SIMULATION AND OPTIMIZATION OF A SOLAR DRIVEN AIR CONDITIONING SYSTEM FOR A HOUSE IN CHILE

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Abstract

The increase of the cost of electrical energy generation and the increase in the environmental restrictions have strengthened in the scientific field the investigation of air conditioning and refrigeration systems that use solar resource as motive energy. Nevertheless, in Chile, the solar energy is mainly used for applications of solar domestic hot water and production of electrical energy in rural areas , not having until now the solar cooling, a favorable scene of investigation.
Within the heat assisted technologies, there are so called absorption cooling systems, which base their operation in the production of cold supplying hot water from solar collectors.
The main objective of this work is to develop a computational model that allows the simulation of an hourly basis for an absorption refrigeration system assisted by solar energy and natural gas as auxiliary fuel. This model will be developed using the dynamic simulation program TRNSYS, considering three specifics areas of work: determination of the thermal load for a building survey in the central region of our country; implementation of the computational model for the absorption refrigeration system and finally the parametric optimization of components, which will make possible an approach to optimal sizing of the solar absorption system.
The results of the optimization process of the absorption refrigeration system assisted by solar energy, indicate that an area of 110 m^2 of flat plate collectors with an inclination of 33° and 7 m^3 storage tank provides an annual solar fraction of 70%, getting to cover the demand of air conditioning in a house of 149 m^2 located in Santiago, maximizing the gain of useful energy of the system and minimizing the consumption of auxiliary energy.

1. INTRODUCTION

In general, on residential and commercial applications, the demand for refrigeration and air conditioning is covered by conventional energy, which causes a considerable overload in the electric grid distribution. In Chile, during spring and summer seasons, the use of conventional air conditioning equipment is increasing significantly and in the office sector could be between 30% and 60% of total energy consumption. To this, we can add that the demand for such equipment in Chile has had an important growth in the recent years: between 1997 and 2007, nearly 240,000 equipment, were imported. However, nowadays there are cold production technologies driven by thermal sources of heat supply at low temperatures such as the solar energy. Since most, of the air conditioning demand in Chile occurs in central and northern regions of the country, consumption is associated with a high availability of irradiation, which offers an optimal scenario for the application of solar refrigeration.

The absorption refrigeration system based its principle on the affinity that some substances when get in contact, one absorbs the other. Thus, two pairs of substances are commonly used in these types of facilities: water-lithium bromide (LiBr-H_2O) and ammonia-water, where the first one is mainly used for solar assisted applications due to the non-toxic and non-flammable water's properties as refrigerant.

The incorporation of solar energy to the cold production is not new, since its early history dates back over a century. Furthermore, the investigation of these systems has been developed on two fronts: experimental facilities studies and computer simulation. To date, there are only in Europe 54 installations of solar air conditioning in operation, of which 33 of them are using the technology of lithium bromide-water absorption chiller (Balaras *et al*., 2007). In Puerto Rico, (Meza *et al*., 1998) describes an experimental facility consisting of an absorption chiller of 35 kW (10 TR), driven by an array of 113 m^2 of flat plate collector selective surface, a storage tank of 5.7 m^3 and a cooling tower of 84 kW capacity. The efficiency of the collector array was 30.5%; the nominal cooling capacity was measured at 25 kW with a COP of 0.63. Best y Ortega (1999), summarized the results of a solar cooling project in Mexico. The system includes 316 m^2 of flat plate solar collector, 30 m^3 in storage tank, an absorption chiller with Lithium Bromide-Water with a maximum capacity of 90 kW and a cooling tower of 200 kW. The system achieved an annual solar fraction of 75%, COP values between 0.53 and 0.73 when the hot water was supplied to the chiller at temperatures between 75 and 95°C, cooling water temperatures of 29-32°C and cold water temperatures between 8 and 10°C. Syed *et al.,* (2005), shows a system for a typical house in Madrid (Spain) operating with 49 m^2 of flat plate collectors, 2 m^3 of thermal reservoir and an absorption chiller type LiBr-H_2O of 35 kW capacity. Since the solar system was originally designed for 10 kW cooling capacity, the absorption chiller yielded the maximum cooling capacity of only 7.5 kW, and daily and period average COP were 0.42 and 0.34, respectively. Zambrano *et al*., (2007), presented results of a solar absorption system of 35 kW cooling capacity, installed in the city of Seville (Spain). The installation consists of 151 m^2 of flat plate collectors, a storage tank of 2.5 m^3 and an auxiliary gas heating system. All the installations mentioned above, use flat plate solar collectors. However, solar absorption refrigeration facilities, which use evacuated tube solar collectors, can also be found. In Pongtornkulpanich *et al*., (2007), was designed and installed a solar absorption system with a capacity of 35 kW. The system consists of 72 m^2 evacuated tube collectors and a volume of 0.4 m^3 for the storage tank, which produces an annual solar fraction of 81% for Thailand. Ahmed *et al*., (2008), presents the performance evaluation of real integrated installation of refrigeration. This facility is in operation since 2002, in Oberhausen, Germany (latitude 51°, north). The space includes a floor of 270 m^2, for which the system is designed with an absorption chiller Lithium Bromide-Water with 35 kW capacity, 108 m^2 of solar collection area of evacuated tube collectors with an inclination of 32° and storage tanks of 6.8 m^3 for hot water and 1.5 m^3 for cold water.

