THERMAL PERFORMANCE MODELING OF A SOLAR WATER HEATING SYSTEM INTEGRATED WITH PHASE CHANGE MATERIAL IN A FISH POND

Somchai Jiajitsawat
Faculty of Science, Naresuan University, Muang, Phitsanulok, Thailand, 65000
Corresponding author e-mail: somchaijia@gmail.com

Submitted: 4 October 2022
Revision received: 26 December 2022
Accepted: 26 December 2022

Abstract

In this research work, a transient model of solar water heating system integrated with a phase change material (SWHS-PCM) is proposed to study the effect of solar collector area, the mixed capacities of water and PCM and heat exchanger effectiveness of the SWHS-PCM for heating the fish pond during winter. The simulated results showed that the fishpond with SWHS integrated PCM-Type1 can maintain the water temperature between 28 and 30 °C. The optimum parameters to provide the fish pond temperature between 28 and 30 °C are 1.77 m^2 of the solar collector area, water and 0.4 and 0.007 m^3 of water and PCM-Type1 capacities and 0.5 of the heat exchanger effectiveness. Moreover, it was found that PCM-Type1 heated the fish pond in form of sensible heat. However, with PCM-Type2, the studies revealed that 1.77 m^2 of the solar collector area with water and PCM-Type2 capacities of 0.4 and 0.2 m^3 and the heat exchanger effectiveness of 0.8 gave the maximum temperature of the pond. It was observed that PCM-Type2 heated the pond in form of latent heat.

Keywords: Solar hot water system, Fish farming, Phase change material

1. Introduction

Currently, aquaculture of plants and animals is becoming popular, especially, freshwater fish farming (Gabriel *et al.*, 2013). Thailand is one of freshwater fish producing countries where the fishes are nurtured in warm water. In northern part of Thailand or highland, the weather is generally cold during winter or rainy season. The coldness causes the discontinuous growth or death of the fish due to its less eating.

The water temperature of fish pond between 28 and 30 °C is an important factor to assist its growth (Korawat, 2010).

In Thailand, there are various potential renewable energy sources in usage such as biomass energy, wind energy as well as solar energy. Particularly, solar energy is one of renewable energy sources having high potentiality, large amount, and no environmental pollution. A yearly average value of total solar radiation for Thailand is approximately 18 MJ/m^2-day, which can be used to produce electricity and heat (Department of alternative energy development and efficiency, 1999). There have been some studies on employing solar radiation for heating fish pond. Dilip (2007) proposed a greenhouse for heating a fish pond during extreme winter. A mathematical model was used for system analysis. The results from simulation showed that the fish pond with greenhouse system could provide the favorable water temperature from 16 to 35 °C against 5 to 15 °C temperature of ambient air from prawn fish farm during winter season. Tribeni *et al*. (2006) developed a mathematical model to predict fish pond temperature during India winter. In this research, greenhouse integrated with solar water heating to warm fish pond. The results showed that when the greenhouse and the greenhouse integrated with solar water heating could warm up the fish pond, with increasing of fish pond temperature between 3.12 and 5.64 °C and between 4.13 and 6.92 °C, respectively. Korawat (2010) experimentally studied a solar hot water system with assisted heat pump to warm a fish pond. It was found that the system could maintain the temperature of 30 °C in cold weather. Gabriel *et al.* (2013) proposed 3 different system designs of heating fish pond by using phase change materials (PCM). The first design is a system using PCM to store heat from solar collector through external heat exchanger. The second one is the PCM mounted at the bottom of a fish pond to store heat from the sun. The final is a PCM tank storing the heat from sea and transferring to a fish pond. In this research work, a mathematical model was developed for each design in order to predict their thermal performance. The results from simulation were found that using PCM with solar collector for heating the fish pond provided a positive impact. Somchai *et al.* (2021) developed and experimentally tested a solar water heating system (SWHS) integrated with PCM for heating the fish pond. The system could heat up and control pond water temperature between 28-30 °C.

2. Research Objectives

In this work, the objectives are to propose mathematical model of the developed system by Somchai *et al.* (2021) and then analyze the effect of SWHS with PCM on heating the fish pond based on collector area, water and PCM capacities in a solar hot water tank, and heat exchanger effectiveness.

3. Research Methodology

3.1 System Description

Solar water heating system (SWHS) with natural circulation or thermosiphon system is proposed to heat a fishpond (Somchai *et al.*, 2021). A commercial SHWS (Figure 1) used in this research work consists of flat plate collector with a transparent glazing cover, an absorber-exchanger painted in black color and insulated cylindrical water tank called “Solar Hot Water Tank-(SHWT)”. The SHWT was modified by installing PCM cylindrical container, copper tube heat exchanger, and electrical heater with embedded thermostat inside of the SHWT as shown in Figure 2. The PCM in this study was chosen according to the water temperature stored in a domestic hot-water SWHS around 60 °C and its availability in market. The characteristics of the studied system are presented in Table 1.

For system operation, during daytime, the water inside of the collector is heated by solar radiation. Its density is lighter than the water inside of the SHWT. Thus, it flows up from the collector to the SHWT. The accumulated heat in the tank is transferred to fishpond through heat exchanger by a pump. During the nighttime, the heat in the tank is transferred to the fishpond through the heat exchanger.

