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PERFORMANCE EVALUATION OF A SMALL CAPACITY SOLAR COOLING ARS

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Abstract: *Air conditioning systems has known a steady grow in recent decades which has a major impact on energy demand and environment. Systems using solar energy as fuel have been developed more than 100 years ago. The paper present such an alternative system, ammonia-water absorption refrigeration system (ARS) powered by low temperature energy, using renewable sources for cooling. A short numerical calculation is made for determine the performance of the machine. The results obtained using EES program are also presented and first measurements on prototype machine.*

Key words: *absorption, cooling, performance.*

1. Introduction

Currently, space heating and cooling together with water heating are estimated to account for nearly 60% of global energy consumption in buildings. They therefore represent the largest opportunity to reduce buildings energy consumption, improve energy security and reduce CO_2 emissions, particularly due to the fact that space and water heating provision in some countries is dominated by fossil fuels. Meanwhile, cooling demand is growing rapidly in countries with highly carbon-intensive electricity systems such as Association of Southeast Asian Nations, China and the United States [8].

Due to the negative impact on the environment as a result of the intensive use of fossil fuels, effects felt across the planet through global warming, the scientific community has shifted research towards a clean energy source and accessible all over the world, solar energy. Solar refrigeration systems has been evolved over 100 years and become more efficient. However, they still have to be improved in order to become competitive.

In Figure 1 are reviewed and classified the most popular and advanced processes for obtaining artificial cold that can use solar renewable energy. We will elaborate more on the use of one, namely the ammonia-water absorption system.

In Figure 2 many of the technologies reviewed are compared in terms of performance and initial cost based on ideal assumptions by Kim and Ferreira 2008.

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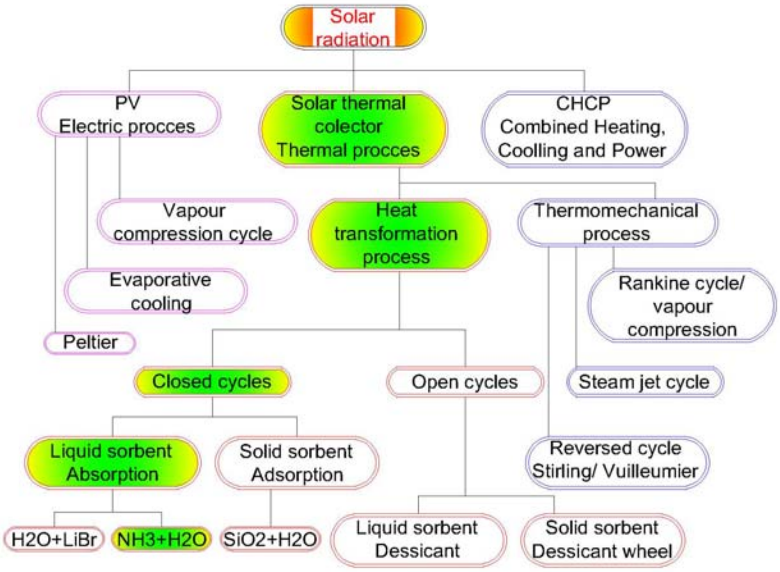

Fig.1. *Classification of the main processes that use solar energy for obtaining artificial cold [1, 2, 9, 12, 15*].

