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AN EXPERIMENTAL PLANT TO EVALUATE THE PERFORMANCES OF AN ABSORPTION REFRIGERATOR

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ABSTRACT

Refrigeration cycles powered by waste heat or heat produced by solar systems represent a promising way to reduce CO_2 emissions; among the various technical solutions, H_2O-LiBr absorption cycles seem to be particularly interesting. The experimental plant described in the paper has a double task: to verify the machine performances by varying the operating conditions and to validate simulation models. The core of the plant is a single-stage H_2O-LiBr absorption machine; the generator is powered by hot water produced by an electrical boiler; the cooled water is used to feed some fan-coils. The measurement facilities include differential pressure transducers to measure flows, thermoresistances and thermocouples; all the variables are converted into electric signals and elaborated through an acquisition data system. After the first acquisitions on the plant, realized to verify the machine, the circuits and the reliability of instrumentation, an experimental campaign was conducted by varying the temperatures and the flow rate of the hot water. The energy performances of the plant are presented as well as the results given by the models.

INTRODUCTION

One way of limiting CO_2 emissions and therefore greenhouse effect is to use energy waste, such as low temperature heat, which would otherwise remain dissipated in the environment. Refrigeration cycles supplied with waste heat or water heated through solar collectors represent a promising application for energy-environmental issues; among the potential technical solutions is the absorption cycle with Water and Lithium Bromide, suitable for air conditioning.
The refrigerant-absorbent pair H_2O-LiBr, in fact, has numerous advantages such as high enthalpy of vaporization, no need of rectification; it is neither toxic nor dangerous
At the Department of Industrial Engineering of the University of Perugia research groups have been actively working on alternative refrigeration technologies and in particular on absorption systems; the main topics dealt with were the measurements of thermo-physical properties of new fluids (Cotana *et al*., 1992, Felli *et al*., 1991) the evaluation of new cycles and machines (Felli *et al*., 1991), and the creation of new prototypes (Coppi and de Lieto Vollaro, 1990).
The experimental plant described in this paper has dual validity: on the one hand, it has scientific validity since it aims at verifying the performances of the machine as operational conditions vary and at validating the thermodynamic models developed, and on the other, it has didactic purposes.
Activities were funded by a national research project "Inverse thermodynamic cycles for refrigeration and heat pumps: development of solutions with low environmental impact – non conventional refrigeration systems".

1 DESCRIPTION OF THE ABSORPTION MACHINE

The Japanese-manufactured (Yazaki) experimental single-stage absorption machine uses Water-Lithium Bromide as working fluid. It has the four main elements of any absorption group, i.e. generator, evaporator, condenser, and absorber , as shown in figure 1. The machine has a nominal refrigeration power equal to 17 kW and exploits a flow rate of hot water equal to a $1{,}57 \times 10^{-3}$ m^3/s at 88°C. The refrigerated water can drop to a minimum temperature of 8°C; in nominal conditions it is produced at 9°C with a drop in the evaporator of 6°C. The nominal flow rate of cooled water produced is equal to $0{,}83 \times 10^{-3}$ m^3/s: the maximum pressure at the generator and at the evaporator are

equal to respectively 98 kPa and 295 Pa.
To cool the absorption and condenser, a water flow rate from the aqueduct equal to 2,22x10^{-3} m^3/s is necessary, which is heated from 29.5°C to 34.5°C; the maximum pressure in the cooling circuit is equal to 295kPa.
The machine is equipped with a recirculation between the concentrated and diluted solutions in the generator and absorber, with an exchanger to recover heat. The machine is also equipped with a heater with a palladium-cell to extract hydrogen produced inside; it does not have mechanical devices since fluid circulation is achieved through distillation and gravity.

