Simulation of a solar absorption chiller and a PV-driven electric chiller

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Abstract:
Popularity of solar cooling techniques is increasing due to its environmental friendliness and its use of renewable energy, leading to reduction in capital investment cost. In this study, hourly simulation will be done on a model of small solar powered $4.7kW_{th}$ absorption chiller, and a model of PV-driven $7.1kW_{th}$ electrical chiller. For absorption chiller, 2 scenarios will be considered, one where the hot water is left in collectors to cool down during OFF hours, and another where hot water from the collectors will be drained back to store the thermal energy. Furthermore lifecycle costs were calculated for economic comparison of the systems. Simulation results show that the modeled systems are able to provide cooling, and the lifecycle costing shows, that for small size systems, grid operated chiller is more economically feasible than a solar powered absorption chiller and PV-driven electric chiller.

Keywords: *Absorption Chiller; ASRC-CIE Sky Model; Electric Chiller; Lifecycle Cost; Simulation*

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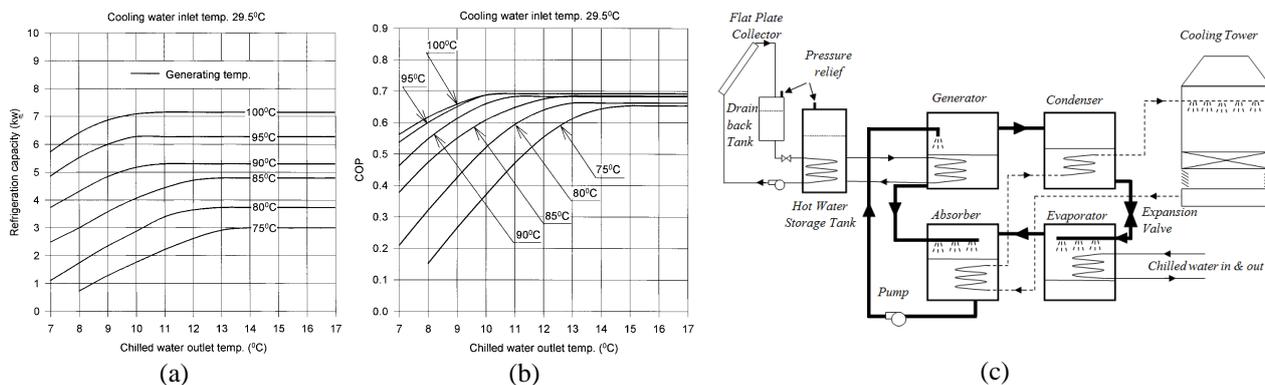*E-mail address:furugaan.ibrahim@gmail.com*

1. Introduction

Solar cooling techniques are becoming popular due to its environmental friendliness and its use of renewable energy to bring the desired outcome. Studies show that the increasing popularity and technological innovations results a decreasing trend of cost for solar cooling systems (Otanicar et al., 2012). In this study, a solar absorption chiller will be modeled and simulation will be carried out using hourly meteorological data measured for 1 year. Following that, simulation will be carried out for a PV-driven electric chiller. Finally, life cycle costing will be done to compare the systems.

2. Modeling the systems for simulation

ASRC-CIE sky model and uniform sky model was used to evaluate the irradiance on the inclined plane (Kobav & Bizjak, 2013; Chirarattananon, 2005b). Meteorological data of year 2000 in Bangkok was used to get the irradiance on plane inclined at 13.6° facing south.

2.1 Absorption System

Fig. 1(c) shows the $4.7kW_{th}$ single effect Li-Br chiller system used in this study. For simulation 2 scenarios will be assessed, a direct loop system and open loop system. In the direct Loop system hot water will be left in the collectors during OFF times while in the open loop system hot water from the collectors will be drained back to an insulated drain back tank. The model and specification of absorption chiller was based on the chiller performance curves in the study of Li & Sumathy (2001).

Fig. 1 (a) Refrigeration heat of chiller. (b) COP of the chiller. (c) Absorption chiller diagram

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Since a single effect absorption system was used for the simulation, a flat plate solar collector of 26 m^2 was used. Efficiency curve 'ϵ' of the flat plate collector is given by Eq.(1), where T_f, T_{amb}, and $E_{t\theta}$, are the output temperature of the collector, ambient temperature, and the irradiance on the plane (Föste et al. 2014).

Absorption chiller COP and refrigeration heat (Qr) was evaluated by interpolation from the performance curves in Figs.1(a) and (b) at cooling water inlet temperature of 29.5ºC (Li & Sumathy 2001). The values were then re-evaluated based on the cooling water inlet from the cooling tower output using the Eqs. (2) and (3). T_{wo} is the cooling tower output, and $y_{intercept}$ will be first derived at 29.5 and then with it known, new Qr and COP will be evaluated based on the T_{wo}s obtained from cooling tower model. These straight line approximations were derived base on the study of Li & Sumathy (2001) and the study of García Cascales et al.(2011) which is also for a similar size chiller system.

