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Modeling and Performance Evaluation of Heat Pump Water Heater Systems

Arslan Saleem
School of Engineering
Cardiff University
Cardiff, United Kingdom
SaleemA7@cardiff.ac.uk

Tehmina Ambreen
School of Engineering
The University of Sheffield
Sheffield, United Kingdom
T.Ambreen@sheffield.ac.uk

Carlos E. Ugalde-Loo
School of Engineering
Cardiff University
Cardiff, United Kingdom
Ugalde-LooC@cardiff.ac.uk

***Abstract*—Countries around the world have introduced strict energy policies to mitigate the adverse effects of global warming and climate change. These policies call for a change on a massive scale to decarbonize existing energy systems and to provide energy flexibility. Building stock accounts for a large percentage of carbon emissions. To support the decarbonization of buildings, this paper investigates the performance of a heat pump water heater (HPWH) system under a hot water draw-off load profile. The HPWH system was modeled in TRNSYS using a water-to-water heat pump, a hot water storage tank, and hydraulic components. A simulated load profile tapped a net useful energy content of 11.655 kWh in terms of domestic hot water. The coefficient of performance of the heat pump was calculated. In addition, the temperature distribution inside the storage tank and the water heating efficiency were obtained. The performance estimation of HPWH systems under daily heat load schedules may help in the design and selection of an energy efficient system which would, in turn, contribute to the decarbonization of building stock.**

Keywords—heat pump water heater, hot water storage tank, load profile, TRNSYS

I. INTRODUCTION

A major shift has occurred all over the world in the past decades to combat the adverse effects of climate change. UK committed to reduce greenhouse gas emissions to net-zero by 2050 to limit the effects of global warming [1], [2]. More than a third of UK emissions result from heating and cooling applications in the building stock [3] while, at the same time, thermal demand is on the rise. Keeping up with the ever-rising energy demand all the while decarbonizing the energy sector has shifted the attention toward renewable energy sources [4].

The major challenges associated with buildings are reducing thermal losses and improving energy efficiency [5]. Heat pumps (HPs) are widely used in residential and commercial settings to meet hot water demand for space heating in cold climate regions, sanitation, and desalination. Use of different renewable energy sources like underground water, ground, and solar fields in conjunction with HP technology can result in increased energy efficiency. Among the available technologies, a water-to-water HP (i.e. ground-source) leads to a better energy performance and lower operational cost compared to air-source HPs [6].

The concept of a HP water heater (HPWH) was introduced since the 1950s. However, it has been gaining significant attention again with recent and progressively stringent energy policies. Reference [7] investigated different methods of producing domestic hot water in net-zero energy homes for the weather conditions of Montreal and Los Angeles. A HPWH indirectly coupled with a space conditioning ground-source HP was used. An experimental rating method for seasonal performance analysis of air-source HPWHs was developed in [8]. The rating technique relied on the HP's performance for heat-up operation. A system optimization of an air-source HPWH was conducted in [9], and multiple factors for the improvement of system performance were proposed. A comprehensive review of HPWH systems was carried out in [10]. This reference is relevant as a classification of studies found in the literature was done. Reference [11] explored the performance of five integrated HPWHs using a laboratory scale facility. Energy simulation models under different operating conditions considering the US climate were used. It is claimed in this reference that HPWHs can significantly improve the energy savings up to 64% compared to other types of water heaters. The impact of HPWH sizing on the demand and energy savings was investigated in [12]. It was reported that an adequate sizing based on usage in gallons per day is imperative to maximize the value to utilities.

A quasi-steady state performance analysis of a cascaded HPWH system was carried out in [13]. This helped determining its transient behavior and solving problems associated with high compression ratios and a low ambient temperature. The system considered a water storage system with refrigerants R134a and R410a. A sensitivity analysis based on theoretical models to identify the key performance parameters of air-source HPWHs in Australian residences was conducted in [14]. It was concluded that careful consideration should be given to the technical specifications of the HPWHs based on site specific characteristics. Other studies in the literature considered the modeling of storage tanks in HPWHs using thermodynamic modeling and computational fluid dynamics software [15], [16].