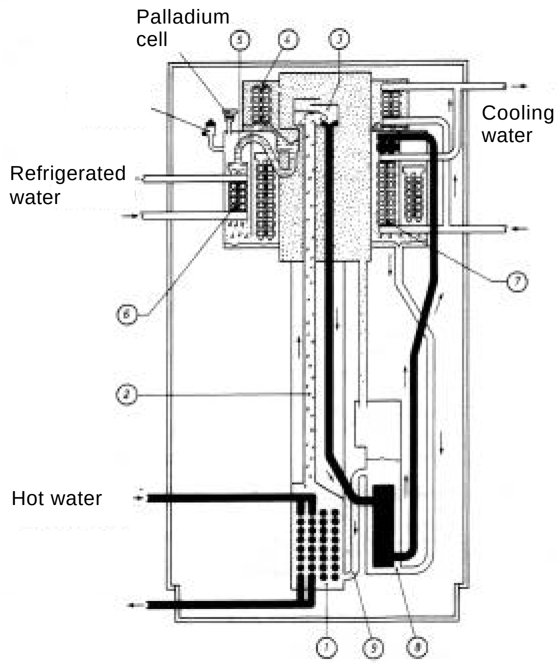

Figure 1: layout of the absorption machine

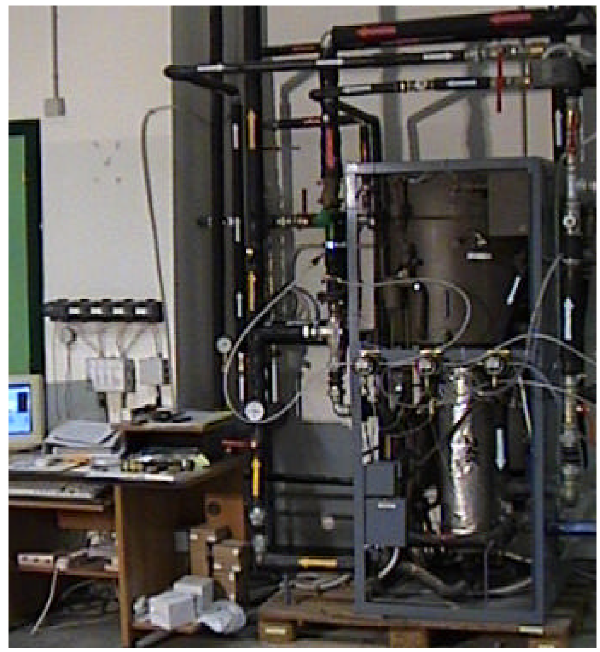

Figure 2: full view of the experimental plant

The machine components are placed as shown in figure 1. They are: 1) generator, 2) tube for steam produced in the generator, 3) separator, 4) condenser, 5) U-shaped tube to allow pressure drop from the condenser to the evaporator, 6) evaporator, 7) absorber, 8) solution heat exchanger, 9) generator inlet

2 DESCRIPTION OF THE EXPERIMENTAL PLANT

2.1 External Circuits

Figure 2 shows a view of the plant at the Labs of the Department of Industrial Engineering of the University of Perugia; the layout is shown in figure 3.
The central part of the plant is the absorption machine; the external circuits guarantee the continual flow of the fluids at the inlet and outlet of the machine. The generator is supplied with hot water produced in an electric boiler with three heating resistances of 10 kW each and a thermostat with a remote control switch, which acts on the resistances once water has reached the operating temperature; the heating circuit is linked to an expansion tank. Absorber and condenser are cooled thanks to water taken from the aqueduct and than dispersed. An initial layout of the plant included a specific reservoir for storing cooled water. The first tests showed however that the tank was not large enough to guarantee steady conditions to be reached due to the gradual decrease in temperature of the water in the tank; so a refrigerating device was inserted made up of two fan coils. The hot and cooling water flows are produced by two identical pumps; each pump of the hot circuit carries a flow rate of 3,3x10^{-3} m^3/s with a discharge head equal to 68.6 kPa; each pump of the cooling circuit carries a flow rate of 3,0x10^{-3} m^3/s with a discharge head equal to 46.0 kPa.
The proposed layout allows setting the temperature of the hot water supplying the machine; it is also possible to partially regulate the different flow rates of the fluids of the external circuits.

