SELECTION OF A SOLAR COOLING SYSTEM FOR STRAWBERRY STORAGE IN THE SOUTH OF BRAZIL

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ABSTRACT

Solar energy is an alternative to reducing dependence on non-renewable energy sources in various productive sectors. The present work has its main objective to simulate, evaluate and select a solar cooling system using a double absorption cycle (H2O – LiBr). The heat source of the generator-absorber is the water heated through different technologies of solar thermal collectors: Evacuated Tube Collector (ETC) and Parabolic Trough Collector (PTC). Five different arrangement areas were tested for each collector type. The systems were simulated in the TRNSYS® software. A 334.4 m³ cold chamber must be maintained at a constant temperature of 0 ºC. The thermal and energy analysis results indicate that the ETC configuration has the best system efficiency and the highest solar fraction throughout the year. The best option evaluated is the ETC configuration with a collector area of 100 m². In addition to supplying the thermal demand, it presents the most significant collector efficiencies, a better solar ratio, the highest savings at the end of the analysis period, and the lowest required investment value, showing as a sustainable option.

Keywords: solar absorption cooling, solar thermal energy, TRNSYS®, strawberry storage, double absorption cycle (H2O – LiBr)

INTRODUCTION

The use of technologies whose energy source is solar radiation has proved to be an attractive alternative for heating or drying (Alves et al., 2019; Rodrigues & Basso, 2020), cooling (Montagnino, 2017; Jordan et al., 2018; Lazzarin & Noro, 2018), and refrigeration (García et al., 2018) applications. In the case of refrigeration systems, it is possible to reduce the use of synthetic refrigerants (Kim & Infante Ferreira, 2008) and decrease CO2 emissions with all its benefits and challenges (McGee & Greiner, 2019; Xu et al., 2019).

On the other hand, this system requires a much higher initial investment than traditional systems. The authors Kim & Infante Ferreira (2008) present an overview of the state-of-the-art of different types of systems that use this technology, as well as a comparison of their potential as competitive sustainable solutions.

Air conditioning systems that use solar thermal energy as a hot source (García et al., 2018) are presented as alternatives to reduce the dependence on non-renewable sources for the maintenance of the heat source. In this case, two types of collectors are the most commonly used: flat plate (FPC) and evacuated tube (ETC) collectors. The second is the most efficient for operation at high temperatures.

The amount of solar energy received per unit of area is called solar irradiation, in MJ/m^2 or kWh/m^2, which can also be interpreted as the "solar resource" of a given location. The greater the solar resource in a region, the greater the availability of radiant energy and the greater the demand for air conditioning and refrigeration systems (Ge et al., 2018).

Asim et al. (2016) simulated, through TRNSYS®, a single-effect solar absorption cooling system optimized for a residential application, with a cooling power of 1 TR and water heated by an ETC. They observed that it was possible to maintain a room in a typical Pakistani residence at 26°C during the summer, with an average maximum temperature of approximately 35°C.

A study on single, double, and triple effect absorption heating and cooling systems was conducted by Shirazi et al. (2016). Again, TRNSYS® was used for the simulations. Their results suggested that using ETC, single and double-effect absorption systems required a smaller collector area than systems using parabolic solar collectors (PTC) or linear type collectors, like Fresnel (LFC). In addition, the double-effect absorption system - using water heated by ETC as a heat source - had a better economic and thermal performance.

Lazzarin & Noro (2018) state that, currently, the cooling costs using photovoltaic solar energy are even more favorable due to the low cost of photovoltaic modules. However, according to their projections, the prices of solar thermal collectors tend to decrease to become economically competitive in the future.

Cascetta et al. (2017) carried out a performance analysis of a dual effect solar absorption cooling system for an agro-industrial application in Naples, Italy. The computer simulation's objective in TRNSYS® was to ensure that a room measuring 334.4 m³ was maintained at a constant temperature of 10 °C throughout the year. To do so, they simulated a double-effect absorption refrigeration system (H_2O - LiBr), with a nominal capacity of 150 kW and a nominal COP of 1.15, aided by an auxiliary boiler of 50 kW and a cold storage tank of 5 m³. Two different types of solar collectors were studied: ETC and PTC. The results indicated that the PTC was more efficient during the summer than the ETC, as the high temperatures prevented the auxiliary boiler from being used. During winter, ETC was more efficient than PTC due to a more significant solar fraction and greater primary energy savings. For Brazil, no similar studies are available in the consulted literature.