The literature review revealed that the performance of a HPWH is significantly affected by the site-specific weather and operational conditions. Therefore, an accurate prediction of its performance is crucial not only to meet the heat demand, but also to contribute to energy flexibility and decarbonization of buildings. To support this process, this paper presents the transient analysis of a HPWH system conducted in TRNSYS to determine its performance under a specific water draw-off load profile. In comparison to a steady-state analysis where conditions of the process would not change in time, the transient analysis conducted in this work allows for the dynamic simulation of the whole system—thus providing a deeper insight into flow physics and thermal stratification within the storage tank. Load profile L was adopted from EESTI standards [17] for a realistic performance rating of the HPs for domestic hot water utilization. The modeling approach used in the paper is amenable to estimate the performance of the HPWH and to facilitate the selection of a suitable system that meets different heat demands.

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II. METHODOLOGY

A. *Working Principle of a HPWH system*

A HPWH system transports heat from one place to another using electricity. It is significantly more energy efficient (2-3 times) compared to conventional electric water heaters. A schematic summarizing the HPWH cycle is shown in Fig. 1. The HPWH uses a low-boiling temperature refrigerant to absorb heat from the atmosphere in the HP's evaporator. The refrigerant is then compressed to a high temperature and a high pressure, and it then changes to vapor in the compressor. Later in the condenser, the vapor transfers the heat to the water to supply hot water. Finally, the refrigerant goes through an expansion valve to revert to a liquid phase.

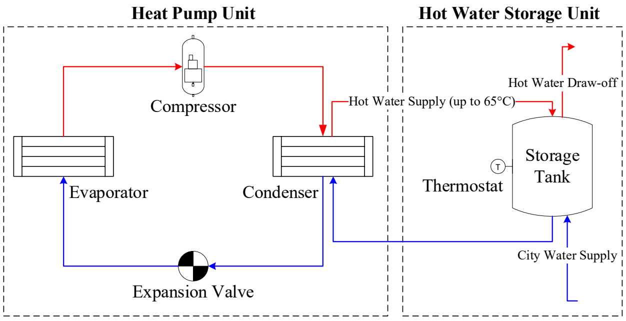

Fig. 1. Schematic of the HPWH cycle.

B. *Modeling Approach*

Energy flows of key components are of vital importance when performing dynamic modeling of energy systems. The TRNSYS software package solves mathematical models allowing the transient simulation and analysis of energy systems [18]. Moreover, its modular environment enables the numerical modeling of components with specific parameters. For a HPWH system, this facilitates investigating the system performance under different hot water draw-off load profiles and to establish flow control through the system.

A screenshot of the HPWH cycle modeled in TRNSYS is shown in Fig. 2. The volumetric capacity of the storage tank is 200 liters. The height of the inlet and outlet ports was defined as the ratio of the port height to the tank height, where 0 signifies bottom of the tank and 1 the top. The cold-water inflow and outflow port (to HP) are located at the bottom of the tank, the hot water draw-off port is at the top, and the inflow port (from the HP) is positioned at a height fraction of 0.65. Considering the minimum value of hot water draw-off flow rate (in liters per minute) and the smallest tapping duration (of 5 minutes, as shown in Table I), a timestep size of 1 second was selected. This value is small enough to accurately simulate the desired energy draw-off from the storage tank. The total simulation time was 15 hours.

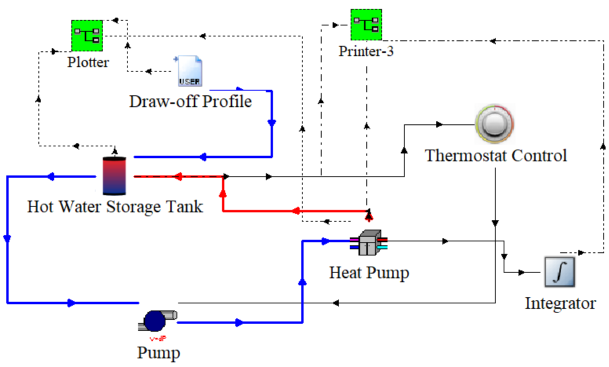

Fig. 2. Schematic of a HPWH system modeled in TRNSYS.