2.2 Measurement equipment and data acquisition

The equipment to measure the parameters of the plant is made up of:

- analog thermometers in each external circuit of the machine (one at the inlet and one at the outlet) and in the hot and cold tanks;
- manometers on all circuits;
- Sections to measure flow rates connected to differential pressure transducers on the external circuits;
- thermoresistances Pt 100 inserted in ceramic material and immerged in oil in appropriate cavities to measure temperature in the external circuits and inside the machine (in the evaporator and in the condenser);
- J thermocouples with clip to measure the temperatures of the solutions and in particular the temperature of the concentrated solution at the outlet of the generator and at the inlet of the absorber, and the temperature of the diluted solution at the inlet of the generator and at the outlet of the the absorber.

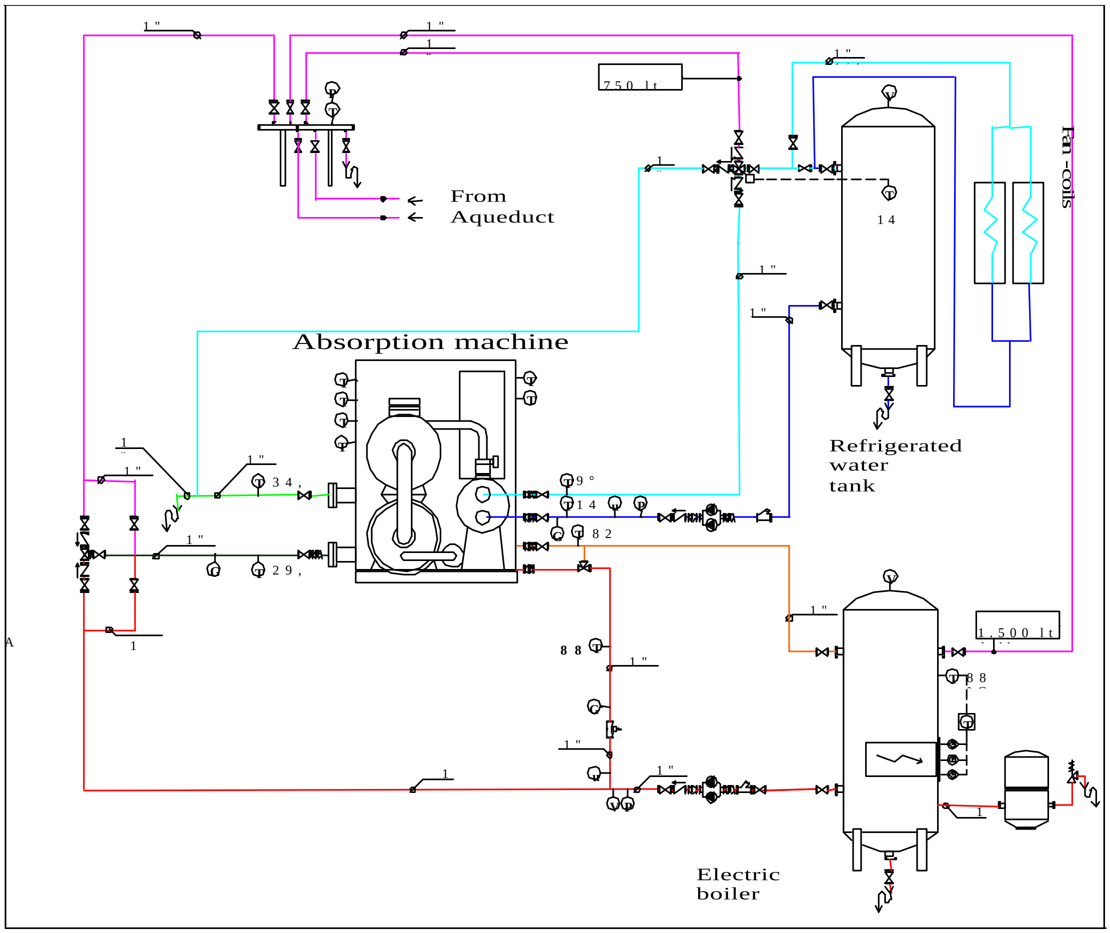

Figure 3: layout of the experimental apparatus

All measured quantities are converted into electric signals and elaborated through a data acquisition system (Field Point); the software allows to visualize and memorize all the parameters examined with the possibility to choose how often acquiring data. The flow of data from the acquisition points placed at various areas of the machine to the software system makes it necessary to electrically connect the sensors to the inlet area of the computer; sometimes the cables needed were some meters long and inevitably this decreased the signal/noise ratio. Therefore, it was necessary to correct the signal at the inlet of Field Point in function of the distance from the acquisition point. Figure 4 shows a typical layout of the software during the normal operation of the plant.

