated during residential peak demand periods [6]. From the environmental perspective, the projected pool energy usage in 2017 will contribute approximately 1.9 Mt per year of greenhouse gas emissions [7] and this corresponds to approximately 0.35% of Australian's total annual greenhouse gas emissions [8].

Besides pool filtration, pool heating is another major driver of the energy demand, which accounts for around 27% of the total energy usage of a pool [9]. Approximately one third of Australian pools are heated and whilst some gas heaters and heat pumps are utilised, about 90% of heated, residential pools in Australia are heated using solar collectors [10,11]. In comparison to a heat pump or gas heating, solar pool heating has significantly lower operating costs and carbon emissions, as presented in Table 1 [12]. The data shows that solar pool heating uses only about 14% of the energy of a heat pump, and 3% of the energy of a gas heater, with similar savings on greenhouse gas emissions.

Other active pool heating systems utilizing other renewable energy sources (RES) can also be found in the literature. Katsaprakakis [13] compared various passive and active pool heating systems in Southern Europe, which included the pool enclosure,

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Table 1
Energy usage and GHG emissions of different pool heating types [12].

	Solar pool heating	Heat pump pool heating	Gas pool heating
Estimated daily energy usage	6 kWh	43 kWh	218 kWh
Greenhouse Gas Emissions per week	45 kg	290 kg	360 kg

insulating covers, biomass heaters coupled with solar collectors, and geothermal heat exchangers combined with geothermal heat pumps in Southern European locations [13]. The results show that the use of pool insulation covers led to considerable savings in pool heating loads, and the remaining energy demand could be met by a RES based system with an investment payback of less than 5 years. More complex pool heating systems using heat recovery options were also investigated in various studies [14,15]. Such systems use the waste heat produced by cooling devices to heat the pools (for example, one system used waste heat from an ice rink to heat a nearby swimming pool). However, such studies are outside the scope of the present work, which is focused on residential pool heating and in particular, solar pool heating systems.

For pool pump systems associated with filtration and cleaning of pool water, considerable energy savings have been achieved through the use of multi-speed or variable speed pumps. By operating pool filtration pumps at 25–35% of a typical flow rate for a pool, pump running times are increased however, energy savings of the order of 60–80% have been achieved [16–18]. To date however, there have been very few reports of this approach being adopted for solar pool heating systems. Hence, the objective of this work is to examine if solar pool collectors can be operated at lower flow conditions to minimize the pump energy while still providing sufficient thermal energy output to heat the pool.

2. Literature review

In the past few decades, there has been considerable research into the direct use of solar thermal collectors for swimming pool heating [19–29]. As the thermal performance of the solar collector depends largely on the water flow rate [30], a wide range of mass flow rates per unit collector area ($\dot{m}/A_C$), have been reported in the literature for solar pool heating collectors.

An early technical report by Czarnecki [19] addressed the basic design considerations of solar pool heating systems. It recommended a minimum value for $\dot{m}/A_C$ of 0.02 kg s^{-1} m^{-2} in order to ensure a low operating temperature of the solar collectors. A similar value for the mass flow rate per unit collector area of 0.018 kg s^{-1} m^{-2} was adopted by Sodha and Kumar [23] when investigating the solar heating of open swimming pools in India. They pointed out that the swimming season could be largely extended when a plastic solar collector was used (area of 75% of the pool area) along with a pool cover. Cusido and Puigdomenech [21] designed and built a high efficiency, low cost solar collector used for pool heating in Mediterranean climate and a flow rate of 1.4 kg s^{-1} was chosen to avoid any turbulent flow in the pool. This translates to a much higher $\dot{m}/A_C$ of around 0.13 kg s^{-1} m^{-2} given that the collector area was only 11 m^2. Molineaux and Lachal [26] carried out an experimental analysis of five unglazed, plastic solar collectors used for heating outdoor swimming pools in Switzerland. Their results indicated that the collector efficiency was not affected significantly by large heat losses due to the low temperatures involved. As such, the unglazed solar collectors were considered as suitable for low temperature applications like swimming pool heating. The experimental data was obtained by operating the solar collector under five different $\dot{m}/A_C$ values, which ranged from 0.028 to 0.11 kg s^{-1} m^{-2}. Dongellini and Falcioni [29], more recently, modelled the performance of three types of flat solar collector (unglazed, glazed and evacuated). The study highlighted that the unglazed and evacuated collectors were appropriate for swimming pool heating due to their high efficiency at low values of $\Delta T/G$ (temperature difference between pool water and ambient air over the solar irradiance), while the evacuated collector was more suitable for larger pools. In their simulations, the authors used a fixed value of $\dot{m}/A_C$ of 0.015 kg s^{-1} m^{-2}. It is important to note that for all the literature cited, the values for $\dot{m}/A_C$ were simply chosen by the authors with no justifications provided.

In contrast, very few studies have addressed the issue of the optimal flow rate for solar pool collectors and very few have considered the pump energy required. Medved and Arkar [27] analysed an unglazed solar pool collector and the optimization of the flow rate was performed only based on maximising the thermal efficiency of the collector without considering the energy consumed by the pump. The suggested flow rates ranged from 0.008 to 0.023 kg s^{-1} m^{-2} for steel absorbers, and 0.014–0.027 kg s^{-1} m^{-2} for aluminium absorbers. Further their model was simply validated with a fixed wind speed due to the incomplete data during the short experimental period. Similarly, the required pump energy was also excluded by Baughn and Young [31], who conducted a computer based optimization of the flow rate for a typical solar domestic hot water (SDHW) system. They reported an extremely low optimal value for $\dot{m}/A_C$ of 0.005 kg s^{-1} m^{-2}, which led to a very low pump power (<1 W). Therefore, the pump energy was deemed to be negligible if the pump was properly sized. This approach (ignoring the pump energy) however is not appropriate for a solar pool heating system, where the pump needs to move much larger volumes of water, provide sufficient pressure to overcome the total dynamic head of the system and importantly to ensure the vacuum relief valve remains closed [32,33]. As water pumps are an essential component in solar pool heating, some studies accounted for the associated energy when optimizing the flow rate. Kovarik and Lesse [34] and Winn and Winn [35] discussed the optimal control of flow rate to achieve the maximum difference between the collected thermal energy and pump energy. A solar hot water system was examined and the optimal flow rate was reported as 0.027 kg m^{-2} s^{-1} at peak solar irradiance [34].

Also there are numerous studies that have considered exergy for optimizing solar thermal system performance [36,37]. However, maximising exergy is only an appropriate objective when the goal is to maximise the amount of useful work to be done by system [38]. For solar pool collectors and for many other solar thermal systems, the objective is to produce low grade heat, not work. Therefore, in these cases maximising exergy is not the correct objective, and it is more appropriate to maximise the coefficient of performance (COP) in order to obtain the maximum thermal energy with minimum electrical energy input and cost [30,39].

To the authors knowledge, only Cunio and Sproul [28] have evaluated the solar pool heating collector performance at lower flow rates and lower pump power in order to improve COP. Their experimental results showed that the solar collector's thermal efficiency was only reduced by approximately 15% when operating at lower flow rates, while the COP of the system increased substantially. More importantly, up to 80% of the pumping energy could be