In this sense, this article aims to evaluate the system based on the model by Cascetta et al. (2018) subjected to climatic conditions and the irradiation profile of a city in the south of Brazil. The thermal system (Soares, 2019), also simulated in TRNSYS®, must maintain a cold chamber at a constant temperature of 0ºC throughout the year, thus allowing the storage of strawberries (ASHRAE, 2018). The choice to keep the absorption refrigeration cycle, using thermal energy as a hot source, lies in the fact that it is a promising option whose source can be supplied by waste heat from other processes or by using thermal solar collectors (Al-Tahaineh et al., 2013).

MATERIALS AND METHODS

TRNSYS® software enables the transient simulation of the behavior of several thermal systems. Its use is internationally recognized for simulating passive and active solar systems. It has a highly flexible graphic environment, giving the user freedom to assemble the thermal system to be analyzed. It is based on the interconnection of components, system equipment called types. The parameters and connections required for each type are user-defined. TRNSYS® solves the system's differential equations, guarantees the results' convergence, and generates the output information at each defined instant (timestep) of the simulation.

According to Specht & Blume (2011), the largest strawberry-producing city in Rio Grande do Sul is Feliz, with an average annual production of 1,800 t. Feliz is approximately 90 km from Porto Alegre, the state capital. The simulated building aims to be a refrigerated environment where strawberries are taken for storage after harvest. After the recommended storage period, these are distributed to sales outlets in the state capital and the metropolitan region. For this reason, the city of Porto Alegre was chosen as the location for the simulation.

The thermal load was calculated using the methodology presented in the ASHRAE Handbook: Refrigeration (ASHRAE, 2018). According to their recommendations, strawberries should be stored at a temperature of 0ºC for up to 7 days. It is assumed that 35 t of strawberries are stored during each storage period, equivalent to 7 days of average annual production in the city of Feliz (Specht & Blume, 2011). Subsequently, a new load is stored, and so on.

The simulated thermal system (Soares, 2019) was based on the work of Cascetta et al. (2017), Cascetta et al. (2018) and Buonomo et al. (2018). The collector areas, the constructive characteristics, the types of collectors (ETC and PTC), and the dimensions of the cold chamber are the same used by Cascetta et al. (2018); that is, 11 m in length, 9.5 m in width, and 3.2 m in height totaling 334.3 m³. There are no rooms adjacent to the cold room. For calculation simplification, the hypothesis that the fruits enter the cold chamber at the average temperature of the analyzed month was considered.

The floor comprises the following layers: 15 cm of concrete, 15 cm of polyurethane, and another 5 cm of concrete. All walls and roof have an insulating layer of 15 cm of polyurethane, characterizing an adiabatic boundary condition. The door has dimensions of 3 m high by 2.5 m wide, a flow factor of 70 %, and a curtain with an efficiency of 75 %. The door is open six hours a week for fruit loading and unloading. Lighting consumes 8 W of electricity per unit of floor area, and indoor and outdoor air has a velocity of 1 m/s (Soares, 2019).

The thermal system is based on absorption refrigeration equipment that uses lithium bromide (LiBr) as an absorber and water (H_2O) as a refrigerant in a closed cycle. The effects of water boiling and/or freezing and pressure drops in pipes are not considered. Therefore, the values found for the performance factors are higher than those of a real system.

The components of this system and their respective types of TRNSYS® are shown in Table 1. Two different configurations were simulated, Figure 1 and Figure 2, with different types of solar collectors, i.e., ETC and PTC, respectively. The mass flow rate of the system was set at 10 L/min.

Table 1. System components and their respective TRNSYS® types.

Component	Type
Pump	3d
Pipe	31
Absorption chiller	677
Climate data	15-3
Building (Chamber)	56
PTC	1288

Component	Type
Boiler	700
Thermal load	682
Controller	2b
Diverter	11b
ETC	71
Cold storage tank	4c

Hot storage tank	4c	Thermostat	108
Cooling tower	510	Valve	11h

Using a solar thermal system is justified when the costs of collectors, other equipment, and conventional reserve fuel are lower than the costs to obtain the same result using another energy source (Kalogirou, 2014). Thus, the methodology for assessing the life cycle economics proposed by Kalogirou (2014) was used for the economic and financial evaluation (Soares, 2019).

This methodology is based on the premise that the total savings obtained by using a solar thermal system are given by the difference between its life cycle cost and the life cycle cost of a system that uses conventional fuel. It means that these savings are equivalent to the total present value of the gains from the solar thermal system compared to the profits from the system that operates only with conventional fuel.