3 MEASUREMENTS

3.1 Measurement conditions

The experimental campaign carried out focused on analysing the plant behaviour during two sets of trials. In the first set, the temperature of the supplying hot water was varied; in the second set the supply flow rate was varied instead. The temperature and the flow rate at the inlet of cooling water were considered as independent variables since the water is sent to the machine directly from the aqueduct.
Table 1 reports the fixed values of the quantities being dealt with.

Cooling water temperature (inlet)	15-20 °C
Cooling water flow rate	0.65 kg/s
Refrigerated water flow rate	0,37 kg/s

Table 1: parameters of the machine while running

3.2 Measurement modality

The preliminary tests, performed to verify the operation of the plant, showed how steady conditions were reached within 60-70 minutes after turning the machine on. However, every measure lasted at least 6 hours so to show possible fluctuations of the thermodynamic parameters when operations were prolonged. Every quantity was acquired at intervals of 1.5 seconds and memorized every 10 minutes with real time display of the value (fig. 4) and trend of each parameter (fig. 5).

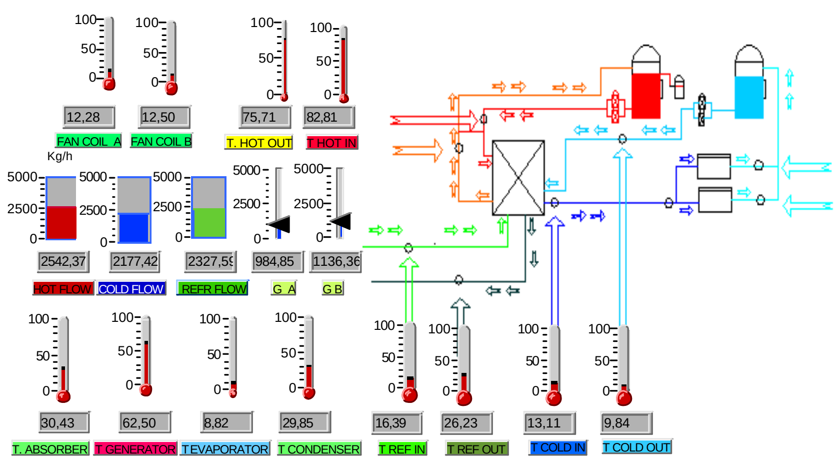

Figure 4: real time output of the data acquisition system

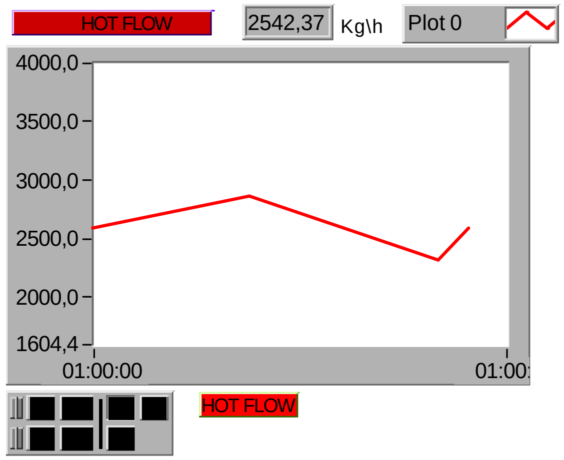

Figure 5: graphic output of the data acquisition system

4 RESULTS

4.1 Data analysis

The results of the two mentioned sets of measurements were computed under steady conditions; for example, tables 2 and 3 report the results of the parameters of the external circuits in the two series.