3.2 MATHEMATICAL MODELING OF THE SYSTEM

In this modeling, temperatures of water in both fish pond (T_p) and SHWT (T_{st}) integrated with phase change material (PCM), respectively, are assumed to be homogenous, so that their temperature gradient is neglected.

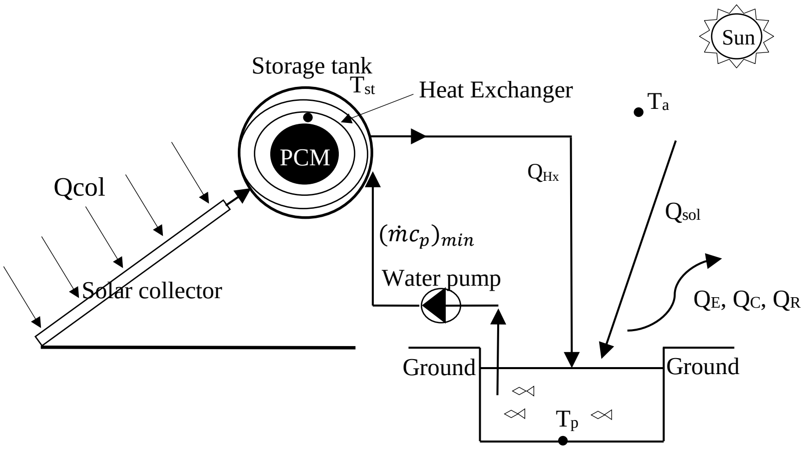


Figure 1 Flat plate SWHS with natural circulation for heating a fish pond

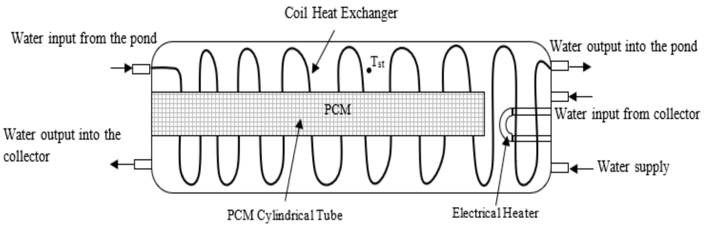


Figure 2 Heat exchanger in solar hot water tank (SHWT)

3.2.1 Fish Pond

From energy balance of the studied system as shown in Figure 1, the water temperature in a fish pond can be calculated as the following equation:

$$V_p(\rho c)_w \frac{dT_p}{dt} = Q_{sol} + Q_{Hx} - Q_E - Q_C - Q_R \tag{1}$$

where $V_p(\rho c)_w$is the product of volume, density, and specific heat of water in the pond, respectively. Q_{sol}, Q_{Hx} are the heat gain into the pond by mean of solar radiation and heat exchanged between SHWT and the pond, respectively. Q_E, Q_C, Q_R are the heat losses from the pond by means of evaporative, convective, radiation heat losses, respectively.

Table 1. Parameters for simulation

Parameters	Values
Solar hot water system (SHWS)	
Collector area (A_C, m^2)	1.77 (Somchai *et al.*, 2021), 4, 6, 8
Water capacity in tank (V_w, m^3)	0.2 (Somchai *et al.*, 2021), 0.4, 0.6, 0.8, 1
Collector heat loss coefficient, ($F_R U_L$, W/m^2 K)	8.4 (Somchai *et al.*, 2021)
Collector transmission and absorption coefficient ($F_R(\tau\alpha)$)	0.66 (Somchai *et al.*, 2021)
Overall heat transfer coefficient of tank (UA, W/K)	4.25 (Somchai *et al.*, 2021)
Heat exchanger	
Effectiveness of Heat Exchanger (ε_{Hx})	0.9 (Somchai *et al.*, 2021)
Mass flow rate ($\dot{m}$, kg/s)	0.02 (Somchai *et al.*, 2021)
Specific heat capacity of water, (c_p, J/kg K)	4,180
Density of water, (ρ ,kg/m^3)	1,000
Phase change material storage (PCM)	
Specific heat capacity in solid phase ($c(s)_{p\_pcm}$, J/kg K)	Type1:2900 (Murat & Khamid, 2007), Type2:3000 (Al-Hamadani & Shukla, 2011)
Specific heat capacity in liquid phase ($c(l)_{p\_pcm}$, J/kg K)	Type1 and 2: 2100 (Murat & Khamid, 2007; Al-Hamadani & Shukla, 2011)
Density in solid phase ($\rho(s)$, kg/m^3)	Type1:830 (Murat & Khamid, 2007), Type2:1007 (Al-Hamadani & Shukla, 2011)
Density in liquid phase ($\rho(l)$, kg/m^3)	Type1:770 (Murat & Khamid, 2007), Type2:862 (Al-Hamadani & Shukla, 2011)
Latent heat of fusion (L_f, kJ/kg)	Type1:266 (Murat & Khamid, 2007), Type2:180 (Al-Hamadani & Shukla, 2011)
PCM capacity in storage (V_{pcm}, m^3)	0.0007 (Somchai *et al.*, 2021), 0.1, 0.2, 0.3
Melting temperature (T_m, C$^{\circ}$)	Type1:52-54 (Murat & Khamid, 2007), Type2:40-43 (Al-Hamadani & Shukla, 2011)
Fish pond	
Diameter (m)	1.6 (Somchai *et al.*, 2021)
Water depth (m)	0.36 (Somchai *et al.*, 2021)
Volume of fish pond (m^3)	0.724 (Somchai *et al.*, 2021)
Wind velocity (m/s)	0.5

