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Models Based Simulation of the Coefficient of Performance of a Domestic Heat Pump Water Heater

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ABSTRACT

Sanitary hot water production make up to over 50 % of the monthly electrical energy consumption in South Africa residential sector. Employing an effective and efficient mechanism for sanitary hot water heating can lead to a substantial energy saving and demand reduction as well as creating a benign environment owing to the decrease of the carbon dioxide emission. Most of the renewable energy devices for sanitary hot water heating utilized the free and abundant solar energy. Domestic air source heat pump (ASHP) water heater is one of the renewable energy device used for sanitary hot water production. In this study, a data acquisition system (DAS) was constructed to measure the predictors (E, electrical energy consumed) and (λ, average product of ambient temperature and relative humidity) and relevant parameters to compute the COP during the vapor compression refrigerant cycle (VCRC) of the ASHP unit. The coefficient of performance (COP) of an ASHP water heater under two different heating up cycle scenarios were critically examined. Modelling and simulation of the COP of the system provided a distinctive opportunity for optimization and prediction of its performance under different operational conditions. It was depicted that the mean COP in the both scenarios of the heating up cycles (firstly, where there was no successive hot water draw off and secondly, with simultaneous hot water draw off) was on average 2 and above. Finally, using the mathematical models in the both scenarios, it was revealed that increases in both predictors (E and λ) can result to decrease in the COP. The one way analysis of variance (ANOVA) test showed, the mean COP of 1.96 and 2.14 for the heating up scenario of simultaneous hot water drawn off and without a successive hot water drawn off. Predictors' weight ranking demonstrated that the contribution from the input parameters was 100 times more during the heating up scenario whereby successive hot water drawn off occurred. The modelled equations were used in the mathematical blocks of the Simulink to design the simulation application of the COP of an ASHP water heater. We therefore concluded that the COP of an ASHP water heater during simultaneous hot water drawn off was higher than without successive hot water drawn off.

Key words: Air source heat pump (ASHP); Coefficient of performance (COP); Data acquisition system (DAS); Models; Simulation application; Vapor compression refrigerant cycle (VCRC).

INTRODUCTION

The residential ASHP water heater is an efficient and a renewable energy device for sanitary hot water production [1]. The COP of an ASHP water heater can range from 2 to 4 and depends on the component design of the system, ambient weather conditions, duct space and the speed of the cold and dehumidify expelling air [2; 3]. The optimal COP of an ASHP water heater can be achieved by an efficient installation of the system [4]. The system COP can also be enhanced by the use of a primary refrigerant of an excellent thermo-physical properties [5]. It is crucial to allude that extensive research has been conducted on the simulation and mathematical modelling of the performance of heat pump water heaters. More elaborately, the performance of a heat pump water heater was simulated using the TRYSYN simulation software package [6]. However, it should be noted that the TRYSYN simulation cannot effectively model the performance of an ASHP water heater owing to the complexity of the metal fins embodying the evaporator. Furthermore, an analytical, mathematical model was also presented to predict the COP of a solar assisted heat pump water heater in correlation to temperatures [7]. A quantitative method can be used to compute the COP of an

ASHP water heater based on the quantity of electrical energy consumed and the thermal energy gained. Precisely, Tangwe *et al.*, [8] developed and built a surface fitting multiple linear regression model to predict performance of a domestic split type ASHP water heater under first hour heating rating (standby losses and heating cycles due to hot water drawn off). The residential ASHP water heater technology is fast gaining maturity in the market. These systems can be classified into two categories; namely the split and the integrated type. The major focus on this study was to develop and build a multiple linear regression model of the COP of an ASHP water heater (split type comprising of a SIRAC ASHP of 1.2 kW power input and a 200 L kwikot high pressure geyser with its 4 kW element disabled) in correlation to the electrical energy consumed (E) and product of average ambient temperature and relative humidity (λ) as the predictors in the VCRC; with simultaneous hot water draws and without successive hot water drawn off [9]. Simulink environment of MATLAB was used to develop the architectural algorithm of the simulation application [10].

