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SIMULATION OF AN ABSORPTION REFRIGERATION SYSTEM WITH SOLAR THERMAL ENERGY FOR USE IN REMOTE LOCATIONS

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Abstract. *This paper presents the results of a study with a refrigeration absorption system assisted by solar thermal energy and applied to the cooling of ecotourism lodge located in a remote location, not connected to conventional electricity grid. The system consists of a water-lithium bromide absorption chiller, solar thermal collectors, hot and cold water tanks, heat exchangers, pumps and control systems. The system is designed to meet the thermal cooling loads of six rooms and a dining room. A computational model using TRNSYS was developed to simulate three system configurations. The influence of the following parameters on the system performance was analyzed: area and mass flow rates of two types of collectors (flat plate and evacuated tubes), volumes of high and low temperature thermal reservoirs, the chiller temperature activation, and cooling water temperature. In the first configuration, the heated water from solar collector is stored in a thermal reservoir and used directly by the absorption chiller when its temperature is equal or higher than the chiller activation temperature, without auxiliary heating. The cold water is stored in another reservoir, where it is available to meet the thermal loads. With this model it was observed that for 120 m² of evacuated tube collectors is possible to reach a solar fraction index higher than 0.87. The second configuration is similar to the first, but with an auxiliary heater. It was observed that the auxiliary energy consumption, for 120 m² of flat plate collectors and evacuated tube collectors, is less than 195 and 150 GJ, respectively, achieving in the last a unitary solar fraction. In the third configuration is implemented a reusing cooling water system, to supply hot water for showers. In this configuration it was noted that the reuse of cooling water does not affect the auxiliary energy consumption.*

Keywords: *water-lithium bromide absorption chiller, thermal solar collector, auxiliary heater, simulation.*

1. INTRODUCTION

Energy consumption by air conditioning (AC) systems has a great impact in the energy mix of a country in relation to the consumption of electricity. According Vidal et al. (2009) in Chile during the months of spring and summer, the electricity consumption with AC systems ranges from 30 to 60% of the total energy consumed by industries and commercial offices. In Brazil, the energy consumption with these devices in hotels reached 23% of total energy consumed in 2004, and in Brazilian airports the consumption was around 50%. According to Ayadi (2011), consumption of electricity for the North American residential cooling reached 25.8% of total energy consumption in 2009. The generation of electricity worldwide has tripled since the early 70s of last century, yet the supply of electricity is not enough, since over 1.5 billion people live without it, according to Dilay (2008). Along with the increase of electricity generation, global consumption of coal, oil and natural gas doubled, resulting in increased generation of greenhouse gases. To control greenhouse gases, regulatory measures worldwide began to be taken, such as the Kyoto Protocol (1997). In 2009 the European Union (EU) approved a program of cuts in greenhouse gas emissions by encouraging increased use of renewable energy.

Because of sustainability issues and also for environmental reasons, there is a growing demand for new energy sources for use in refrigeration systems, one of which solar energy. Its use can be through direct generation of electricity with photovoltaic modules, using conventional cooling systems, or thermal energy produced by solar collectors for use in absorption refrigeration systems.

Refrigeration absorption systems with solar thermal energy can be used in remote and isolated areas where the basic infrastructure does not meet the minimum requirements of electricity required for the use of conventional cooling systems. They can be used in hotels, inns, restaurants and other establishments, thereby improving the quality of facilities and services, further promoting ecotourism and consequently the socio-economic development of these remote locations. The main obstacles for using absorption systems is the high manufacturing cost and low thermal performance when compared to conventional cooling systems. The cost of implementing an absorption system may be 20 to 30% greater than conventional cooling equipment. This cost can be reduced from detailed studies of the project to be implemented.

This cost could be reduced with help of project studies. In this sense, this work proposed a simulation study with a refrigeration system attended by solar thermal energy for a small inn to supply the air conditioning demand.

2. ABSORPTION COOLING SYSTEMS

The absorption cooling system is similar to the mechanical vapor compression system since it also comprises a condenser, an expansion device and an evaporator. Both systems remove heat by refrigerant vaporization at a low pressure and reject heat by condensing the refrigerant at high pressure. In compression refrigeration systems, a mechanical compressor is responsible for elevating the pressure of the fluid. In the absorption system, it uses a system called generator-absorber, thereby compresses a fluid in the liquid phase using a pump, as represented in Fig. 1.