In relation to the contributions made in the area of simulation the study in K4RES-H. (2006), mentions that one of the recommendations to bring down one of the main barriers to the penetration of solar absorption refrigeration in the market (the high initial cost) is to develop new models and tools for dynamic simulation of these systems, which will allow to do an optimum sizing of the system, long-term performance studies and economic feasibility analysis of projects. Assilzadeh *et al*. (2005) developed a *TRNSYS* simulation model of a solar assisted absorption refrigeration system for Malaysia. The estimated cooling load of the building studied in that work is 3.5 kW, which is covered with an absorption chiller of simple effect, with mixture of Lithium Bromide and Water, 1 TR capacity. The arrangement of collectors for this system is with evacuated tubes, which after a process of parametric optimization gives an optimum of 35 m^2. The optimum inclination for the same arrangement has been determined at 20°. As the volume of the reservoir, the development of the model concludes it should have a capacity of 0.8 m^3. Florides *et al*. (2002), presents a *TRNSYS* model that allows the parametric optimization of a LiBr-H_2O solar assisted absorption system for the city of Nicosia (Cyprus). The final optimized system consists of a 0.6 m^3 tank and a hot water set-point of 87°C, an array of parabolic collector, 30° tilted and an optimal area of 15 m^2 which was obtained through an economic analysis. Sridhar (2002), also built a *TRNSYS* model that allows the parametric optimization of a solar assisted absorption refrigeration system with a capacity of 100 kW (*Yazaki* WFC-30). It is obtained for the city of Hyderabad (India) and a commercial building of 650 m^2, an optimum value of 500 m^2 of flat plate collectors 30° tilted, 6 m^3 volume reservoir and set point of hot and cold water of de 80°C and 15°C, respectively.

The main objective of this paper is to develop a computational model that allows performing the simulation of an hourly basis for an absorption refrigeration system assisted by solar energy using the *TRNSYS* software, considering as study region the city of Santiago. It is pretended the simulation allows determining the proper sizing of system components and parameters, in the search for its optimization and the minimization of the auxiliary energy required.

2. SYSTEM DESCRIPTION

Figure 1 shows the schematic diagram of an absorption refrigeration system of simple effect assisted by solar energy and natural gas, which has been the basic concept used in most research on this topic. Its main components are: flat plate solar collectors, a hot water storage tank, the absorption chiller, a cooling tower and an auxiliary heater. The operation of this system begins storing on a thermal reservoir of water the energy received by the solar collectors. Then, the hot water accumulated in the tank is supplied to the generator of the absorption chiller to produce the separation between the absorbent and the refrigerant which is achieved through an endothermic process mixing Lithium Bromide and water. The generator of absorption chiller requires a minimum inlet temperature of hot water to avoid the crystallization phenomenon. When solar energy is not able to raise the water temperature up to that point, the auxiliary heater provides the energy deficit for the correct operation of the chiller. After that, the refrigerant (water) evaporates and passes directly to the condenser, leaving in the generator a strong solution of absorbent, which is deposited then in the absorber.

