EXPERIMENTAL ANALYSIS OF THERMAL STORAGE TANK CONFIGURATION IN A SOLAR COOLING INSTALLATION WITH AN ABSORPTION CHILLER.

R. Salgado[(1)], P. Rodríguez [(1)]*, M. Venegas[(1)], M. Izquierdo[(2)], A. Lecuona[(1)]

[(1)]Universidad Carlos III de Madrid (UC3M) Departamento de Ingeniería Térmica y de Fluidos Avda. Universidad 30, 28911 Leganés, Madrid, Spain
[(2)]Instituto C. C. Eduardo Torroja (CSIC) C/ Serrano Galvache s/nº, 28033 Madrid, Spain
Unidad Asociada de Investigación en Energía y Medioambiente UC3M-CSIC
* Corresponding author: Phone: +34 91 6249406 Fax: +34 91 624 9430 E-mail: **rsalgado@ing.uc3m.es**

ABSTRACT

There are two basic configurations of a thermal storage tank in a solar cooling facility. These are Stratification and Well-mixed configuration. Experimental results show that for solar cooling applications, having a well-mixed temperature in the thermal storage tank produce more daily cooling energy than in a stratified one, although the solar field efficiency is lower. This gives the facility more autonomy of operation in the afternoon, when the sun goes down and radiation is not enough for the application and there is still a considerably amount of thermal load in Spanish dwellings. Effects on the facility produced by Well-mixed configuration are: efficiency reduction on the solar collector's field, 0,27, higher daily COP's (Coefficient Of Performance of chiller), 0,33 , and extended solar cooling time of about two hours more than in stratified configuration. Using the experimental data, a well mixed storage tank model is tunned. Then is applied as a tool for the accurate determination of optimal equivalent storage capability.

INTRODUCTION

The use of air conditioning systems in Spanish dwellings is gaining popularity, as the installed units grows by 0,8 million per year [1]. The most popular air conditioning system today is the vapor-compression cycle. This kind of system consumes a considerable amount of electric energy as it incorporates a mechanical compressor in its cycle and utilizes refrigerants that can be dangerous to the environment. An option less aggressive for the environment to this kind of equipment can be found in Solar Facilities, configured to produce cold water for air conditioning purposes by means of an absorption chiller. This kind of equipment can be driven by a heat input produced by the solar facility. This machine consumes a very low amount of electric energy and presents great advantages for the environment. Nevertheless, the need of a heat reservoir to operate in the afternoon hours, where solar radiation is not enough to drive the chiller, is indispensable in a solar facility designed to operate under Spanish summer conditions (see as in Figures 4 and 5, a time delay of near 4 hours can be observed between the maximum solar radiation and the maximum ambient temperature). To serve this purpose, a thermal storage tank has to be included in the facility.

In this system, solar radiation is transformed in useful heat by solar collectors and stored in a Thermal Storage Tank (TST) to produce a heat reservoir, enabling the use of the absorption chiller with solar energy during the sunset period. The thermal storage tank will dictate the time of operation autonomy for the installation using solar energy, making this component indispensable. Experimental results show that depending on the configuration of the TST, the installation will have more or less efficiency and operation autonomy after sunset for the production of cold water.

There are two basic configurations of TST in a solar thermal installation: Stratification and Well-mixed. A brief description and evaluation of each configuration applied to solar cooling is presented and discussed.

SOLAR THERMAL FACILITY

The solar facility installed at Universidad Carlos III de Madrid (UC3M) is configured to produce cold water for air conditioning purposes by means of a WFC-10 Yazaki absorption chiller (Figure 1.). The facility consists of 4 main circuits. The Primary circuit consisting of 20 flat-plate solar collectors, each one having 2,5 m^2 collecting surface, making a total collection surface of 50 m^2. The Secondary circuit consisting of the Thermal Storage Tank (TST), having a capacity of 2000 liters. The collector's field and the TST are linked by two heat exchangers. The Tertiary Circuit consisting of the Absorption Chiller (Yazaki WFC10). Finally, the Quaternary circuit consisting of a fan-coil (10 kW) for the desired final output of cold air. Additionally, a cooling tower (not numbered in Figure 1) is included in the system, in order to evacuate waste heat. For a more detailed description of the facility please refer to [2].

