THE EFFECT OF PRESET STORAGE TANK TEMPERATURE ON THE STAGNATION OF A FORCED CIRCULATION TYPE SOLAR WATER HEATING SYSTEM

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Abstract**—** This study focuses on the modelling and simulation of an existing active forced circulation solar water heating system in the College of Science and Technology under the Royal University of Bhutan. The installed prototype solar system consists of five flat-panel collectors connected in parallel, with a gross surface area of 10 m^2, and a 500-litre water storage tank with a built-in heat exchanger to preheat the water in the student mess. The TRNSYS (Transient System Simulation Software) program is used to model and simulate an identical replica of the installed system. The simulation model is validated by comparing the simulation results with actual measurements. The effects of hot tank temperature and stagnation are simulated. When the temperature of the hot tank reaches a preset value of 60 °C, the circulation pump is turned off, causing the temperature of the solar collector to increase exponentially to stagnation. However, by increasing the hot tank set temperature to 80 ˚C, the stagnation time could be extended by two hours, during which the system can generate 25.425 kWh of thermal energy, while 60 ˚C provides only 18.45 kWh. The overall efficiency of the system increased from 27.13% to 37.88%.

Keywords— solar flat-plate collector, an active system, storage tank, solar pump, stagnation, efficiency

I. INTRODUCTION

Renewable power generation has been increasing over the years and has become mainstream around the world. Renewable energy has become an important part of the energy mix due to limited non-renewable resources, environmental impact, and rapid decline in the cost of renewable energy. Falling prices are especially evident for solar photovoltaic and wind. Between 2010 and 2018, the weighted average levelized cost of global utility-scale solar PV fell by 77% [1], while the levelized cost of wind energy fell by approximately 34% [1] over the same period.

Bhutan is endowed with huge solar and wind potential, which can help the country in diversifying the energy mix and reduce the dependency of hydropower. The solar radiation in Bhutan varies from 1600 to 2700 kWh/m²/year and average peak sun hour of 4.0 to 5.5 kWh/m^2/day favoring the potential of solar photovoltaic and solar thermal [2]. The solar irradiance is better than many regions of the world, such as Germany and the United Kingdom, which have achieved more in solar power generation. The Alternative Renewable Energy Policy, implemented in 2013, aims to generate 20 MW of electricity by 2025, including 5 MW from solar PV, 5 MW from wind, and 3 MW from solar hot water [3].

Solar thermal systems use solar radiation to generate thermal energy, which involves the use of solar thermal collectors. The manufacture of solar water heaters began in the early 60s and expanded rapidly in different parts of the world. The solar water heater is a thermal system that collects solar radiation and produces hot water. Such systems can be found on the market and generally fall into two categories: active (forced circulation) systems and passive (thermosiphon) systems [4].

An active (forced circulation) domestic hot water system built in the College of Science and Technology (CST) was modelled and simulated in this study to investigate system performance and predict overall system performance under various operating conditions. A simulation model of the solar water heating system was developed using the Transient Simulation Program (TRNSYS) [5]. The TRNSYS simulates and analyzes the performance and sizing of all system circuit components without the need for actual experimentation.

II. Modeling and Simulation Solar water heating system (SWHS)

2.1 Salient Features of Installed SWHS at CST

A solar water heating system (SWHS) captures the sun's energy and converts it to heat energy in the fluid contained within the solar collector. In a typical solar water heater, the water is heated by solar thermal energy absorbed by the collector. The hot water with a lower density rises, while the cold water with a larger density sinks, and the heated water is collected in a hot storage tank. The system configuration can be broadly classified as active and passive systems as shown in Figure 1.

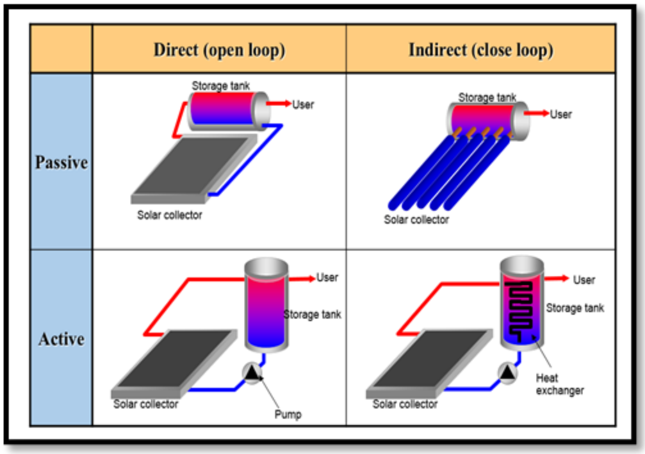

Fig. 1. Type of Solar Water Heating Systems

2.2 Active SWHS

An active SWHS implemented by CST is shown in Figure 2. A pump is required in an active system to circulate solar fluid between collector and tank (which is also known as forced circulation). The fluid circulation is regulated by a differential thermostat, which turns on the pump when the temperature at the collector exceeds the temperature at the tank's bottom by an adequate margin to ensure temperature control [5]. The presence of a heat exchanger, either internal or external, divides the active system into direct and indirect systems. In a direct system, there is no heat exchanger, the water is directly circulated between the collectors and the storage using a pump. On the other hand, in the indirect active system, the heat exchanger is required. The active system has flexibility in the placement of the solar collector and storage tank [6].