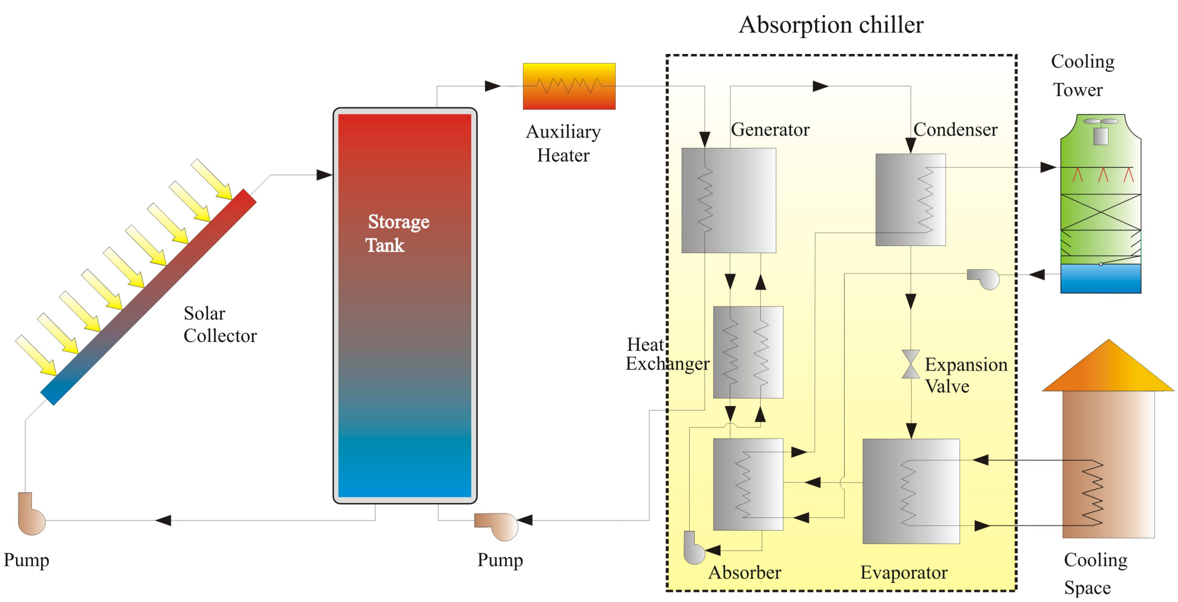

Figure 1. Absorption refrigeration system assisted by solar energy and natural gas.

In the condenser, the refrigerant vapour is cooled down by the addition of cooling water coils that comes from a cooling tower outside the system and then deposited in the evaporator, passing through an expansion valve to lower its temperature further. Once in the evaporator, the refrigerant evaporates at very low temperatures because the device is close to vacuum pressure, extracting heat from an external liquid circuit in order to produce air conditioning. In the absorber, due to the enormous affinity absorbent-refrigerant, the strong solution of absorbent attracts the refrigerant vapour from the evaporator, turning back into a weak solution, which is then pumped to the generator to start the cycle again.

In particular, the absorption refrigeration system works with four main circuits: a circuit of solar collection, which is responsible for absorbing solar energy through a working fluid which is then stored in a thermal reservoir; a circuit to supply the absorption chiller, which is the heart of the system and, thanks to the energy contained in the water reservoir produces chemical reactions necessary for the production of cold water; a cooling water circuit, which is necessary to dissipate the energy of the absorption and condensation process that occur inside the chiller, and finally a charging circuit that delivers the required cooling demand for the production of air conditioning.

3. DESCRIPTION OF THE COMPUTATIONAL SIMULATION

To perform the dynamic simulation of an installation of solar assisted absorption refrigeration should be considered some basic issues. The first one refers to the type of meteorological information and solar irradiation available for the area under study.

Climatic database and solar irradiation

If required to estimate the thermal performance at the system in the long term, it is suggested to have a database for a Typical Meteorological Year (TMY) in the locality under study. In this work, the climate database was built using the information provided by the Meteorological Direction of Chile and the software *Meteonorm* (Remund *et al*., 2004). In the figure 2, the data from monthly average daily radiation values on the horizontal surface and the ambient temperature are shown graphically.

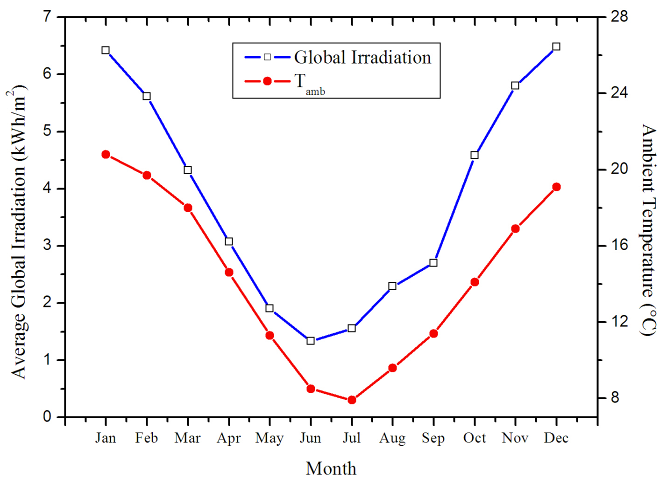

Figure 2. Monthly average daily radiation and ambient temperature for Santiago (33,4°, S).

