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Energy Procedia 110 (2017) 243 – 249

Energy Procedia

1st International Conference on Energy and Power, ICEP2016, 14-16 December 2016, RMIT University, Melbourne, Australia

Solar thermal energy with molten-salt storage for residential heating application

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Abstract

Heating application is one of the areas in residential building where residents pay a significant part of energy bill. Thermal energy from solar irradiance can be collected by solar thermal collector (STC) and absorbed by heat transfer fluid (HTF) to transport heat to the heat-exchanger and to the load. This paper investigated various solar collectors and considered parabolic trough collector (PTC) to develop a residential heating application. The system structure mainly consists three subsystems: solar thermal absorption subsystem, thermal energy storage subsystem and underfloor heating subsystem. Because of temperature range and specific heat capacity Nitrate salt ($0.54KNO_3+0.46NaNO_3$) was considered in the model. A typical house in Melbourne with heating area of approximately 240m² is considered as thermal load. Model was evaluated for summer, winter and yearly load demand and result showed that molten-salt storage helped the system to operate consistently even at night-time (19:00 – 05:00) without solar radiation.

Peer-review under responsibility of the organizing committee of the 1st International Conference on Energy and Power.

Keywords: Solar thermal energy; Heat transfer fluid; Solar irradiance; Parabolic trough collector; Molten salt storage.

1. Introduction

Solar power technology, both photovoltaic (PV) and solar thermal technology have been proven great advantages in past years, which provides various alternative options for commercial as well as residential application. The idea of solar thermal power is to utilize solar thermal energy by the use of thermal collectors [1]. As the solar radiation varies with time and season, therefore applying energy storage with thermal power application is significantly beneficial to

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Peer-review under responsibility of the organizing committee of the 1st International Conference on Energy and Power.
doi:10.1016/j.egypro.2017.03.134

buffer energy for different weather conditions, enhance capacity factor and provide stable operating condition during peak demand period. Concentrated solar power (CSP) with thermal storage can operate more than 7 hours either grid or off-grid applications [2]. This paper explained different types of CSP technologies also explained various salt properties to use as thermal energy storage and mainly explained the mathematical model of thermal energy system for residential heating application. Model was evaluated with Melbourne weather condition and found that yearly heating load demand can be met from solar thermal application with the utilization of molten-salt as storage medium.

2. Background

Solar energy is the most abundant source of renewable energy. Solar energy falling on earth in the form of solar radiation; for example in Australia this radiated energy is approximately 10,000 times the Australia's yearly energy consumption [3]. Solar thermal technologies are based on the concept of concentrating solar radiation to produce thermal energy. CSP has more potential and Australian government spent $1.5 billions for the construction of large solar power stations [3]. CSP technologies include solar reflector and tracking device, thermal heat exchanger, thermal storage and thermal load. Direct normal radiation harvested through concentrating devices, which depends on solar geometry of sun and earth. CSP collector technologies are summarised in Table 1.

Table 1. Different CSP technologies [4]

CSP Technology	Concentration ratio	Cost	Temperature range (°C)	Maturity
Fresnel Liner reflector	25-100	High	50-300	Mature
Central tower	10-150	Low	300-2000	Recent
PTC (New IST)	50-400	Low	50-400	Most Mature
Dish-Stirling	1000-3000	Very high	150-1500	Recent

These technologies use HTF to export concentrated thermal energy to use in steam turbine or to store. The benefit of storage is also to buffer energy in different weather condition. Molten salt storage are in use with different commercial applications for storing thermal energy. PTC system can be indirect or direct based on the HTF used in the system.

Different types of PTC has different performance based on its properties. Most of the PTC plants in commercial utilization consider synthetic oil as HTF that operates in temperature range of 200°C to 400°C that also depends on the stability property of the oil. In indirect system, HTF is synthetic oil and two exchanger is required; heat exchange from oil to molten salt and from molten salt to load [5]. In direct system, molten salt works as HTF as well as thermal storage medium, providing higher operating temperature range that is up to the salt maximum temperature [6]. Only one heat exchanger is required in direct system that reduces thermal losses and bring higher efficiency to the thermal system. Figure 1 shows the schematic of a direct system with one heat exchanger.

