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Modelling of cold store for agro-products using solar-driven adsorption chiller under Rwandan environmental conditions

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ABSTRACT

There has been an increasing need to address the lack of food cold chain in order to save wasted food in Sub-Saharan Africa. TRNSYS has been considered as a powerful tool to simulate transient energy systems. In this study, TRNSYS has been utilised to model a standalone year-round adsorption cooling system driven by solar thermal energy to preserve fruits and vegetables after the harvest in Rwanda. The required solar collector area and heat storage size were optimised to run the adsorption refrigeration system 24/7, meet the cooling demand of the cold room and maintain its conditions. A combination of evacuated tube solar collector area of 45 m^2 with a hot storage size of 10 m^3 and 50 m^2 with 8 m^3 were found optimal to drive the cooling system 24/7 and maintain a cold room of 38 m^3 at the desired operating temperature of 10 ^oC to preserve a selected range of fruits and vegetables.

Keywords: TRNSYS, Solar thermal energy, Adsorption cooling system, Food cold chain, Food waste.

NOMENCLATURE

Abbreviations	
COP	Chiller coefficient of performance
Q_{chw}	Chilled water energy
Q_{hw}	Chiller inlet hot energy
Q_{IT}	Total incident solar radiation
Q_{useful}	Solar collector gained energy
SF	Solar fraction
TMY	Typical Meteorological year whether file
TRNSYS	Transient system simulation
Symbols	
η_{col}	Solar Collector efficiency
η_{sys}	Total system efficiency

1. INTRODUCTION

Nowadays, food wastage has been considered as a profound issue that threatens food security all over the globe. Around one-third of the produced food worldwide is wasted, primarily because of the lack of cooling. The wasted food not only affects food security but also damages the environment and squanders the resources substantially. About 1.6 Gtonnes of food is wasted globally, 1.3 Gtonnes is edible food, resulting in emitting about 3.3 Gtonnes CO_2-equivalent in a form of methane gas from landfills, which is considered third top emitter in the world after the USA and China. Besides, nearly 250 km^3 of irrigation water is lost due to the food wastage, which is equal to about three folds the Lake Geneva volume. Furthermore, about 1.4 million hectares of arable land are occupied by uneaten food, which acts about 30% of the total world-wide's agricultural land area [1].

One of the main causes of wastage of perishable foodstuffs in Sub-Saharan Africa (SSA) is the lack of food

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cold chain. Foodstuff losses due to the lack of cold chain represent about 40-50% of the cultivated crops (e.g. vegetables, fruits, tubers and roots). One of the possible solutions to address such a challenge is to develop sustainable cooling packages, which reduces the food wastage, encourages agricultural production and improves access to markets [2]. One of the impediments hampers this development is the energy poverty and the lack of accessing the grid [2,3]. Therefore, developing an alternative energy source to drive cooling systems is crucial to address such a challenge.

Transient System Simulation (TRNSYS), owing to its large meteorological database and its capability to simulate a wide range of integrated systems, has been widely used and validated to investigate various solar-driven systems. Solar-driven adsorption cooling systems have been previously investigated using TRNSYS under weather conditions of Qatar and Egypt [4-6]. TRNSYS has also been utilised to simulate various solar-driven absorption cooling systems at different geographical sites such as Spain, USA, Pakistan and Iran employing different solar collectors such as flat plate, parabolic trough and evacuated tube collectors [7-10]. In such case studies, TRNSYS was capable to imitate such systems and analyse their performance.

Although many studies have been carried out on solar-driven cooling systems, there are few studies focused on addressing the lack of food cold chain in sub-Saharan Africa to attain food security. The current study aims using TRNSYS to investigate the hourly year-round solar thermal energy requirements provided by an evacuated solar collector to drive an adsorption chiller to maintain a cold store used for cooling foodstuffs at the desired operating conditions for Kigali, a Rwandan geographical site. TRNSYS model is utilised to optimise the solar collector area and hot storage size needed to run the adsorption cooling system for 24/7 and meet the cold store cooling demand. Factors such as system efficiency, refrigeration coefficient of performance and the solar fraction are employed to examine the system performance and optimise its components.

2. MODEL DESCRIPTION

TRNSYS 18 is employed to simulate the yearly transient behaviour of the solar-powered adsorption cooling system used for cooling a food cold store. An existing cold room of 38 m^3, currently used for preserving dairy products in Rwanda, is adopted as a case study in this work. its operation was extended to store a range of crops such as banana, potatoes and tomatoes at farm level before marketing to preserve their nutrition and increase their market values.