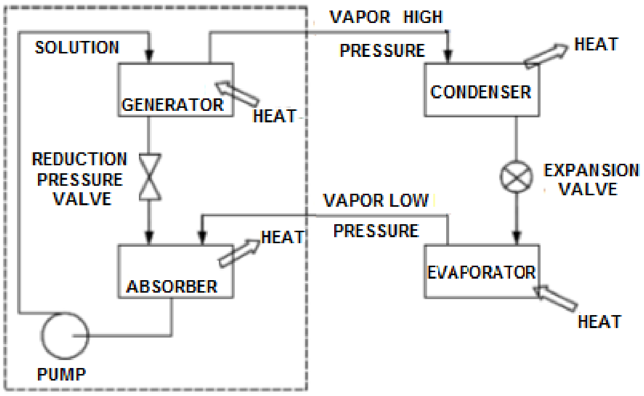

Figure 1. Representation of a single-effect absorption cooling cycle.

In absorption systems, the increase of refrigerant pressure, from saturated vapor to the condensation pressure, is carried out with the aid of the absorption phenomenon. For this, two fluids are used which act as a refrigerant and absorbent. The absorbent fluid that serves as a transport fluid absorbs the refrigerant, becoming a mixture in the liquid phase. Absorption cooling systems can be characterized according to the pair refrigerant- absorbent, that is related to the number of stages (or effects) of the cycle; the cooling capacity and the application (air conditioning, food storage and freezing).

2.1 Working Fluids

The pair refrigerant-absorbent used in absorption refrigeration systems must meet some specific features: the fluid must be physically and chemically compatible, low cost, not be harmful to health and the environment, stable, secure, non-corrosive and non-flammable. The most widely used pairs of refrigerants are ammonia (NH_3) and water (H_2O), where ammonia is the refrigerant and water the absorbent, and the pair water (H_2O) and lithium bromide (LiBr), where water is the refrigerant and lithium bromide the absorbent.

Absorption refrigeration equipment operating with LiBr-H_2O cannot reach temperatures below 3 °C due to the water freezing (crystallization). These devices are used mainly for air conditioning systems. Balghouthi et al. (2008) reported that such absorption machine is commercially available with refrigeration capacities from 35 kW and COP between 0.7 and 1.2, depending on the number of effects. According to Hudson et al. (2002), the pair NH_3-H_2O is used in absorption refrigeration applications requiring low temperatures since it may reach temperatures near -55 °C, once ammonia has its melting point close to -78 °C. According Steu (2010), the COP of these devices can range from 0.5 to 1.8. For single effect equipment, the COP is between 0.5 and 0.7. According Balghouthi et al. (2008), this type of absorption machine is commercially available with capacities ranging from 10 to 90 kW.

2.2 Heat sources

As a rule, the use of absorption systems is economically feasible when there is a free or low-cost heat source available. The major existing commercial equipment on the market use natural gas and steam as energy source but the advantage would be the use of waste heat like exhaust gases or solar thermal energy. The most common is that the absorption refrigeration systems use more than one source of thermal energy. When using solar energy, the solar collector is the device responsible for transforming the solar radiation into thermal energy through heat transfer with a thermal fluid. There are several types of solar collectors that can be used, from flat plate collectors to concentrator collectors, depending on the required process temperature.

3. METHODOLOGY

Three configuration models were analyzed, called A, B and C and the figure of merit used was the ability of each to meet the cooling heat load. The simulations were performed using TRNSYS (Transient System Simulation Tool), version 17. Each equipment and control used was modeled according to the functions (Types) available in the program.

3.1 System configurations

a) Solar collector - thermal reservoir - absorption chiller (Model A)

In this model, the water is heated by the solar collector and stored in a high temperature thermal reservoir, feeding the absorption chiller. The cold water produced by the chiller is stored in the low temperature heat reservoir, where it is available for consumption. Figure 2 shows a schematic diagram of the proposed model.