Fig. 2. The active Solar Water Heating system installed at CST

Figure 3 depicts the schematic design of the active solar water heating system installed at the CST. It is an indirect type and the heat exchanger is located inside the tank. A 500-litre storage tank was deployed, along with five parallel solar flat panel collectors, each with a total area of 2 m^2.

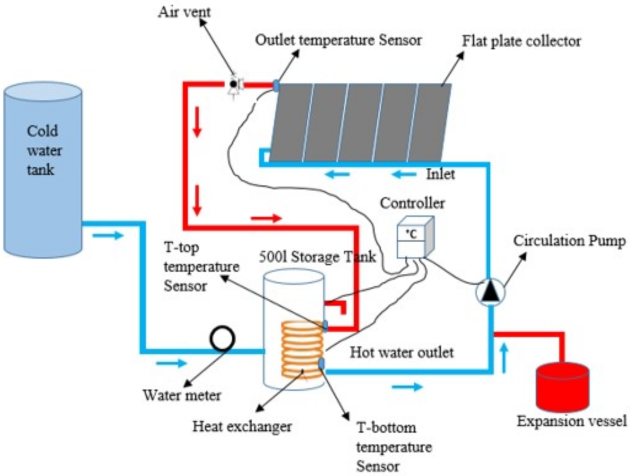

Fig. 3. The schematic design of the active SWH system installed at CST

2.3 Passive SWHS

The Passive SWHS (also known as natural circulation) works on the thermosiphon principle, where warm water rises on top of the tank due to natural convection. The water tank is located above the collector. Whenever the solar energy in the collector adds energy to the water in the collector and establishes a density difference, the water circulates by natural convection [4]. The system can be an open system or a closed system. In the open-loop system (the direct system), water is directly used as the circulating fluid, which flows through the collector and then to the tank. Whereas, the closed-loop system (an indirect system), uses a heat transfer fluid that circulates in a close loop between a heat exchanger and the solar collector.

2.3.1 Solar Thermal Collector

The solar collector is an essential component that converts the light energy from the sun into thermal energy and then transfers this thermal energy to the storage tank as a fluid with low heat loss. There are many different types and designs of solar collectors for different applications. Two types of solar collectors commonly used in the solar thermal system are flat-plate collectors (FPC) and evacuated tube collector (ETC) shown in Figure 4. Flat-plate collectors (FPC) can be designed for applications requiring energy delivery at moderate temperatures, up to 100°C above ambient temperature and the major applications of these types are in solar water heating, building heating, air conditioning and industrial processes heat [8]. The flat-plate collectors can be further classified into unglazed and glazed flat-plate collectors. Unglazed collectors are the simplest kind of solar collector which does not have glazing or insulation.

Fig. 4. Types of solar thermal collectors

2.3.2 Storage tank

Figure 5 shows a typical tank used in a CST solar water heating system. Tanks can be vertical and horizontal cylindrical, with capacities ranging from 150 liters to 1000 liters. The tank used is a pressurized tank system. A higher tank capacity is not widely used as the insulation losses increase with size [9]. The hot water rises to the top of the tank until the whole volume is heated up.

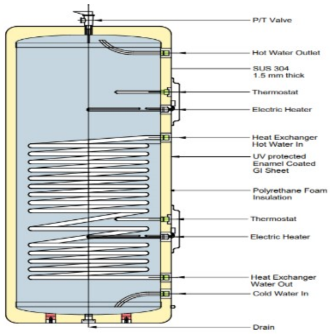

Fig. 5. Solar Storage Tank

2.3.3 Solar circuit and Controller

The Solar water heating system is comprised of two solar circuits. The closed-loop primary circuit consists of stainless-steel pipes (hot wires) connecting the solar collector terminal, solar pump, expansion valve, and storage tank through a heat exchanger in the tank. The solar fluid facilitates the transport of heat from the solar collector to the storage tank. The secondary circuit consists of cold-water input at the bottom of the tank while the hot water is drawn from the top of the tank. A safety pressure valve is installed on the hot end of the collector and the expansion vessel in the primary circuit to protect against pressure rises at stagnation temperature. Pipes should be properly insulated to minimize heat loss when transporting the solar fluid from the collector to the storage tank. Insulation materials, such as Aeroflex or Armaflex, must be temperature resistant. In the CST solar water heating system shown in Figure 6, solaflex tube and coil insulation are deployed. The insulating material is a tubular, black, EPDM-based, flexible, closed-cell elastomeric thermal insulation.