A heat grain by direct and diffuse solar radiation incident to the water in the pond can be calculated as

$$Q_{sol} = \alpha I A_P \tag{2}$$

where α is the effective absorptance of solar radiation, I is the total solar irradiance, and A_p is the water surface area of the pond.

Another heat grain into the pond by heat exchange between SHWT and the pond can be calculated by means of

$$Q_{Hx} = \varepsilon_{Hx}\left(\dot{m}c_p\right)_{min}\left(T_{st} - T_p\right) \tag{3}$$

where ε_{Hx} is effectiveness of heat exchanger between SHWT and the pond, $\left(\dot{m}c_p\right)_{min}$ is heat capacity of cold water.

Heat losses from evaporation, convection, and radiation of water surface of the pond are shown as the following equations (7), respectively.

$$Q_E = 16.273{\times}10^{-3}h_c \times A_p\left[\,P\left(T_p\right) - \gamma_a P\left(T_a\right)\right]/\left(T_p - T_a\right) \tag{4}$$

$$\mathrm{Q}_C = h_c \times A_p\left(T_p - T_a\right) \tag{5}$$

$$\mathrm{Q}_R = \sigma\varepsilon A_p\left[\left(T_p + 273\right)^2 + \left(T_a + 273\right)^2\right]\left(T_p - T_a + 546\right) \tag{6}$$

Where $h_c = 2.8 \times 3.0v$, is convective heat transfer coefficient (W/m^{2}K), $P = exp[25.317 - 5144/(T + 273.15)]$, is partial pressure (N/m^2), γ_a is relative humidity (%), T_a is the ambient temperature ($^{\circ}$C), σ is Stefan-Boltzmann constant (W/m^2 K^4), ε is the emissivity of water in fish pond.

3.2.2 Integrated PCM-Solar hot water tank (PCM-SHWT)

In this tank, the water and PCM are mixed as one equivalent lump. The water temperature in PCM-SHWT can be derived from energy balance as:

$$\left((\rho V)_{eq} c_{p\_w}\right)\frac{dT_{st}}{dt} = Q_{Col} - Q_{Hx} - Q_{loss} \tag{7}$$

Where Q_{Col} is the heat gain into the SHWS by mean of heat absorbed by solar collector, Q_{loss} is the heat losses from the tank to the ambient air. $(\rho V)_{eq}$ and c_{p_w} are the product of density and volume of the mixed and the specific heat capacity of water, respectively. They were expressed in (Abdulhaiy, 2004).

$$(\rho V)_{eq} = \left[(\rho V)_w c_{p\_w} + (\rho(s)V)_{pcm} c(s)_{p\_pcm}\right]/c_{p\_w} \qquad \text{For } T_{st} < T_m \tag{8}$$

$$(\rho V)_{eq} = \left[(\rho V)_w c_{p\_w} + ((\rho(l) + \rho(s)/2)V)_{pcm} L_f\right]/c_{p\_w} \qquad \text{For } T_{st} = T_m + \delta \tag{9}$$

$$(\rho V)_{eq} = \left[(\rho V)_w c_{p\_w} + (\rho(l)V)_{pcm} c(l)_{p\_pcm}\right]/c_{p\_w} \qquad \text{For } T_{st} > T_m \tag{10}$$

Where L_f is latent heat of fusion, c_{p_w}, $c(s)_{p\_pcm}$, $c(l)_{p\_pcm}$ are specific heat capacity of water, phase changer material in solid and liquid states, respectively. The heat received by collector is estimated by the following equation:

$$Q_{Col} = A_c[F_R(\tau\alpha)I_T - F_R U_L(T_{st} - T_a)] \tag{11}$$

Where A_c is area of the collectors connected in parallel, F_R is the collector heat-removal factor, τ, α are the transmission coefficient of glazing and absorption coefficient of plate, respectively. I_T is the solar radiation on tilted surface, U_L is the collector overall heat loss coefficient.

The heat loss of solar water storage is estimated as:

$$Q_{loss} = UA(T_{st} - T_a) \tag{12}$$

where UA is the overall heat loss coefficient of SHWT.

3.2.4. SYSTEM SIMULATION

SHWS integrated with PCMs to heat the water in a fish pond was mathematically modeled. The weather data as solar radiation, ambient temperature, and relative humidity, recorded during winter season on cloudy day (Somchai *et al.*, 2021), was used in this simulation as shown in Figure 3 and 4.