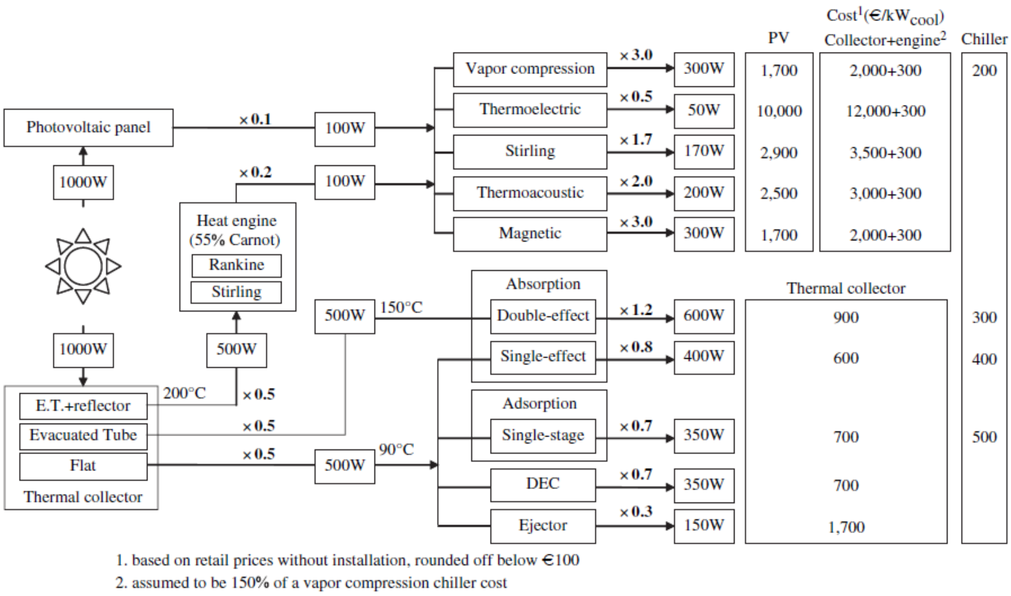

Fig. 2. *Cost-efficiency for different solar cooling systems*. [9]

Artificial cooling with solar energy involves the use of solar radiation converted by thermal solar panels or using solar photovoltaic panels and different thermodynamic cycles or electric process.

As can be see absorption and adsorption are comparable in terms of performance but an adsorption chiller is more expensive because of the bigger components required for the same capacity. The biggest disadvantage for absorption refrigeration system is high initial investment at about 1000€/kW [9] of which the biggest portion is for solar collectors.

The developments in cooling systems programs show a growing interest in the application of absorption systems. The first important European project SACE (Solar Air Conditioning in Europe) with more than 60 case studies, was initiated in 2002 and was supported by the European Commission. Then followed programs from IEA (International Energy Agency) Task series (25, 30, 32, 38 and 48), IEA-SHC, Solair, Solera, SolarCombi+, Medisco, Climasol. Together, Green Chiller and Tecsol projects reached at almost 1000 absorption systems documented in 2012. Now days probably the number is higher as can be seen the trend line in Figure 3.

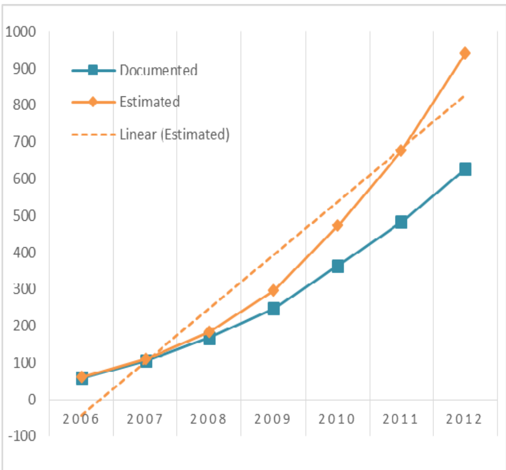

Fig.3. *Market development of solar cooling small capacity machine (Green Chiller, Tecsol, IEA SHC Task 38)*

Optimization of energy conversion systems becomes more important due to limitations of fossil fuels and the environmental impact during their use. Opportunities for improving solar ARS can came from cheaper solar collector, chiller COP increased, lower driving temperature to work with actual solar heating systems, use of air for dissipation of heat instead of cooling towers. Two types of absorption air-conditioning systems are widely used, LiBr-H_20 and H_2O-NH_3. New working pairs have also been developed [5, 10, 14, 16] and their performance studied but there seems not to be a choice that supersedes the characteristics of the already mentioned common two [13].

Both LiBr and NH_3 systems have their advantages and disadvantages. NH3 systems can work at low temperatures and air cooled condenser and absorber make them suitable for heat pump operation. NH3 is accessible and inexpensive not like LiBr which is more expensive. NH3 have high latent heat of vaporization but they have to work at high pressure and have a high grade of toxicity but have no environmental impact such as global warming potential and greenhouse effect.

It is lighter than air and the leak of ammonia can easily detect smell at a concentration below a dangerous level. NH_3 is corrosive to Cu and its alloys but not to steel. LiBr systems are limited to work over 5˚C, can be used as heat pumps. Also most operate in vacuum condition and at high concentrations may cristalize if are not used substance for solubility like $ZnBr_2$. The biggest advantage of LiBr is that it does not need rectifier like NH_3 system but it must be kept leak free that can affect the capacity of the machine and can became corrosive in presence of O_2.

Theoretical and experimental works have been done on different systems with single, half, double, triple effect cycles and have been extensive reported [Gosney, Herold, Henning, Kim, Grossman, Ziegler, Jakob, Chiriac, Serban, Boian, Gomri, Kaynakly, Sencan, Sosen, etc] but for low temperature grade the single effect was find to be best suitable.