Fig. 6. Solar Circuit and Insulation material

Fig. 7. RESOL Controller

The Resol controller has a built-in data logging system for controlling the circulator pump. When the sensor detects a temperature difference between the collector output temperature and the tank bottom temperature, the pump is activated and the heat transfer fluid is delivered through the collector. The switching temperature can be set to the desired temperature; for example, the CST solar water heating system has an opening temperature of 6 K and a closing temperature of 4 K as shown in Figure 7.

2.4 Data Collection and Modeling

The main input data required for simulation are solar irradiance, temperatures, and specifications of the installed SWHS.

2.4.1 Solar Irradiance at CST

Solar irradiance data collected from a weather station installed on top of the CST library was sampled at one-hour intervals during 2015-2018. The data for one hour of each day is aggregated for an entire year, and then the four-year average is calculated to obtain the precise solar radiation per unit area facing the sun for one hour. Figure 8 shows the monthly solar irradiance of the CST varies from 140 to 185 Wh/m^2, distributed throughout the year.

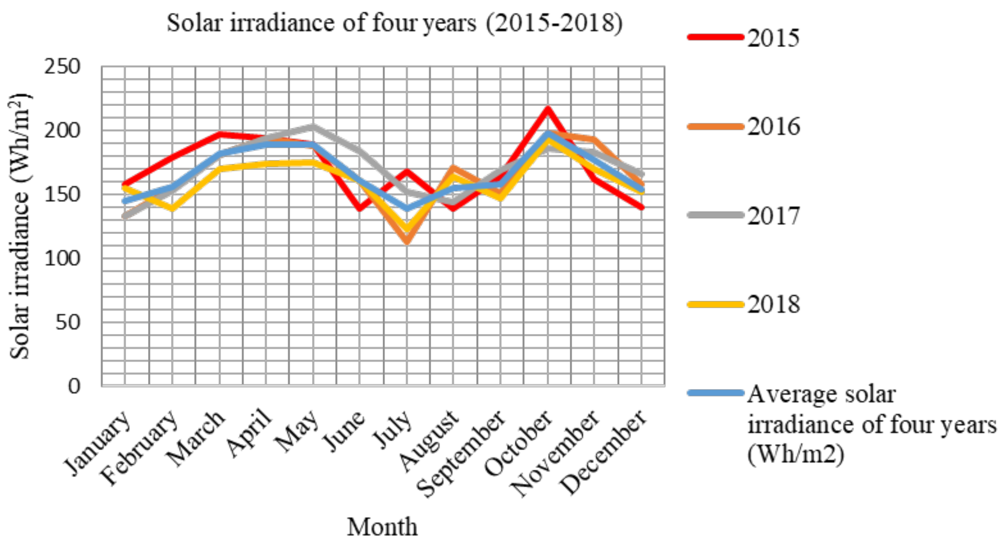

Fig. 8. Average solar irradiance of four years (2015-2018)

Table 1 shows the average peak sunshine hours for each month. Phuentsholing region receives an average of 4.00 kWh/m^2 of solar energy per day, with the highest in October and the least in July due to the monsoon season [2].

TABLE 1. Average peak sun hour per month

Month	Jan	Feb	Mar	April	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
solar irradiance ($kWh/m^2/day$)	3.47	3.75	4.37	4.52	4.54	3.86	3.32	3.71	3.78	4.75	4.25	3.72

2.4.2 TRNSYS Model

Transient Simulation TRNSYS is a transient system simulation program of a simulation engine, which has a rich mathematical model library of various components. It is a compiler for high-level computers designed for connecting component models of transient systems and the differential equations that describe them. Each component model is built in FORTRAN. It has the provision to print, plot, or integrate various quantities [5].

Simulations are created by iteratively solving system equations in a discrete stage called time steps. Each component of the system is modeled separately and interconnected and configured in TRNSYS to get the replica of the actual system. The input parameters given in Table 2 are fed into the TRNSYS model for simulation [7].