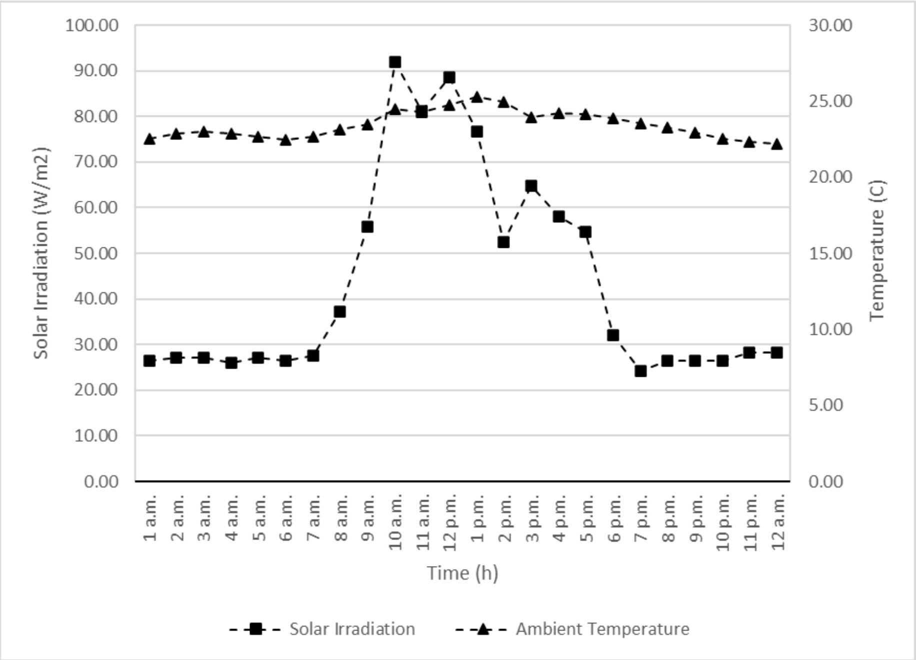


Figure 3 Solar radiation and ambient temperature on a cloudy day in winter season (Somchai *et al.*, 2021)

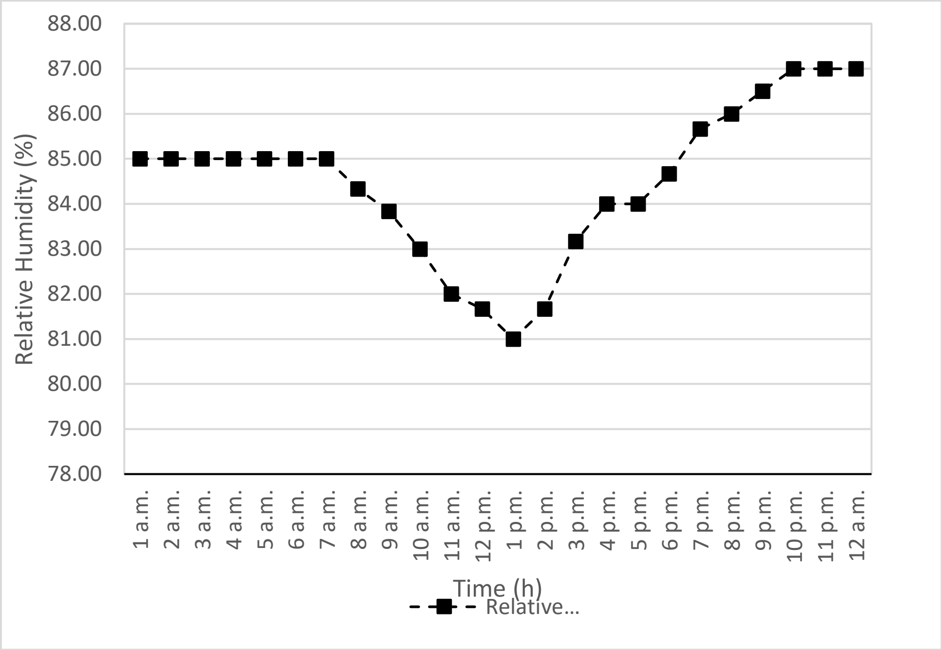


Figure 4 Relative humidity on a cloudy day in winter season (Somchai *et al.*, 2021)

Several computer simulations were conducted to study the various parameters of solar water heating integrated with PCMs that effect on the water temperature in fish pond. The parameters to be optimized are provided in Table 2. For optimizing the parameters, a single parameter was changed, while other parameters were kept constant. They also were optimized in view of water mixed with PCM temperature in the SHWT and water temperature in fish pond