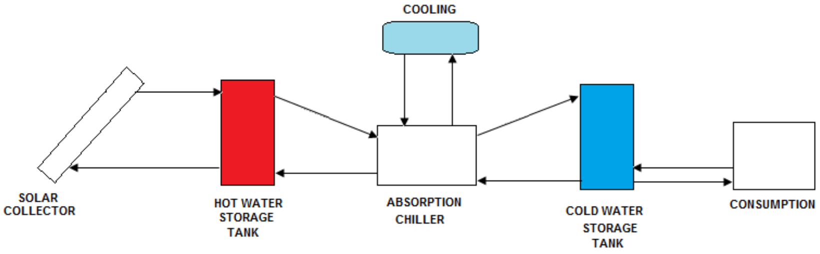

Figure 2. Schematic representation of model A.

b) Solar collector - thermal reservoir - auxiliary heater - absorption chiller (Model B)

This model is identical to the Model A with the inclusion of an auxiliary heater to feeding water to the absorption chiller, as the layout of Fig. 3. Thus, the absorption chiller can be connected where necessary to meet the consumption, since the auxiliary heater will maintain the temperature of the water necessary for their activation.

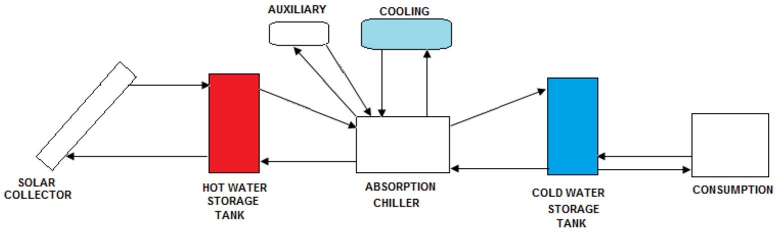

Figure 3. Schematic representation of model B.

c) Solar collector - thermal reservoir - auxiliary heater - absorption chiller – hot water consumption (Model C)

Model B was modified to use the cooling water from the condenser to provide hot water for the bathrooms and showers. The heated water in a heat exchanger is stored in a thermal storage tank. The temperature required for consumption is achieved by the mixture of this water with the hot water from the thermal storage tank of the solar heating system, using a mixing valve. Figure 4 shows a schematic representation of the proposed system.

3.2 Simulations

Several simulations were performed to verify the influence of different parameters on the amount of energy absorbed by the fluid in the solar thermal collector, in the auxiliary energy consumption, and in the percentage of attendance of each thermal load. The parameters analyzed were: thermal solar collector area, water mass flow rate in the solar collector, and volumes of thermal reservoirs of hot and cold water. The simulations were performed considering two types of solar collector: flat plate with selective surface and evacuated tubes.

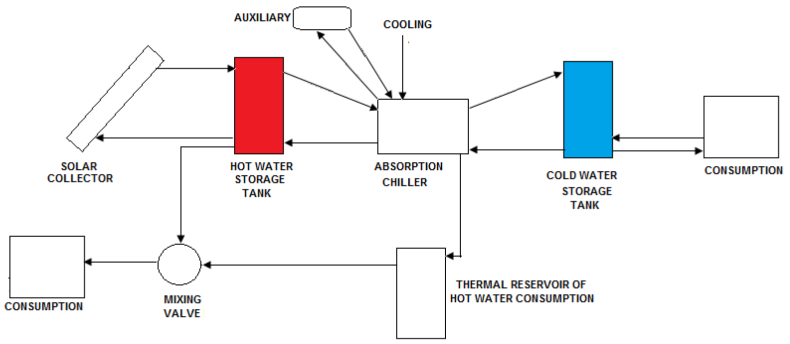

Figure 4. Schematic representation of model C.

3.3 Input data

The input data and the key features of the system in the simulation study are described as follow:
a) Meteorological data of Manaus, Amazonas State - Brazil;
b) Single effect absorption chiller, WFC-SC10 – Yazaki (Yasaki, 2012), with H_2O-LiBr and cooling capacity of 35.16 kW;
c) Cold water temperature set point: 8 °C for cold room and 10 °C for bedrooms and dining room;
d) Solar thermal flat plate collector with selective surface with F_RU_L = 4.089 W/(m² °C) and $F_R(\tau\alpha)$ = 0.743 and with evacuated tubes with F_RU_L = 0.975 W/(m² °C) e $F_R(\tau\alpha)$ = 0.624, both inclined 10° from the horizontal;
e) The water circulation pump of solar thermal collector is triggered when a minimum temperature difference of 2 °C, between the output of the collector and the bottom of the hot water thermal reservoir;
f) The operation of the chiller occurs when the cold water temperature in the reservoir is between 8 and 5.5 °C;
g) The estimated daily consumption of hot water, from 18 to 20 h, was 1000 L and the water temperature set point of 38 °C;
h) The cooling water inlet temperature at the condenser is 31 °C;
i) The hot water inlet temperature in the absorption chiller (activation temperature) is 85 °C;
j) After the initial simulations, the volume of the thermal reservoir was kept constant at 3 m³;
l) The thermal loads for each application and environment as well as the usage times are shown in Tab. 1.