The quantities are as follows:

- $T_{h,in}$ water temperature at the inlet of the generator [°C];
- $T_{h,out}$ water temperature at the outlet of the generator [°C];
- $T_{r,in}$ water temperature at the inlet of the evaporator [°C];
- $T_{r,out}$ water temperature at the outlet of the evaporator [°C];
- $T_{c,in}$ water temperature at the inlet of the absorber and the condenser [°C];
- $T_{c,out}$ water temperature at the outlet of the absorber and the condenser [°C];
- G_h flow rate of the hot circuit [kg/s];
- G_r flow rate of the refrigeration circuit [kg/s];
- G_c flow rate of the cooling circuit [kg/s].

TEMPERATURE						FLOW RATE		
$T_{h,in}$	$T_{h,out}$	$T_{r,in}$	$T_{r,out}$	$T_{c,in}$	$T_{c,out}$	G_h	G_r	G_c
80,7	76,0	11,6	8,5	18,	26,9	0.99	0.37	0.65
75,9	72,3	14,0	10,7	19,1	26,7	1.04	0.36	0.66
72,4	69,1	14,2	11,2	18,1	24,8	1.00	0.36	0.65
67,3	65,0	15,3	12,6	19,	23,9	0.99	0.37	0.65

Table 2: results of the measurements performed as the feeding temperature of the hot circuit varied.

	TEMPERATURE						FLOW RATE	
G_h	$T_{h,in}$	$T_{h,out}$	$T_{r,in}$	T_{rout}	$T_{c,in}$	$T_{c,out}$	G_r	G_c
0.73	82	74.6	13	11.1	16.5	26.1	0.55	0.66
0.64	83.7	75.2	13.4	11.6	16.5	26.3	0.55	0.64
0.52	85.5	75.5	13	11.2	16.6	26.3	0.53	0.65

Tab. 3: results of the measurements performed as the inlet flow of the hot circuit varied.

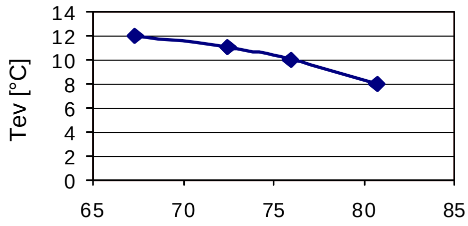

Figure 6: variation of the temperature in the evaporator Vs supplying hot water temperature

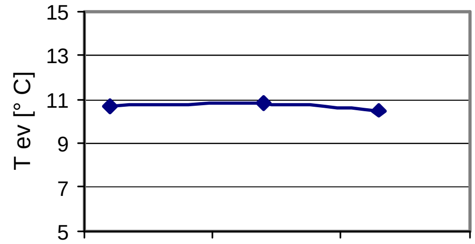

Figure 7: variation of the temperature in the evaporator vs supplying hot water flow rate

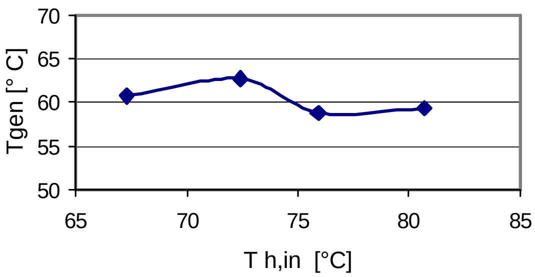

Figure 8: variation of the temperature in the generator vs supplying hot water temperature

