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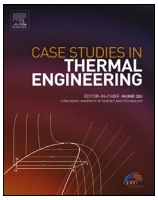

Solar adsorption air conditioning system – Recent advances and its potential for cooling an office building in tropical climate

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ABSTRACT

Solar adsorption air conditioning system (SADCS) is an excellent alternative to the conventional vapour compression system (VCS). SADCS has advantages over VCS system notably that it is a green cooling technology that utilizes solar energy to drive the adsorption/desorption cycle, using pure water as a green HFC-free refrigerant, mechanically simple and can be operated without moving parts other than the magnetic valves. In the last decade, several developments and innovations have been achieved in the field of SADCS research. However, further research is needed to bring this technology to practical level. Hence, this paper first discusses the literature survey that adds insights into the research of SADCS technologies with emphasis placed on the practical research that has been conducted at lab-scale and commercial level. Then, the potential of SADCS for cooling applications of an office building in tropical climate is discussed using simulation in TRNSYS. From the simulation we found that the solar fraction of the SADCS system is as high as 63 %, with the temperature and the relative humidity of an office space can reach an average of 20 °C and 60 % respectively, which are within the range of the thermal comfort level for the occupants.

1. Introduction

The majority of energy consumption of buildings in tropical climates is done by air conditioning (AC) systems [1]. Being recognized as essential and crucial systems to enhance the thermal comfort and living conditions of the occupants, air conditioning (AC) system are also effective in dealing with problems stemming from heat-stress. It is forecasted that by the year 2100, air conditioning power consumption will expand to 33-fold worldwide [2] which is attributed to the ongoing and expected income rise in the developing world and the continuous advances of urbanization. Thus, major factors that are likely to cause for the need for more air conditioning systems, or that cause a higher demand, are the higher global temperature or warm spells.

The most common air-conditioning system for buildings in hot and humid countries is the vapour compression air conditioning systems (VCS). In VCS the integration of the dehumidification and cooling process has led to higher energy wastage and CO_2 emissions.

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In addition, these systems use high global warming potential (GWP) hydrofluorocarbon (HFC) and CFC refrigerants [3]. Henceforth, it is crucial to utilize more environmentally friendly air conditioning systems as an alternative to the conventional types, and that require less energy consumption, thus promote energy efficient buildings to meet the cooling demand. One of the most attractive alternative solutions is the incorporation of solar energy into air conditioning and refrigeration unit, which is known as a 'solar-driven air conditioning' system, such system can promote green cooling technologies and many researchers have worked on in recent years [4].

There are many conceivable processes for the transformation of solar energy in cooling, from a thermodynamic point of view. There are two different types of processes namely electric process and thermal process [5]. The electric process will power the vapour compression cycle air-conditioning system. However, due to the large area required for the solar panel to generate electricity, it is not suitable for air-conditioning systems. Furthermore, the electric process via photovoltaic required inverter to change the direct current (DC) to alternative current (AC) before being used in the air-conditioning systems. On the other hand, the most popular solar-driven air-conditioning system is through the thermal process and can be further categorized into heat transformation process and thermochemical process. The former, is the common one and can either be in a close or open system.

Fundamentally, in open cycle systems, humidity, or moisture in the air is removed using the desiccant dehumidification cooling system in order to maintain a desirable level of air humidity, and simultaneously lower the heat load from the air that is to be cooled [6]. During the adsorption mode the working air which carries water vapour and heat will be transported into and out of the packed bed of solid adsorbents/reactor. Meanwhile, during the desorption mode, the working hot air stream will enter the adsorbent bed/reactor and desorbs the water from the adsorbent and exits the bed at cooler temperature and in saturated state [7]. It is also crucial to note that, in an open cycle, the working air is in contact with the desiccant. Three main components are coupled to form a desiccant cooling system, which are (i) cooling device, (ii) chemical dehumidifier and (iii) thermal source for regeneration [8]. Henceforth, these three main units are the basis for the configuration of a desiccant cooling system. Moreover, depending on the selection of the cooling device, the desiccant cooling system's configurations can be grouped into evaporative and hybrid desiccant cooling systems [9]. In the closed cycle systems, the working air is not directly in contact with the adsorption materials. Rather, the chilled water is used to provide cooling either by (i) its distribution with a chilled water network inside the building to the rooms to serve decentralized room installations (such as chilled ceilings and fan coils), or (ii) air handling units (AHU) for cooling and de-humidification processes. The closed system can be categorized into absorption and adsorption system.

The absorption process can be defined as a process in which the sorbate diffuses into the liquid or solid sorbent accompanying a phase change and/or a chemical reaction [10]. The absorption materials that are commonly used are aqueous solutions of Calcium Chloride ($CaCl_2$), Lithium Chloride (LiCl), Lithium Bromide (LiBr), Sodium Hydroxide (NaOH), Potassium Hydroxide (KOH) and Ammonia [11]. Absorption systems require energy for the regeneration process, typically known as the driven energy. Previous researchers have used absorption systems driven by industrial waste energy as in Refs. [12,13], automobile exhaust [14] and solar energy [15,16]. Some of the researchers also researched on cascading absorption systems combined with vapour compression system to improve their performance [17]. However, improvements on low coefficient of performance (COP) are required in the reactor design, with low manufacturing costs.