In a heat-driven refrigeration machine, solar collectors provide heat to the thermal compressor (or the heat engine). As we know, the working temperature is the main factor in solar collector efficiency. At a higher working temperature, the collector loses heat to the ambient. Consequently, it delivers less heat. On the other hand, the heat engine or thermal compressor generally works more efficiently with a higher temperature (Torgal et al., 2016). Considering these two opposing trends, a solar thermal system is designed (Kim & Infante Ferreira 2008).

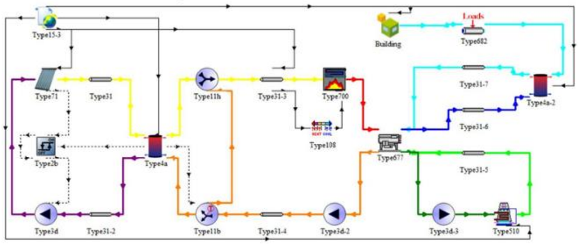


Figure 1. Schematic of the simulated system using ETC (Soares, 2019).

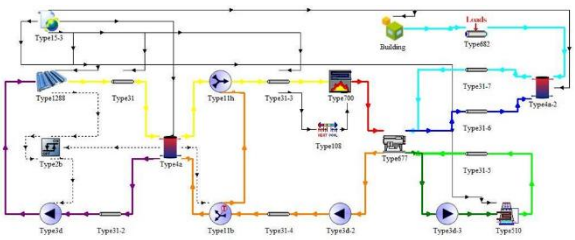


Figure 2. Schematic of the simulated system using PTC (Soares, 2019).

RESULTS

Figure 3 shows the monthly averages of the system thermal load and the dry-bulb temperature (DBT), considering that it is located in Porto Alegre, RS. The most significant thermal demands occur in the summer months, around 11 MWh. The average DBT varies approximately between 14 °C and 25 °C.

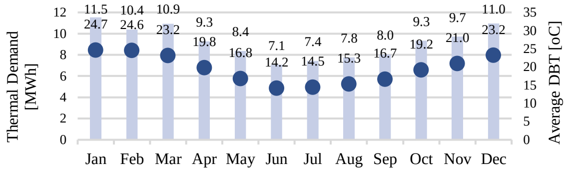


Figure 3. Monthly Thermal Load, in MWh, and average DBT, in oC.

In the case of ETC, Figure 4 shows that the efficiency per collector area presents a practically linear behavior. The extreme values are a maximum of 52.21% for 100 m² and a minimum of 41.20% for 300 m². On the other hand, PTC has less linear behavior, with a maximum efficiency of 24.08% (100 m²) and a minimum of 8.03% (300 m²). When compared, it can be seen that the ETC is always more efficient than the PTC for any area configuration. The ETC has higher efficiencies in all months of the year, as it has lower thermal losses by convection and conduction due to the vacuum sealing between its tubes.

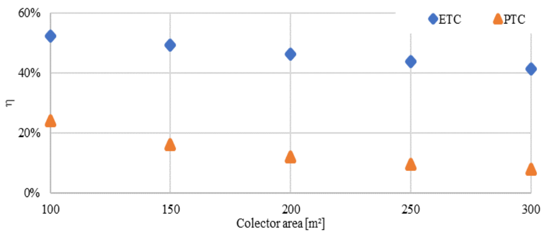


Figure 4. Efficiency per collector area.

For example, evaluating the more efficient case (100 m²) makes it possible to observe an essential characteristic of the PTC. This type of collector depends on the direction of solar radiation incident on the reflector, which must be fixed. In this case, constant tracking of solar radiation becomes essential. In periods when the solar resource becomes scarce, its efficiency is impacted. This behavior can be seen in Figure 5, where we have expressively low values for the months of May to August. In the case of ETC, the values are relatively closer, with only a significantly low value observed in July. These results differ from those (Cascetta et al., 2017), indicating that the PTC wasn't more efficient during the summer than the ETC for our type of climate and solar resource. On the other hand, the same behavior is observed in winter, where ETC was more efficient than PTC.

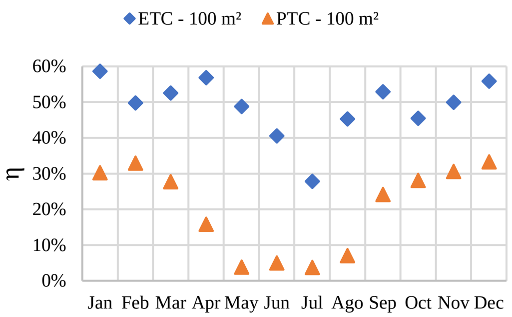


Figure 5. ETC and PTC monthly efficiency for an area of 100 m2.