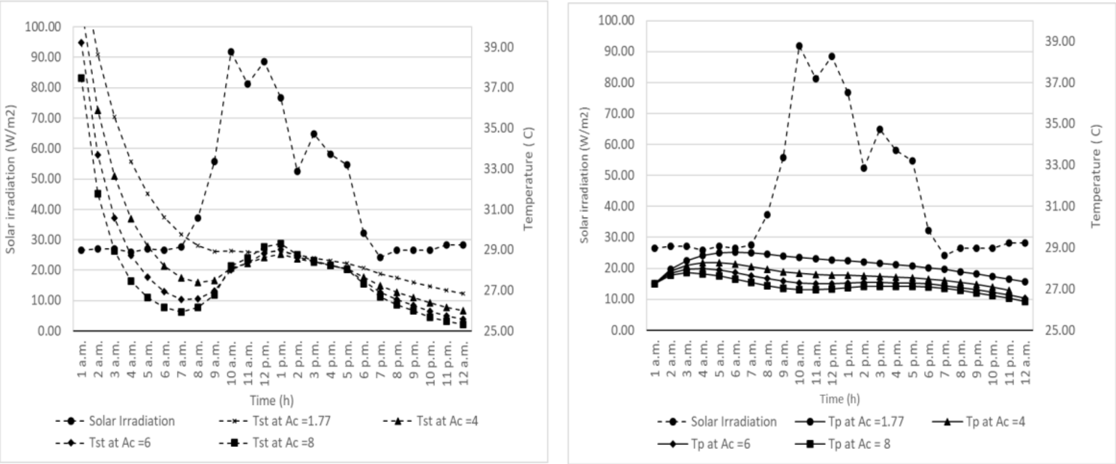
Table 2. Parameters under study

Optimized parameters	**Parameter range**			
	Collector area (m^2)	**Water tank capacity (m^3)**	**PCM storage capacity (m^3)**	**Effective of heat exchanger**
Collector area (m^2)	1.77, 4, 6,8	0.2	0.0007	0.5
Water tank capacity (m^3)	1.77	0.2, 0.4, 0.6, 0.8	0.0007	0.5
PCM storage capacity (m^3)	1.77	0.4	0.0007, 0.1, 0.2, 0.3	0.5
Effective of heat exchanger	1.77	0.4	0.007 (Sensible heat effect) 0.2 (Latent heat effect)	0.5, 0.6, 0.7, 0.8

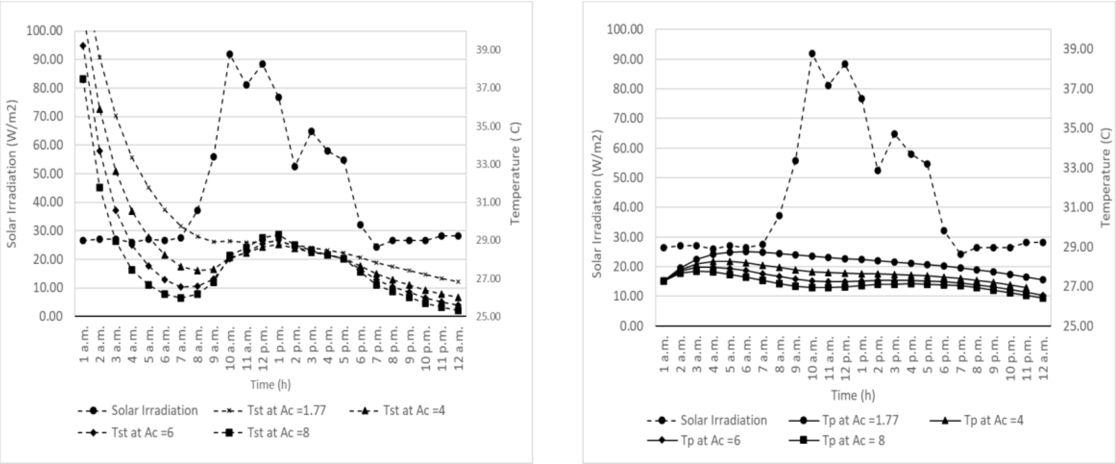
4. Results

4.1 Effect of collector area on water temperature in fish pond and SHWT

In this simulation, the collector area was varied between 1.77 and 8 m^2, while the other parameters were kept constant. The effect of collector area on water temperature in a fish pond and SHWT integrated with two different melting point PCMs is shown in Figure 5. Increase of collector area not only causes the water temperature in the SHWT decreased during night time due to more collector heat loss but also increased during day time due to more heat gain from solar radiation. However, while increasing the collector area, the water temperature in fish pond slightly decreases. 1.77 m^2 of collector area should be an optimum area to provide the water temperature in the fish pond between 28 – 30 °C required (Somchai *et al.*, 2021). There is no temperature difference in the SHWT and fish pond between two types of PCM shown in Figure 5a and 5b.