Adsorption is a process where the molecules of the adsorbate adhered to the porous adsorbents (solid sorption material). This is mainly depending on the surface characteristics of the adsorbent which categorized into three categories of pores sizes i.e. micropores, mesopores and macropores as illustrated in Fig. 1 [4]. In the case whereby water vapour is used as the adsorbate, during the adsorption stage, the water molecules are adhered on the porous surface of the adsorbents and the heat that is stored during desorption will be released. The reverse of the adsorption is the desorption process in which the heat is put into the adsorbents and releasing the molecules from the respective surfaces. Adsorption chillers are the system that utilizing this adsorption-desorption cycle in their operation.

In general, an adsorption chiller has four chambers: an evaporator, a condenser, and two adsorption chambers that operate at nearly a full vacuum [18,19]. Adsorption chiller uses solid sorption materials such as silica gel as the adsorbent. It is filled in the adsorption chambers, eliminating the need for moving parts as well as noise associated with those moving parts. For silica gel-water sorption pairs, the silica gel creates a low humidity condition that causes the water refrigerant to evaporate at a low temperature. As the water evaporates in the evaporator, it cools the chilled water. The effects of evaporation in the evaporator chamber will transfer low-temperature heat from the chilled water. Meanwhile, the silica gel will be regenerated (desorption) via hot water through solar

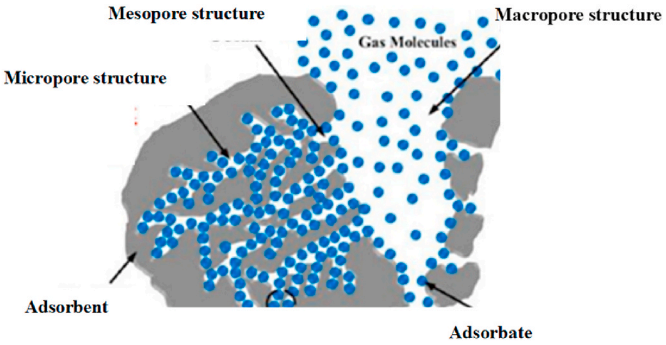

Fig. 1. Concept of adsorption process. Image is partly taken from [4].

thermal as the heat source. Table 1 compares the absorption and adsorption cooling system. The adsorption cooling system appears to be a better alternative to conventional refrigeration technologies mainly due to lower operating temperatures and greater lifetime.

1.1. Research contribution

The focus of this paper is to review the lab-scale and commercially available solar driven adsorption cooling system that has been reported in the literature in the recent years, and to investigate its potential as an alternative cooling technology in hot humid climate. The paper is structured as follows. First, it details the literature conducted in recent years on the lab-scale and commercially available solar driven adsorption cooling system. Then, the potential of solar adsorption cooling as a promising alternative to cooling technology for office building in tropical climate is discussed by conducting a simulation case study for three different countries in Southeast Asia namely; Malaysia, Singapore and Thailand using Transient System Simulation Tool (TRNSYS).

2. Lab scale and commercial prototype solar adsorption air-conditioning

2.1. Lab scale solar adsorption air-conditioning system

There are lab-scale prototypes of solar adsorption chiller developed in various countries. For example, Ramli et al. [25] built a lab-scale solar adsorption chiller using silica gel and water as the working media to investigate the performance of evaporator. The evaporator design, which had four-pass arrangement, was based on the findings of [26], however, the dimensions were smaller for the prototype to be portable. The heat source for their system was set at relatively low temperature of 50 °C as the solar collector in the system can only provide maximum temperature of 60 °C. The results of their lab-scale systems show that their designed heat exchangers suitable to generate cooling power at 50 °C and 60 °C with the highest specific cooling power was 454 W/kg at the highest supplied temperature for both hot water and chilled water.

In Yunnan China, Du et al. [27] developed a solar adsorption refrigeration system using a working pair of activated carbon-methanol. Finned adsorption tube was used which contained the mass transfer channel and fins for heat transfer. A composite parabolic trough condenser was incorporated into the adsorption bed with two parabolic focal points to ensure the maximum utilization of solar irradiance. The authors used concentrating ratio of 1.24. To run the experiments, the adsorption refrigeration system was subjected to light from a steady state solar simulator which contains 15 xenon lamps. The performance of the system was observed for irradiance levels of 600 W/m^2 and 400 W/m^2. Their experimental results showed that under low irradiation condition the temperature of the adsorption bed with parabolic concentrating structure could rise to 100 °C. However, when the irradiation intensity is 600 W/m^2 and 400 W/m^2, the average temperature rising to desorption temperature reached 0.67 °C/min and 0.50 °C/min, respectively. Their method could effectively solve the problem of the conventional adsorption bed that experience difficulties in reaching the required desorption temperature due to the low power density of the sunlight. In their experiment, when exposed to the irradiance of 600 W/m^2 and 400 W/m^2, the system COP was 0.166 and 0.143, respectively. A group of researchers in Iraq investigated a domestic SADCS system with silica gel/water and evacuated tube solar collector of 4 m^2 in size [28]. The system was operated with inlet temperature of 90 °C and the system's performance was investigated at different fluid flow rates. Under the climatic conditions of Iraq, at optimum flow rate of 30 l/min, the specific cooling power (SCP), coefficient of thermal performance (COP$_{th}$) and evaporator temperature are 39 W/kg, 0.55, and 6.6 °C, respectively. An innovative and compact solar adsorption desiccant cooling system was introduced by Wang et al., [29]. The system comprises of a solar collector/adsorbent bed, a micro-pipeline vacuum pump, a condenser and an evaporator. In this study, the researchers have used the activated carbon-methanol as the working pair with a micro vacuum pump to create the refrigerant flow between the condenser and the adsorbent bed. Another highlight of the research is the use of heat and mass transfer enhancement technique using external finned tube in the condenser. The collector was tested indoor under halogen solar simulator. At the average light radiation intensity of 630 W/m^2, the maximum COP$_{th}$ is 0.142, which is 35.9 % higher compared with the average COP of the adsorption refrigeration system without enhanced heat and mass transfer.