Figures 6 and 7 show the solar ratio for the ETC and PTC collectors, respectively. The solar ratio is the ratio between the useful energy delivered for heating water and the amount of radiation incident on the collector's plane. This ratio can be interpreted as the collector's efficiency for a one-hour interval. Again, the ETC collector has the highest solar ratios. The arrangement with 100m^2 presents the best situation.

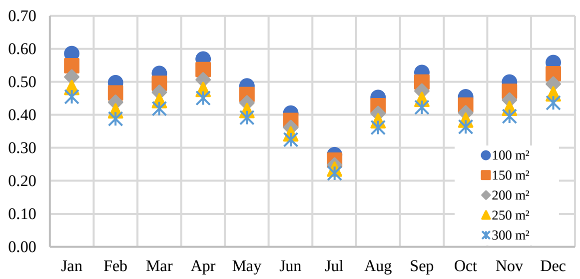


Figure 6. ETC monthly solar ratio.

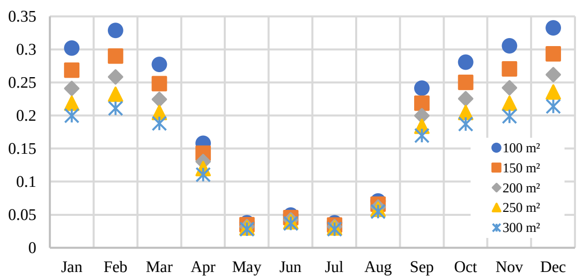
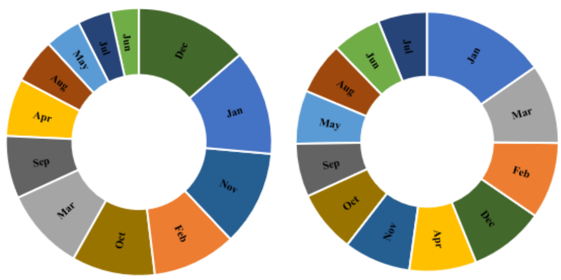


Figure 7. PTC monthly solar ratio.

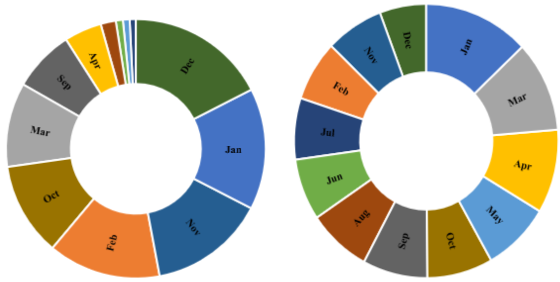
Using ETC, the mean monthly solar irradiance and the mean amount of auxiliary energy are presented in annual proportions concerning all areas, Figures 8a and 8b, respectively. In the colder months, the solar resource is low, and the amount of auxiliary energy is also low. It is because the ambient temperature, or DBT, remains low.



(a) (b)

Figure 8. (a) Mean Monthly Solar potential and (b) Auxiliary Energy for ETC.

Figures 9a and 9b refer to the same situations as Figures 8a and 8b, but for the PTC. We can observe the same behavior. However, in this case, the mean monthly solar irradiance is smaller in the winter months, according to the low efficiency observed in these months, Figure 5.



(a) (b)

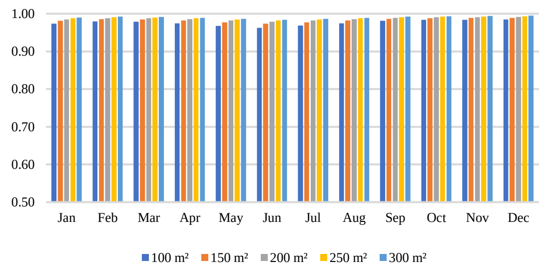
Figure 9. (a) Mean Monthly Solar potential and (b) Auxiliary Energy for PTC.

In applications that use solar energy, economic analysis is a way to determine the sizing of an application to optimize the use of solar energy and auxiliary energy. Solar energy is naturally intermittent and, therefore, unable to satisfy 100% of the demand of a given system. Such a configuration would be overestimated, causing a surplus of energy in the summer months. Thus, it seeks to satisfy around 100% of the demand in the best conditions (summer) and rationally use the additional energy source in the most critical months (winter). In Soares, 2019, the author made the Solar Heat System (SHS) economic analysis using the method indicated by Kalogirou, 2014.