NOMENCLATURE

E = total electrical energy consumption in kWh

P = average power consumption in kW every 5 minutes

t = constant time interval of 5 minutes

n = number of successive 5 minutes in a heating up cycle

Q = total thermal energy gain in kWh

c = specific heat capacity of water in $kJ(kgk)^{-1}$

m = mass of water in kg in every 5 minutes

T_{in} = ASHP inlet water temperature in ^oC

T_{out} =ASHP outlet water temperature in ^oC.

λ = average of the product of the mean ambient temperature and relative humidity in (^oC.%)

AT = average ambient temperature in ^oC every 5 minutes

RH = average relative humidity in % every 5 minutes

COPcal = average calculated coefficient of performance

COP_{mod} = average modelled coefficient of performance

δ_0 = forcing constant

δ_1 = electrical energy scaling constant in $(kWh)^{-1}$

δ_2 = product of average ambient temperature and relative humidity scaling constant in $(^oC.\%)^{-1}$

MATERIALS AND METHODS

The following list of equipment, transducer, sensors and data logger shown in Table 1 was used in the study

TABLE 1: MATERIALS USED IN THE STUDY

Materials	Number
1.2 kw input SIRAC ASHP unit	1
200 L kwikot geyser	1
T-VER E50B2 power and energy meter	1
T-minol 130 flow meter	2
12 bits S-TMB temperature sensor	3
12 bits S-THB ambient temperature and relative humidity	1
S-UCC electronic input pulse adapter	3
S-UCD electronic input pulse adapter	2
U30-NRC hobo data logger	1

The ASHP water heater composed of an ASHP unit retrofitting a 200 L geyser with its element disabled as shown in the Figure 1. The temperature sensors were installed in the pipe of the ASHP inlet and outlet and measured the temperature of the water flowing in and exiting the ASHP. A temperature sensor was also installed on the hot water pipe of the geyser delivering hot water to the building. The T-minol 130 flow meters were connected to the ASHP inlet pipe and the geyser outlet pipe and measured the volume of water heated by the ASHP and the volume of hot water drawn off into the building. Each of the flow meter measurements was recorded by the data logger via connecting cable integrating S-UCD electronic input pulse adapter. The flow meter measurements were stored in counts and 1 count represented 3.7854 L. The T-VER E50B2 power and energy meter was installed to measure the active energy in watt hour (Wh), the reactive energy in reactive voltage ampere hour (VARh) and the current capacity in ampere hour (Ah). These three measurements were stored into the data logger using the three S-UCC electronic input pulse adapters. In the data logger, all these measurements were stored as pulses and the data logger was configured such that 1 pulse equal to 1 Wh and 1 VARh while 100 Ah was equal to 1 pulse. The ambient temperature and relative humidity sensor measured ambient temperature and relative humidity and the data was also stored in the data logger. The ambient temperature and relative humidity sensor was protected by a solar radiation shield. All the temperature sensors and the ambient and relative humidity sensor were integrated with electronic input pulse adapters in their connecting cables and these also converted the analogue signals to digital in a bid to eliminate the interference of noise. All the sensors and the transducers were accommodated by the U30-NRC 15 channel data logger [11]. The U30-NRC data logger was configured to log every one minute interval. The study was conducted in a middle income family residence (2 adults and a child) in Fort Beaufort, in the Eastern Cape Province, South Africa from January – May 2014.

It is worthwhile to mention that the ASHP water heater was installed in January 2013.

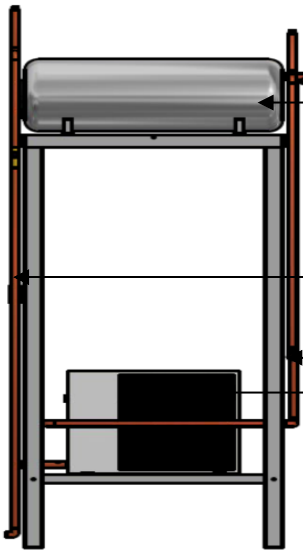

Figure 1: Shows a schematic of the ASHP water heater

CALCULATIONS AND THEORY

The total electrical energy consumed during a heating up cycle is given in equation 1.