a) PCM-Type1

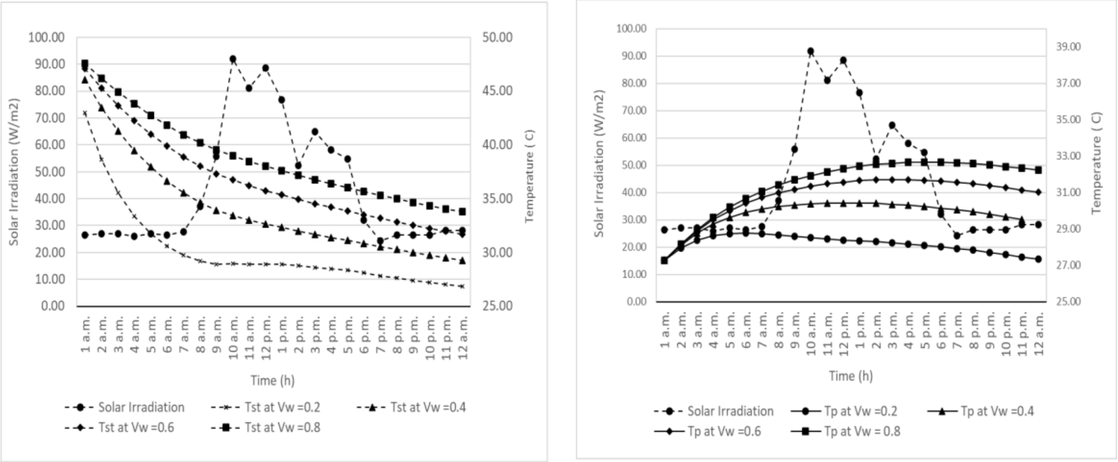


b) PCM-Type2

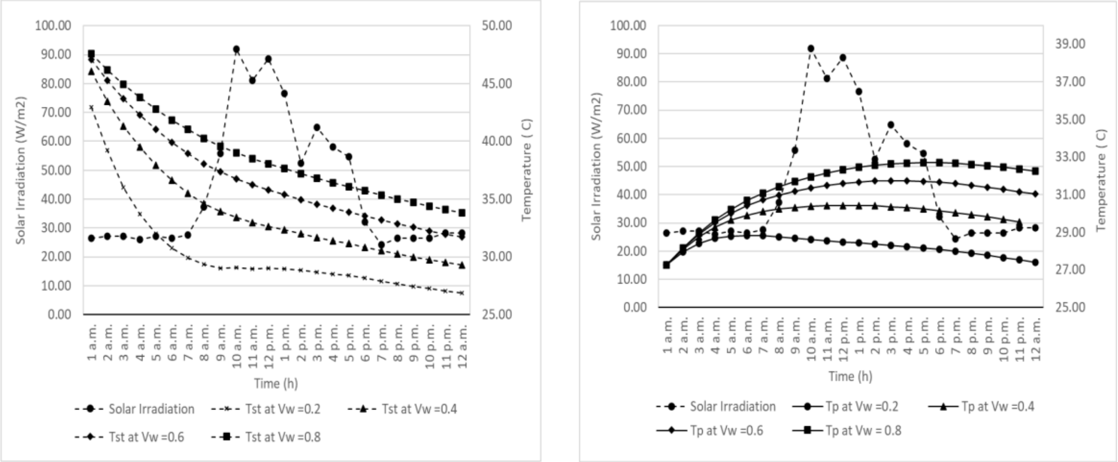
Figure 5 Effect of collector area on water temperature in fish pond (Tp) and SHWT (Tst): a) with PCM-Type1 and b) with PCM-Type2

4.2 Effect of water capacity of SHWT on water temperature in fish pond and SHWT

To study the effect of water capacity of SHWT on water temperature in the pond and the SHWT, the water capacity was varied between 0.2 and 0.8 m^3 at 0.2 m^3 increment and results are shown in Figure 6. With increasing of the water capacity, the water temperature in both the SHWT and the fish pond increases due to initially accumulated thermal energy. The water capacity of 0.4 m^3 is an optimum parameter to provide the water temperature in the pond between 28 – 30 °C. There is no temperature difference between two types of PCM as shown in Figure 6a and 6b.



a) PCM-Type1



b) PCM-Type2

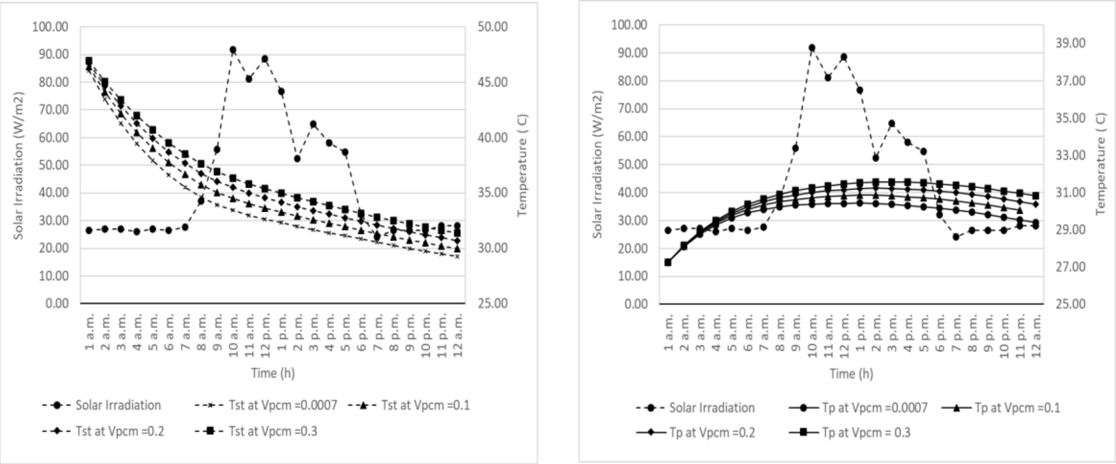
Figure 6 Effect of water capacity in the SHWT on the water temperature in fish pond (Tp) and SHWT (Tst): a) with PCM-Type1 and b) with PCM-Type2