The thermal behaviour of the cold room is simulated using Multizone building simulation toolbox. The building geometry is generated using TRNSYS3D integrated with SketchUp software. Subsequently, the zones' cooling demand was used as inputs to the cooling system. The room setpoint temperature was 10 ^{o}C which represents the optimal temperature to store these crops [11]. Accordingly, the required time-dependent cooling load is obtained and applied to the cooling system. the cooling demand associated with the crops daily loading and respiration rate was considered as internal energy gain to the zone model. An internal energy gain of 1383 kJ/h was used, corresponding to the cold room capacity of 10 tonnes and crops daily loading rate of 500 kg/day.

Typical Meteorological Year (TMY) weather file for Kigali was integrated using TRNSYS weather component "Type15", which reads and interpolates the data from the TMY file regularly at each time step providing all required environmental data to be used with all relevant components.

predefined module "Type71" was used to model the evacuated tube solar collector that provides the heat required to drive the chiller. The optical efficiency (80%), first loss coefficient (1.5 W/m^2.k) and second loss coefficients (0.0016 W/m^2.k) were chosen [9]. To store the thermal energy and provide continues system operation, hot and cold storage tanks were integrated using "Type4a" and "Type158" modules respectively.

Type909 module was utilised to simulate the adsorption chiller which relies on a normalised data file of COP ratio and the capacity ratio at different inlet temperatures of cooling, hot and chilled water. The rated chiller capacity and COP are set as 3kW (corresponding to cooling demand) and 0.6, respectively. The outlet cooling temperature is cooled down using a dry cooler employing the ambient air temperature using "Type511" module. Also, a simplified cooling coil "Type32" integrated with a fan "Type146" was used to extract the cooling energy from the chilled water loop. Auxiliary components such as pumps are integrated as shown in Figure 1.

To evaluate the performance of the solar cooling system, factors such as collector efficiency, COP, system efficiency and solar fraction were used, equations 1-2.

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$$\eta_{sys}=\eta_{col}\times COP \quad (1)$$

$$SF=\frac{Q_{useful}}{Q_{hw}} \quad (2)$$

Where, η_{sys} and SF denote system efficiency and solar fraction, respectively. To examine a range of collector areas and hot storage sizes, an auxiliary heater embedded in the hot storage tank is used to set the lowest chiller inlet hot water temperature to 65°C.

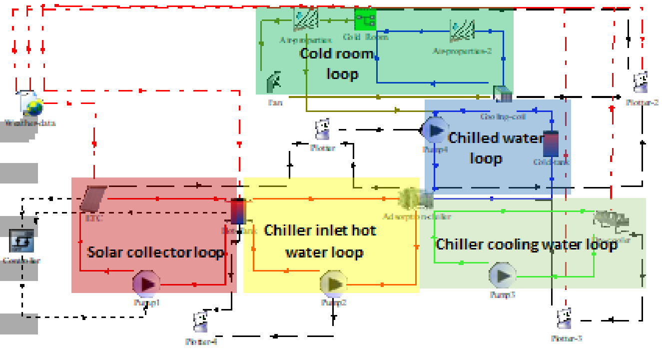

Fig 1 TRNSYS components diagram

3. RESULTS AND DISCUSSION

TRNSYS was capable to simulate every component of the integrated solar thermal-driven adsorption cooling system. The model was utilised to size and optimise the components of the system, specifically, the area of the solar collector and hot storage size required to drive the adsorption chiller year-round 24/7 and maintain the cold store at a temperature of 10°C. Figure 2 shows the effect of the heat storage size on the collector efficiency at four different collector areas. It was observed that the collector efficiency increased as the storage size increases for all collector areas; while it decreases as the collector area increases for all storage sizes due to the increase in heat losses with increasing the collector area. The collector efficiency depends on other system parameters such as chiller performance needed to achieve the cold room set temperature.

Chiller COP is also affected by the hot storage size and the collector area as presented in Figure 3. It was observed that the COP decreases as the storage size increase for relatively low collector areas of 35 and 40 m^2 but the decrease rate for 35 m^2 is higher compared to 40 m^2.

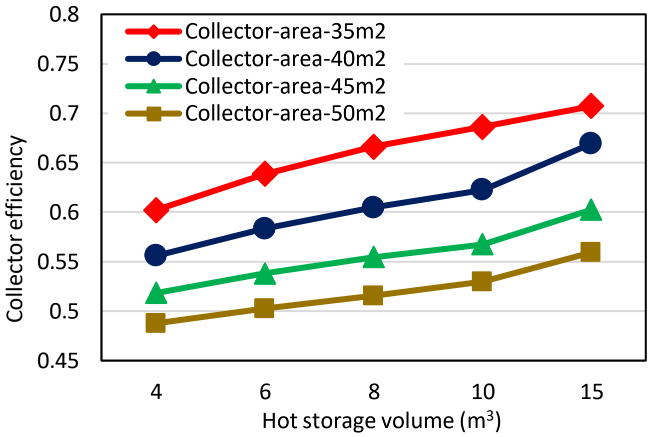

Fig 2 Collector efficiency versus hot storage size at different collector areas

This attributed to the reduction in the chiller inlet hot water temperature when the storage size increases which decreases the COP. However, at higher collector areas of 45 and 50 m^2, the trend is reversed where the COP increases with the increase in the storage size except for 45 m^2 and storage size of 15 m^3 where the COP decreases. This was because at a relatively high collector area, smaller storage size exhibits higher collector heat losses, whereas for larger storage size the thermal storage capacity is sufficient to increase the chiller inlet hot water temperature which increases the COP.