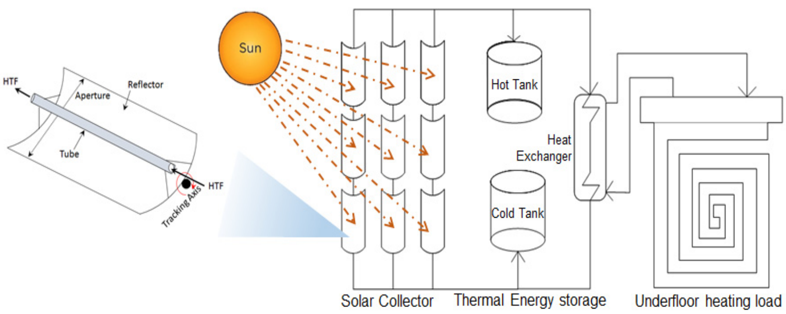

Fig. 1. Schematic of residential heating system using PTC technology

It was found from literature that molten salt is used as thermal energy storage in various application. Molten salt is a liquid salt that can flow through PTC pipe/tube to carry thermal energy collected by collector. Cold temperature is the lowest temperature under which salt will become solid and can block the PTC pipe. Hot temperature indicates stability; over which system becomes unstable. Table 2 illustrates various salt properties.

Table 2. Various salt properties [7]

Salt types	Tcold (°C)	Thot (°C)	Density ρ (Kg/m³)	Specific heat capacity Cp (KJ/kg °C)	Thermal conductivity (W/m.k)
NaCl	200	500	2160	0.85	7
Lithium liquid salt	180	1300	510	4.19	38.1
Nitrite Salts	250	450	1825	1.5	0.57
Nitrate Salts	265	564	1870	1.6	0.52

For residential heating application, Nitrate salt (0.54KNO3+0.46NaNO3) can be considered as HTF and thermal energy storage, also operating temperature is suitable for residential applications [8]. In this paper, a mathematical model of thermal heating system was develop for a residential house in Melbourne, Victoria, Australia. A CSP system with two-tank storage is considered that requires a solar thermal collector, hot tank, thermal load and cold tank.

3. Model Development

Complete model was evaluated for solar collector performance, thermal energy storage performance in order to meet the load consumption. New IST is a space frame PTC with aperture width (a) of 2.3 m, length (l) of 49 m, and peak optical efficiency of 0.78 was considered as solar collector [9]. Two-tank direct storage system is considered to use and molten salt is used as HTF and storage medium. Thermal losses in PTC is considered and based on research overall thermal efficiency (ηthermal) is defined as 0.7 [9]. The following parameters were calculated for the model.

3.1. Solar Geometry:

Earth rotates around the sun and as well as itself with an angle of 23.45°C. Solar energy hitting onto the earth can be calculated by knowing solar declination angle (δ), solar hour angle (h), solar zenith angle (θZ), solar altitude angle (α), solar azimuth angle (γ) and capture location (latitude, longitude). δ is positive in winter in southern hemisphere and negative in summer [10]. Solar incidence angle (θ) is the angle between sun light on PTC aperture panel and normal to that panel and maximum solar radiation absorbed when incidence angle become minimum or zero, therefore PTC's rotation system set as single axis (horizontal east-west) to always track the sun [11]. Extra-terrestrial solar radiation (I) passes through the atmosphere, which reduced due to the reflection and absorption by air and water. The energy directly hitting onto the earth surface is direct solar beam radiation (Eb) [12]:

$$E_b = I \times \exp(0.8662 \times T_{lk} \times m_{opt} \times d_{rm}) \quad (1)$$

where T_{lk} is Linke turbidity factor for different atmosphere, m_{opt} is Optical air mass and d_{rm} is Rayleigh optical thickness. T_{lk} in this study is consider as pure Rayleigh atmosphere condition (T_{lk}=1) in order to obtain optimum performance.