4.3 Effect of PCM capacity on water temperature in the fish pond and the SHWT

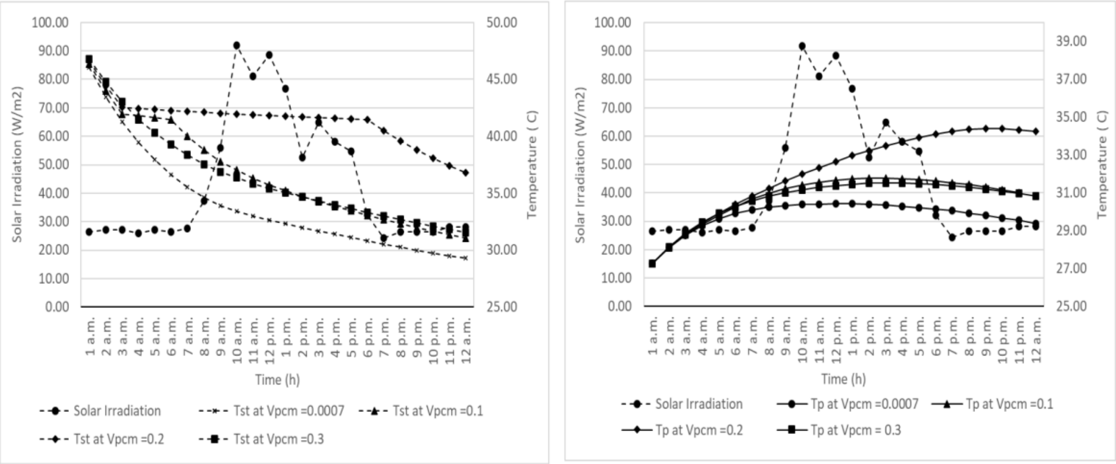
In this section, the objective is to study the effect of 2 type-PCM capacity on the water temperature in the pond and the SHWT. Each type of PCM has different melting points of 52-54 °C and 40 – 43 °C, respectively. Their capacity was varied between 0.0007 and 0.3 m^3. The simulated results were shown in Figure 7. In Figure 7a, it was found that increase of type-1 PCM slightly rises the water temperature in both of the fish pond and the SHWT due to initially sensible heat accumulated. In addition to that, 0.007 m^3 of the PCM is optimum to provide the water temperature in the pond within 28 -30 °C. Whereas, with type-2 PCM, the water temperature in the SHWT is not only maintained between 40 – 43 °C due to latent heat of fusion (Constant temperature) but also provided the maximum water temperature in the fish pond as shown in Figure 7b. In this case, 0.2 m^3 of the PCM was chosen as an optimum parameter to present the latent heat effect on the SHWT temperature.

4.4 Effect of effective heat exchanger on water temperature in fish pond and SHWT

In this simulation, the effectiveness of heat exchanger was varied between 0.5 and 0.8. The results were shown in Figure 8. In Figure 8a, it was observed that the water temperature in the SHWT integrated with PCM-Type1 decreases with increase of heat exchanger effectiveness, which results in more heat transferred from SHWT to the fish pond. 0.5 of the effectiveness provided the optimum temperature of the fish pond. The same results are applicable with PCM-Type2 except for the heat exchanger effectiveness of 0.5 and 0.8 maintaining the SHWT temperature constant as shown in Figure 8b. However, 0.8 of the heat exchanger effectiveness provides the maximum temperature in the pond.