C. *Water Draw-off Load Profile*

The EESTI standard provides a performance rating method of HPs for domestic water heater units [17]. In addition, it includes different water draw-off load profiles which are useful to assess system performance, where a load profile is a given sequence of water draw-offs. For this study, load profile L from the EESTI standard was considered. This 24-hour profile consists of off-peak product where the water heater is energized for a maximum of 8 hours between 22:00 and 07:00, while a tapping pattern is followed for the remaining duration of the profile (from 07:00 to 22:00). The tapping pattern is shown in Table 1.

TABLE I. WATER DRAW-OFF LOAD PROFILE [17]

Tapping number	Time (hr: min)	Hot water energy content (kWh)	Hot water flow rate (l/min)
1	0:00	0.105	3
2	0:05	1.4	6
3	0:30	0.105	3
4	0:45	0.105	3
5	1:05	3.605	10
6	1:25	0.105	3
7	1:30	0.105	3
8	1:45	0.105	3
9	2:00	0.105	3
10	2:30	0.105	3
11	3:30	0.105	3
12	4:30	0.105	3
13	4:45	0.105	3
14	5:45	0.315	4
15	7:30	0.105	3
16	8:30	0.105	3
17	9:30	0.105	3
18	11:00	0.105	3
19	11:15	0.105	3
20	11:30	0.105	3
21	12:00	0.105	3
22	13:30	0.735	4
23	14:00	3.605	10
24	14:30	0.105	3

D. *Mathematical Model*

Thermal stratification in the storage tank was measured using the following dimensionless parameter:

$$\mathrm{Str} = \frac{\left(\frac{\partial T}{\partial y}\right)_t}{\left(\frac{\partial T}{\partial y}\right)_{t=0}} \quad (1)$$

$$\frac{\partial T}{\partial y} = \frac{1}{J-1}\left[\sum_{j=1}^{j-1}\left(\frac{T_{j+1}-T_j}{\Delta y}\right)\right] \quad (2)$$

where j is the number of nodes in the tank.

The performance of the HPWH system for the whole load profile was measured by calculating the useful energy Q_{HP-tap} during each hot water draw-off, given by

$$Q_{HP-tap} = \frac{1}{60\times1000\times3600}\int_0^{t_{tap}} c_p \times \rho(T) \times f(t) \times \left(T_{WH}(t) - T_{WC}(t)\right) dt \quad (3)$$

where $f(t)$ is the useful water flow rate, t_{tap} is the draw-off duration, c_p is the specific heat of water, $\rho(T)$ is the density of water as a function of temperature, and $T_{WH}(t) - T_{WC}(t)$ is the temperature difference between the hot and cold water at the outlet and inlet of the storage tank.

For draw-offs with a peak temperature T_p of 55°C, this temperature cannot always be achieved by the HP alone. During the draw-off it was then assumed that the missing temperature difference to the required T_p was produced by an additional electrical resistance heater. For that case, the energy coming from the electrical heater Q_{EL-tap} is given by:

$$Q_{EL-tap} = \frac{1}{60\times1000\times3600}\int_0^{t_{tap}} c_p \times \rho(T) \times f(t) \times \left(T_{WC}(t) + (T_p - 10) - T_{WH}(t)\right) dt \quad (4)$$

where Q_{EL-tap} was set to zero if numerical evaluation resulted in a negative value.

The draw-off was stopped when $Q_{HP-tap} + Q_{EL-tap}$ was equal to the required energy for the draw-off. The overall tapping energy Q_{LP} of the load profile was measured using

$$Q_{LP} = \sum_{i=1}^{n_{tap}} Q_{HP-tap_i} + \sum_{i=1}^{n_{tap}} Q_{EL-tap_i} \quad (5)$$

where n_{tap} is the number of draw-offs during the load profile and i is the index for the draw-off.