$$E = \sum_{i=1}^{n} P_i t \tag{1}$$

The total thermal energy gained by the hot water in the storage tank is given by equation 2.

$$Q = \sum_{i=1}^{n} c\, m_i (T_{out} - T_{in})_i \tag{2}$$

The product of average ambient temperature and relative humidity is given by equation 3.

$$\lambda = \frac{1}{n} \sum_{i=1}^{n} (AT)_i (RH)_i \tag{3}$$

The ASHP water heater calculated COP is defined by the ratio of the useful thermal energy gained (Q) and the input electrical energy (E). Equation 4 shows the calculated equation of the COP.

$$COP_{cal} = \frac{Q}{E} \tag{4}$$

The multiple linear regression model of the COP correlating E and λ is given by equation 5. E and λ were the predictors.

$$COP_{mod} = \delta_0 + \delta_1 E + \delta_2 \lambda \tag{5}$$

RESULTS AND DISCUSSION

The performance of the ASHP water heater was monitored from the 1 st of January to the 30 th May 2014. The results were critically analyzed under two scenarios; where the heating up cycle was simultaneously taken place with hot water drawn off into the building and in heating up cycle without successive hot water drawn off.

Heating up cycle with simultaneous hot water draws

The Table 2 shows some typical results achieved during the five months of monitoring of the performance of the ASHP water heater under the scenario of a simultaneous hot water drawn off during the heating up cycles.

Table 2: Important results achieved during the heating cycle

t (h)	RH %	AT °C	Vdo L	Pa kW	Pm kW	E kWh	Q kWh	COP
1.08	55.9	30.8	114	1.36	1.60	1.59	3.92	2.47
0.75	60.2	26.7	27	1.24	1.57	0.93	1.88	2.02
0.50	63.7	31.3	11	1.33	1.64	0.67	1.53	2.30
0.58	64.3	28.6	42	1.35	1.63	0.79	2.01	2.55
0.83	85.2	24.6	45	1.26	1.60	1.05	2.51	2.38

t = time taken, RH = average relative humidity, AT = average ambient temperature, Vdo = volume of hot water drawn off, Pa = average power, Pm = maximum power, E = electrical energy consume, Q = thermal energy gain, COP = average coefficient of performance

It can be delineated from Table 2 that huge hot water drawn off, resulted in an increase in the duration of the heating up cycles. Furthermore, it can be depicted that increase in average ambient temperature as well as average relative humidity could lead to an increase in the COP of the ASHP water heater. The maximum increase in the system COP was associated with the highest average power consumption. The average power consumption was slightly higher than the manufacturer rating due to the inclusion of the power consumption of the water circulation pump.

Heating up cycle without simultaneous hot water draws

The Table 3 shows some typical results achieved during the five months of monitoring of the performance of the ASHP water heater under the scenario without a successive hot water drawn off during the heating up cycles.

Table 3: Important results recorded during the heating cycle

t (h)	RH %	AT °C	Vdo L	Pa kW	Pm kW	E kWh	Q kWh	COP
0.50	47.8	31.1	0	1.43	1.62	0.71	1.91	2.68
0.75	87.8	19.2	0	1.18	1.52	0.88	1.58	1.78
0.25	26.5	36.1	0	1.16	1.62	0.29	0.94	3.23
0.33	30.1	37.1	0	1.18	1.61	0.39	1.26	3.20
0.41	44.9	33.0	0	1.28	1.63	0.53	1.38	2.59

t = time taken, RH = average relative humidity, AT = average ambient temperature, Vdo = volume of hot water drawn off, Pa = average power, Pm = maximum power, E = electrical energy consume, Q = thermal energy gain, COP = average coefficient of performance

It can be deduced from Table 3 without the loss of generality that the average power consumption during the heating up cycle under no successive hot water draws was lower as compared to the scenario whereby there occurred a simultaneous hot water drawn off. The electrical energy consumed was also lower irrespective of the ambient temperature and relative humidity during these heating up cycle's scenario. Most significantly , with reference to Table 3, it was revealed that the longer the heating up cycle, the lower the COP achieved as a result of the possibility of a huge hot water drawn off that resulted in the start of the VCRC. And the water in the storage tank was at a much lower temperature to the hot water set point temperature (55 ^{o}C).