TABLE 2. Input parameters TRNSYS Model of CST SWH

	Value	**Unit**
Number of collectors	5	-
Tank volume	500	l
Collector area	10	m^2
Fluid specific heat	4.190	kJ/kg·K
Tested flow rate	0.020	kg/(s·m^2)
Intercept efficiency[η_0]	0.732	-
Efficiency slope [a_0]	3.957	[W/m^2·K]
Efficiency curvature [a_1]	0.023	[W/m^2·K^2]
1st -order IAM [b_0]	0.910	-
2nd -order IAM [b_1]	0	-
T set	60	°C
Power (pump)	99	W
Upipe	0.393	W/ m^2·K
U tank	2.8082	kJ/hr·m^2·K^2
Collector slope(β)	26	°

Figure 9 shows a copy of the CST SWH simulation model created in TRNSYS. The input parameters are the same as those used in the system, while others were obtained from the datasheet of the specific component. Each component model is individually verified and the entire simulation results are compared to the actual recording from the data logger. The primary circuit in the model consists of a solar collector and pump which absorbs solar energy and delivers it to the storage tank. The blue color indicates the cold water flowing in the circuit and the red one is the hot water delivered to the storage tank. An additional plug-in like forcing functions, Type 14 b, was used to represent other components of the system.

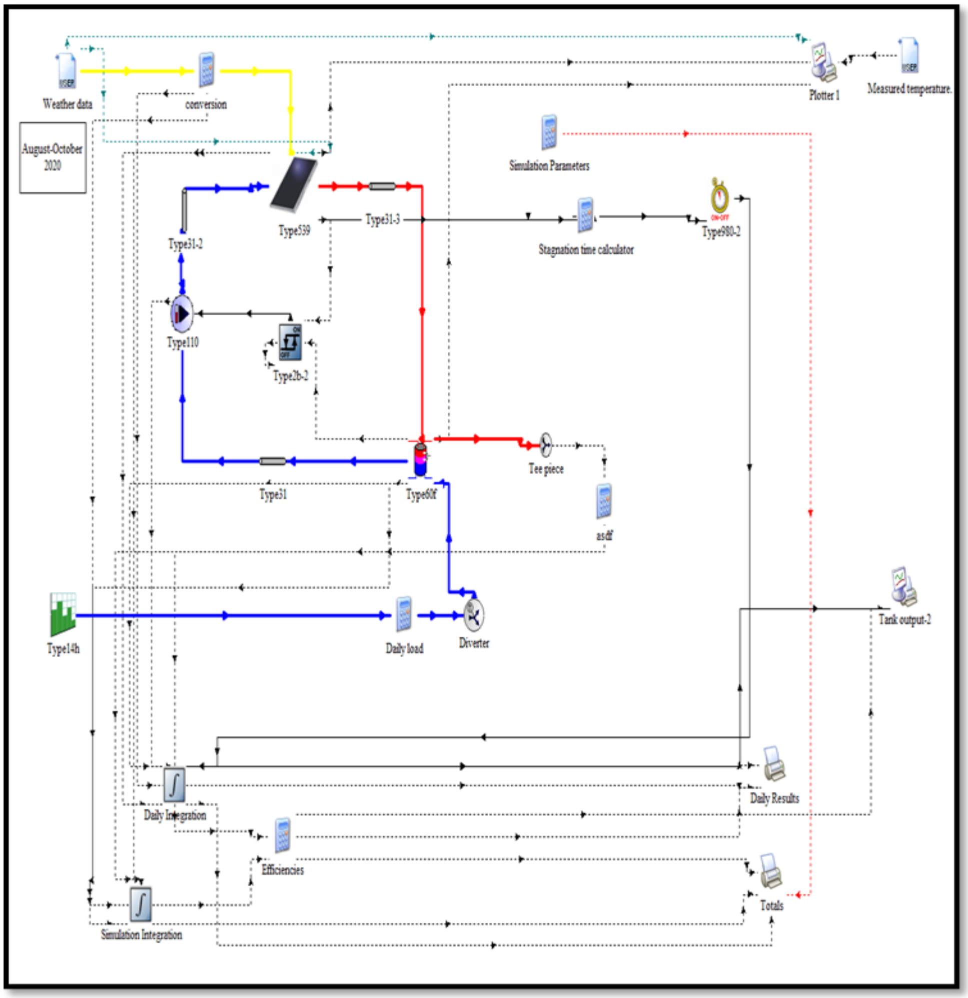

Fig .9. TRNSYS Simulation model of CST SWH System [5]

III. Simulation Results and Discussions

3.1 Simulink Model Validation and Discussion

The results of the two case studies were measured, simulated, and compared. The installed system is measured and simulated exactly as it is in the first case. The tank temperature is raised from 60°C to 80°C in the second case, and the temperature stagnation in the collector and the system performance, are investigated.