Figure 1: Configuration of the Solar Thermal Facility at UC3M. Numbers in the figure refers to the circuits of the facility.

AUTOMATION OF THE FACILITY

The Solar facility has to incorporate an automation system to take a good advantage of it. To design a good control system, some parameters have to be defined first like configuration of the TST and the start-stop sequence of the circuits pumps.

The Well-mixed control system will depend on the homogeneous temperature inside the TST. To not lose operating temperature during the charging time, the pump of the secondary circuit will work when the temperature at the outlet of the collector's field reaches 6 ºC above the temperature of the TST. The generator of the absorption chiller has an operating temperature between 60 - 85 ºC [2][3]. So the TST will begin feeding the generator when it reaches a temperature above 60 ºC. This way the TST will maintain an adequate working temperature during the whole period of the day when cooling load is significant.

CONFIGURATION OF THE THERMAL STORAGE TANK

The TST can adopt practically any configuration. It will depend on the location of the inlet and outlet streams of the hot and cold fluids. Basic configurations and their behavior are presented.

Stratification

The stratification phenomena involve temperature segmentation of the TST. If the hot water is forced to enter at the top of the tank, no convective currents will develop from the temperature difference inside the TST. From the Bousinesq hypothesis, only the density of the thermal fluid will change with temperature fluctuations. As density diminishes with increasing temperature, the hot fluid will stay at the top of the TST while the cold fluid will stay at the bottom, creating temperature segmentation. Heat transfer is mainly done by conduction.

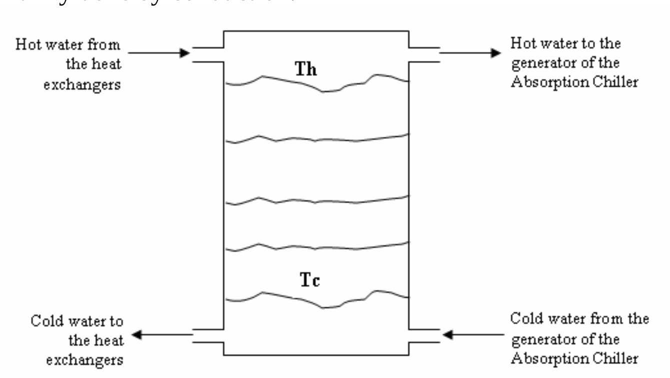

Figure 2: Basic configuration of a stratified TST: Th>Tc.

Well-mixed

In the Well-mixed configuration a relatively equal temperature is achieved along the TST. In this case, the hot water is forced to enter at the bottom of the tank. Convective heat transfer will develop by the stirring of the thermal fluid induced by the inlets of the TST, achieving the well-mixed temperature. Heat transfer is mainly done by convection.

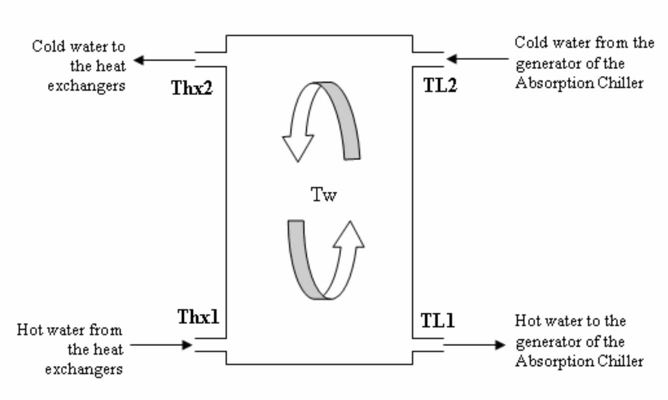

Figure 3: Basic configuration of well-mixed TST.

EXPERIMENTAL RESULTS

The facility was operated under both configurations to compare their behaviors. For July 15, 2004, the facility was working under stratification configuration and for August 26, 2004 under well-mixed configuration.

Solar radiation for each day is presented on Figure 4. As can be appreciated, the solar radiation for July 15 is greater than for August 26. Integrating the curve, solar radiation for July 15 reaches 410,4 kWh/day and for August 26 reaches 366,5 kWh/day.