Table 1. Thermal loads data.

Ambientes	*#*	*Thermal load, kW*	*Time operation, h*	*Daily energy, MJ*	*Annual energy, GJ*
Cold room	*1*	*1.0*	*10*	*36.0*	*13.14*
Dining hall	*1*	*7.03*	*7 to 8*	*126.54*	*46.2*
			11 to 13		
			19 to 21		
Bedrooms	*6*	*2.93*	*20 to 24 h*	*253.44*	*92.5*
			TOTAL	*416.52*	*151.84*

4. RESULTS

The simulations were performed on an annual basis using the climate file (TMY) of the hypothetical installation location. The thermal loads were considered constant throughout the year. Similarly, the results presented are also an annual basis.

4.1 Model A - solar collector – thermal reservoir – absorption chiller

The scheme used for the simulation in TRNSYS is shown in Fig. 5. The system works as follows: the water heated by the solar collector is stored in the hot water reservoir. A differential temperature controller drives the circulation pump of the solar heating system. The absorption chiller is fed by the hot water stored in the hot water reservoir and the cold water produced by the chiller is stored in the low temperature thermal reservoir. The operation of the chiller, the chiller pump and the cold water pump are also accomplished by a temperature difference controller and a thermostat.

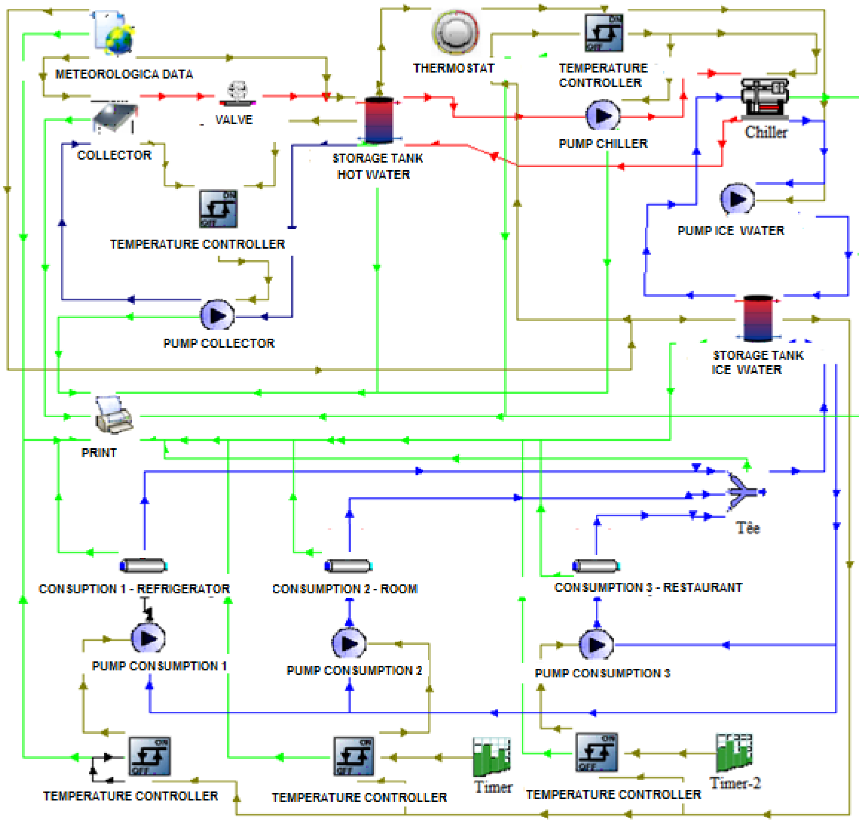

Figure 5. Model A configuration in TRNSYS.

The chiller is connected whenever necessary to meet the temperature conditions for consumption and if there is hot water in the minimum temperature for its activation. In the Trnsys simulation the water mass flow and water inlet temperature were supplied for the chiller. The minimum temperature for activation of the chiller was considered 70 °C, as indicated by the manufacturer. The condenser of the absorption chiller operates with water.