The following characteristic of the system was simulated and validated by comparing the simulation and the performance measurement;

i. Solar irradiance and ambient temperature

ii. Collector outlet temperature (T_o)

iii. storage tank temperature (T_{top}, T_{bottom})

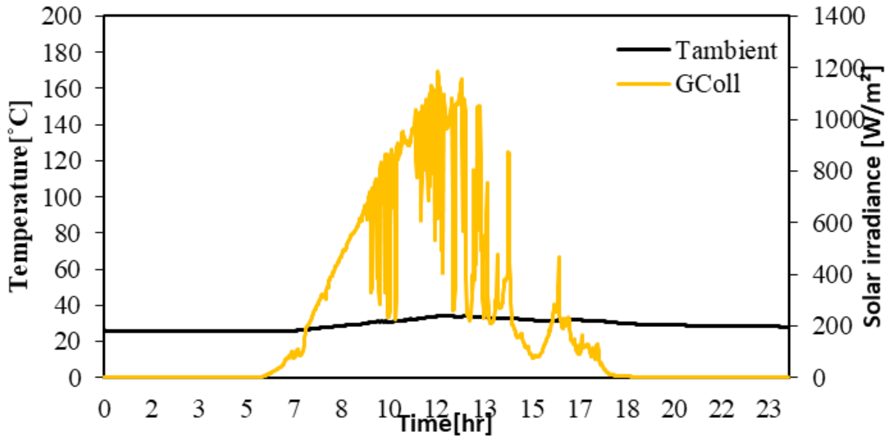

Fig. 10. Solar irradiance (G) and ambient temperature (T_a)

Figure 10 depicts the solar irradiance and ambient temperature on August 2, 2020, simulated the model based on experimental input data on that day.