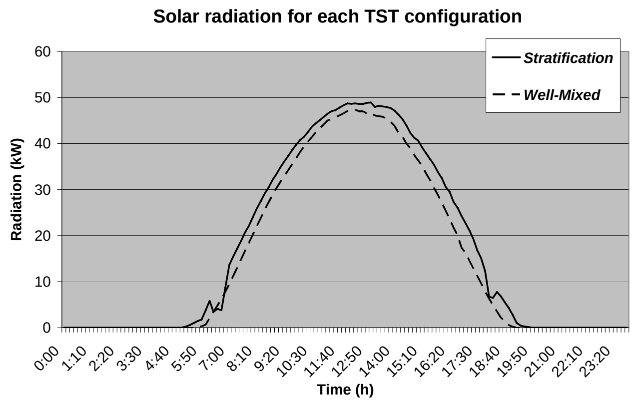

Figure 4: Solar Radiation on the horizontal plane for each configuration.

Ambient temperature and relative humidity can be seen on Figures 5 and 6. It can be appreciated that for central hours when the thermal load reaches its maximum value, ambient temperature and relative humidity for both days are similar.

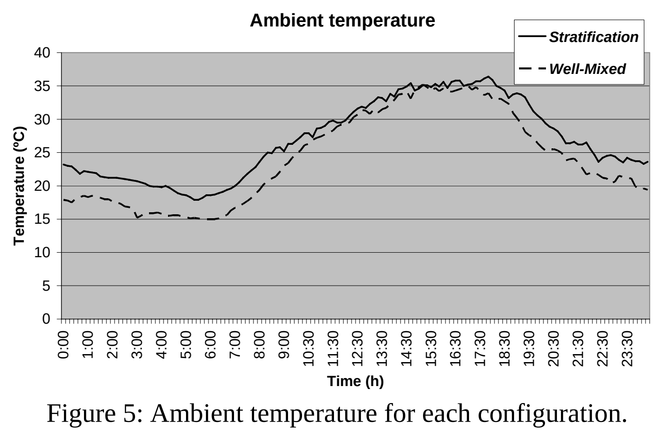

Figure 5: Ambient temperature for each configuration.

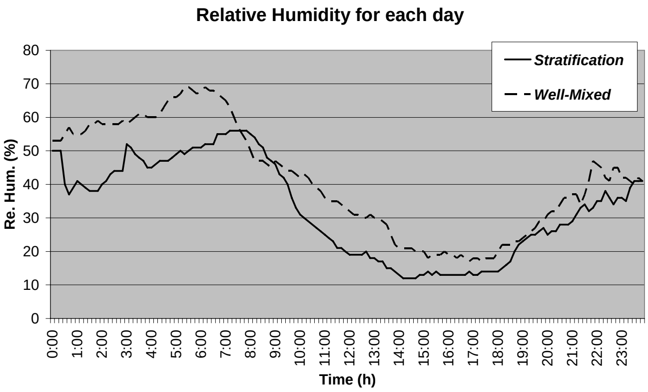

Figure 6: Daily Relative humidity for each configuration.

Looking at the solar radiation, ambient temperature and relative humidity values, an almost equal behavior can be expected for the facility. So changes during the comparison between the days would be induced by the configuration of the TST.

Figure 7 depicts the solar collector's field efficiency for each configuration. In stratification mode the collector's efficiency reaches higher values, 0,35 for the day, because of the temperature entering the collector's field is lower than in well-mixed mode. This causes a lower average temperature inside the collectors, thus smaller losses to the environment. In well-mixed configuration occurs the opposite, having reduced solar collector's field efficiency, 0,27 for the day. Solar Collector's efficiency defined as:

$$\eta_{CO} = \frac{(\dot{m}_{CO})(C_P)(T_{Cout} - T_{Cin})}{Q_{solar}} \qquad (1)$$

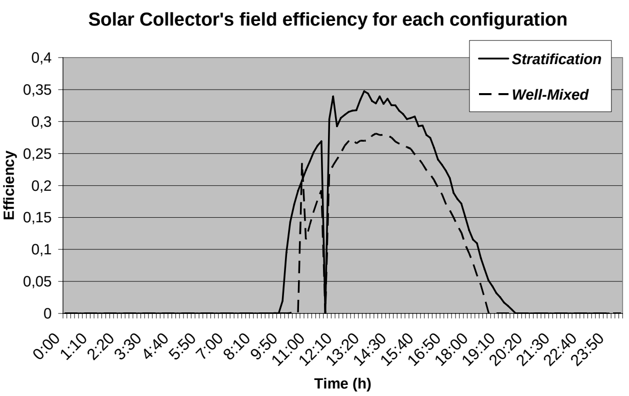

Figure 7: Solar collector's field efficiency for each configuration.