Model of heating up cycle with simultaneous hot water draws

The data set of over 100 values of the predictors (E and λ) and their corresponding responses (COP) in the five months of the monitoring period were used to develop and build the multiple linear regression model. The modelled equation is given in equation 5 and Table 4 shows the scaling values and the forcing constant of the derived mathematical model.

Table 4: Shows the mathematical model scaling constant

Predictor	Symbol	Scaling constant	Output
Product of AT and RH	λ	-5×10^{-5}	COP
Electrical energy	E	–0.10	
Forcing constant	…	2.34	

From the modelled equation scaling constants presented in Table 4, it can be expressed that increases in λ and E resulted in a decrease in the COP. The determination coefficient between the calculated COP and the modelled COP was 0.962 and the p-value was 0.927. This justifies that there was minimal deviation and a significant correlation between the calculated and the predicted COP. The table 4 also depicted that for a constant electrical energy, increase in the value of the product of average ambient temperature and relative humidity was associated with a decrease in the COP. Figure 2 shows the plot of the calculated COP (dash-black line) and modelled COP (solid-cyan line) of 19 observations from the data set of the heating up scenario where hot water drawn off also occurred simultaneously. By using the reliefF algorithm [12], it was shown that both predictors were primary factors with the ranking by weight of importance of contribution to the COP as 0.022 and 0.026 for λ and E respectively.

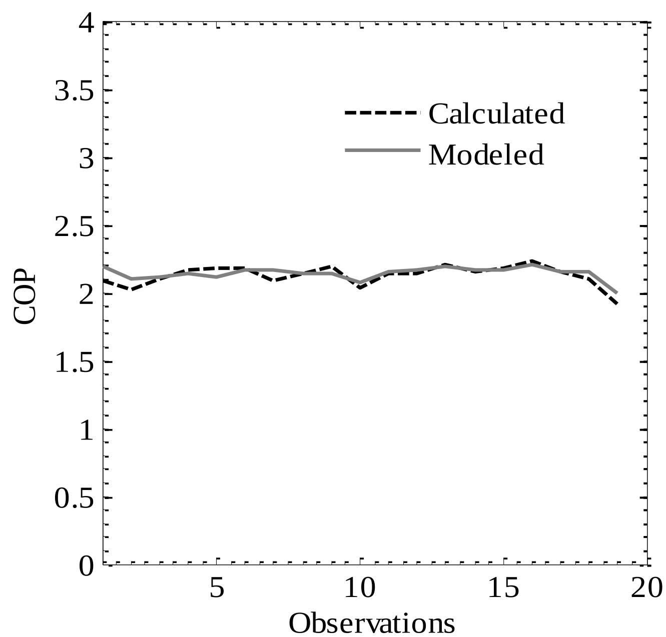

Figure 2: Shows calculated and modelled COP in the heating up cycle scenario with simultaneous drawer

Model of heating up cycle without simultaneous hot water draws

The data set of over 70 values of the predictors (E and λ) and the corresponding output (COP) in the five months of the monitoring period were used to develop and build the multiple linear regression model. The modelled equation is given in equation 5 and the Table 5 shows the scaling values and the forcing constant of the derived mathematical model.

Table 5: Shows the mathematical model scaling constant

Predictor	Symbol	Scaling constant	Output
Product of AT and RH	λ	-2.05×10^{-4}	COP
Electrical energy	E	–1.15	
Forcing constant	…	3.18	

From the modelled equation scaling constants shown in Table 5, it can be observed that increases in λ and E resulted in a decrease in the COP. The determination coefficient between the calculated COP and the modelled COP was 0.972 and the p-value was 0.932. This also confirmed that there was marginal deviation and a very strong correlation between the calculated COP (dash-black line) and the modelled COP (solid cyan line). Figure 3 shows the plot of the calculated COP and modelled COP of 19 observations from the data set of the heating up scenario where there existed no successive hot water drawn off.