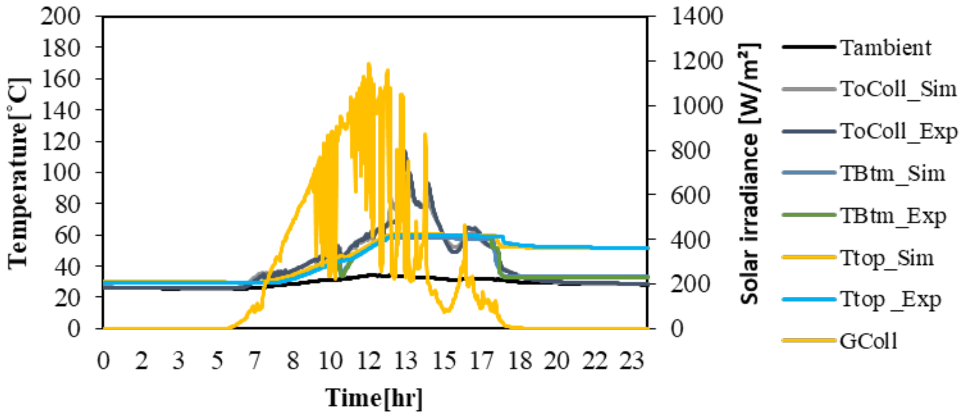

Fig. 11 a. Responses of Collector &Tank temperatures and Irradiance

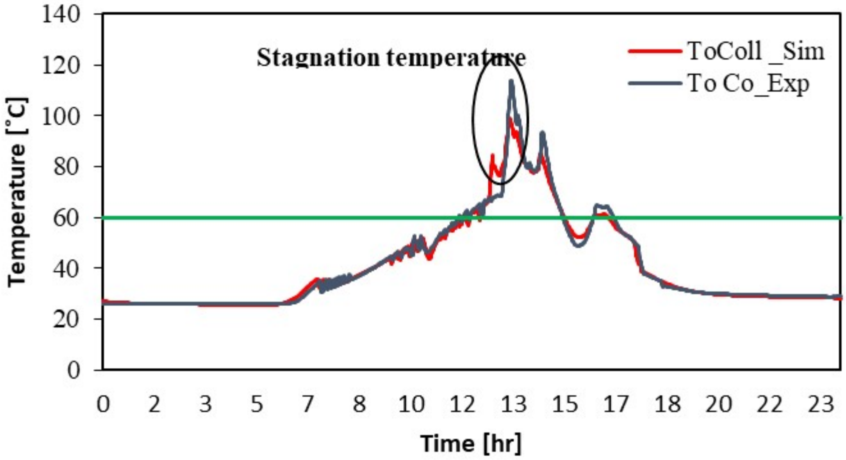

Fig. 11 b. Collector temperature (T_0) at 60 °C

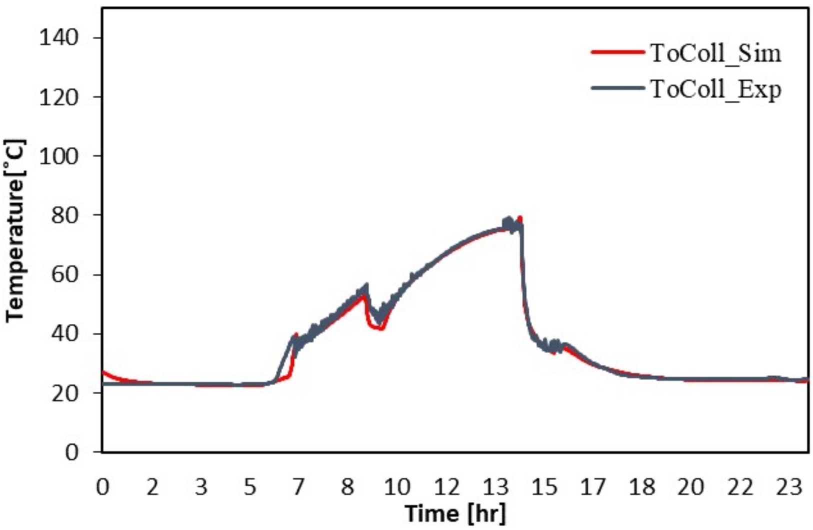

Fig. 11 c. Collector temperature (T_0) at 80 °C

Figure 11a & 11b show the simulated and measured collector outlet temperature responses, showing a good agreement with each other. However, the collector temperature increased rapidly after 60°C above the maximum set temperature of the tank. This happens when the circulation pump is turned off because it is designed to operate with a temperature difference of 10°C between the collector and the bottom of the tank.

However, it can be seen in Figure 11c, that when the maximum temperature of the tank is set to 80°C, the collector temperature does not reach stagnation mode for all peak sunshine hours (PSH). In other words, the stalled process can be avoided by increasing the maximum temperature of the hot tank.

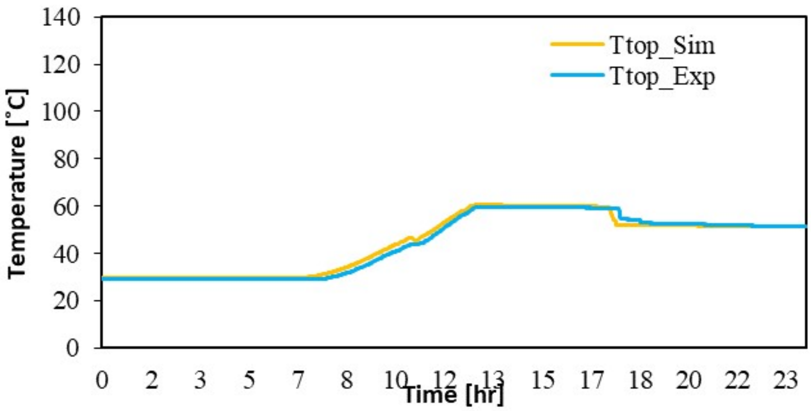

Fig. 12a. Hot water temperature at Tank (T_{top},) at 60 °C

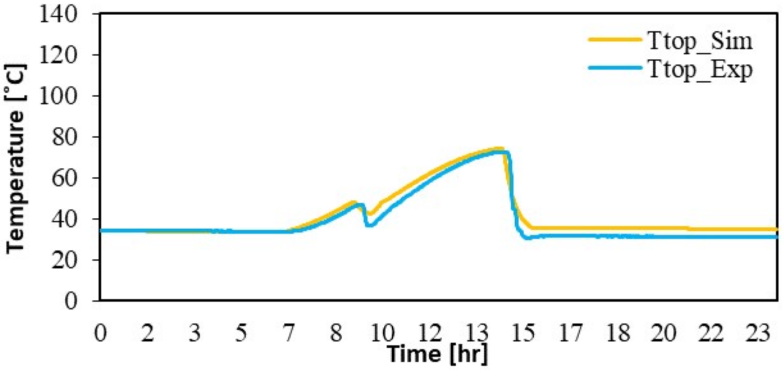

Fig. 12b. Hot water temperature at Tank (T_{top}) at 80 °

Figure 12a shows the simulated and measured responses of the upper tank temperature, which reached a maximum preset value of 60°C for a few hours of sunshine and then remained constant. However, in Figure 12b, it can be shown that the temperature of hot water continues to rise up to the set value in all sun peak hours. The plot also shows that the hot water is drained twice a day, once around 11 am and the other around 3 pm.