2. Solar powered single effect solar ammonia - water absorption refrigeration system prototype.

An absorption chiller uses heat as driving energy, as compared to vapour compression chiller (VCC) that use electricity. For a solar absorption cooling system, this heat is taken from sun energy. The absorption cooling system (single effect) has a coefficient of performance, COP, somewhere between 0.6 - 0.8 according to literature. The solar-powered cooling system, Figure 4, generally comprises three main parts: the solar energy conversion equipment, the refrigeration system, and the consumer.

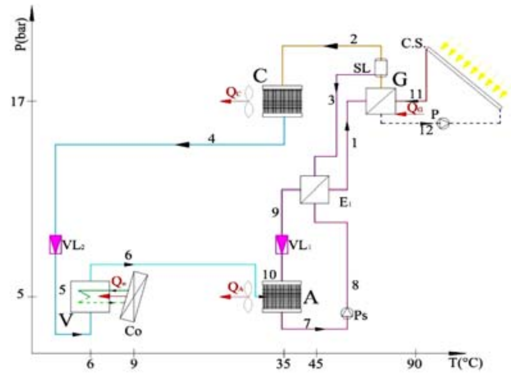

Fig. 4. *Solar cooling [10]*
G – generator; C – condenser; VL_1, VL_2 – control valves 1,2; V – evaporator; E_1 – economizer; A – absorber; LS – liquid separator; CS – solar collectors; Ps – solution pump; Co – consumer.

The main components of a single effect absorption cooling system are the generator (G), the absorber (A), the condenser (C), the evaporator (E=0), the pump (Ps), the expansion valve (VL1), the reducing valve (VL2) and the solution heat exchanger (E_1). The generator is a plate heat exchanger with 2.5 mm minichanels. After boiling, is resulting a biphasic solution, constituted by poor solution and ammonia vapors, which are separated in the liquid separator LS, from where they go to the condenser, consisting in 2 mm minichanels, fined heat exchanger, and air cooled with a fan. Ammonia condenses in the condenser by removing the heat from the refrigerant vapor and the resulting liquid is laminated by the control valve VL_2 where its pressure is reduced to the low pressure, after which the liquid enters the evaporator which is also a plate heat exchanger with 2.5 mm minichanels. Here, the liquid ammonia vaporizes, by taking the heat from the cooled water, which comes with 12°C. Vapors are then being absorbed in the absorber, by weak ammonia solution come from liquid separator.

The absorber is an original construction, consisting of mini/micro channels, arranged in two vertical rows and have efficient finned outer surface, with superior distributor for the poor solution and lower collector for the strong solution; ammonia vapor injection, to be absorbed is done through the median distributor, connected to the mini/micro channels by individual connections [4]. The result is a strong ammonia solution, which is heated in the economizer then being pumped into the generator by the solution pump. The solution pump is a pulse pump having a reciprocating motion. It discharges strong solution to the generator by means of a flexible sealing diaphragm The weak solution, poor in ammonia resulting in the generator, is separated in liquid separator is cooled in the economizer E_1, then laminated by the control valve VL_1 and finally absorbed in absorber, where a strong ammonia-water solution is formed. With the preheated strong solution returning to the generator the cycle is completed. [4]

The absorber is the most important component of absorption machines, in general, its performance impacts directly in the size and energy supply of all absorption devices. Absorption cooling and heating cycles have different absorber design requirements: in absorption cooling systems, the absorber works near to ambient temperature, therefore, the mass transfer is the most important phenomenon in order to reduce the generator size and power of pumps; in the other hand, in heating absorption systems, it is important to recover the heat delivery by the exothermic reactions produced in the absorber, for this reason, the absorber heat transfer coefficient is an important parameter.[7]

3. Energy analysis

A mathematical model is developed to analyze the performance of the experimental system ARS based on the mass and energy balances [6]. Temperatures and pressures of working fluid are based on designed values. Water and ammonia properties are obtained from standard properties of pure substances table in the ASHRAE [18], Refrigerating Plants [3] and Dühring plot. Figure 5 represent the schematic components and cycle for better state point identification in EES simulation.