Cooling power produced by the facility for each configuration is shown on Figure 8. It is appreciated that working in stratification regime in the TST the facility began producing cooling power earlier than in well-mixed configuration, reaching an acceptable value of 5 kW at 13:50 hours. Nevertheless, working in well-mixed configuration, the cooling power production reaches 5 kW at 15:00 hours but the autonomy of operation during the sunset time is extended two hours, where the well-mixed temperature plays its role in the production of cooling load. This behavior is more convenient because the acclimatizing demand grows in afternoon hours in Spanish houses (see ambient temperature curves in Figure 5). Average value of cooling power in stratification configuration reaches 2,53 kW and a total cooling load supplied during the day of 23,06 kWh/day. Average value of cooling power in well-mixed configuration reaches 3,96 kW and a total cooling load during the day of 35,94 kWh/day. Cooling power is defined as:

$$Q_{cool} = \dot{m}_{fc} C_p (T_{fcout} - T_{fcin}) \qquad (2)$$

Evaluating the behavior of the facility during the day, the solar coefficient of performance (SCOP) [2] for stratification reaches 0,056 and for well-mixed reaches 0,098. SCOP is defined as:

$$SCOP = \frac{Q_{cool}}{Q_{solar}} \qquad (3)$$

Looking at the SCOP value, a higher value for coefficient of performance (COP) working in well-mixed configuration is expected. COP is defined as:

$$COP = \frac{Q_{cool}}{Q_G} \qquad (4)$$

Daily COP value for stratification configuration reached 0,28 and for well-mixed configuration reached 0,35 [4].

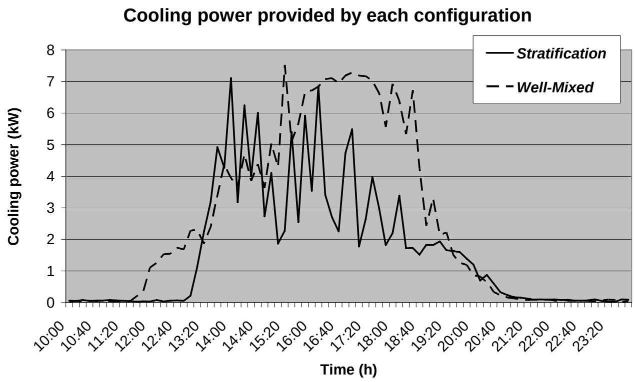

Figure 8: Cooling power produced by the facility for each configuration. Peaks in the figure are induced by the temperature control of the fan-coil.

An increment of SCOP working under well-mixed configuration is obtained during the day, indicating that the well-mixed configuration is more efficient for cooling purposes using solar energy under Spanish weather conditions.

MODELING THE WELL-MIXED CONFIGURATION TST

The governing equation for the well-mixed configuration can be determinate from the energy balance in the TST (see Figure 3).

$$\rho V C_p \frac{dT}{dt} = \dot{m}_1 C_p (T_{hx1} - T_{hx2}) - \dot{m}_2 C_p (T_{L1} - T_{L2}) - UA(T_W - T_a) \qquad (5)$$

Where $T_{hx's}$ and $T_{L's}$ will depend of solar radiation and thermal load respectively.

The TST can be divided into two working modes, charge and discharge. In the charge mode, T_W will be influenced by T_{hx1} and T_{L2} as they both will be incrementing its values as solar radiation and thermal load increments during morning and early afternoon. In the discharge mode only T_{L2} will influence T_W as the thermal load decreases until T_W reaches its lowest useful temperature during mid afternoon and sunset. This lowest useful temperature will be set by the generator of the absorption chiller. In the case of the Yazaki WFC10 the generator temperature ranges from 60 – 85 ºC, so the lower useful value will be 60 ºC. When the TST drops below 60 ºC it stops feeding the generator preserving that energy to start-up next day. In the well-mixed configuration model T_{hx2} and T_{L1} have to be equal to T_W, then expressions for T_{hx2} and T_{L1} in terms of T_W can be obtained from experimental and technical data.