In Guangzhou, Zhu et al. [30], explored the use of vehicle radiators coated with composite adsorbent of Zeolite 13X/CaCl$_2$ in the adsorption bed. In their study, water was used as the refrigerant. Six single-glazed flat plate solar collectors with a total area of 12 m^2 were used to supply the hot water for the desorption process. The system was initially preheated for 2 h. The results from their experiment showed that, when driven by the solar panels at average and maximum solar radiation of 570 and 880 W/m^2 respectively, the specific cooling power of the system (SCP) was as high as 208.2 W/kg. In their study, in addition to COP$_{th}$ which was found as 0.24,

Table 1
The comparison between adsorption and absorption cooling systems.

	Solar Absorption Cooling (AB)	Solar Adsorption Cooling (AD)
Operating temperature [20]	Higher charging temperature	Lower charging temperature (20–40 °C lower than absorption cooling)
Coefficient of performance	Higher COP (0.7–1.4) [21]	Lower COP (with the maximum of 0.65) [22]
Corrosion effect ([23] cited in Ref. [24])	Corrosion protection is required	Corrosion protection is not required
Crystallization ([23] cited in Ref. [24])	No crystallization	Very high
Additional benefit [20]	–	Integration with water desalination from the condenser.
Lifetime ([23] cited in Ref. [24])	Greater than 30 Years	Between 7 and 9 years
Water temperature [20]	Both types of sorption cooling devices cannot fully reach the refrigeration effect of compression technology due to the limitation of the evaporation condition.	

the energy efficiency ratio (EER) which is defined as the ratio between the thermal output and the electrical input attributed by the pumps, valves, and control system was also calculated. At the aforementioned environmental conditions, the EER was calculated as 4.5.

2.2. Solar adsorption cooling system in the market

In the Netherlands, SolabChiller (Fig. 2a) was introduced by SolabCool [31]. It was designed for domestic application for small office building at a cooling power operational range of 3–5 kW. The adsorption component can be connected to solar panels for hot water input between 60 and 95 °C meanwhile, the chilled water piping system can be connected to the existing heat distribution system of the dwelling or small building. Similar to SolabChiller, a German company introduced SOLACS08 (Fig. 2b), a compact adsorption chiller with a nominal cooling capacity of 7.5 kW [32]. The chiller is designed to suit the solar cooling demand in the private and small commercial sector. Silica gel and water are used as the sorption-refrigerant pairs and the system can be operated with inlet hot water temperature of 70 °C. Adsorption chiller ACS 08/15 developed by SorTech AG [33] is another example of a commercial compact adsorption chiller. SorTech AG is the spin-off of the Fraunhofer Institute for Solar Energy Systems (ISE). It also runs with pure water as refrigerant at hot water inlet temperature as low as 55 °C. The device is also designed to be operated as a heat pump in winter. From our survey, a manufacturer in China [34] produced a solar adsorption cooling system at 5–30 kW cooling capacity. According to the manufacturer, the COPth of the SADCS is 0.4 with the lowest inlet hot water temperature is 60 °C. Meanwhile, Fig. 2c shows a product called AdRef-Noa from a Japanese company called Mayekawa. AdRef-Noa operates using Zeolite and water as the sorption and refrigerant pair. Another Japanese manufacturer, Mitsubishi Plastics [35], in collaboration with Union Industry Co., Ltd. has commercialized its adsorption chiller also using zeolite and water sorption refrigerant pair as shown in Fig. 2d. It is designed as an easy-to-install compact adsorption chiller with an integrated cooling tower. The chiller can be incorporated into a solar water-heater, as a result electricity use can be significantly reduced, and energy can be saved. Another highlight of the design is that the heat exchanger in the adsorption bed is coated with the sorption materials, enhancing the heat transfer which will minimize the consumption of energy of the chillers.

FAHRENHEIT, a German company [37] which originally known as SorTech AG has introduced three different types of adsorption cooling system using silica gel-pure water at cooling capacity between 8 and 100 kW capacity, zeolite-pure water (20 kW–40 kW) and a hybrid adsorption-compression cooling system that covers peak and bridge loads and hence has the highest maximum cooling capacity (46.7 kW–192.8 kW). For the adsorption chiller model that uses silica gel-pure water as the sorption-refrigerant pair, it runs at inlet hot water temperature between 50 and 95 °C, pressure level of 4 bar and at COP_{th} up to 0.65. Meanwhile, the zeolite-water model runs at inlet temperature between 75 and 95 °C, pressure level of 2 bar and at COP_{th} up to 0.5. BryChill™ Adsorption Chiller is a product by Bry-Air [38]. The adsorption chiller is designed with a smart energy system that uses (silica gel - water pair) that is claimed to cut the cooling costs up to 99 %. The technology can harness solar heat available from solar plants for the low-cost process of cooling and air-conditioning. Bry-Air has introduced an innovation in the sorption materials that they have incorporated in their technology. A special silica gel called BRYSORB 200 is used in the adsorption chamber for the sorption-desorption process with regeneration temperature as low as 60 °C.