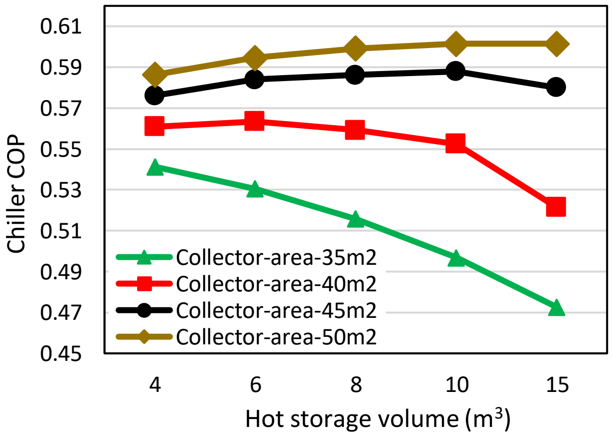

Fig 3 Chiller COP versus hot storage size at different collector areas

The combination of the collector efficiency and chiller COP provides the total system efficiency as shown in Figure 4. For collector areas of 40, 45 and 50 m^2, the system efficiency increases with increasing the storage size as the collector efficiency dominate the COP. Collector area of 40 m^2 showed a lower increase rate due to lower COP at higher storage sizes compared with 45

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and 50 m^2. However, for these three collector areas, the system efficiency decreases as the collector area increases where the collector efficiency dominates. On the other hands, the collector area of 35 m^2 has a different trend where the system efficiency firstly increases as the storage size increases until reaches the maximum value at a storage size of 8 m^3. However, for higher storage sizes, 10 and 15 m^3, the system efficiency decreases where the lower value of COP dominates the collector efficiency.

The system performance affected by the size of different system components as indicated by previous factors is not the only one needed to be examined.

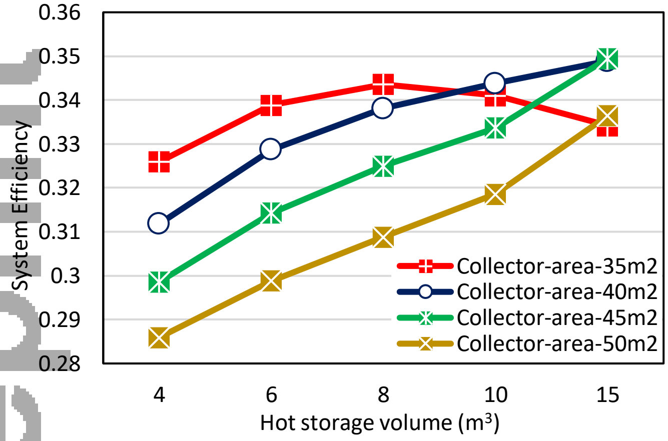

Fig 4 System efficiency versus hot storage size at different collector areas

Figure 5 presents the effect of the collector area and storage size on the solar fraction. For a collector area of 35 m^2, the solar fraction trend follows exactly the system efficiency trend for the same collector area. The highest solar fraction obtained was about 91% at a storage size of 8 m^3 whereas the lowest is 84% at 15 m^3. For 40 m^2, the highest solar fraction of about 98% was achieved at storage sizes of 10 and 15 m^3. A solar fraction of about 100% was obtained for 45 m^2 at storage size of 10 and 15 m^3 whereas for 50 m^2, 100% is achieved at 8, 10 and 15 m^3.