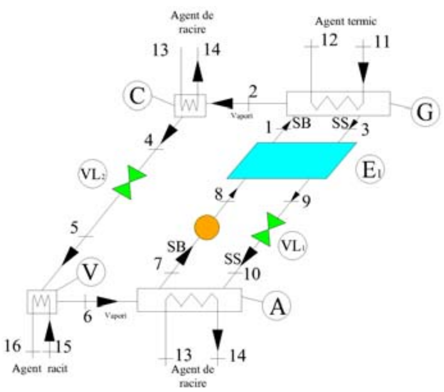

Fig. 5. *EES schematic*

The theoretical model use input data, main assumptions and operating conditions that are presented below.

The input data (operating conditions) are:

- The cooling power of the evaporator, which is fixed in all calculations $\dot{Q}_0 = 5{,}0[kW]$

- The inlet and outlet temperatures of the external fluids, air, water: hot water = 90˚C, cold water = 7-12˚C, air = 35˚C.

- The minimum temperature difference in the heat and mass exchangers = 3-5˚C

- Concentration of vapors leaving G-LS = 0.998.

The output data are:

- The pressures (p), temperatures (T), mass flows ($\dot{m}$), concentrations (ξ), enthalpies (h), of each state point.

- The thermal or, in the case of the solution pump, mechanical power of the main components.

- The $\text{COP} = \dfrac{\dot{Q}_o}{\dot{Q}_g + W_p}$ where $\dot{Q}$ is the thermal power (kW), W_p the pump power (kW), 0 the evaporator, G the generator and P the pump.

Assumptions:

- It is a steady state cycle
- There are no heat and pressure losses
- The refrigerant leaving the condenser is saturated liquid
- The refrigerant leaving the evaporator is evaporated completely as saturated vapor.
- The strong solution leaves the absorber at the absorbent temperature as saturated liquid.
- The solution and refrigerant valves are adiabatic.
- Pump is isentropic.

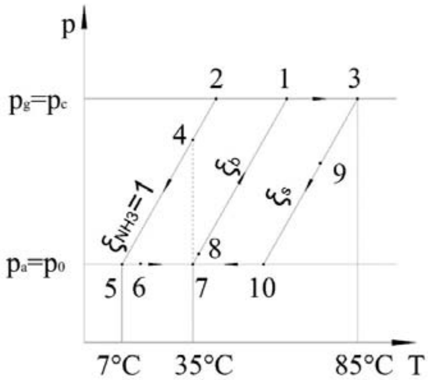

Fig. 6. *Thermodynamic cycle of the installation processes in p-θ-ζ diagram*

First the pressures are determined:

$p_0=f(T_0)=p_A$ (1)

$p_C=f(T_C)=p_G$ (2)

Then we must check the degassing breath which is the difference between the strong and weak concentrations. This must be bigger than 5% otherwise circulation factor f will be larger than 13 which means a bigger mass flow of solution.

$$\xi_{ss}=\xi_3=f(p_G,T_G=T_3) \quad (3)$$

$$\xi_{sb}=\xi_7=f(p_A,T_A=T_7) \quad (4)$$

Circulation coefficient *f,* evaporator specific capacity $\dot{q}_o$ and mass flow of refrigerant $\dot{m}_0$ are stated below:

$$f=(\xi_2-\xi_{ss})/(\xi_{sb}-\xi_{ss}) \quad (5)$$

$$\dot{q}_o=h_6-h_5\ [kJ/kg] \quad (6)$$

$$\dot{m}_0=\dot{Q}_0/\dot{q}_0\ [kg/s] \quad (7)$$

Mass balance is:

$$\dot{m}_{ss}=\dot{m}_{sb}-\dot{m}_0\,[kg/s] \quad (8)$$

A thermal balance exists:

$$\dot{Q}_g+\dot{Q}_o+W_p=\dot{Q}_a+\dot{Q}_c \quad (9)$$

Where generator capacity is:

$$\dot{Q}_g=[h_2+(f-1)\cdot h_3-f\cdot h_1]\cdot\dot{m}_0\ [kW] \quad (10)$$

Absorber capacity is:

$$\dot{Q}_a=[h_6+(f-1)\cdot h_{10}-f\cdot h_7]\cdot\dot{m}_0\ [kW] \quad (11)$$

Condenser capacity is:

$$\dot{Q}_c=[h_2+(f-1)\cdot h_3-f\cdot h_1]\cdot\dot{m}_0\ [kW] \quad (12)$$

Economizer capacity is:

$$\dot{Q}_c=[h_2+(f-1)\cdot h_3-f\cdot h_1]\cdot\dot{m}_0\ [kW] \quad (13)$$

And finally the solution pump:

$$W_p=[f\cdot(h_8-h_7]\cdot\dot{m}_0\ [kW] \quad (14)$$

Efficiency of ARS is described in the term of coefficient of performance COP which is desired output (Q_0) divided by required input ($Q_g + W_p$).

$$\text{COP}=\frac{\dot{Q}_o}{\dot{Q}_g+W_p} \quad (15)$$

To be more precise same equations were used to EES which contains procedures for thermodynamic properties of ammonia-water solution.