Modelling of air conditioning demand

The building under study is located in the surroundings of the Santiago city. It is a summer dwelling with a 149 m^2 area and consists of three bedrooms, two bathrooms, a living room, a dining room and a hall, which contains a lounge area and an office, as shown in figure 3. For a proper determination of the refrigeration loads in the building under study, it is a vital requirement an appropriate consideration of the load components in the space will be conditioned, (Dorota, 2008). For this, results imperative to consider the following parameters: the building orientation, its dimensions and materials, besides the configuration of doors and windows contribute mainly to determine the amount of energy that enters or leave in an external way to the building (external loads).

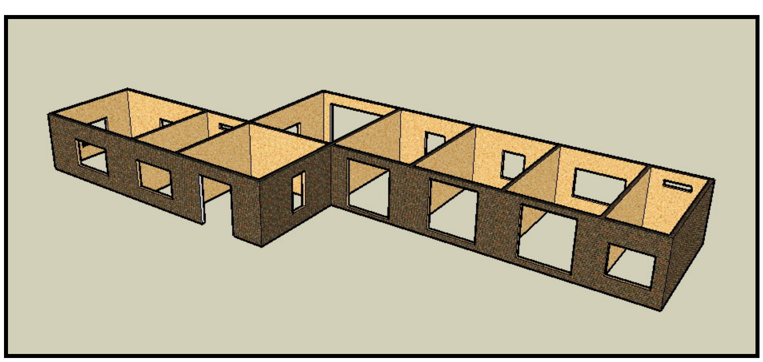

Figure 3. Building model.

Furthermore, the number of occupants and their activities, the lighting and the appliances also contribute energy to the site in an internal way (internal loads). Thus, a thermal balance on the site will determine the amount of energy that needs to be removing hourly in order to maintain the comfort conditions inside the building. The parameters above are included in the component *Type* 56 of *TRNSYS* (Klein *et al.*, 2007), for multi-zone thermal projects, through a graphical interface called *TRNBuild*, which facilitates the entry of them. *TRNBuild* allows providing results for the distribution of air temperature inside each of the zones (with and without air conditioning) on the analysis period described, besides the air conditioning load required to reduce the indoor air temperature until the conditions of the comfort temperatures defined in the model.

Construction of the solar absorption system model using TRNSYS

To perform and know the operational performance of the solar refrigeration system was used *TRNSYS* 16. This simulation program has a modular structure that divides the system into a series of components (types) that are interconnected with each other and compiled through the interface *TRNSYS* Studio. Each component is modelled using mathematical equations programmed in *FORTRAN*. Consequently, if a system component is not included in the *TRNSYS* library, the physical model can be programmed in *FORTRAN*, *MATLAB*, C++ or *EES*. A description of the mathematical models used in each component can be found in *TRNSYS* (Klein *et al.*, 2007).

The absorption system at its original size consists of:

a) 130 m^2 solar collector area of flat plate collectors. They are oriented 35° towards the geographic north and land Ecuador. For the development of modelling are used two collectors of different quality: the collector Type I, with parameters of the efficiency curve: $F_R\ U_L$ = 3 W/ m^2 K, $F_R(\tau\alpha)_n$ = 0.74 . And the collector Type II, with efficiency parameters: $F_R\ U_L$ = 3.33 W/ m^2 K, $F_R(\tau\alpha)_n$ = 0.72, both with incidence angle modifier 0.2.
b) 6 m^3 thermal reservoir, with a cylindrical shape and a height of 2 m.
c) A circulation pump with a maximum flow capacity of the dependent variable solar collector area and testing flow of the collector as recommended by the manufacturer, which has a value of 50 kg/hr m^2.
d) A controller ON-OFF acting on the pump to control the on-off circuit. It has a high cutting temperature, which is activated if the inlet collector temperature is greater than 98°C. Were considered 2°C and 0.15°C as values of upper dead band and lower dead band, respectively.
e) A pressure relief valve, which acts above temperatures of 98°C.
f) An absorption chiller, single effect, trademark *YAZAKY*, model WFC-SC10 employing LiBr-H_2O solution as working fluid and it is energized by a flow of hot water between 75 and 105°C. It has a nominal capacity of 35 kW, and a nominal COP equal to 0.7, which is sufficient for the load requirements of the system.
g) An auxiliary heater with natural gas as fuel, which has a maximum capacity of 125 kW, with an average efficiency of 85% and a setting temperature of 80°C to supply the energy deficit.