From Table 2, we may conclude that, in general, the adsorption materials that have been widely used at lab-scale and commercial level, is silica gel due to its hydrophilic properties. However, when silica gel particles come into touch with liquid water or a salt solution, they become extremely fragile (frail), resulting in particles turning into powder after many cycles [39]. Zeolite is also a well-known solid adsorption material. In general, zeolites have water uptake of 0.3 kg per kg of material which implies that zeolites are more hydrophilic than silica. However, there is a major drawback of zeolites when used for solar-driven systems, which is the high temperature required to its regeneration or for charging [7]. Operating the cooling system at lower temperature will not result in high performance of the system.

The performance of an adsorption cooling system is highly dependent on the performance of the adsorption materials. Improving the uptake of sorbate (g sorbate/g sorbent) and conductivity of the sorption materials is an area that can be further researched to enhance the COP and specific cooling property of the adsorption cooler. Recent advances in material science offers adsorbent materials made of composite thermochemical materials. Composite materials are formed by impregnating hygroscopic salt such as $CaCl_2$, $MgSO_4$, LiCl into the pores of porous desiccant host material such as silica gels, vermiculite, zeolites, and carbon fibre [40]. These

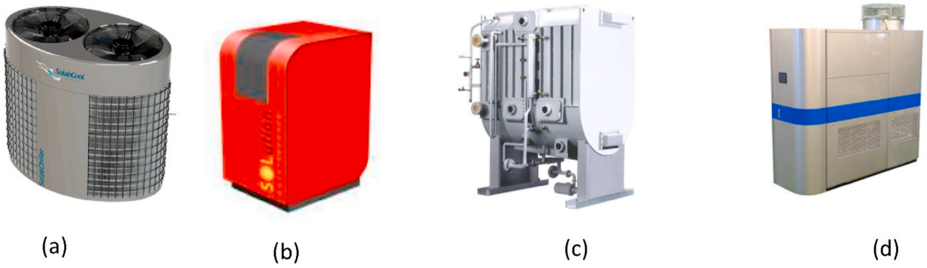

Fig. 2. (A) SolabChiller from SolabCool, Netherlands [31], b): SOLACS08 from solarcombi+ [32], c) Adref noa mayekawa Japan [36] and d) adsorption chiller by MITSUBISHI PLASTICS [35].

Table 2
The summary of the lab-scale and commercially available solar adsorption cooling.

Sorption-refrigerant pair	Hot water temperature range	COP	Remarks	Ref/country
Silica gel-water	50 °C and 60 °C	N/A	Lab-scale prototype	[25] Malaysia
Silica gel -water	90 °C	0.55	Lab-scale prototype with evacuated tube solar collector of 4 m^2 in size	[28] Iraq
Activated carbon-methanol	N/A	0.142	Micro vacuum pump heat and mass transfer enhancement technique using external finned tube in the condenser were introduced	[29]China
Zeolite 13X/ $CaCl_2$-water	N/A	0.24	For adsorption bed, they used vehicle radiators coated with composite adsorbent of Zeolite 13X/ $CaCl_2$. Six single-glazed flat plate solar collectors with the total area of 12 m^2	[30] China
N/A	between 60 and 95 °C	0.6	Cooling capacity = 2.5 kW–5 kW	[31] Solabcool, The Netherlands
Silica gel-water	The lowest 70 °C	N/A	Cooling capacity = 7.5 kW	[32] SOLACS08, Germany
N/A	The lowest 55 °C	N/A	Can be operated as a heat pump in winter.	[33]SorTech AG, Germany
N/A	The lowest 60 °C.	0.4	Cooling capacity 5–30 kW	[34] China
Zeolite-water	N/A	10 (the system can also produce hot water)	Cooling capacity = 90 kW and can produce low temperature hot water	[36] Adref noa, Japan
Zeolite-water	50–80 °C	N/A	Cooling capacity 10 kW	[35] Mitsubishi Plastics in collaboration with Union Industry Co., Ltd. Japan
Silica gel-pure water	50–95 °C, pressure level of 4 bar	0.65	8–100 kW	[36]FAHRENHEIT, Germany
Zeolite-water	75–95 °C, pressure level of 2 bar	0.5	25 kW–75 kW	[36]FAHRENHEIT, Germany
Silica gel-water pair	The lowest is 60 °C	N/A	11 kW–35 kW	[38] BryChill™ by Bry-Air

materials are capable of adsorbing humidity and have been identified to attain deep dehumidification.

From previous research, the materials applied for adsorption cooling system include silica activated carbon with $CaCl_2$ [41] with COP of 0.7, and zeolite 13X with $CaCl_2$ with water uptake 420 % higher than zeolite 13X on its own [42]. Vermiculite-$CaCl_2$ is a type of composite materials that have been actively investigated by researchers mainly in solar thermochemical heat storage application [43]. Among the promising characteristics of vermiculite as the host material on the application of thermal storage are; i) the porosity which is represented by the specific area, ii) its energy density which is close to that of zeolites and silica, iii) its low cost and market availability [43]. For a solar driven adsorption cooling system, Vermiculite impregnated with $CaCl_2$ appears to exhibit good qualities and is an excellent candidate as sorption materials paired with water as the refrigerant and it is worth the effort to be further explored by researchers in this field.