3.2. Power received by PTC (Q_{ptc}):

Thermal power absorbed by PTC is the overall solar radiation on PTC panel; it depends on direct solar radiation, collector aperture area, solar incidence angle, optical efficiency and incidence angle modifier. Power received by PTC can be calculated by equation 2 [1]:

$$Q_{ptc} = E_b \times cos\theta \times Aa \times \eta_{opt} \times K(\theta) \quad (2)$$

Where Aa is aperture area (a×l) of collectors, K (θ) is incident angle modifier [13]. K(θ) is related to the influence of incidence angle differences in a specific collector, expressed by equation 3 [14]:

$$K(\theta) = 3 \times 10^{-5} \times \theta^2 - 0.0072 \times \theta + 1.2257 \quad (3)$$

Thermal efficiency is the ratio of effective heat (Qu) to the overall thermal energy received (Qptc), therefore useful thermal power received at HTF side can be calculated by equation 4:

$$Q_u = Q_{ptc} \times \eta_{(thermal)} \quad (4)$$

3.3. PTC model:

Nitrate salts for HTF and thermal storage medium was selected with operating temperature range of 280°C to 550°C considering freezing point (265°C) and stability (565°C). The equation for calculating maximum mass flow rate is based on the maximum power received by the collector. Based on equation 2, considering 2015 solar radiation data in Melbourne maximum power received in January is 255000W from simulation. Using first law of thermodynamic in relation to compute power absorbed by PTC, the mass flow rate was calculated as 2125kg/h by using equation 5.

$$Q_{ptc} = mC_p\Delta T \;\; \therefore m_1 = m_2 = \frac{Q_{ptc}}{C_p \times \Delta T} \tag{5}$$

Where m1 and m2 are the salt mass flow rate of HTF from PTC to hot tank to heat exchanger and from heat exchanger to cold tank back to PTC respectively. Total mass of the required molten salt as HTF is ($M = m \times T = V \times \rho$) 4250kg to circulate the system in 2 hours and the required volume of storage tank is 2.27 m^3. Therefore, both hot and cold storage tank size is designed as height of 2 m and radius of 0.6 m. Therefore the output temperature at the PTC is

$$Q_u = C_p \times m_2\left(T_{ptc,o} - T_{ptc,i}\right) \;\; \therefore T_{ptc,o} = \frac{Q_u}{C_p \times m_2} + T_{ptc,i} \tag{6}$$

3.4. Hot Tank model:

The output temperature of PTC (Tptc,o) is the input temperature of hot tank (Th,i) and performance of storage tank depends on the thermal losses from hot tank and cold tank. Thermal loss in hot tank can be calculated as

$$Q_{htl} = U \times A \times (T_{hi} - T_a) \tag{7}$$

Where *U* is the global heat transfer coefficient (30W/m^2. k) considering thermal conductivity of storage medium [15], T_a is the ambient temperature of storage medium, *A* is the tank area and output temperature of the hot tank is

$$Q_{ht} = Q_u - Q_{htl} = C_p \times m_2 \times (T_{hi} - T_{ho}) \;\; \therefore T_{ho} = T_{h,i} - \frac{Q_{ht}}{C_p \times m_2} \tag{8}$$

3.5. Load model:

A typical 4 bedroom residential house in Melbourne is considered as load with heating space of 240m2. For a new building average heating load is 50 to 70W/m2 considering heat losses. Therefore maximum capacity of the required heating system is $Q_l = 70W/m^2 \times 240m^2 = 16.8kW$. A control was applied by selecting a stop temperature (Tstop) to control heating system operation and avoid salt to go in freezing point [16].