The cold water circulation pumps for each load are controlled by a timer and a temperature controller. Thus, the chiller operation only occurs in certain times, as shown in Tab. 1 when the temperature of cold water in the thermal reservoir is lower than the temperature required for consumption.

First of all, simulations using the model A were held (Fig. 2) to verify the influence of some parameters on the overall system performance, considering the consumption of cold room, dining room and bedrooms of the lodging. This model was called Model A1.

The relationship between the annual energy produced by the field of solar collectors and mass flow rate of working fluid by unit area is shown in Fig. 6, for the two types of solar collectors. The energy produced increases with the mass flow rate and for evacuated tubes collector is significantly higher than for flat plate collector.

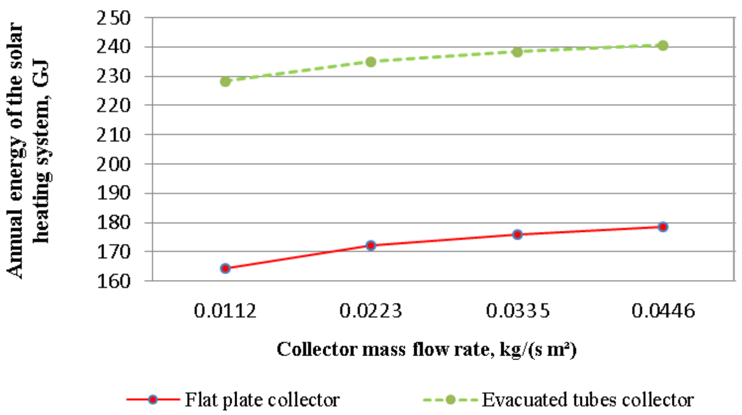

Figure 6. Influence of mass flow rate on the annual energy produced by solar system – Model A1.

However, with the increase of the mass flow rate the average temperature of thermal reservoir decreases, as can be seen in Fig. 7, affecting the performance of the absorption refrigeration system.

The fraction of the annual cooling load supplied by the solar absorption refrigeration system is shown in Fig. 8 for each individual thermal load. The results are quite sensitive with respect to hot water temperature. Comparing Figs. 7 and 8, as the temperature decreases with increasing mass flow rate, the amount of cold water produced by the chiller also decreases, and thus, the annual fraction of the assisted thermal load decreases.

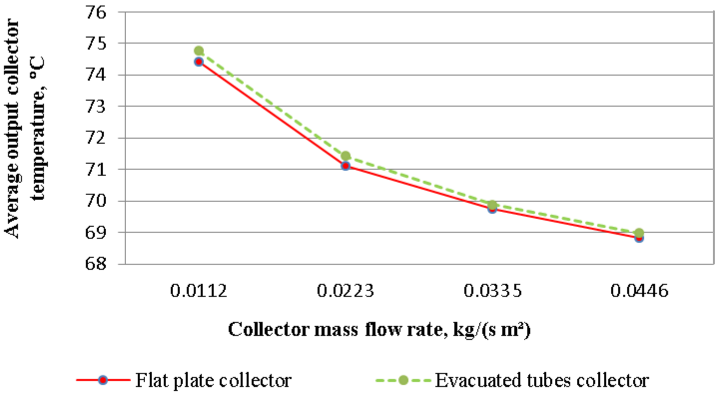

Figure 7. Average water temperature versus mass flow rate – Model A1.

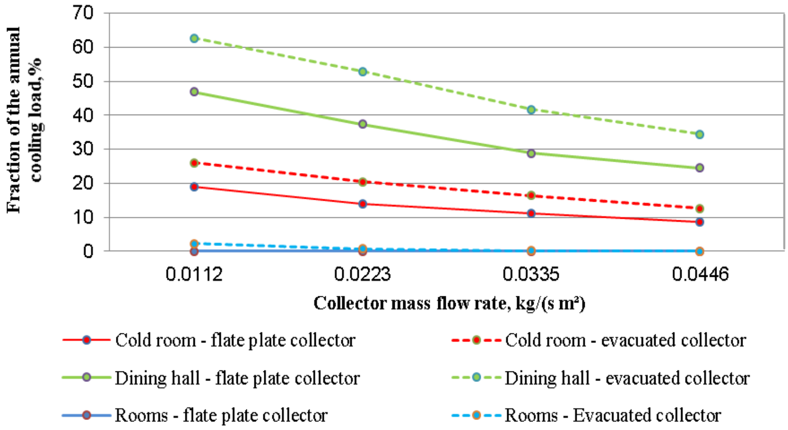

Figure 8. Influence of mass flow rate on the annual fraction of the assisted thermal load – Model A1.