The total measured electrical energy consumption during the draw-offs ($W_{El-M-LP}$) was determined by the correlation:

$$W_{El-M-LP} = 2e - 8 \times T_{hi}^6 - 4e - 6 \times T_{hi}^5 + 0.0003 \times T_{hi}^4 - 0.0087 \times T_{hi}^3 + 0.1571 \times T_{hi}^2 - 1.4321 \times T_{hi} + 6.0236 \quad (6)$$

where T_{hi} denotes the hot water coming from the HP. $W_{EL-M-LP}$ during the simulated load profile was corrected using:

$$W_{EL-LP} = W_{EL-M-LP} - W_{EL-Corr} + Q_{loss} + Q_{EL-LP} + W_{EL-OFF} \quad (7)$$

where W_{EL-LP} is the electric energy consumption during the load profile, $W_{EL-Corr}$ is the correction for the hydraulic pumps, W_{EL-OFF} is the off-peak product electric energy consumption, Q_{loss} is the heat loss in 24 hours, and Q_{EL-LP} is additional electrical input. Q_{loss} was defined as

$$Q_{loss} = (24 - t_{TTC}) \times P_{es} \quad (8)$$

where t_{TTC} is the load profile time in hours and P_{es} is the standby power input in kW.

The coefficient of performance (COP) for domestic hot water COP_{DHW} was measured using

$$COP_{DHW} = \frac{Q_{LP}}{W_{EL-LP}} \quad (9)$$

The ambient correction term Q_{cor} considers that the HP is installed in a non-isothermal place. Q_{cor} is expressed in kWh and calculated using

$$Q_{cor} = -k \times 24 \times P_{stby} \quad (10)$$

$$P_{stby} = CC \times P_{es} \quad (11)$$

where k and CC are coefficients defined in [17]. P_{stby} is the primary standby heat loss in kWh.

The daily electrical energy consumption Q_{elec} in kWh was calculated with

$$Q_{elec} = \frac{Q_{ref}}{Q_{LP}} \times W_{EL-Lp} \quad (12)$$

where Q_{ref} is the reference energy content of the considered load profile in kWh, and Q_{LP} is the total useful energy content during the load profile in kWh. Finally, the water heating energy efficiency η_{wh} in % is defined as:

$$\eta_{wh} = \frac{Q_{ref}}{(CC \times Q_{elec}) + Q_{cor}} \quad (13)$$

III. Results and Discussion

A. Storage Tank Charging and Discharging

Water inflow and outflow profiles of the storage tank are presented in Fig. 3. The mass flow rate entering the tank is represented with a positive sign and leaving the tank with a negative sign. The city water supply enters the tank at a constant temperature of 10°C. The mass flow rate of the supply water (black trace) is kept the same as the hot water draw-off flow rate (red trace). Moreover, the tank water leaves to and returns from the HP at a mass flow rate of 17 liters per minute (blue and green traces, respectively). The maximum hot water draw-off flow rate from the storage tank is 10 liters per minute though (as shown in the profile in Table I).

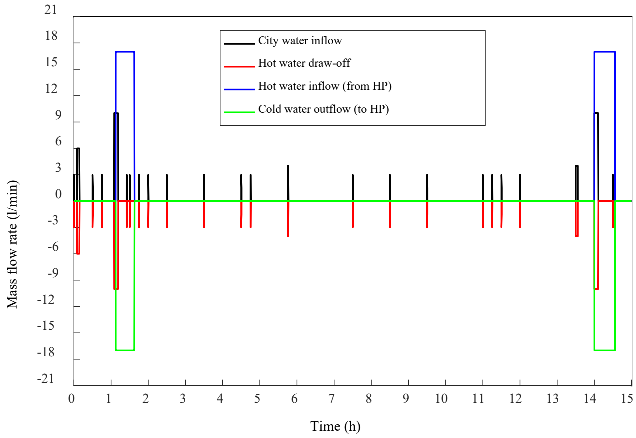

Fig. 3. Inflow and outflow profile for the storage tank.

The operation of the HP is controlled using the thermostat positioned at 0.5H (where H is the height of the storage tank). When the temperature of the thermostat drops below 50°C, the HP starts supplying hot water to the tank. The circulation temperature difference (ΔT) of the HP is 10°C. The HP turns off when the thermostat temperature reaches 60°C.

The amount of energy absorbed (red trace) and released (blue trace) during the charging and discharging process of the storage tank is shown in Fig. 4. A cluster of large energy draw-offs of 3.605 kWh appears at the beginning and end of the load profile representing the hot water demand in the morning and evening. Moreover, small energy draw-offs of 0.105 kWh occur periodically throughout the day with a 0.315 kWh draw-off around noon. The two schedules of energy gain coincide with the large energy draw-offs since the HP becomes operational to maintain T_p.