$$T_{stop} = \frac{Q_l}{C_p \times m_1} + T_{h,min} = 297.8^oC \tag{9}$$

Molten salt flows into the heat exchanger for underfloor hot water heating system. During the heat exchange the salt temperature is expressed by equation 10, where η_{hx} is the heat exchanger efficiency and it is taken 0.9 [17]. The water is heated to 35oC for room heating from 25oC and the control pump operates if temperature variation reaches 10oC.

$$T_{s,o} = T_{s,i} - \frac{T_{w,o} - T_{w,i}}{\eta_{hx}} \tag{10}$$

3.6. Cold Tank model:

It is similar like hot tank system but the salt input temperature from heat exchanger output ($T_{s,o} = T_{c,i}$). Thus thermal loss (Q_{ctl}) in cold tank, thermal energy of hot salt in heat exchanger (Q_{hx}), thermal energy of cold tank (Q_{ct}) and output temperature of cold tank ($T_{c,o}$) can be expressed by equation 11, 12, 13 respectively.

$$Q_{ctl} = U \times A \times (T_{c,i} - T_a) \tag{11}$$

$$Q_{hx} = C_p \times m_1 \times (T_{h,o} - T_{s,o}) \tag{12}$$

$$Q_{ct} = Q_{hx} - Q_{ctl} = C_p \times m_1 \times (T_{c,i} - T_{c,o}) \therefore T_{c,o} = T_{c,i} - \frac{Q_{ct}}{C_p \times m_1} \tag{13}$$

4. Results

The thermal energy collected by PTC considering solar radiation data of Melbourne in 2015 is passed to the hot tank by molten salt as HTF. It was then passed to the heat exchanger from where load is taking the thermal energy. After transporting heat to the load, HTF passed to the cold tank. A control pump applied to maintain designed temperature difference between the hot and cold tank. The sun hour is from 5:00AM to 7:00PM and achieved maximum power at noon as illustrated in the output Figure 2 to 4 from the model. Daily summer, winter and yearly energy received is distributed in a, b and c of Figure 2 to 4 respectively. Figure 2 shows the thermal energy collected by PTC. Figure 3 shows the temperature rise and output temperature of HTF. Figure 4 shows the molten salt temperature at the cold tank. From the simulation, it is found that system temperature maintained between 310oC to 520oC, which is within the salt temperature operating range. Lowest temperature variation in winter is about 105.9°C from simulation results and considering constant mass flow rate, thermal power of hot tank carried by salt in winter is:

$$Q = C_p \times m_2 \times \Delta T = \frac{1600J}{kg}°C \times \frac{0.59kg}{s} \times 105.9°C = 99969.6kW \approx 100kW \tag{14}$$

Heating load computed before is 16.8kW. For constant mass flow rate and the designed tank size to rise load water temperature of 10°C, 16.8kW thermal energy is required. In winter minimum thermal energy required is 99969.6W, i.e. 5.95 times of load. The time period for one circulation of molten salt is 2 hours, therefore minimum operation time is 11.9 hours, which ensures night-time (19:00-05:00, without solar radiation) load demand.

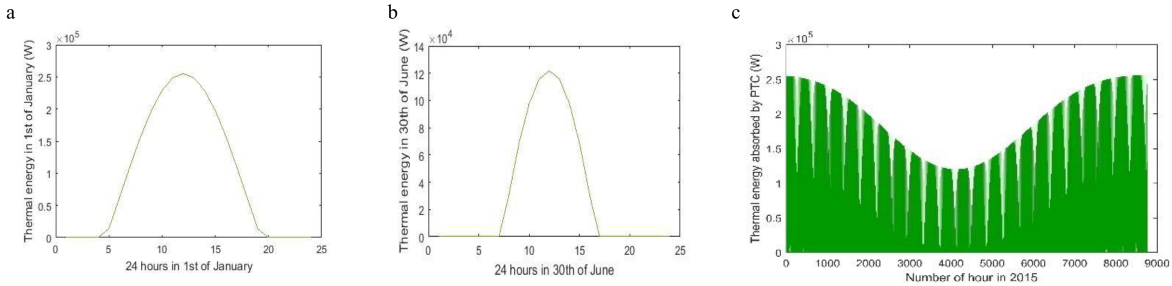

Figure 2. Thermal energy collected by PTC (a) Qptc in 1st January; (b) Qptc in 30th June; (c) Qptc in 2015.