Each component is represented by a constant number of parameters, input and output data dependents of the simulation time. One output data of a component can be used as input data to another (or others) component(s). The final system is assembled by connecting all inputs and outputs in an appropriate manner to simulate the real solar absorption system. Finally, it is done the construction of the model that will be used to simulate the solar absorption system. The resulting model with the main *TRNSYS* components and all the interconnections of the system are shown in Figure 4.

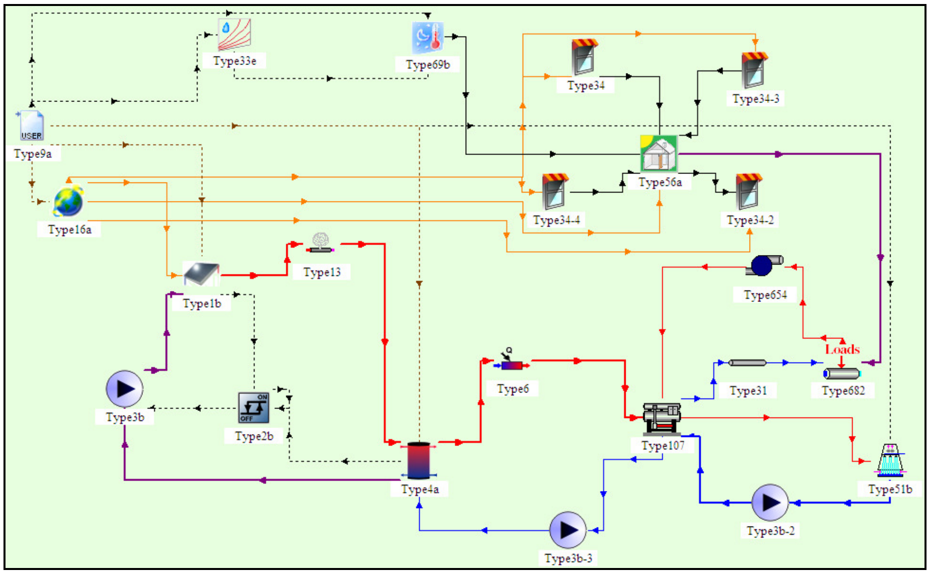

Figure 4. TRNSYS model of the solar absorption refrigeration system.

4. ANALYSIS AND DISCUSSION OF RESULTS

The case study considered in this work corresponds to a solar absorption refrigeration system serving a demand for air conditioning under the climate of the city of Santiago. From the simulation done with the *TrnBuild* (Type 56) of *TRNSYS* to determine the demand for air conditioning in the house under study, we obtained results that indicate that this demand starts from August to April, with critical periods for the months of December and January in which occurs the maximum load of 23 kW (6.55 TR).
It should be remembered that the parametric optimization process is aimed at finding a proper sizing of components and operational conditions of the system (Vidal and Colle, 2006), beginning with an initial size of it, which has been defined based on actual facilities and research found in literature.
Multiple simulations are performed with *TRNSYS* model to evaluate the most relevant factors that make possible an idea of the optimal size of solar absorption refrigeration system and analyze the effects of key variables that influence its performance. Among the factors investigated are the effect of the area, slope and type of solar collector, thermal reservoir volume, the gain of useful heat and consumption of auxiliary energy (thermostat setting of the auxiliary heater).

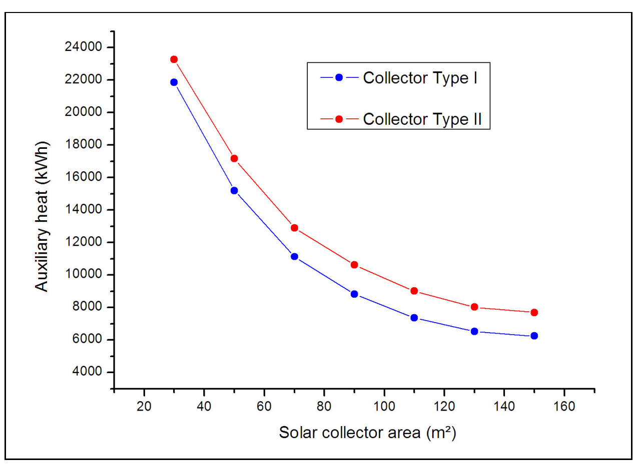

Figure 5. Effect of the collector area on the auxiliary heat of the system.

Initially, as shown in figure 5, the influence of solar collection area and the type of solar collector on the auxiliary energy of the system will be analyzed. The range of analysis included for the collection area variable covers from 30 m^2 to 150 m^2, with variations of 20 m^2 and its observed that an increase in the collection area leads to a decrease in the solar energy requirements on the auxiliary heater. The effect is amplified when using a solar collector of higher performance. However, the process of optimizing the solar collection area requires a thermo economic analysis, which is the reason this factor is discussed in more detail later.

