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Life-cycle evaluation of different types of cooling systems in buildings

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Abstract

Cooling system represents a growing market in buildings worldwide, with a particularly significant growth rate observed in commercial buildings. Solar driven cooling system can be a promising alternative to traditional electrical cooling system. It can be used in combination with solar thermal collectors or photovoltaic collectors to release the duty caused by electrical cooling system. In this study, the performance of three different solar cooling systems is examined, namely: 1) a solar electrical, 2) a solar thermal and 3) a traditional electrical cooling system. The first system employs photovoltaic module to drive a conventional electrical chiller. The second system uses solar thermal collectors to drive a heat driven adsorption chiller and the third one utilizes the grid power to feed the electrical chiller. Assessment of life-cycle costs of these three systems are conducted to verify the best option for buildings. A case study in Hong Kong is conducted to assess the three cooling systems.

Keywords: cooling system for buildings; life-cyle evluation;

1. Introduction

Energy consumption of building sector accounts for approximately 40% of final energy consumption in the worldwide [1], and 14.6% was taken by the cooling load. Conventional cooling systems was driven by use grid electricity. Nowadays solar cooling system offers a sustainable and reliable solution, which can be divided in two main categories: solar thermal cooling and solar electric cooling [2-3]. Recent years, many researchers had taken the

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possibility of operating an adsorption chiller with solar energy into account both numerically and experimentally, for example [4-5]. The performance of a solar powered adsorption air–conditioning system, installed in the green building of Shanghai Research Institute of Building Science, was investigated by Zhai et al. [6]. Meanwhile, several researchers had compared the performance of solar thermal cooling systems with solar electrical cooling systems [7]. However, there is a limited study comparing the performance of solar electrical cooling systems with adsorption solar thermal cooling systems.

In this paper, assessment of life-cycle costs of the solar electrical cooling system, solar thermal cooling system and traditional cooling system are conducted to verify that which is the best option for buildings. TRNSYS building energy model is used to calculate the operation cost of these three cooling systems.

2. Description of the examined cooling system

2.1. Solar thermal cooling system

Fig. 1(a) shows a conceptual solar thermal cooling system. It includes four parts, i.e. solar thermal collector, storage tank, adsorption chiller and building user. Solar thermal collector is employed to collect the solar energy and then convert the solar energy into heat. The storage tank, considered as hot heat transfer medium, receives the heat collected from solar thermal collector. Adsorption chiller, which is powered by heat, supplies the cooling to the building user. A detailed and comprehensive description of adsorption chiller's operation principle can be found in [8].

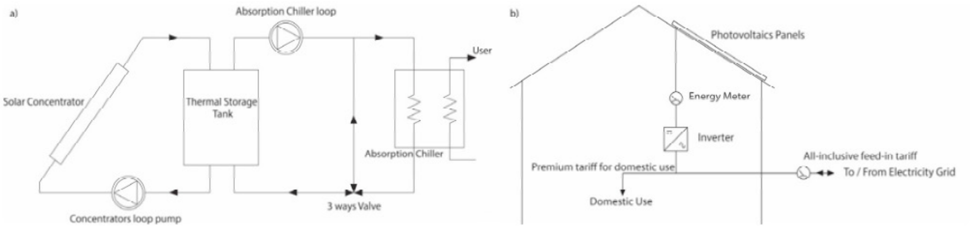

Fig. 1. (a) Solar thermal cooling system; (b) Solar electrical cooling system [9]

2.2. Solar electrical cooling system

Fig. 1(b) shows a conceptual solar electrical cooling system. It consists of four main parts - i.e., photovoltaic module, inverter, electrical chiller and building user. The photovoltaic module is used to collect the solar energy and then convert it into electrical energy. It is found that the electricity produced in the PV module is in the type of DC. The inverter converts it into AC to drive the electrical chiller. The chiller supplies the cooling to the building user.

3. Model of the examined cooling system

The TRNSYS software is used to model and simulate the hourly cooling load of building based on the typical meteorological (TMY) weather data of Hong Kong. The building energy model could also simulate energy consumption and temperature variations of the system. In this study, the daily working hour of HVAC system is from 8:00am to 20:00pm and the cooling season is from March to November. From December to February, the free cooling is used to supply the cooling to fulfill the thermal comfort.