In Table 1 characteristics of every state point are presented and in Table 2 heat transfer of components and performance parameters of the system. Also the the properties for all states points, COP for the ammonia–water ARS are obtained using the Engineering Equation Solver (EES)[11], Table 3 and 4.

Thermodynamic properties of the absorption system Table 1

CALCULATION				
State point	p [bar]	T [°C]	h [kj/kg]	x [kg/kg]
1	13.5	68	90	0.53
2	13.5	80	1410	0.998
3	13.5	85	150	0.44
4	13.5	35	95	0.998
5	4.97	4	95	0.998
6	4.97	7	1200	0.998
7	4.97	35	-90	0.53
8	13.5	36	-85	0.53
9	13.5	46	-58.65	0.44
10	4.97	43	-58.65	0.44

Heat transfer of components and performance parameters Table 2

CALCULATION	
Component	Heat transfer rate(kW)
Evaporator	5
Absorber	6.57
Generator	7.38
Condenser	5.95
Solution pump	0.14
Solution heat exchanger	4.91
Performance parameters of ARS	
Circulation ratio	6.20
Coeficient of performance	0.66

Thermodynamic properties of the absorption system - Table 3

EES				
State point	p [bar]	T [°C]	h [kj/kg]	x [kg/kg]
1	13.51	71.1	84.39	0.53
2	13.51	80	1433	0.99
3	13.51	85	146.3	0.44
4	13.51	35	158.9	0.99
5	4,97	4.4	158.9	0.99
6	4,97	7.4	1176	0.99
7	4,97	35	-81.39	0.53
8	13.51	36	-76.18	0.53
9	13.51	42.5	-45.66	0.44
10	4,97	42.7	-45.66	0.44

Heat transfer of components and performance parameters - Table 4

EES	
Component	Heat transfer rate(kW)
Evaporator	5
Absorber	7.08
Generator	8.19
Condenser	6.26
Solution pump	0.15
Solution heat exchanger	4.80
Performance parameters of ARS	
Circulation ratio	6.11
Coeficient of performance	0.59

4. Measurements.

A data acquisition system and a set of transducers have been used to monitor the operation of this prototype plant. Errors between 10 to 20% have been noticed. Figure 9 shows the temperatures recorded for every state point compared with the results from EES. The first result are not satisfactory but new adjustment will be made until we get closer to the calculations. In order to improve the system design of the solar powered absorption air-conditioning system, a parametric study must be carried out to investigate the influence of key parameters on the overall system performance. Experiments will be used to perform the parametric study, effects of one key parameter on the overall system performance will be monitored. Generator inlet temperature of the chiller is still the most important parameter in the design and fabrication of a solar powered air-conditioning system.

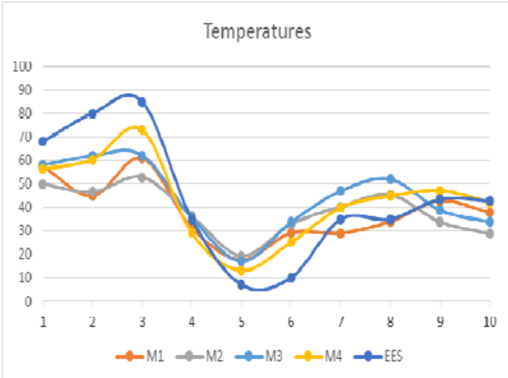

Fig.9. *Temperatures measured versus EES calculated for all state points*

Conclusion

There are many benefits of ARS:

• Can be driven by low grade thermal energy, as waste heat, biomass, solar thermal energy or heat from cogeneration so they will be a better solution for cooling in the future because of the rising prices announces for fossil fuels and the return payback will be shorter along with mass production.

• Absorption chillers are silent and vibration free.

•High protection of the environment is done due to the energy used and the refrigerants, NH_3-H_2O, which have zero ODP and GWP thus protecting the ozone layer and does not contribute to global warming as chloro- fluorocarbons

Owing to the fact that there is always enough roof area to install solar collectors, solar-powered integrated energy systems are auxiliary heat sources to supplement solar-powered cooling systems.

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