Figures 8 and 9, depicts experimental temperatures for an average day of July.

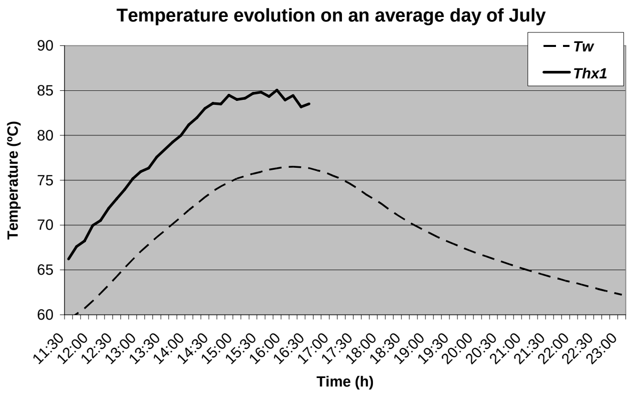

Figure 8: Experimental temperatures for T_{hx1} and T_W for an average day of July.

It can be appreciated that for charge mode T_{hx1} follows T_W plus a constant K_1. From experimental data (Figure 8) can be seen that $K_1 = 6$ºC at the beginning of operation corresponding to the automation of the facility. But then, this value comes to be $K_1 \approx$ 11 ºC where the value of K_1 will be characteristic of the heat exchanger design parameters. So the expression for T_{hx1} in terms of T_W will be:

$$T_{hx1} = T_W + 11^{o} C \tag{6}$$

An expression for T_{L2} in terms of T_W can be found applying an energy balance in the generator of the absorption chiller (Figure 9).

$$\dot{m}_2 C_p (T_{L1} - T_{L2}) = UA \ \Delta T_{LMTD} \tag{7}$$

Where,

$$\Delta T_{LMTD} = \frac{(T_{gen1} - T_{L1}) - (T_{gen2} - T_{L2})}{\ln \dfrac{(T_{gen1} - T_{L1})}{(T_{gen2} - T_{L2})}} \tag{8}$$

Assuming a constant generator temperature because of the change phase of the refrigerant, $T_{gen1} = T_{gen2} = T_{gen}$. From experimental data T_{gen} can be approximated as 68 ºC (see Figure 10). Rearranging for T_{L2}:

$$T_{L2} = T_{gen} + (T_W - T_{gen}) e^{-\frac{UA}{\dot{m}_2 C_p}} \tag{9}$$

Substituting (6) and (9) in (5) the model for charge mode can be obtained for the defined temperatures and automation described above.

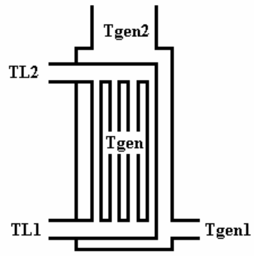

Figure 9: Schematic representation of the generator of the Yazaki WFC10.

In Figure 10 two interesting behaviors are noticed (marked by circles). This "bumps" in both temperatures T_{L2}, T_{gen} corresponds to the actuation of the dissolution control that incorporates the Yazaki WFC10 to compensate sudden ups and downs in temperature values inside the generator. This control works increasing or decreasing the dissolution concentration [5]. The first bump indicates that the temperature in the generator is reaching a value inside the range of operation of the chiller, so refrigerant is removed from the dissolution, reducing the bubble flow in the generator. The second bump indicates the opposite, temperature in the generator is not enough and refrigerant is liberated into the dissolution, raising the bubble flow in the generator. This control keeps a constant ΔT value between the inlet and outlet of the hot water feeding the generator along the whole period of operation. So the first bump clearly marks the charge mode in the TST.