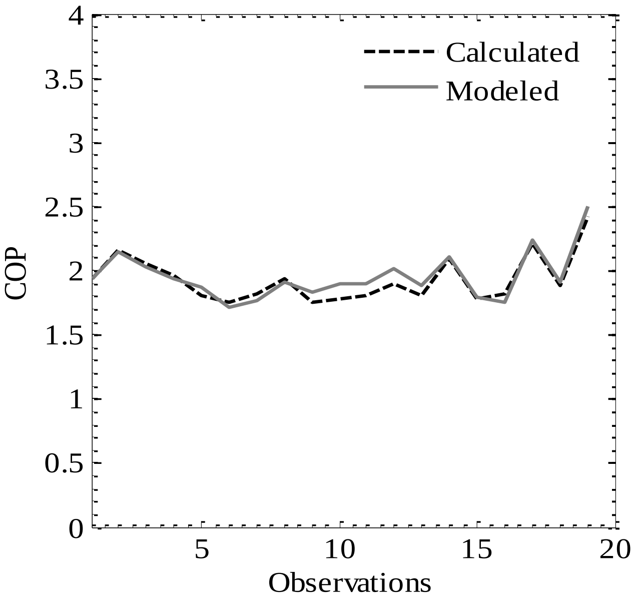

Figure 3: Shows calculated and modelled COP in the no draw heating up cycle scenario

The reliefF algorithm also affirmed that the both predictors were primary factors with the ranking by weight of importance of contribution to the COP as 0.00029 and 0.00027 for λ and E respectively.

Simulation application to model the system performance

The COP of the ASHP water heater was simulated in the Simulink environment using the developed and built mathematical models. The Figure 4 shows the schematic architectural algorithm of the design simulation application.

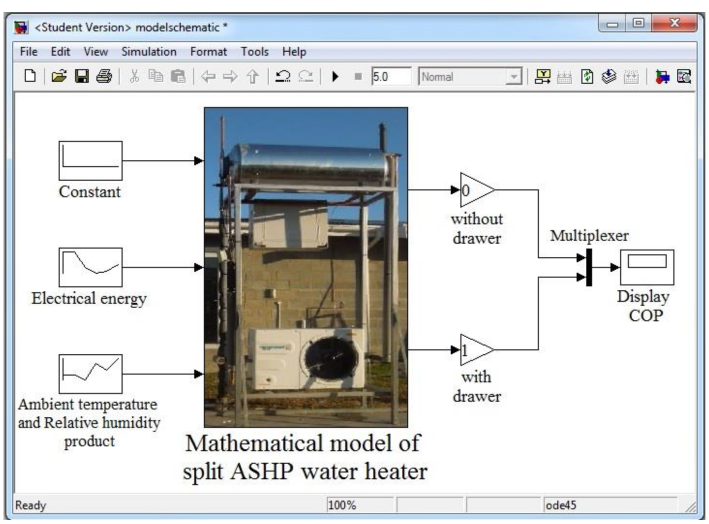

Figure 4: Simulation application of an ASHP water heater performance

The derived mathematical models for both the COP with simultaneous hot water drawn off and COP without successive hot water drawn off were combined into a system block represented by the schematic diagram of the real ASHP water heater. All the predictors were loaded into the respective source blocks (sequence interpolate blocks) while the desired output were displayed in the sink blocks represented by a scope block contained in the Simulink libraries. The both responses were combined with the help of the multiplexer. By setting the respective gain block to the value 1, the performance of that particular scenario could be monitored. On the other hand, if the gain block is set to 0, by default the particular scenario would displayed COP of zero over the entire observations. The simulation was configured to start at observation assigned as 1 and stop at observation assigned as n (where n correspond to the last observation), since the analyzed data inputted into the source blocks of the simulation corresponded to a finite number of observations. Figures 5 and 6 illustrate both the modelled COP in the case of simultaneous hot water drawn off and without successive hot water drawn off scenarios from the analyzed data in the Tables 2 and 3 respectively. The difference between the modelled coefficient of performance and the calculated coefficient of performance in the both scenarios showed a deviation of $\pm 7\%$. The Figure 5 illustrates the modelled COP (black line plot) and the observations using the Table 2 data set and was generated from the scope block after running of the simulation. The COP associated with the no successive hot water drawn off (cyan line plot) was set to zero by default.