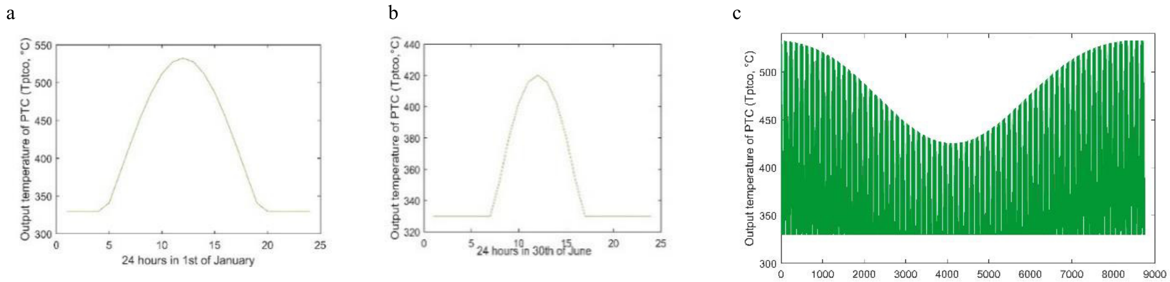

Figure 3. Output temperature from PTC (a) Tptc,o in 1st January; (b)Tptc,o in 30th June; (c). Tptc,o in 2015

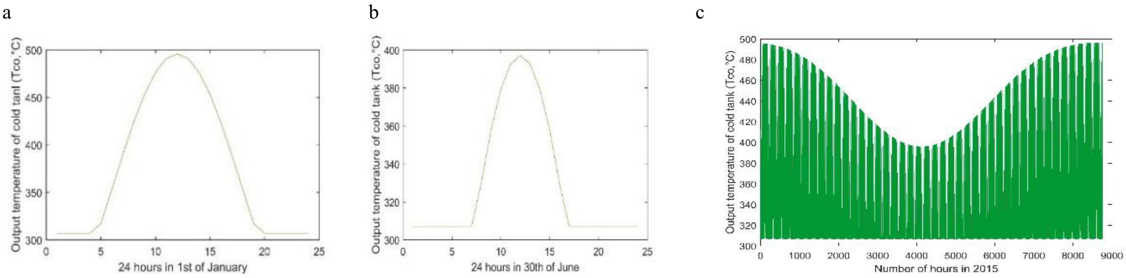

Figure 4. Output temperature of molten salt from cold tank (a) Tc,o in 1st January (b) Tc,o in 30th June (c)Tc,o in 2015

5. Conclusion

This paper considered parabolic trough collector to collect solar thermal energy and used Nitrate salt as HTF and energy storage to buffer energy to meet load demand at night. Two-tank direct system is used in model as it has higher efficiency due to less thermal losses in heat exchange compared to indirect system. Mathematical model was developed considering Melbourne load demand and simulated for summer, winter daily load demand and checked for yearly load demand to evaluate the performance of the heating system. Model output was checked by observing the temperature variation considering stable mass flow rate of HTF. Outcomes of minimum 11.9 hours independently operation which ensures night-time load demand without solar radiation. Therefore, the model is feasible under thermal losses with varying solar radiation. In addition, the system has better autonomy in summer compared to winter due to better solar radiation in summer. Although the outcome is inspiring however there are some scope for improvement, particularly by investigating this model with variable thermal loss in PTC, variable mass flow rate, variable salt heat capacity and with variable load temperature.

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