Cooling tower was modeled based on the correlation in Eq. (4) derived by Braun et al. (1989) where NTU, m_a, and m_c, are the Number or Transfer Units, mass flow rate of air, and mass flow rate of cooling water respectively. 'a' and 'n' are two constants depending on the cooling tower design. The values of 'a' and 'n' used in this study are 0.9325 and 0.4887 based on a 17kW$_{th}$ cooling tower (Chirarattananon, 2005).

For simplification, the hot storage tank was assumed to be 1500 liter cylindrical tank. The tank was insulated with R-15, and 47m pipe (for connections) insulated with R-3 grading where R is given in h.ft2.ºF/Btu. Heat loss was then evaluated using Eq. (5), where Q_{loss} and $T_{initial}$ are the heat loss and the initial temperature of hot water.

$$\epsilon = 0.780 - 2.14\frac{(T_f - T_{amb})}{E_{t\theta}} - 0.0110\frac{(T_f - T_{amb})^2}{E_{t\theta}} \qquad (1)$$

$$Qr = -0.44 \times T_{wo} + y_{intecept} \qquad (2)$$

$$COP = -0.0288 \times T_{wo} + y_{intecept} \qquad (3)$$

$$NTU = a\left(\frac{m_c}{m_a}\right)^n \qquad (4)$$

$$Q_{loss} = \frac{Area}{R \times 0.176110}(T_{initial} - T_{amb}) \qquad (5)$$

2.2 PV-Driven Chiller
An hourly energy flow model developed by Khatib & Elmenreich (2014) was used for the PV powered 7.1 kW$_{th}$ electric chiller equipped with 18 kWh battery bank system. This model is given by Eqs. (6) and (7) where P_{pv} is power output of the panel, P_{peak} (5.9kW) is peak power of PV system, E_{st} and T_{st} are standard conditions of solar cell. E is irradiance on the panel, T_c is the collector temperature, α_T is the temperature coefficient of the PV module, $NOCT$ is the nominal operation cell temperature, and η_{wire} and $\eta_{inverter}$ are the efficiencies of wire and inverter. Inverter efficiency curve was modeled based on the relation by Demoulias (2010) given in Eq. (8). For simplification, the chiller was assumed to operate at constant COP of 2.29.
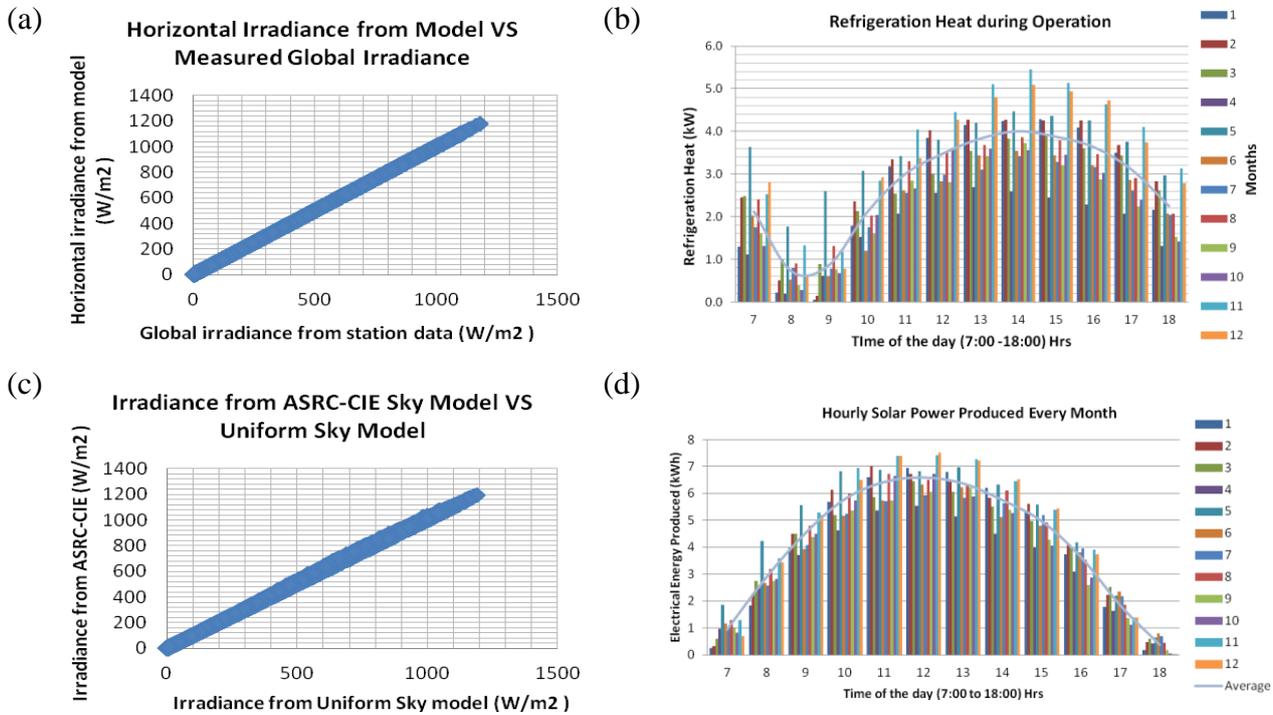
$$P_{PV}(t) = \left[P_{peak}(\frac{E(t)}{E_{st}}) - \alpha_T[T_c(t) - T_{st}]\right] \times \eta_{inverter} \times \eta_{wire} \qquad (6)$$