3. Solar Adsorption Cooling Systems under tropical climatic conditions

The potential of the solar adsorption cooling system under tropical climate conditions has been evaluated using TRNSYS 18. The schematics of the TRNSYS layout is presented in Fig. 3. Meanwhile, Table 3 summarises the system components and the associated element used in TRNSYS.

In our study, the adsorption cooling system is of the conventional type with silica gel and water as the sorbent adsorbent pair. In order to explore the potential of the SADCS in tropical climate conditions, the dynamic behaviour of an adsorption cooling system that is solar-driven using the conventional silica gel -water sorbent adsorbent pairs for a typical day of hot climate condition in Malaysia, Singapore and Thailand was studied. The room being cooled as a case study is an office room at 4.5 (L) x 4.5 m (w) x 4.5 m (height) m in size. The internal gain was set to be generated from the people, lights, and office equipment. The daily cooling load for one year for all three selected weather pattern is presented in Fig. 4a. The weather was obtained from the weather files in the “Meteonorm” directory in TRNSYS 18. We have concluded that the cooling load for our case study is approximately 2.0 kW, and the cooling capacity of the adsorption chiller was set at 2.5 kW. To simulate the system, the temperature of the auxiliary heater was set at 85 °C, which is the typical regeneration temperature for the silica gel in adsorption chiller application. The following key performance parameters are considered in the evaluation; i) Solar fraction (*SF*), ii) the useful thermal energy produced by the evacuated tube solar collector $Q_{collector}$ and the heat generated by the auxiliary heater $Q_{auxiliary}$, and finally iii) the temperature profiles T_{office} and relative humidity RH_{office} of the office room and the supplied air from the cooling fan T_{fan}.

3.1. Solar fraction

The solar fraction (SF) is defined as the ratio of the useful heat generated by the solar collector to the total rate at which energy was removed from the flowing hot water for the purpose of operating the adsorption chiller, Q_{heat}, all of which is represented in equation

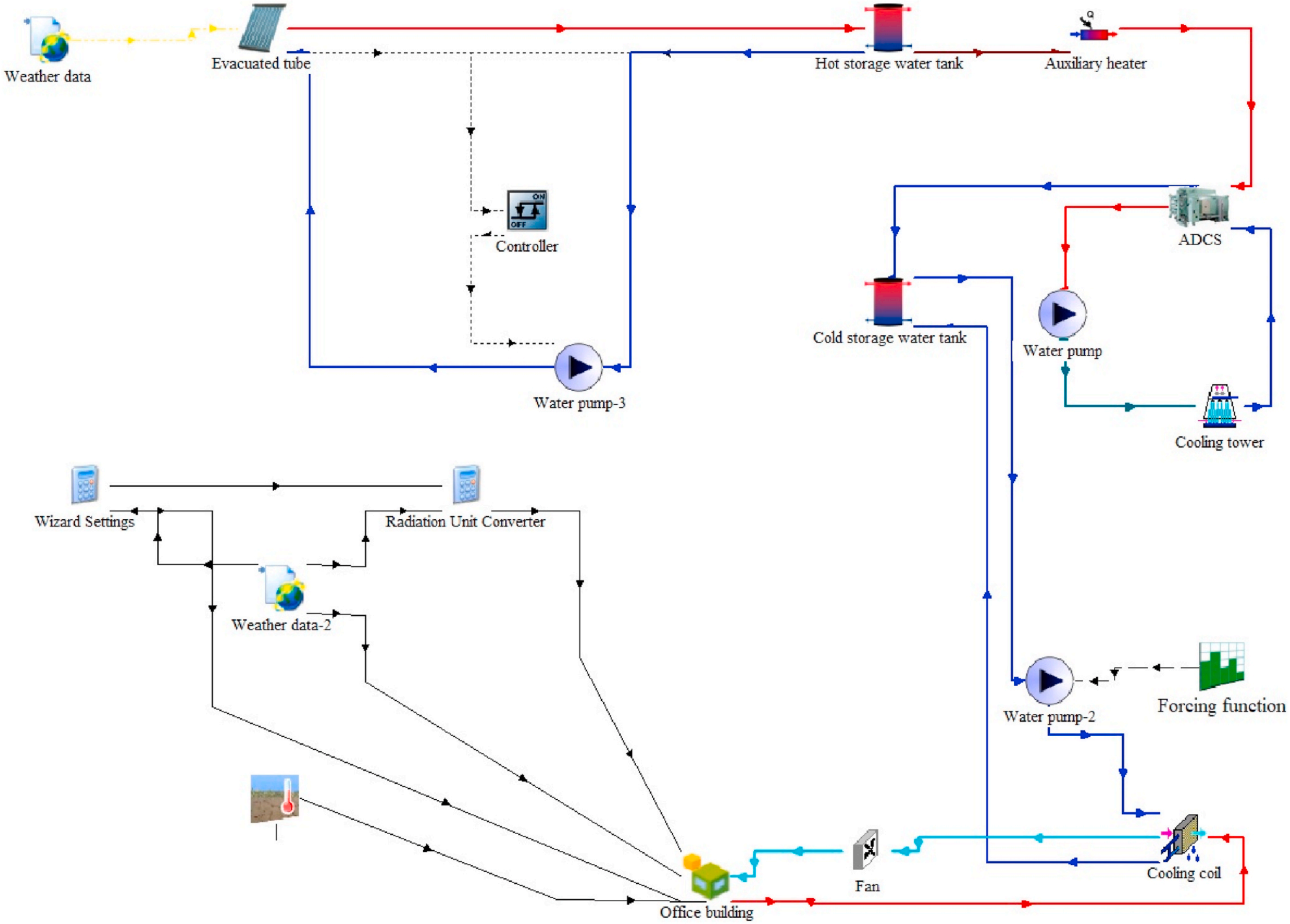

Fig. 3. Solar Adsorption Cooling Systems layout in TRNSYS 18.