The influence of the hot water tank volume, ranging between 1 to 10 m^3, in the fraction of the annual cooling load was not observed. However, the variation of the cold water reservoir volume affects significantly, as can be seen in Fig. 9.

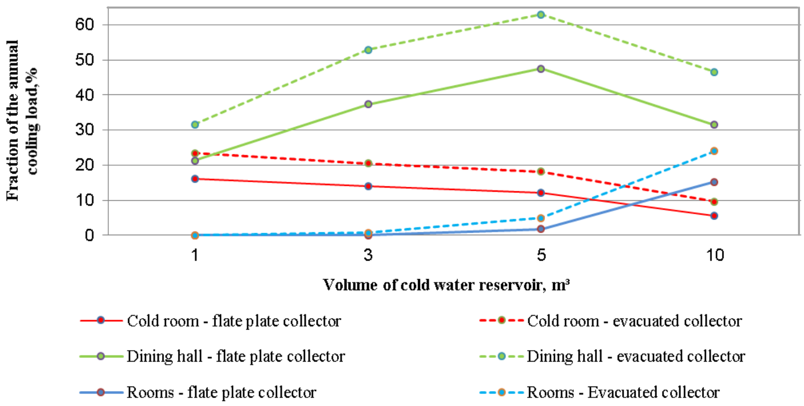

Figure 9. Annual fraction of the assisted thermal load versus cold water reservoir volume – Model A1.

The influence of collector's field area in the annual production of thermal energy can be seen in Fig. 10, for a water mass flow rate of 0.0112 kg/(sm²). Energy production grows linearly to approximately 120 m². From this value, the energy production rises more sharply. It is observed that the system behavior with both models of collectors is similar. The heating system using evacuated tube collector produces about 40% more energy than the system with flat plate collector, regardless of the area. The increase in the solar collector area also increases the annual fraction of assisted thermal load, as can be seen in Fig. 11. However, the fraction to the bedrooms is extremely low and two factors motivate this behavior. Firstly, the thermal loads are high and secondly the time for use is overnight, as shown in Tab. 1. At this time, the temperature of the water in the cold storage tank is not low enough to meet the thermal load of the rooms and the chiller has no hot water at the activation temperature to continue operating.

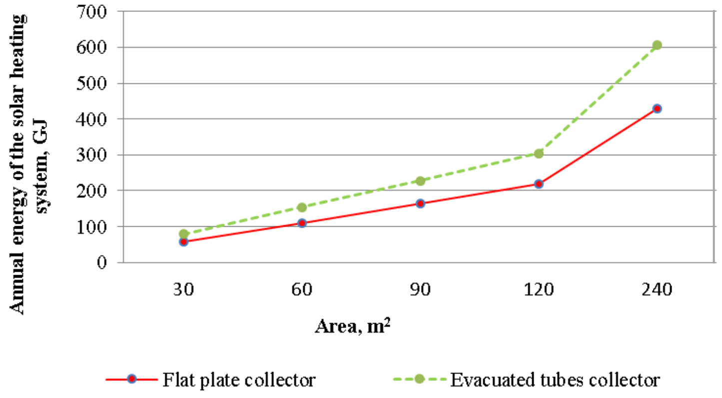

Figure 10. Annual energy produced by solar system with solar collector area – Model A1.

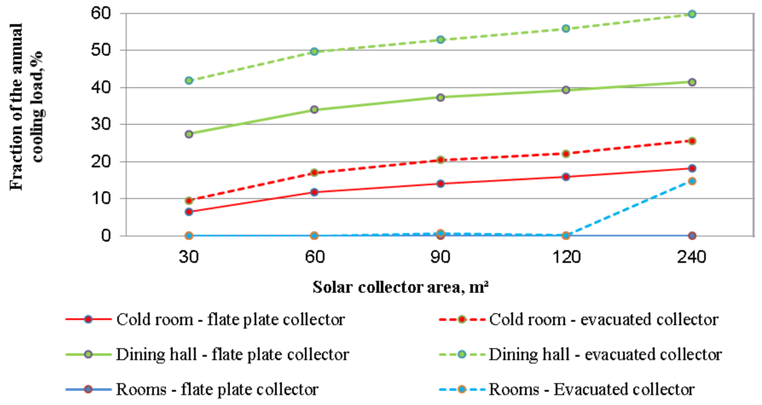

Figure 11. Fraction of annual cooling load with solar collector area – Model A1.