The discharge mode begins when T_W begins to descend in the TST. But for certain period of operation T_W has a higher value than T_{gen}, so the assumption of T_{gen} constant remains. When T_W reaches the temperature in the generator the second bump appears and a new equation for T_{L2} in terms of T_W has to be defined. It can be appreciated that T_{L2} follows T_W minus a constant K_2, where the value of K_2 will be 3 ºC according to experimental data. Then:

$$T_{L2} = T_W - 3^{\circ}C \qquad (10)$$

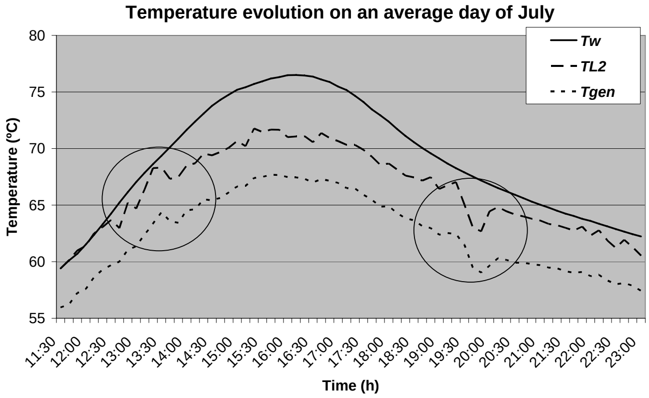

Figure 10: Experimental temperatures for T_{L2}, T_{gen} and T_W for an average day of July.

By the matching of model with experimental temperature data, an equivalent value of $\rho V C_p$ can be obtained for the facility. Combining this result with real flow rate data entering and leaving the tank, characteristics times of heat storage preparation and consumption can be evaluated. Finally, results can be used in a new TST design accordingly with the application requirements.

CONCLUSIONS

- Two configurations of TST (stratified and well mixed) have been experimentally tested during the summer season, in a solar cooling application.
- Results show that stratified mode for TST lead to higher solar collector efficiency, as usual [6].
- A higher value of daily cooling energy and averaged SCOP is achieved by the well mixed TST configuration.
- Additionally, this mode of operation allows a better time matching between thermal load and solar cooling production.
- Based on experimental temperature data, a non stationary TST model has been developed. This model predicts the time evolution of TST mean temperature. This way, an effective storage capacity can be evaluated for the facility.
- Further work has to be done in order to perform an experimental comparison trough a season averaged set of operating parameters.

ACKNOWLEDGMENT

This work has been partially funded by the Spanish government research grant M. C. y T. CLIMABCAR project DPI 2003-01567, TRANSMACA project DPI 2002-02439 & MINICOM project (FIT 0204-2004-68 and FIT 020100-2003-233). Their contribution is greatly appreciated.

NOMENCLATURE

Tc	Cold temperature.	^{o}C
Th	Hot temperature.	^{o}C
T_{Cin}	Inlet collector's field temperature.	^{o}C
T_{Cout}	Outlet collector's field temperature.	^{o}C
T_W	Well-mixed temperature.	^{o}C
T_{fcin}	Inlet fan-coil temperature.	^{o}C
T_{fcout}	Outlet fan-coil temperature.	^{o}C
T_{hx1}	Inlet tank temperature from heat exchangers.	^{o}C
T_{hx2}	Outlet tank temperature to heat exchangers.	^{o}C
T_{L1}	Inlet generator temperature from tank.	^{o}C
T_{L2}	Outlet generator temperature to tank.	^{o}C
T_a	Ambient temperature.	^{o}C
T_{gen1}	Diluted dissolution temperature.	^{o}C
T_{gen2}	Concentrated dissolution temperature.	^{o}C
T_{gen}	Generation temperature.	^{o}C
$\dot{m}_{fc}$	Fan-coil mass flow.	kg/s
$\dot{m}_{CO}$	Collector's field mass flow.	kg/s
$\dot{m}_1$	Circuit 1 mass flow.	kg/s
$\dot{m}_2$	Circuit 2 mass flow.	kg/s
C_p	Specific heat.	J/kgK
ρ	Density.	m^3/kg
V	Volume.	m^3
A	Heat transfer area.	m^2
U	Overall heat transfer coefficient.	W/m^2K
Q_{cool}	Cooling power.	W
Q_{solar}	Solar energy.	W
Q_G	Heat power supplied to the generator	W
ΔT_{LMTD}	Logarithmic mean temperature difference.	K
COP	Coefficient of performance.	
$SCOP$	Solar coefficient of performance.	
η_{CO}	Collector's field efficiency.	

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