Table 3
System component in TRNSYS.

System component	TRNSYS element	Remark
Office building	Type 56	The building consists of 2 office rooms at 4.5 × 4.5 × 4 m in size, a reception area, and a hallway. We scheduled the office to be cooled by the adsorption cooling system 7 days a week, from 6 a.m. to 6 p.m.
Cooling coil	Type 508	The cooling coil is modeled using a bypass approach. In this study we have set the setpoint temperature for the air outlet temperature to be equal with the inlet temperature. The cooling coil is set to operate only from 6 a.m. to 6 p.m.
Fan	Type 146	The fan to supply the cold air into the room is set to operate only from 6 a.m. to 6 p.m. However, for the room ventilation, the fan is operated continuously to ensure low humidity level.
Water pump	Type 114	The water pump for the air collector and cooling coil is set at 50 kg/h. The water pump for the adsorption chiller is set at 500 kg/h
Controller	Type 165	–
Evacuated tube	Type 71	Solar collector specification Intercept (maximum) efficiency 0.819 ($\alpha = 0.90$, $\tau = 0.91$). Negative of first order loss coefficient 1.7 W/m^2/K Negative of second order loss coefficient 0.008 W/m^2/K.
Auxiliary heater	Type 6	Auxiliary heater is set at 85 °C for the regeneration temperature of silica gel
Storage water tank (hot and cold)	Type 4	–
Adsorption cooling system	Type 909	The adsorption cooling system is the conventional type using silica gel and water
Cooling tower	Type 126	For the condenser

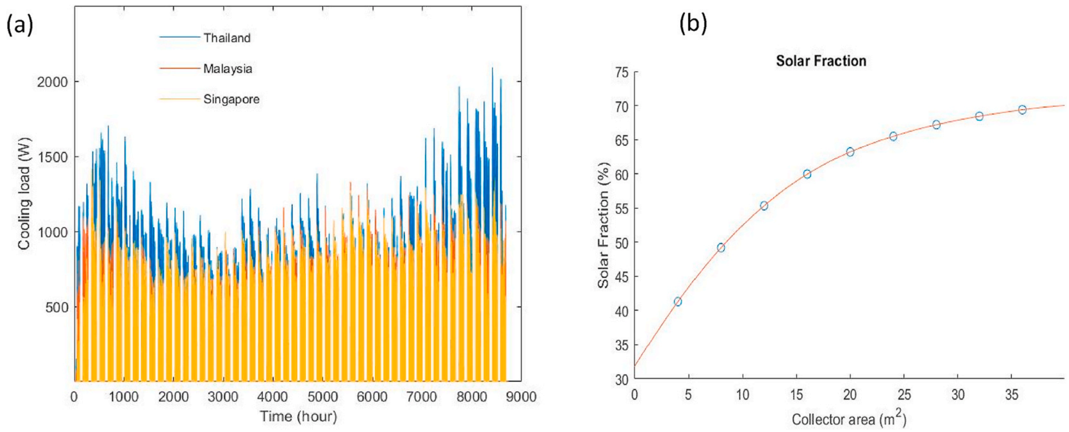

Fig. 4. a) The simulated annual cooling load for an office building in south east asian countries and b): the variation in SF with the change in collector area.

(1) [44].

$$Solar\ Fraction,\ SF = \frac{Q_{collector}}{Q_{heat}} = \frac{Q_{heat} - Q_{auxiliary}}{Q_{heat}} \qquad (1)$$

The average SF was calculated for different collector area, the results of which is shown in Fig. 4b.

From Fig. 4b we have selected 20 m^2 as the suitable collector area for the cooling system. At the aforementioned collector area, approximately 63% of the total energy required by the solar adsorption cooling system is contributed by the solar energy. Using the collector area, the maximum solar energy gained by the evacuated tube solar collector was evaluated for each country for typical days in November. It is selected based on the cooling load trend in Fig. 4a whereby the average peak cooling load was estimated to occur around that time of the year.

3.2. Evacuated tube solar collector and auxiliary heater

The useful solar energy that has been generated by the evacuated tube solar collector $Q_{collector}$ and the heat generated by the auxiliary heater $Q_{auxiliary}$ to meet the regeneration temperature requirement for the adsorption chiller are compared as shown in Fig. 5. It should be noted that the hot water produced by the collector was stored in the heat storage tank, acting as the preheated water for the adsorption chiller system. From the simulation, the evacuated tube can produce an average thermal energy as high as 4 kW and the value varies with the change in the solar irradiance throughout the day. The trend in the power consumption by the auxiliary heater may be explained as follows. In the morning, the water temperature supplied by the storage tank is much lower than the required temperature (i.e., 85 °C). Therefore, the power consumption is the highest. However, it shows a decreasing trend with the change in