The influence of the collector area on the solar fraction of the solar system is shown in Figure 6, in which it is observed that an increase in the collector area increases the value of the annual solar fraction, an effect that also increases if in the simulation is considered a collector with higher efficiency.

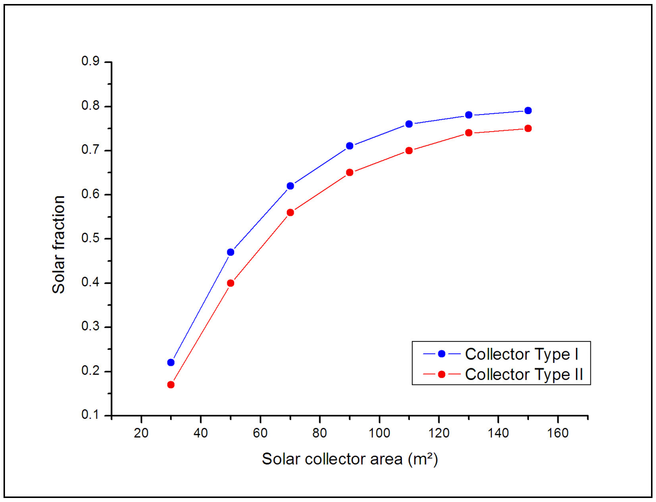

Figure 6. Effect of the collector area on the solar fraction of the system.

The gain of useful heat in the solar collector for different volumes of reservoir is shown in Figure 7. This shows that progressive increases in the size of the tank results in slight increases in the gain of useful energy collector, which is positive but that does not allow optimization of the storage tank.

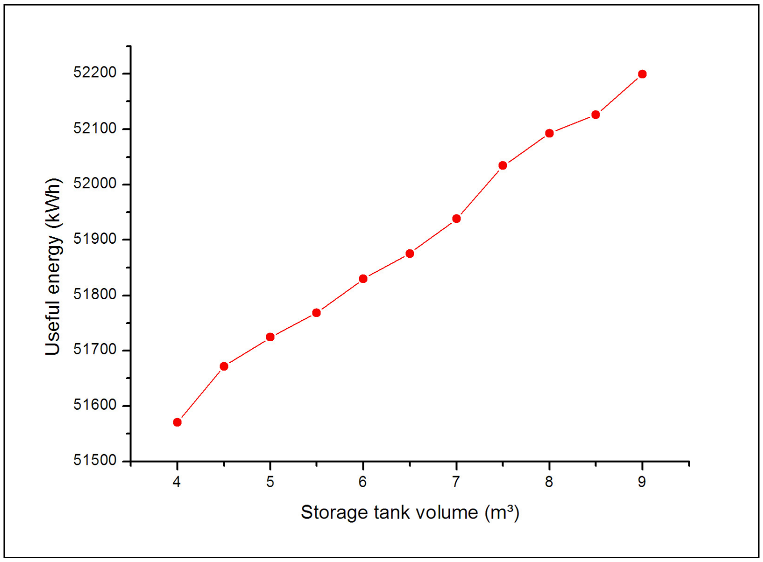

Figure 7. Effect of the reservoir size on the useful heat of the collector.

Because of this, it is chosen to investigate the effect of the volume size of the storage tank on the consumption of auxiliary energy of the system. The results of this simulation are shown in Figure 8, where we can see that the auxiliary energy used reaches a minimum value for a reservoir volume of 7 m^3.

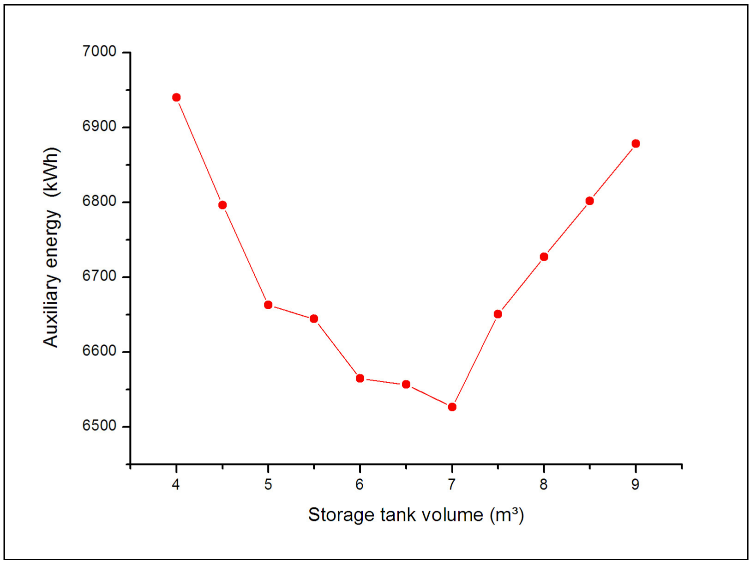

Figure 8. Effect of tank volume on the consumption of auxiliary energy for the system.