3.1. Model of solar thermal cooling system

The solar thermal collection can be computed by Eq. (1) [10, 11]. Where, W_{sc} is the power of solar thermal collector which could be calculated by Eq. (2), A_a and η_{sc} is the total aperture area and efficiency of solar thermal collector, I is the hourly irradiance (kWh/m2), CL_{peak} is the cooling capacity of adsorption chiller, COP_{ad} is the COP of adsorption chiller. The needed aperture area of solar thermal collector can be calculated by Eq. (3).

$$W_{sc} = A_a \times \eta_{sc} \times I \quad (1)$$

$$W_{sc} = \frac{CL_{peak}}{COP_{ad}} \quad (2)$$

$$A_a = \frac{CL_{peak}}{COP_{ad} \cdot \eta_{sc} \cdot I} \quad (3)$$

The aperture area of solar thermal collector can be obtained according to the cooling capacity of adsorption chiller. The life-cycle of the solar thermal collector and adsorption chiller is assumed to be 20 years. The annualized total cost of solar thermal system TC_{st} contains the annualized capital costs of solar thermal collector, storage tank and adsorption chiller and the annual operation cost when the solar thermal collector cannot supply enough heat to adsorption chiller, as shown in Eq. (4). Where, CC_{stc} is the annualized capital cost of solar thermal collector, CC_{st} is the annualized capital cost of storage tank, CC_{ac} is the annualized capital cost of adsorption chiller, OC_{ac} is the operation cost of adsorption chiller. The operation cost of adsorption chiller can be calculated by Eq. (5). Where, CL_i is the hourly cooling load, $W_{sc,i}$ is the hourly power of solar thermal collector.

$$TC_{st} = CC_{stc} + CC_{st} + CC_{ac} + OC_{ac} \quad (4)$$

$$OC_{ac} = \sum_{i=1}^{8760} \frac{CL_i}{COP_{ad}} \cdot \max\left(\frac{CL_i - W_{sc,i} \cdot COP_{ad}}{\left| CL_i - W_{sc,i} \cdot COP_{ad} \right|}, 0 \right) \quad (5)$$

3.2. Model of solar electrical cooling system

The photovoltaic module power generation can be computed by Equation (6) [13, 14]. Where, A_{pv} is the total area of photovoltaic module (m^2), h_{pv} is the photovoltaic module efficiency, h_{pc} is the power conditioning efficiency, I is the hourly irradiance (kWh/m^2). The total area of photovoltaic module can be calculated by Equation (7). Where, COP_{elec} is the COP of electrical chiller.

$$W_{pv} = A_{pv} \times \eta_{pv} \times \eta_{pc} \times I \quad (6)$$

$$A_{pv} = \frac{CL_{peak}}{COP_{elec} \cdot \eta_{pv} \cdot \eta_{pc} \cdot I} \quad (7)$$

Usually, the COP strongly depends on the operating PLR. Once the other operating parameters such as condensing and evaporating temperatures are maintained at a constant level, the COP is higher when the chillers operate at a larger PLR, as shown in Equation (8). Where, D_0-D_3 are the coefficients that can be identified from chiller catalog or field measurement data. The PLR is usually determined by the number and size of operating chillers. It is simply defined as the ratio of the required cooling load (CL_{re}) to the available cooling capacity (CL_{ava}) (i.e., that of operating chillers) as shown in Equation (9).

$$COP_i = D_0 + D_1 \cdot PLR_i + D_2 \cdot PLR_i^2 + D_3 \cdot PLR_i^3 \quad (8)$$

$$PLR = \frac{CL_{re}}{CL_{ava}} \quad (9)$$

Based on the annual cooling load distribution, the cooling capacity of electrical chiller can be determined and then the total area of photovoltaic module can be obtained. In fact, the peak cooling load only accounts for a very small proportion of the entire cooling season. Therefore, when the actual cooling load is less than the cooling capacity of electrical chiller, the surplus power generated by the photovoltaic module will be supplied to the power grid. The annualized total cost of solar electrical cooling system TC_{se} contains the annualized capital cost of photovoltaic module CC_{pv}, inverter CC_{in} and electrical chiller CC_{ch}, the cost of surplus power generated CS_{pv} and the annual operation cost of electrical chiller OC_{ec} when the photovoltaic module cannot supply enough power to electrical chiller, as shown in Equation (10).

$$TC_{se} = CC_{pv} + CC_{in} + CC_{ch} + CS_{pv} + OC_{ec} \quad (10)$$

The cost of surplus power sold to the power grid can be represented by Equation (11). Where, P_{pv},i is the hourly power generated by photovoltaic module, $P_{ch,i}$ is the required hourly power consumed by electrical chiller, C_{gp} is the electrical price saled to the grid. The operation cost of electrical chiller can be calculated by Equation (12). Where, CL_i is the hourly cooling load of building, COP_i is the hourly COP of electrical chiller.