For the condition of nominal operation, mass flow rate and temperature ranging between 80 and 90 °C, the chiller hourly capacity is 0.13 GJ and the COP is about 0.7. Operating in partial load condition for most of the time and considering a minimum activation temperature of 70 °C, the chiller average COP is around 0.22. To meet the annual cooling load, the energy required for its operation will be about 696 GJ. To produce this thermal energy, the collector field would require an area greater than 240 m^2. Furthermore, the cold water average temperature to meet the use of the refrigerated chamber is greater than 8°C, preventing its use for storage and food preservation. Thus, use of the absorption system to meet this thermal load is disregarded in other simulations.

Considering this, it was simulated a new system model, for the heat loads of dining room and bedrooms, this model was named Model A2. Considering that system will be installed near a river location is possible to use the river water to the absorption cooling chiller. For this simulation, the temperature of the river water was considered equal to the local ambient temperature.

For this configuration it was evaluated the variation of collector area on the annual fraction of consumption service. In Fig. 12 is possible to see the behavior of annual assisted cooling load with respecting to solar collector area.

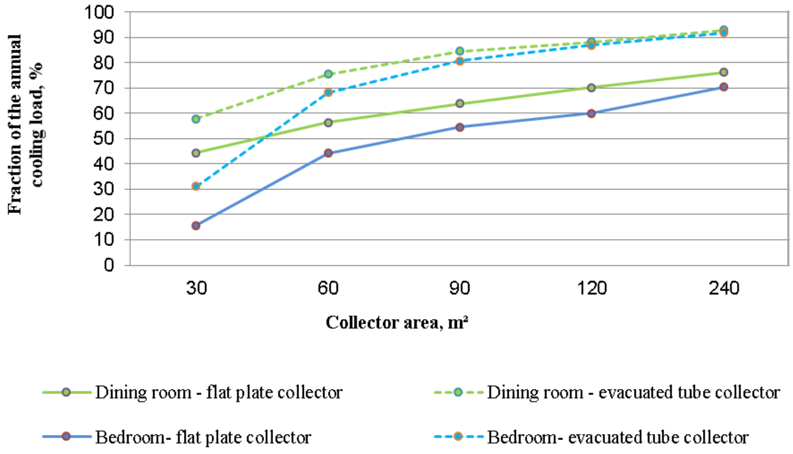

Figure 12. Influence of solar collector area on the annual fraction of the assisted thermal load – Modelo A2.

According to the results of Fig. 12, the consumption for the bedrooms and the dining room had a higher attendance, because the total thermal load is lower. The annual percentage of assisted consumption is higher than 80% with the use of 90 m² of evacuated tube collectors, thus presenting the most satisfactory results. The consumption of this model is related to the air conditioning system of the bedrooms and the dining room, thus annual percentages of attendance lower than 100%, is permitted for use. To define the ideal service percentage should take into account the cost of installation and maintenance of the installed solar thermal collector area.

4.2 Model B: solar collector – thermal reservoir – auxilliary heater – absorption chiller

The Model B, compared to Model A, has an auxiliary heater, according to Fig. 3. The auxiliary heater heat the water stored in the reservoir, if it is below the chiller activation temperature. The system includes temperature controllers and thermostats to manage the use of auxiliary heater. When the operation of the chiller is necessary, the system checks the water temperature in the thermal storage tank. If the temperature is equal or higher than minimum activation chiller temperature of 85 °C, the chiller uses this water. Otherwise, the auxiliary heater comes into operation and supplies water to the chiller, independently of reservoir.

During the use of the auxiliary heater the solar collectors continue heating the water stored in the heat reservoir, whenever irradiation conditions that enable this. The controllers and thermostats verify the temperature at every 20 min, to trigger or off the auxiliary heater.

The purpose of simulation this model is to determine the amount of auxiliary power required, allowing comparison of this model with the model without auxiliary heating. For the simulations of this model were considered only the bedrooms and the dining room consumptions, and the same parameters of the Model A2 were used, with the mass flow rate of 0.0112 kg/(sm²) and the cooling water temperature equal to local room temperature.