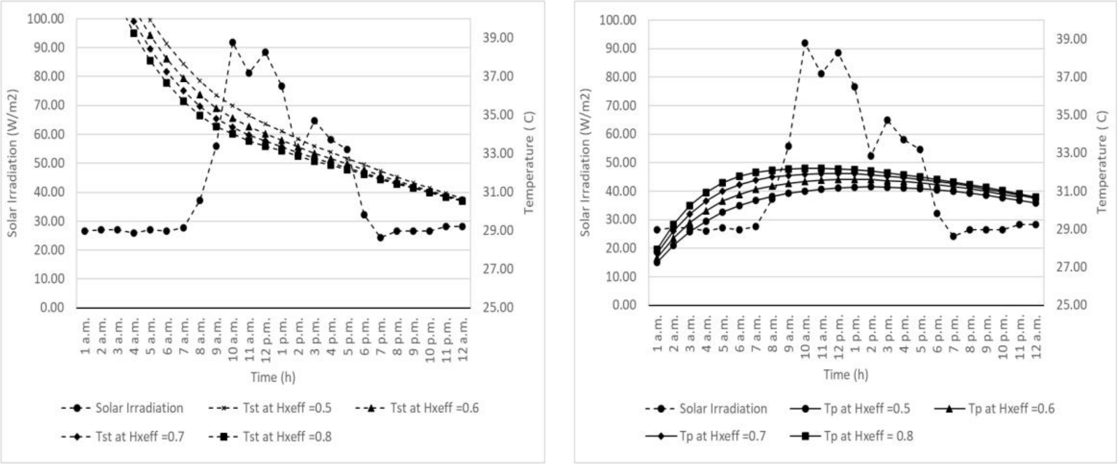


a) PCM-Type1



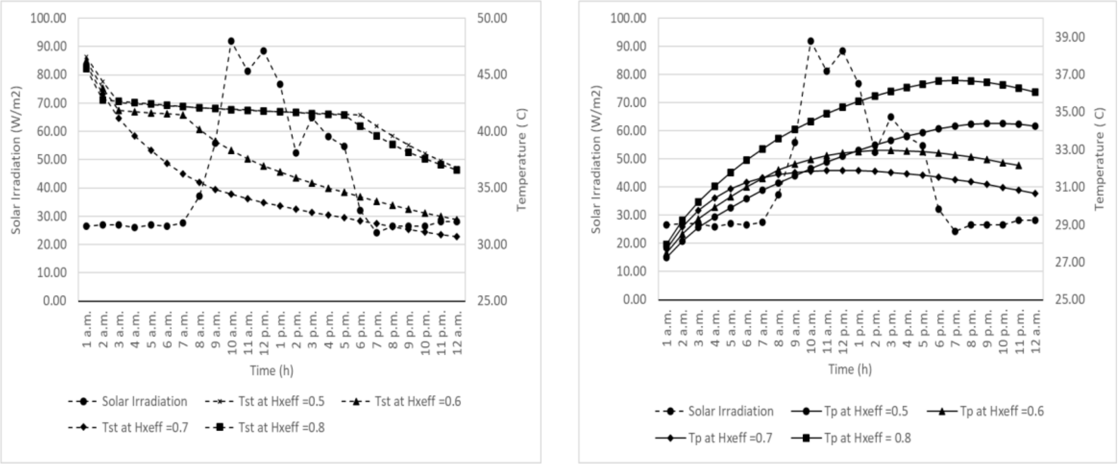
b) PCM-Type2

Figure 7 Effect of PCM storage capacity in the tank on water temperature in fish pond (Tp) and SHWT (Tst): a) with PCM-Type1 and b) with PCM-Type2



a) PCM-Type 1

(Murat & Khamid, 2007)



b) PCM-Type 2

(Al-Hamadani & Shukla, 2011)

Figure 8 Effect of effective heat exchanger in the tank on water temperature in fish pond (Tp) and storage tank (Tst): a) with PCM (Murat & Khamid, 2007) and b) with PCM (Al-Hamadani & Shukla, 2011)

5. Conclusion and Discussion

In this work, the objectives are to propose mathematical model of the developed system by Somchai *et al.* (2021) and then analyze the effect of SWHS with PCM on heating the fish pond based on collector area, water and PCM capacities in a SHWT, and heat exchanger effectiveness. The results showed that the fishpond with SWHS integrated PCM-Type1 can maintain the water temperature between 28 and 30

°C during winter season. The parametric studies showed that 1.77 m^2 of the solar collector area with water and PCM-Type1 capacities of 0.4 and 0.007 m^3 and the heat exchanger effectiveness of 0.5 can provide the optimum water temperature for the fish pond. Moreover, it was found that PCM-Type1 heated the fish pond in form of sensible heat. This is because the solar radiation is not enough to heat the Type1 into its melting point. However, with PCM-Type2, the studies revealed that 1.77 m^2 of the solar collector area with water and PCM-Type2 capacities of 0.4 and 0.2 m^3 and the heat exchanger effectiveness of 0.8 gave the maximum temperature of the pond. It was observed that PCM-Type2 heated the pond in form of latent heat.

6. Acknowledgement

The author would like to thank Naresuan University for facilities in this study. The 2017 research grant support from National Research Council of Thailand are highly appreciated.

7. References

Abdulhaiy, M.R. (2004). Transient performance of a stepped solar still with built-in latent heat thermal energy storage. **Journal of Desalination**, 171, 61-76.

Al-Hamadani, A.A.F. & Shukla, S.K. (2011). Water distillation using solar energy system with lauric acid as storage medium. **International Journal of Energy Engineering**, 1(1), 1-8.

Department of alternative energy development and efficiency. (1999). **Solar energy potential map of Thailand. Ministry of energy.**

Dilip, J. (2007). Modeling the thermal performance of an aquaculture pond heating with green house. **Building and Environment**, 42, 557-565

Gabriel, Z., Cristian, S., Albert, C., Gabriel, P., & Luisa, F.C. (2013). The use of phase change materials in fish farms: A general analysis. **Applied Energy**, 109, 488-496.

Korawat, W. (2010). Solar collector sizing of water heating system with assisted heat pump for controlling fish pond temperature. (Master dissertation). Chiang Mai university, Chaing Mai.

Murat, K. & Khamid, M. (2007). Solar energy storage using phase change materials. **Journal of renewable and sustainable energy reviews**, 11, 1913-1965.

Somchai, J., Eakpoom, B., Sorawit, S., & Phassorn, K. (2021). **Operational study of a solar water heating system integrated with phase change material for temperature control of fish pond**. In Proceedings of the 17th Naresuan Research & Innovation, Phitsanulok.

Tribeni, D., Tiwari, G.N., & Bikash, S. (2006). Thermal performance of a greenhouse fish pond integrated with flat plate collector. **International Journal of Agricultural Research**, 1(5), 406-419.