$$CS_{pv} = \begin{cases} \sum_{i=1}^{8760} C_{gp} \cdot P_{pv,i} & when\ P_{pv,i} < P_{re,i} \\ \sum_{i=1}^{8760} C_{gp} \cdot (P_{pv,i} - P_{re,i}) & when\ P_{pv,i} \geq P_{re,i} \end{cases} \quad (11)$$

$$OC_{ec} = \begin{cases} \sum_{i=1}^{8760} \frac{CL_i}{COP_i} & when\ \ P_{pv,i} < P_{re,i} \\ 0 & when\ \ P_{pv,i} \geq P_{re,i} \end{cases} \quad (12)$$

3.3. Model of traditional electrical cooling system

For the traditional electrical cooling system, the total life-cycle cost contains the capital cost of electrical chiller and operation cost, as shown in Equation (13). Where, TC_{te} is the total cost of traditional electrical cooling system, CC_{ec} is the capital cost of electrical chiller, OC_{ec} is the operation cost of electrical chiller. The operation cost of electrical chiller is related to the cooling load and COP (i.e. It has been mentioned in Section 3.2), as shown in Equation (14). Where, CL_i is the hourly cooling load, COP_i is the hourly COP of electrical chiller.

$$TC_{te} = CC_{ec} + OC_{ec} \quad (13)$$

$$OC_{ec} = \sum_{i=1}^{8760} \frac{CL_i}{COP_i} \quad (14)$$

4. Description of the building cooling load

Fig. 2(a) presents the annual temperature and irradiance in Hong Kong. It can be seen that the highest temperature is 34.6°C in July and the lowest temperature is 6.1°C in February in Hong Kong. As mentioned above, free cooling is used to meet the cooling demand from December to February. We only need to focus on the time from March to November.

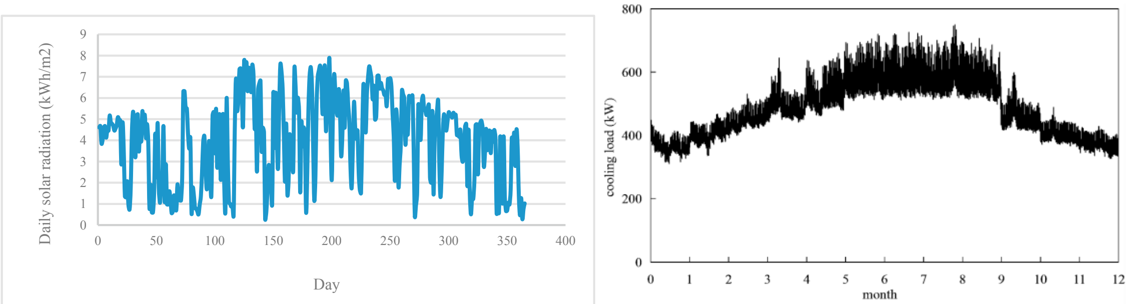

Fig. 2. (a) Annual temperature and irradiance in Hong Kong; (b) Annual cooling load

Fig. 2(b) shows the annual cooling load of a building in Hong Kong. It can be seen that the cooling load varies between 350 and 750kW. The cooling capacity of adsorption chiller and electrical chiller is assumed to be 830kW.

5. Case study

A case study of a building in Hong Kong is conducted to implement and assess the three cooling systems. The building energy model (e.g. TRNSYS) is used to calculate the annual cooling load and thus the required area of solar thermal collector and PV module can be determined, and the total costs of the three cooling systems can be obtained. Finally, comparison among the three cooling systems is conducted to select the optimum cooling system which has the least total life-cycle cost.

5.1. Required area of solar thermal collector and photovoltaic module

According to Eq. (3) and (7), the required areas of solar thermal collector and photovoltaic module are 4800m^2 and 5300m^2 respectively. The lifespan of the three cooling systems is assumed to be 15 years. Capital costs of adsorption chiller and electrical chiller are 0.83 MHKD and 1 MHKD respectively, referring to the data from a manufacture. For the solar thermal collector and PV module, the prices are 1600HKD/m^2 and 800HKD/m^2 respectively. The prices of storage tank and inverter are 150,000HKD and 50,000HKD respectively. Considering the above prices, the annualized capital costs of solar thermal cooling system, solar electrical cooling system and traditional cooling system are 722,000HKD, 440,000HKD and 84,000HKD respectively. Besides, the electricity price used in this study is 1 HKD/kW (note: 1 USD=7.75 HKD), and the electrical price sold to the grid is assumed to be 0.8HKD/kW.