It was verified the influence of thermal reservoir volume of hot water, from 1 to 10 m³, on the annual energy supplied by the auxiliary heater for water. The lower auxiliary power consumption occurs with the use of 1 m³ reservoir, because with this lower volume is possible to reach higher temperatures. With the increase of the thermal reservoir volume of cold water the amount of energy supplied by the auxiliary heater also increases. The lower power supply occurs with the use of a reservoir of 2 m³, and solar collector with evacuated tube.

The influence of the thermal solar collector area on the annual amount of energy supplied by the auxiliary heater was verified, using the parameters already described and the volume reduced of thermal reservoir, the results are shown in Fig. 13.

The results in Fig. 13 show that the amount of energy provided by the auxiliary heater decreases with increasing thermal solar collector area. The variation of energy is not proportional to the collector area, and the area more significantly affects for solar collectors of evacuated tube. According to simulation results, the consumption of dining room and bedrooms is 100% assisted, for all simulated conditions.

4.3 Model C: chiller cooling – hot water for showers

Model C is the Model B with a condenser cooling water reuse system, as shown in Fig. 4. The system recycles the hot water used for cooling the chiller, mixing with hot water stored in the hot water thermal reservoir to use in the showers of the rooms.

In the simulation of this model were adopted the same parameters of Model B, and it was verified the influence of solar collector area, in the required amount of annual auxiliary energy, and it was not observed significant variations.

Comparing the Model B and C for the auxiliary energy required and the percentage of consumption serviced, it turns out that the reuse of cooling water does not affect the auxiliary energy consumption. The volume of hot water consumed from the thermal reservoir in the mixture was small in relation to the volume consumed by the chiller, since the cooling water outlet temperature of the condenser is near the consumption temperature of the water bath.

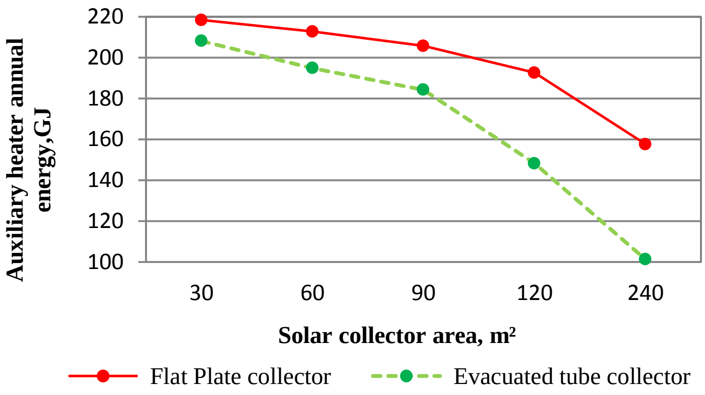

Figure 13. Influence of solar thermal collector area in the amount of annual energy provided by the auxiliary heater - Model B

5. CONCLUSIONS

Simulations of system model A, consisting of solar collector, thermal reservoirs and an absorption chiller, were divided into two sub models according to consumption: Model A1 (cold room, dining room and bedrooms) and A2 model (dining room and bedrooms). In the model A1, it was observed that the only parameter that could be modified, resulting in up to 25% of consumption service, it would reduce the mass flow rate of water in the solar collector from 0.0223 to 0.0112 kg / (m^2s). Rates of up to 26% were obtained in relation to meeting the consumption of cold room.

Moreover, the model A1 it was unable to meet the thermal load, based on the average chilled water temperature that was above 8 °C. Consumption of the rooms was also underserved due to the overnight consumption profile established for simulations. In the A2 model, the simulation disregarded the cold room, and using area of 90 m^2 for evacuated tube collector, 84.5% of dining room consumption and 80.7% of bedrooms were attended.

The system model B, modified the system previously simulated adding an auxiliary water heater. It was observed that for volumes of thermal reservoirs of hot and cold water, 1 to 2 m^3, respectively, and with the use of solar collector with evacuated tubes the annual auxiliary energy consumption was about 185 GJ.

In model C was analyzed the influence of cooling water reuse for use in showers. Comparing the results of auxiliary energy consumption of the model C to B, it turns out that the reuse of water does not affect the auxiliary energy consumption, so the cooling water of condenser can be reused.

5. ACKNOWLEDGEMENTS

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