Another parameter that affects system performance is the angle of inclination of the collecting surface with respect to the horizontal. In figure 9, it is shown the influence of the inclination of the collector plate on the useful energy gain of the system, which is maximized for an angle of 33°.

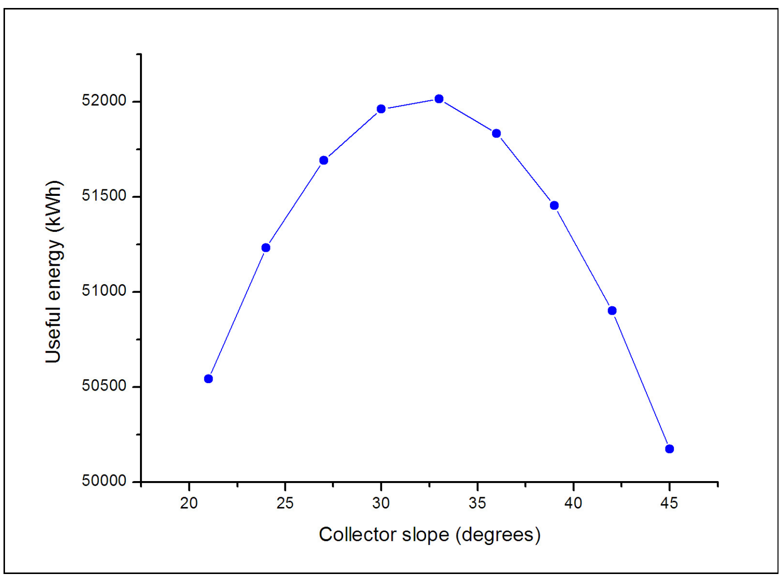

Figure 9. Effect of the inclination angle of the collector on the useful energy of the system.

As mentioned earlier, the optimization of solar collector area requires a thermo economic analysis that will be done using the methodology LCS (*Life Cycle Savings*), combined with the P_1-P_2 method (Duffie y Beckman, 1991). The economic functional that represents the gains obtained during the life cycle of the solar refrigeration system, can be found in (Colle and Vidal, 2004). The results of this economic optimization are shown in Figure 10.

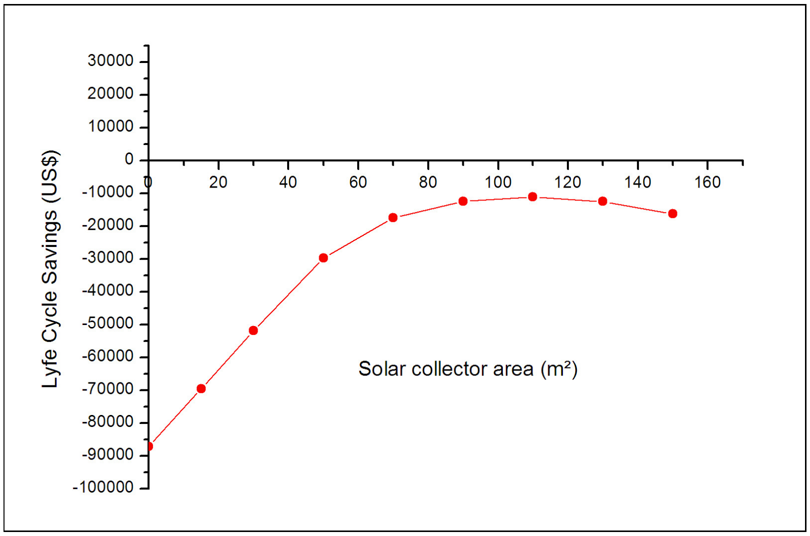

Figure 10 Solar collector area versus LCS in dollars.

It can be seen that the economic functional LCS, reaches a maximum value for an optimum solar collector area of 110 m^2. However, we see that the optimal solution is found for a negative value of LCS, which is mainly due to the low cost of electricity in Chile, which at the time of this study was 0.22 US$/kWh.