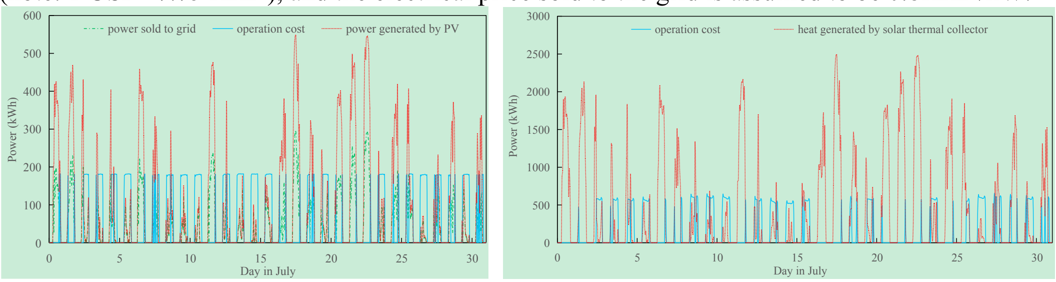

Fig. 3. (a) Solar electrical cooling system; (b) Solar thermal cooling system

Take July as an example to assess the three cooling systems. Fig. 3(a) shows the power generated by PV, the operation cost of electrical chiller and the power sold to grid. It can be observed that the electrical chiller should consume a lot of power from grid for several hours every day. And a great amount of power generated by PV could be sold to the power grid. The power sold to grid and the operation cost are 31,687 HKD and 40,877 HKD respectively. Considering the capital cost of solar electrical cooling system, the total cost of this cooling system in July is 39,190 HKD. Fig. 3(b) presents the operation cost of adsorption chiller and heat generated by solar thermal collector. It can be observed that the operation cost of adsorption chiller is larger than that of electrical chiller. And a great amount of heat is generated by the solar thermal collector and it cannot be fully used when the cooling supplied by the adsorption chiller (i.e., the heat comes from solar thermal collector) cannot fulfill the cooling demand. The total cost of solar thermal cooling system in July is 160,000HKD. For the traditional electrical cooling system, the total cost in July is 72,592HKD. It can be observed that the total cost of solar electrical system is the lowest when compared with the other two cooling systems.

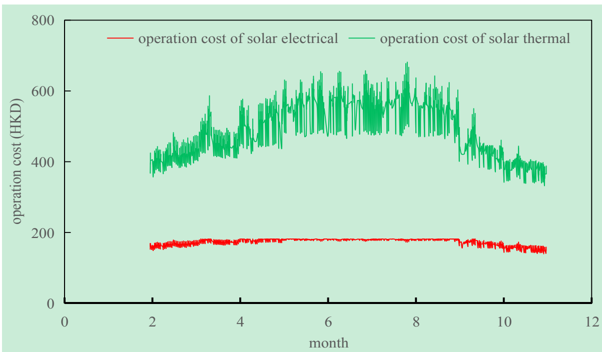

Fig. 4. Operation costs of solar thermal cooling system and solar electrical cooling system

Fig. 4 illustrates the annual operation costs of solar electrical cooling system and solar thermal cooling system when their systems cannot supply enough cooling demand. It can be observed that the operation cost of solar electrical cooling system is around 200HKD per hour. As for the operation cost of solar thermal cooling system, it varies within a wide range. And apparently, it is much larger than that of solar electrical cooling system. Finally, the annual operation costs of solar electrical cooling system and solar thermal cooling system are 389,523 HKD and 970,503 HKD respectively.

Table 1 gives the capital cost and operation cost of the three systems. It can be observed that the annual total cost of solar thermal cooling system is the largest among the three systems. Both the operation cost and the capital cost of solar thermal cooling system are the largest. For the traditional cooling system, the operation cost and the capital cost are 804,892HKD and 84,000HKD respectively. The operation cost and capital cost of solar electrical cooling system are 339,523HKD and 440,000HKD respectively. And it can be reduced by about 12.3% when compared with the traditional cooling system. In Hong Kong, the solar electrical cooling system is available to supply the cooling for the building and the solar thermal cooling system is not available to supply the cooling for the building.

Table 1 Total costs of the three cooling systems

	Operation cost (HKD)	Capital cost (HKD)	Total cost (HKD)
Traditional cooling system	804,892	84,000	888,892
Solar thermal cooling system	925,791	722,000	1,647,791
Solar electrical cooling system	339,523	440,000	779,523

6. Conclusion

By employing the TRNSYS building energy model, the life-cycle total cost of traditional cooling system, solar thermal cooling system and solar electrical cooling system are evaluated. The results show that the solar electrical cooling system is available and economical to be used to supply the cooling for the building. On the contrary, the solar thermal cooling system is not suitable to be used for supplying the cooling. The total cost of solar electrical cooling system could be reduced by 12.3% when compared with the traditional cooling system.

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