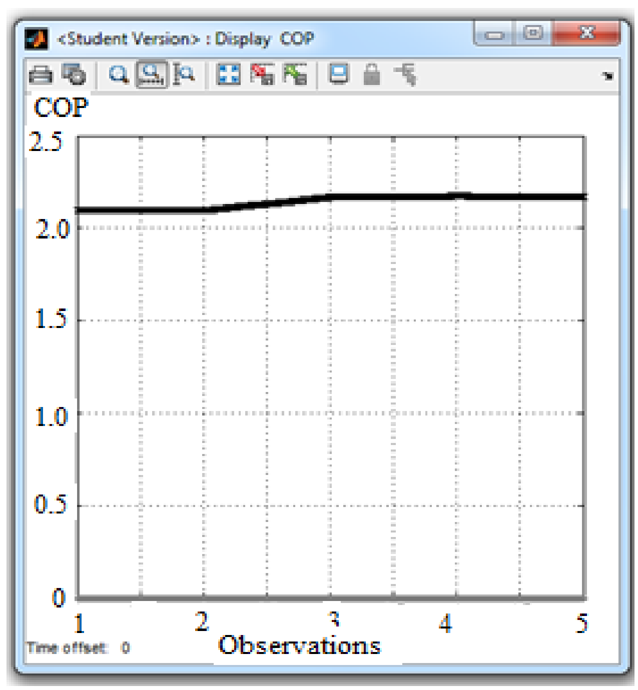

Figure 5: Modelled COP using observations from Table 2

The Figure 6 shows the modelled COP (cyan line plot) in the scenario whereby no successive hot water drawn off occurred and the observation obtained from the Table 3. The modelled plot was generated from the scope block after running of the simulation. The presented simulated plots of the COP actually mimic the calculated COP and hence justified the agreement between the simulated COP results and the calculated COP.

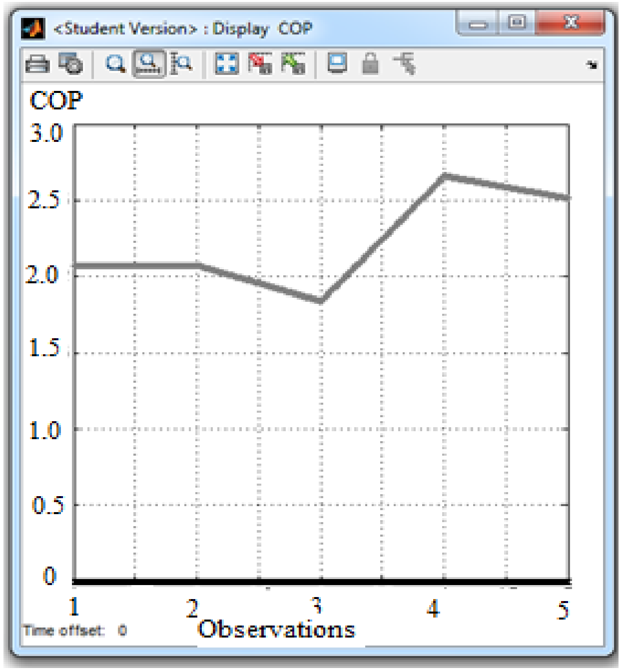

Figure 6: Modelled COP using observations from Table 3

CONCLUSION

It is worth concluding that modelling the COP of an ASHP water heater with the aid of a simulation application can give an in depth into the performance since it can be automated and visualized from a user friendly environment. The increase in both the electrical energy consumed and the product of the average of the ambient parameter which were considered as the predictors can often result in a decrease in the COP. As a final point, the weight of importance of contribution of the predictors to the COP was 100 times more in the scenario of simultaneous hot water drawn off. Thus, the system COP is much better during a heating cycle with simultaneous hot water drawn off.

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