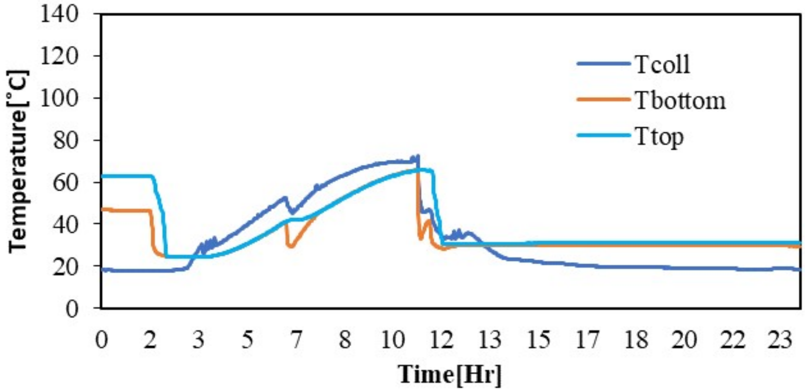

Fig. 12c. Hot water temperature and collector temperature at 80 °

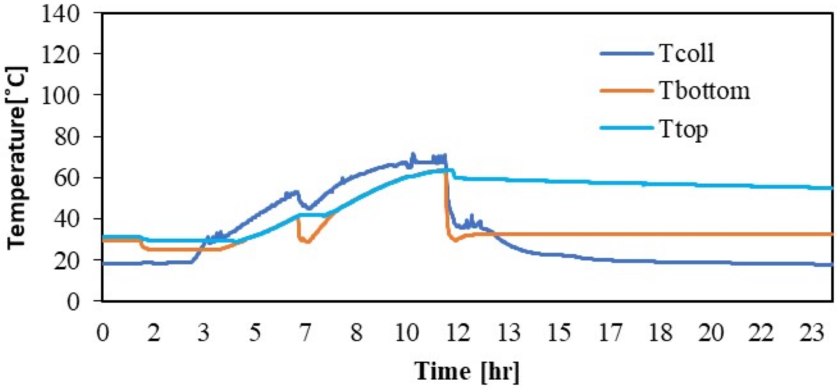

Fig. 12d. Hot water temperature and collector temperature at 80 ° on a particular day

Figure 12c and 12d show the data recorded from the RESOL controller after the preset tank storage temperature has been changed to above 60 °C, particularly at 80 °C, the reduction or elimination of stagnation temperature was achieved. The data recorded clearly indicates the improved system as a whole.

3.2 The Performance of the System at tank temperatures of 60 °C and 80 °C

The system is allowed to achieve the maximum temperature of the tank (**60 °C and 80 °C** respectively) and the parameters are retrieved to compute the useful heat energy produced at two different temperatures [10]. The various temperatures are recorded before and after the hot water is drained out.

Case 1; maximum tank temperature at 60 °C

T_{topmax} = 59.3°C
$T_{bottomax}$ =57.2°C
$T_{top\,min}$ = 32.3°C
$T_{bottomin}$ =20.7°C

Usable energy out

$$Q_{top} = mC_p(T_{top,max} - T_{top,min}) \tag{1}$$

$$Q_{top} = (250\ kg)\ (4.184\ \frac{kJ}{kg.K})(59.3\ K - 32.3\ K)$$

$$Q_{top} = \mathbf{28.242\ MJ}$$

$$Q_{bottom} = mC_p(T_{bottom,max} - T_{bottom,min}) \tag{2}$$

$$Q_{top} = (250\ kg)(4.184\ \frac{kJ}{kg.K})(57.2\ K - 20.7\ K)$$

$$Q_{top} = \mathbf{38.179\ MJ}$$

$$Total\ usable\ Heat = Q_{top} + Q_{bottom} \tag{3}$$

$$= 28.242\ MJ + 38.179\ MJ$$

$$= \mathbf{66.421 MJ}$$

$$= 66.421\ (\frac{10^6 J}{s})/(3600\ )(1000)$$

$$= \mathbf{18.45\ kWh}$$

Efficiency of the system

$$\eta = \frac{Q}{GA} \tag{4}$$

Where:

Q= Usable heat out (18.45 kWh), G= Irradiance (6.8 kWh/m^2), A= Gross area of a collector (10 m^2)

$$\eta = \frac{18.45\ kWh}{6.8\ kWh/m^2(10\ m^2)}(100)$$

$$\eta = \mathbf{27.13\ \%}$$

Case 2; maximum tank temperature at 80 °C

$T_{top\,max}$ = 72.3°C
$T_{bottomax}$ =71.2°C
$T_{top\,min}$ = 32.3°C
$T_{bottomin}$ =23.7°C