B. Tank Temperature Profile

The storage tank is divided into 10 equidistant nodes. The temperature variation at each node as a function of time is shown in Fig. 5. In the figure, T1 denotes the temperature at node 1, which is located at the top of the tank, whereas T10 is the temperature at the bottom of the tank. The temperature at the top, where the draw-off port is located, remains above the desired hot water supply temperature of 55°C for most of the load profile. The temperature in the storage tank drops at two instances within the entire profile, which coincide with the large energy draw-offs from the tank shown in Fig. 4; i.e., 3.605 kWh at mass flow rate of 10 liters per minute.

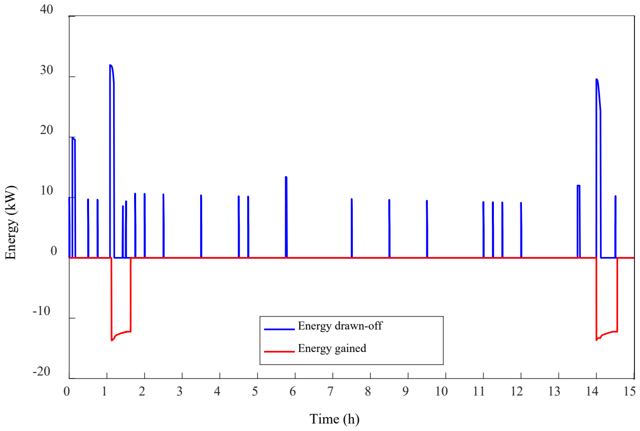

Fig. 4. Energy flow during charging and discharging processes.

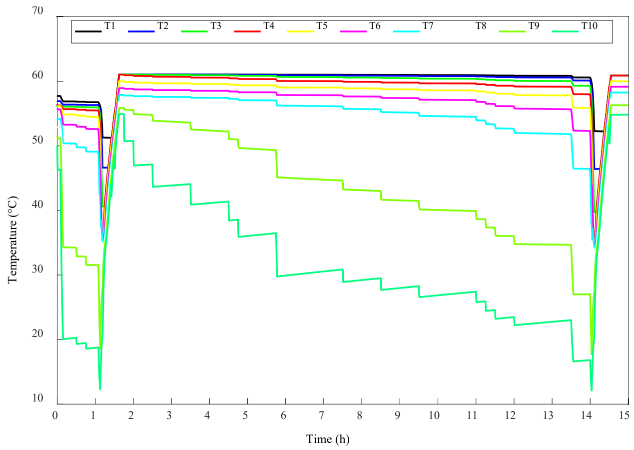

Fig. 5. Temperature distribution in the water storage tank.

Fig. 6 shows the profiles of hot water draw-off temperature (red trace), thermostat temperature (green trace), tank average temperature (blue trace), and hot water inflow to the tank from the HP (cyan trace). The thermostat temperature drops below 50°C on two occasions: when the large hot water draw-offs take place. The complementary operation of the HP is seen accordingly in Fig. 3.

A plot of the stratification number against time is shown in Fig. 7. The behavior of the stratification number shows the tank is well stratified up until the 5th tapping (the first big draw-off occurring at 1:05 hours), which disrupts stratification. The thermal stratification improves with the charging of the tank and continues to build despite multiple small draw-offs, before decreasing again upon reaching the 23rd tapping (the second large draw-off at 14:00 hours). The temperature distribution shown in Fig. 4 demonstrates that the stratification number adequately characterizes the thermal stratification in the tank.

C. *COP and Water Heating Efficiency*

The data curated form the numerical simulation of the load profile was used as an input to the MATLAB code to calculate the COP for domestic hot water and the water heating efficiency of the load profile. The simulation of the HPWH showed a good COP ($COP_{DHW} = 2.4$) and a water heating efficiency of 98%. (**Note**: a COP between 1.8–5.5 for HPWHs is deemed as good [19].) An even higher COP value can be achieved in the absence of the two large energy tappings resulting in significant temperature drop in the tank. Each large energy tapping replaced approximately 66 liters (33% of the tank's capacity) of hot water in the storage tank with cold water disturbing thermal stratification.