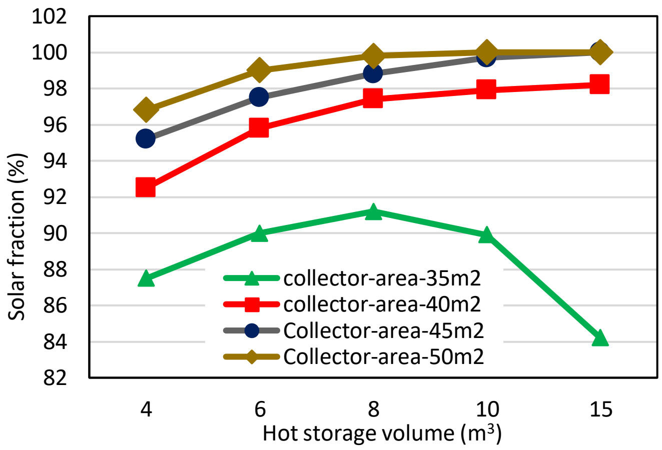

Fig 5 Solar fraction versus hot storage size at different collector areas

Another indicator which directly affected by the size of components is maintaining the room temperature at 10^{o}C. Figure 6 presents the ambient and room temperatures variation with time for collector areas of 35 and 45 m^2. For a collector area of 35 m^2, it was observed that in addition to its relatively low solar fraction, it cannot maintain the room temperature at 10 ^{o}C while using 45 m^2 can provide enough cooling energy to maintain the cold room temperature at 10 ^{o}C.

It is beneficial to place the current results in the context of previous studies which investigated small-scale sorption cooling systems powered by solar thermal energy that used a close dataset. Although the collector efficiency is greatly affected by solar irradiance data which varies from one geographical location to another,

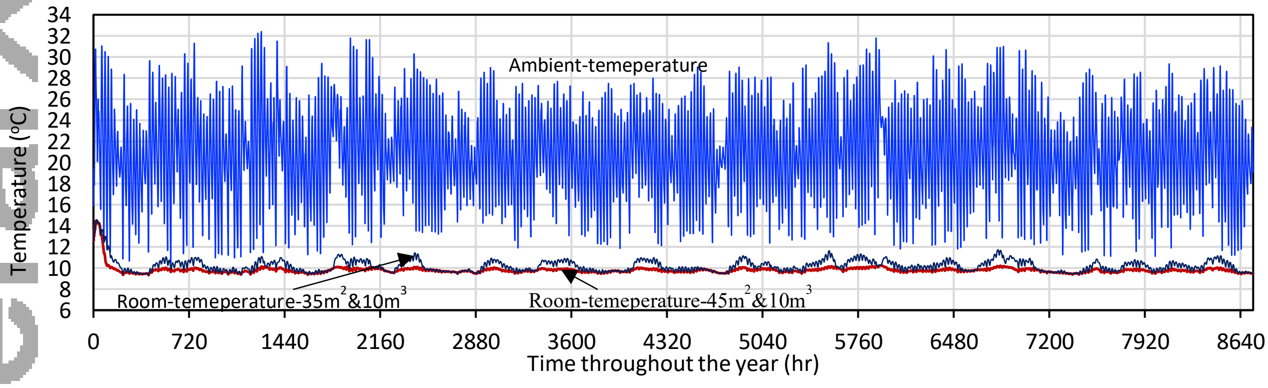

Fig 6 Room and ambient temperatures change with time

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the collector efficiency obtained from the present study which is in the range of 0.49-0.64 is close to results of 0.55-0.58 reported by Reda et al [5] utilising the same range of hot storage size. A similar trend of COP variation with collector area was obtained by Román et al [12]. Also, the current obtained COP values (0.47-0.6) fall within the rage of 0.46-0.62 attained by Román et al [12] for the same range of the chiller inlet hot water temperature (65-90 °C). It is Known that the chiller COP is greatly affected by the inlet hot water and cooling water temperatures [7] which depend on the site metrological data represented by the solar irradiance and ambient temperature.

For the solar fraction variation with the solar collector and hot storage volume, the current result provided a similar trend to that reported in the literature [10, 12]. It was reported by Reda et al [5] that the required collector area and storage volume providing a solar fraction of 100% to drive an adsorption chiller of 8 KW capacity under Egypt weather conditions are 60 m^2 and about 6 m^3, respectively whereas Monné et al [7] reported a collector area of 37.5 m^2 needed to drive an absorption chiller of 4.5 KW for few hours during the day time in Spain. It is found in this work that a collector area of 45 m^2 is required to provide a solar fraction from 95-100% for a storage volume from 4-10 m^3. Reda et al [5] investigated the cooling system for only the summer months (May-September) which reduce the required collector area and storage volume due to higher solar irradiance and lower operating hours compared with the current study where a year-round cooling is required demanding larger collector area and storage volume.

4. CONCLUSIONS

Year-round operation of a solar-driven adsorption cooling system was simulated using TRNSYS. The model is employed to investigate the system performance and the solar collector area and hot storage size required to power the adsorption chiller maintaining the room temperature at the set temperature. It is concluded that solar radiation under the Rwandan weather condition can provide enough energy to drive the cooling system 24/7 throughout the year. The system performance cannot be used alone to determine the size of components required, but other factors such as the solar fraction and room temperature need to be considered. The standalone solar-driven adsorption cooling system was achieved using either collector area of 45 m^2 with a storage size of 10 m^3 or 50 m^2 with 8 m^3 to maintain the cold room at the desired temperature.

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