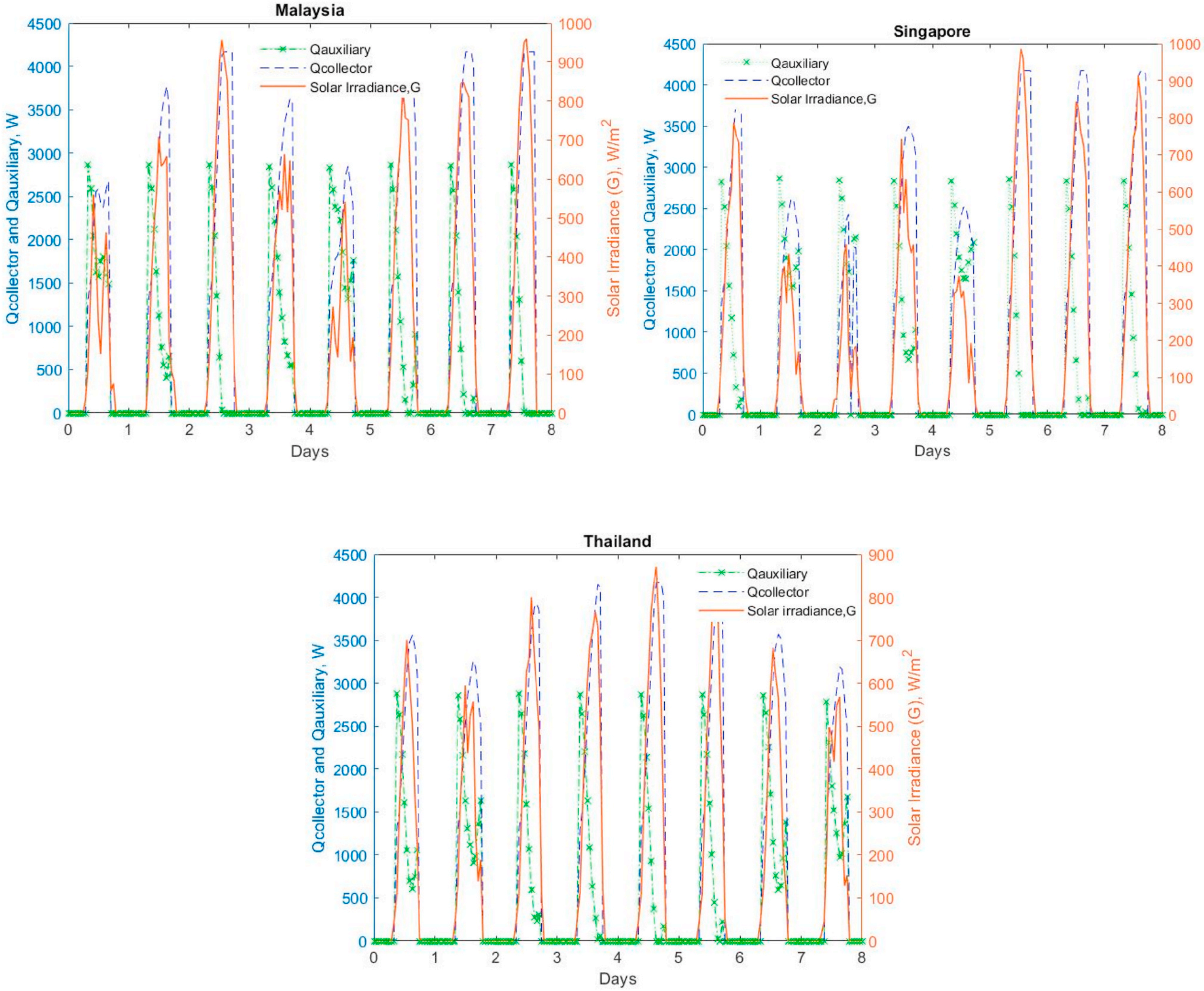

Fig. 5. The variation in the useful energy produced by the solar collector and the auxiliary heater (Simulation time: 8 days).