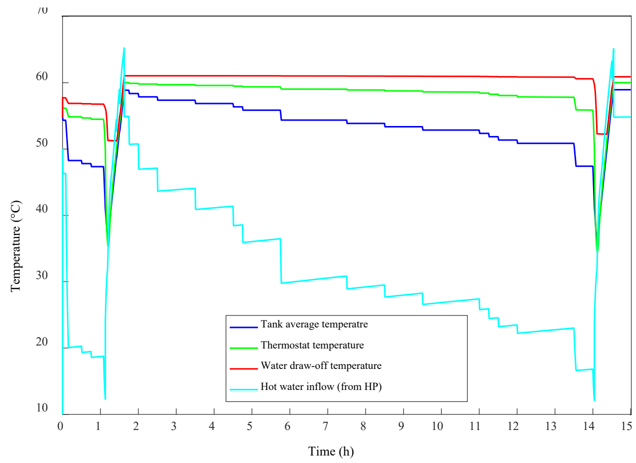

Fig. 6. Hot water draw-off, inflow, tank average, and thermostat temperature variation in the storage tank.

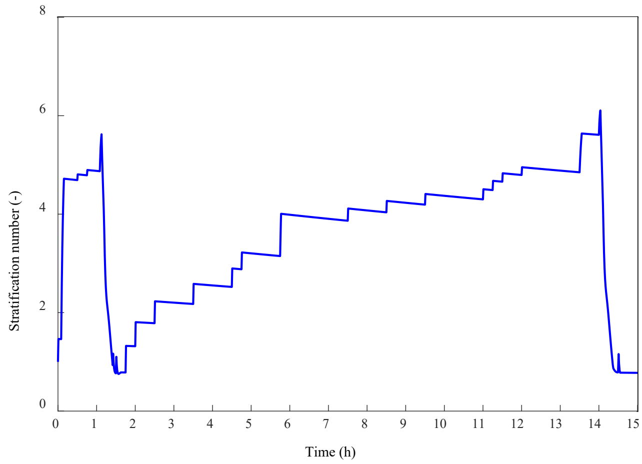

Fig. 7. Thermal stratification as a function of time.

Although a larger storage tank may be utilized to deal with this problem, this may not be a feasible solution considering cost effectiveness and space limitations in residential buildings. A more effective approach may be to place the thermostat at a higher position in the tank or to use more than one thermostat to modify the operational control logic of the HP. The modeling approach utilized in the present study may help design an energy efficient HPWH system to meet the domestic energy demand.

IV. Conclusion

Dynamic modelling of a HPWH system was carried out to simulate a 24-hour water draw-off profile from a hot water storage tank using TRNSYS. The simulated load profile represented realistic hot water demand in a residential dwelling. Thermal distribution of the storage tank and the calculation of a non-dimensional stratification number showed a well-stratified tank.

A MATLAB code was developed using the mathematical formulations and simulation results to calculate the COP for domestic hot water and water heating efficiency for the load profile. Results showed that the HPWH system successfully meets the daily heating demand, and the storage tank exhibits a good heating efficiency.

The simulated draw-off profile provided insight into the performance of HPWH system under realistic operating conditions. The results showed that component sizing and the operational control logic have a substantial impact on the overall performance. Control logic optimization may lead to an improved system performance and efficiency. In addition, a properly sized storage tank and an optimally controlled system may significantly reduce the electric consumption in residential dwellings. This may help providing energy flexibility while simultaneously contributing to the decarbonization of buildings—which is a key objective supported by policy towards mitigation of climate change.

As future work, detailed three-dimensional computational fluid dynamics modelling of the storage tank will be performed to further investigate the accuracy of the models presented in this paper. The impact of ambient conditions, geometric parameters of the storage tank such as cold inflow manifold, partition geometry, and internal heat exchanger on thermal stratification, in addition to the COP, and water heating efficiency under specific load profiles will be explored. Whole-house energy simulations of the HPWH system will be performed to study the building interactions.

From the literature, it has been established that a HPWH system can provide up to three times higher energy savings compared to a conventional water heater system. Future work will consider a direct comparison between the systems and other methods of hot water generation.

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