5. CONCLUSIONS AND RECOMMENDATIONS

The main objective of this study was to simulate an absorption refrigeration system assisted by solar energy and natural gas, through a computer model that allows doing a parametric optimization process in order to search the proper sizing of the system. This objective was successfully achieved, since the model was not only possible to size some design parameters, but also gives the future possibility to simulate new sizes and configurations.

In the modelling of the demand for air conditioning was used the *TRNBuild* module of *TRNSYS*, which allows to simulate in a dynamic way the air conditioning requirements for the building, rather than simple recognize certain patterns of load profiles with simplifying assumptions found in literature.

The results of the parametric optimization of an absorption refrigeration system assisted by solar energy, indicate that with an area of 110 m^2 of flat plate collectors with an inclination of 33° and 7 m^3 of storage tank is achieved to cover the demand of air conditioning of a dwelling of 149 m^2 located in Santiago, maximizing the gain of useful energy of the system and minimizing the consumption of auxiliary energy. Based on these results, it is obtained an annually average solar fraction of 70%, for the solar absorption system proposed.

Finally, the model developed can be used in future works to perform a thermo economic optimization of the system, which will allow evaluating the performance and economic viability of the system on a long term. Additionally, different alternatives to those considered in this investigation can be evaluated, for example: different sizes of absorption chiller, variable flow pumps, different climates, especially in cities of northern Chile.

6. ACKNOWLEDGMENTS

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7. REFERENCES

Ahmed H., Noeres, P., Pollerberg, C. (2008) "Performance assessment of an integrated free cooling and solar powered single-effect lithium bromide-water absorption chiller." *Solar Energy, Vol. 82, 11,* 1021-1030.

Assilzadeh, F., Kalogirou, S.A., Ali, Y., Sopian, K. (2005) "Simulation and optimization of a LiBr solar absorption cooling system with evacuated tube collectors." *Renewable Energy 30,* 1143-1159.

Balaras, C.A., Grossman, G., Henning, H.M., Ferreira, C.A.I., Podesse, E., Wang, L., Wiemken, E. (2007) "Solar air conditioning in Europe – An overview." *Renewable and Sustainable Energy Reviews 11,* 299-314.

Best, R., Ortega, N. (1999) "Solar refrigeration and cooling." *Renewable Energy 16,* 685-690.

Colle, S., Vidal, G.H. (2004) "Upper Bounds for Thermally Driven Cooling Cycles Optimization Derived from the f-$\bar{\phi}$ Chart Method." *Solar Energy 76,* 125-133.

Dorota A. Chwieduk. (2008). "Some aspects of modelling the energy balance of a room in regard to the impact of solar energy." *Solar Energy 82,* 870-884.

Duffie, J.A., Beckman, W.A. (1991) *Solar Engineering of Thermal Processes*, 2nd Edition, John Wiley, New York.

Florides,G.A., Kalogirou, S.A., Tassou, S.A., Wrobel, L.C. (2002) "Modelling and simulation of an absorption solar cooling system for Cyprus." *Solar Energy 72,* 43- 51.

K4RES-H. (2006) "Solar Assisted Cooling-State of the Art, Key Issues for Renewable Heat in Europe, Solar Assisted Cooling-WP3" *Task 3.5, Contract EIE/04/204/S07.38607*, 21p.

Klein, S. A., et al. (2007) *TRNSYS 16 – Reference Manual 15*, Ed. Madison; Solar Energy Laboratory, University of Wisconsin, Madison, USA.

Meza, J.I., González, J.E., Khan, A.Y. (1998) "Experimental assessment of a solar assisted air conditioning system for applications in Puerto Rico." *In: ASME Proceedings of the Solar Energy Division 8,* 149-154.

Pongtornkulpanich, A., Thepa, S., Amornkitbamrung, M., Butcher, C. (2008) "Experience with fully operacional solar-driven 10-ton LiBr/H_2O single-effect absorption cooling system in Thailand." *Renewable Energy 33,* 943 - 949.

Remund, J., Kunz, S. (2004) *Meteonorm (V5.1)- Global meteorological database for applied climatology*, Switzerland.

Sridhar, G. (2002) "Simulation of a solar cooling system for hot climate" *Master Thesis*, European Solar Engineering School, Dalarna.

Syed, A., Izquierdo, M., Rodríguez, P., Maidment, G., Missenden, J., Lecuona, A., Tozer, R. (2005) "A novel experimental investigation of a solar cooling system in Madrid." *International Journal of Refrigeration 28,* 859-871.

Vidal, G.H., Colle, S. (2006) "Modeling and hourly simulation of a solar ejector cooling system." *Applied Thermal Engineering 26,* 663-672.