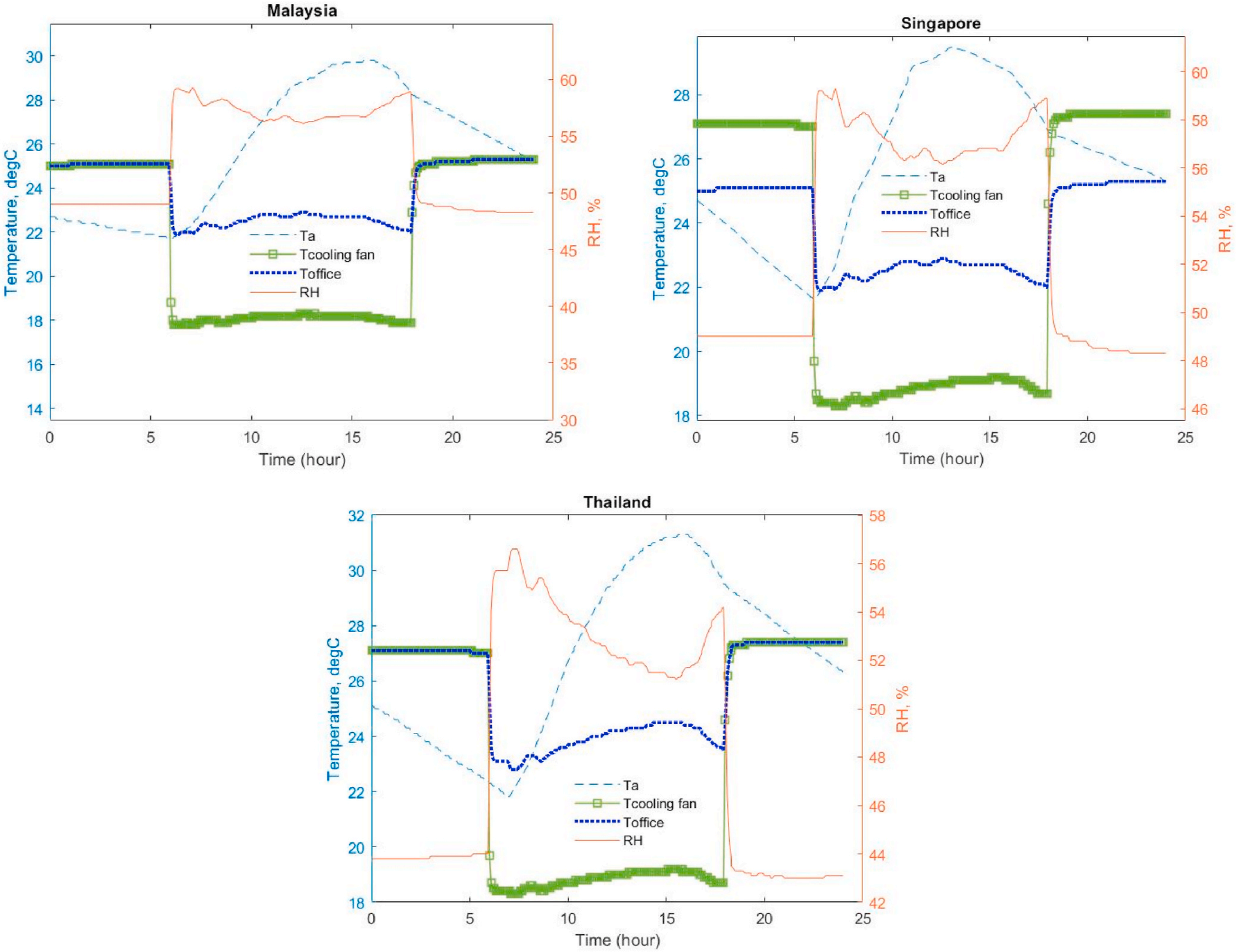

Fig. 6. The dynamic profiles of the temperature of the office, ambient temperature Ta, the cooling fan temperature and relative humidity RH in the office. (simulation time: 24 h).

solar irradiance since the temperature in the storage tank increases with the increase in the energy production by the solar collector. However, on the days when the solar irradiance is, on average, lower than 500 W/m^2, the energy produced by the auxiliary heater is almost consistent from midday towards the end of the day due to the insufficient thermal energy produced by the solar collector.

3.3. Temperature and relative humidity profiles in the office

The dynamic temperature behaviour of the cooled air supplied by the adsorption chiller, and the average temperature of the office area are presented in Fig. 6. It should be noted that, the pump from the cold storage tank is set to operate only during the day (i.e., from 6 a.m. to 6 p.m.). As soon as the pump is switched on, the temperature in the room dropped to approximately 22 °C in about 15 min. On closer evaluation, the temperature was found to slightly increase as the ambient temperature outdoor increases, and slowly decreasing after 3 p.m. Also, when the pump is switched off at 6 p.m., the temperature in the room increases. Meanwhile, for the RH, the value increases as soon as the pump is switched on due to the drop in the dry bulb temperature. Nevertheless, the RH value and the room temperature are still within the accepted thermal comfort range based on ANSI/ASHRAE Standard 55–2010 [45].

4. Conclusion

This paper has discussed different types of solar-driven air-conditioning systems that can serve as an alternative to reduce the energy consumption of conventional electrical driven air-conditioning systems. There are commercially available systems and systems that are limited to lab scale. The latter mostly were focusing on materials-based research. From our review, on the material basis, the commercial prototypes mainly use silica gel and zeolite water pair. Nevertheless, a novel sorption material that is structurally strong, which has excellent sorption kinetics, low cost and practical to produce is needed to further advance the SADCS technology at practical level. From our simulation in TRNSYS, we found that the solar fraction of the SADCS system is as high as 63 %, with the average temperature and the relative humidity of an office space can reach down to an average of 20 °C and 60 % respectively, within the range of the thermal comfort level for the occupants. Hence the system can be considered to have the potential as the next generation of air-conditioning systems that has the advantage of reducing energy consumption to meet the cooling load while employing the abundant solar energy resources.

CRediT authorship contribution statement

Norhayati Mat Wajid: Project administration, Supervision, Conceptualization, Data curation, Writing – original draft, Writing – review & editing, Methodology. **Abdul Murad Zainal Abidin:** Project administration, Supervision, Writing – review & editing. **Mirhamed Hakemzadeh:** Methodology, Investigation. **Hasila Jarimi:** Conceptualization, Data curation, Writing – original draft, Writing – review & editing, Methodology, Investigation. **Ahmad Fazlizan:** Writing – original draft, Visualization, Writing – review & editing. **Mohd Faizal Fauzan:** Project administration, Supervision. **Adnan Ibrahim:** Project administration, Supervision. **Ali H.A. Al-Waeli:** Visualization, Writing – review & editing. **Kamaruzzaman Sopian:** Project administration, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper

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