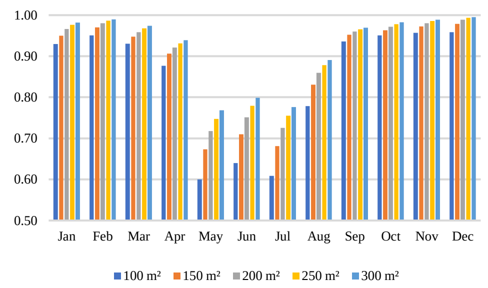
In this context, a crucial factor is the solar fraction, represented by f. The solar fraction is defined as the ratio between the useful solar energy supplied to the system and the energy needed to heat the process water if no solar energy is used, both in GJ, i.e.,

$$f=\frac{L - L_{aux}}{L} \quad (1)$$

where L is the annual load and Laux is the auxiliary yearly load. The solar fraction for each system evaluated is presented in Figures 10a and 10b. During winter, ETC was more efficient than PTC due to a more significant solar fraction and greater primary energy savings, as in the case study previously (Cascetta et al., 2017).



(a)



(b)

Figure 10 – Solar fraction f: (a) ETC and (b) PTC.

The main objective of inserting a solar heating system is to reduce the use of other energy sources, such as gas, electricity, and biomass. The solar fraction also measures the impact of reducing the use of different sources. The behavior of f, evaluated monthly, indicates how much solar thermal energy can supply the chiller's hot water demand. When comparing Figure 10a with Figure 10b, it is possible to verify that a system with ETC-type collectors has a higher solar fraction than a system with PTC-type collectors in all months of the year and for all areas evaluated. The ETC has a maximum average f of 99.02% at 300 m² and a minimum f of 97.83% at 100 m². On the other hand, PTC has a top average f of 92.13% and a minimum f of 84.32% at 100 m².

As f is a function of the radiation received in the collector plane, it is not expected to be constant over the months precisely because it is closely related to the apparent trajectory of the Sun throughout the year. The behavior of f for ETC is practically constant throughout the year, while the behavior of f for PTC presents low values in the winter months. The low conversion efficiency justifies this type of collector's behavior over this period.

The cost of ETC per collector area is based on the survey conducted by Nájera-Trejo et al. (2016), and the cost of the PTC is based on the study carried out by Cascetta et al. (2017). The total cost is calculated as the sum of fixed costs plus the cost portion of the respective solar collectors. The price of ETC is equivalent to 64% of the cost of PTC. More information about the method used, values, and other considerations can be found in Soares, 2019.

Figure 11 shows that economically ETC presents positive savings for all collector areas. The 100 m² collector area savings 176% at the end of the financing, while for 300 m², there are savings of 139%. PTC shows savings of 123% for a collector area of 100 m². However, for an area of 300 m², a deficit of 8% is the only case where there is no economic gain.

So, economically and technically, the ETC with 100 m² of collector area is the best investment option. Such a configuration can meet the system's energy demand throughout the year. It presents the highest financial return at the end of the financing and has the lowest investment cost, around 72% smaller than PTC. These results corroborate what had already been pointed out by Shirazi et al. (2016).

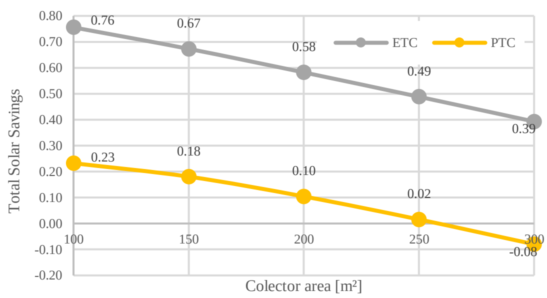


Figure 11 – Solar fraction f: (a) ETC and (b) PTC.

CONCLUSIONS

In this work, a thermal system of solar cooling by absorption of double effect was simulated through the software TRNSYS®. Two types of solar collectors, evacuated tubes (ETC) and parabolic (PTC), were evaluated. In both configurations, a 150 kW double effect absorption chiller of nominal capacity, with a nominal coefficient of performance of 1.21, a hot storage tank of 5 m³, a cold storage tank of 5 m³, and an auxiliary boiler of 50 kW.

It was observed that ETC collectors are more efficient throughout the year and have a higher solar fraction. The ETC has lower convection and conduction thermal losses due to the vacuum seal between its tubes. The PTC has a dependence that the solar radiation incident on the reflector trough is fixed as its direction. This requirement causes the efficiency of this type of collector to be low in the winter period, significantly impacting the solar fraction.

The best configuration analyzed was the one that uses ETC with 100 m². This configuration meets the thermal demand of the system, ensuring that the climate-controlled environment remains at 0 °C throughout the year. It has the lowest investment cost and has the most significant savings at the end of the financing. In this way, the present study fills a gap in the study of the use of thermal solar energy for air conditioning applications in the agro-industrial sector in Brazil.

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