$$T_c(t) = T_{amb}(t) + \frac{NOCT - 20}{800} \times E(t) \qquad (7)$$

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$$\eta_{inverter}(P_{PV}) = 97.644 - 1.995 \times P_{PV} - \frac{0.445}{P_{PV}} \quad (8)$$

3. Results and Discussion
3.1 Absorption Chiller
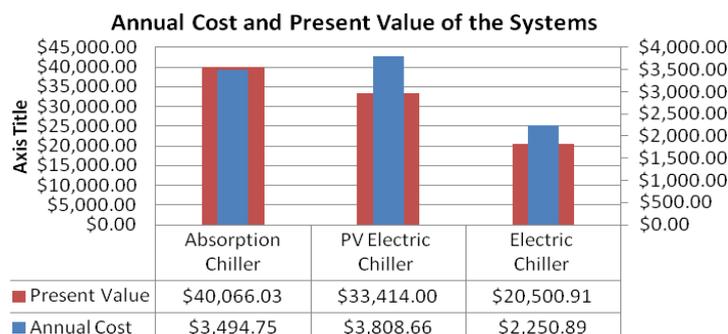
(a)

(b)

(c)

(d)

Fig. 2 (a) Measured horizontal irradiance against irradiance evaluated from sky model (b) Average hourly refrigeration output of absorption system for 1 year (c) Irradiance on inclined plane from ASRC-CIE sky model against uniform sky model (d) PV power produced

Fig. 2(a) shows the comparison of measured global irradiance compared with the irradiance from the sky model. Results show that sky model values were in average within ±0.29% from the measured global irradiance from station. Fig. 2(c) shows irradiance of ASRC-CIE sky model compared to uniform sky model on the inclined plane, and it was found that they were in average within ±1.56%. Fig. 2(b) shows the average refrigeration output of solar absorption system for the open loop configuration. Not a significant improvement was found with an open loop system compared to a direct loop system. Open loop gave an additional of 47 operating hours compared to closed loop system over the year. Average hourly power produced from the PV system over the year is shown in Fig. 2(d). Absorption system operates on stored energy at the beginning of the day and generates enough power to operate itself between 9:00AM and 10:00AM. Similar time is shown for the PV system to be able generate enough power to operate on its own without the backup energy.

3.2 Life Cycle Costing
Table 1 shows the costs and lifetime used for the calculation of lifecycle cost. Electricity tariff was taken to be THB 4.5 ($0.15)/kWh, and non-escalating cost was assumed. Fig. 3 shows that the net present value (NPV) and annualized cost of absorption chiller, PV-driven electric chiller, and same electric chiller if it were to be operated on grid power. Results indicate that, NPV of absorption chiller is the highest among the three, while the PV-driven chiller has the highest annualized cost. Grid operated chiller has the lowest NPV and annualized cost among the three.

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Fig. 3 Lifecycle cost comparison for the three systems

Table 1 Costs and lifetime of absorption system (left) PV-driven electric chiller (right)

Description	Life (Years)	Cost	Description	Life (Years)	Cost
Absorption Chiller (4.7kW$_{th}$)	30	$23,500.00	Electrical Chiller (7.1kW$_{th}$)	15	$1,900.00
Flat Plate Collector (26m^2)	25	$5,965.30	Inverter (6kW)	20	$8,239.00
			Charge Controller	15	$1,480.00
Cooling Tower (17kW)	15	$1,185.00	Photovoltaic Panel (12kW$_p$)	25	$16,800.00
Storage Tank (1500 liter)	10	$1,368.00			
			Battery Bank (18 kWh)	5	$4,995.00
Total(USD)		*$32,018.30*	*Total(USD)*		*$25,434.00*

4. Conclusions

- ASRC-CIE skymodel gives good approximation for diffuse irradiance, and also the results are in close proximity with uniform sky model.
- Open loop system doesn't give a significant improvent in performance compared to a direct loop system.
- Lifecycle costs indicate that for a small size system, grid operated chiller are economically more feasible compared to solar absorption chiller and PV-driven electric chiller.

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