Usable energy out

$$\boldsymbol{Q_{top} = mC_p(T_{top,max} - T_{top,min})} \tag{5}$$

$$Q_{top} = (250\ kg)\ (4.184\ \frac{kJ}{kg.K})(72.3\ K - 32.3\ K)$$

$$Q_{top} = \boldsymbol{41.840\ MJ}$$

$$\boldsymbol{Q_{bottom} = mC_p(T_{bottom,max} - T_{bottom,min})} \tag{6}$$

$$Q_{top} = (250\ kg)(4.184\ \frac{kJ}{kg.K})(71.2\ K - 23.7\ K)$$

$$Q_{top} = \boldsymbol{49.685\ MJ}$$

$$\boldsymbol{Total\ usable\ Heat = Q_{top} + Q_{bottom}} \tag{7}$$

$$= 41.840\ MJ + 49.685\ MJ$$

$$= \boldsymbol{91.525\ MJ}$$

$$= 66.421\ (\frac{10^6 J}{s})/(3600\ )(1000)$$

$$= \boldsymbol{25.424\ kWh}$$

The efficiency of the system

$$\boldsymbol{\eta = \frac{Q}{GA}} \tag{8}$$

Where:

Q= Usable heat out (18.45 kWh), G= Irradiance (6.8 kWh/m^2), A= Gross area of a collector (10 m^2)

$$\eta = \frac{25.424\ kWh}{6.8\ kWh/m^2(10\ m^2)}(100)$$

$$\eta = \boldsymbol{37.388}\ \%$$

When the water tank temperature is 60 °C, the available heat is 18.45 kWh, while the heat gain increases to 25.425 kWh when the storage temperature is set up to 80 °C increase. During stagnation, the collector's efficiency is zero because all heat absorbed equals heat losses from the collector. When the tank's pre-set temperature is raised, the system's efficiency improved from 27.13 % to 37.88 %.

IV. CONCLUSION

The solar water heating system (SWHS) installed at the College of Science and Technology was evaluated experimentally and using simulations in the TRNSYS software program. The simulation evaluates system performance by calculating solar collector efficiency, solar fraction, system dead time, and solar collector useful energy gain.

The stagnant temperature affects the performance of the system, as soon as the collector temperature reaches 60°C, the circulation pump shuts down. In this case, the solar fluid is exposed to high temperatures, which can vaporize and increase excessive pressure in the solar circuit. It is observed that stagnation can be avoided either by draining out the water regularly before the tank temperature attains the maximum limit this study also suggests that the maximum tank temperature limit could be increased higher value such that it does not reach the maximum while facing the average peak sun hours throughout the day. The efficiency of the system is also improved from 27.13 % and 37.88 % with an increase in the maximum permissible limit of storage tank temperature.

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List of abbreviations

MW	Mega Watt
GW	Giga Watt
kWh	Kilo Watt Hour
Wh	Watt Hour
CST	College of Science and Technology
SWHS	Solar Water Heating System
TRNSYS	Transient System Simulation tool
FPC	Flat Plate Collector
ETC	Evacuated Tube Collector
EPDM	Ethylene Propylene Diene Monomer
IAM	Incidence Angle Modifier
FORTAN	Formula Translation
UV	Ultraviolet
T	Temperature
M	Mass
Cp	Specific heat capacity of water
MJ	Mega Joule

REFERENCES

[1] IRENA, "Renewable Readiness Assesment Kingdom," IRENA, Abu Dhabi, 2019.

[2] S. Cowlin and D. Heimiller, "Potential for Development of Solar and Wind Resource in Bhutan," U.S Department of Energy, Colorado, 2009.

[3] DRE, "Bhutan Energy Data Directory 2015," Department of Renewable Energy, Thimphu, 2015.

[4] J. A. Duffe and W. A. Beckman, "Solar Engineering of Thermal Processes, " New Jersey, Hoboken: Jhon Wiley & Sons,Inc, 2013.

[5] University of Wisconsin-Solar Energy Laboratory, "TRNSYS 17: a TRainsient System Simulation program," in Getting Started, vol. 1, Madison, 2012, pp. 1-80.

[6] Earthscan, German Solar Energy Society:Planning and Installing-Solar Thermal System, London: Earthscan Ltd., 2010.

[7] N. Rinzin, C. Delkar and Y. Choden, "Design, Installation and Performance Analysis of Solar Water Heating system in CST," College of Science and Technology, Chukha, 2019.

[8] U. Eicker, Solar Technologies for Buildings, Stuttgart: John Willey & Sons Ltd, 2003, p. 334.

[9] ASHARE, "Measurement of Energy, Demand,and Water Savings,American Society of Heating, Ventilating and Air Conditioning Engineers," Atlanta,GA, 2014.

[10] M. Muttakin, "Optimization of Solar Thermal Collector Systems for the Tropics," Researchgate, Queenstown, 2013.