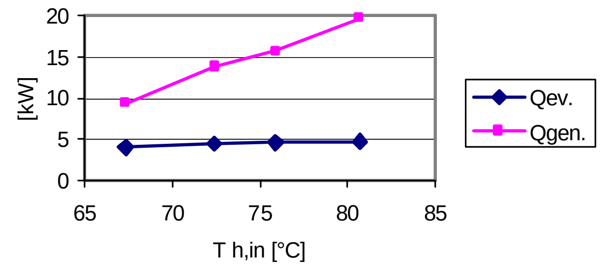

Figure 9: Heat exchanged at the evaporator and generator vs supplying hot water temperature

As the feeding temperature increased, the only parameter which underwent significant variation was the temperature of the evaporator which, as expected, noticeably dropped (figure 6).
As the feeding flow rate decreased, no significant temperature variation was detected at the evaporator (figure 7) instead only an increase in the difference between the inlet and the outlet temperature of the generator was found, as seen in table 3. Figure 8 shows how the temperature of the generator is not affected by the feeding temperature; it should be remembered, however, that the values refer to the temperature of the concentrated solution at the outlet of the generator.

4.2 Calculation of the machine performances

The following energy balance can be written:

$$Q_{abs} + Q_{con} = Q_{ev} + Q_{gen} \quad (1)$$

when assuming heat exchangers efficiencies equal to 1, the terms of (1) are:

$$Q_{gen} = G_h \gamma (T_{h,in} - T_{h,out}) \quad (2)$$
$$Q_{ev} = G_r \gamma (T_{r,in} - T_{r,out}) \quad (3)$$
$$Q_{abs} + Q_{con} = G_c \gamma (T_{c,out} - T_{c,in}) \quad (4)$$

The measured values allow satisfying equation (1), since the error is not greater than 2% (table 4).

$T_{h,in}$ (°C)	Q_e (kW)	Q_{gen} (kW)	$Q_{abs} + Q_{con}$ (kW)	Err.(%)
80,7	4,7	19,6	24,2	0,5
75,9	4,6	15,9	20,8	1.8
72,4	4,5	13,8	18,3	0.05
67,3	4,0	9,3	13,0	2,3

Table 4: heat exchanged in function of the hot water temperature

The COP(Coefficient of performance) of the machine is given by:

$$COP = \frac{Q_{ev}}{Q_{gen}} \quad (5)$$

Figures 10 and 11 report the trends of COP respectively in function of the feeding temperature and of the flow rate.

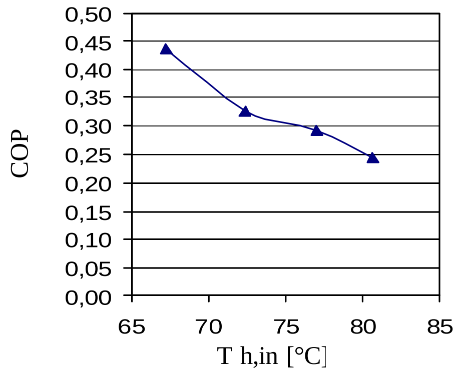

Figure 10: variation of the COP vs supplying hot water temperature

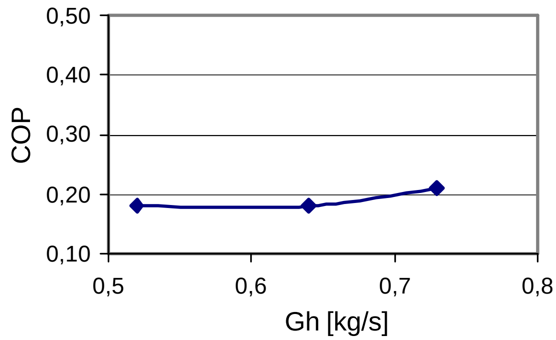

Figure 11: variation of the COP vs supplying hot water flow rate

The rating supplied by the manufacturer show a COP at nominal conditions equal to 0.60, whereas measurements taken by other authors (Sumathy *et al*, 2002) on the same machine model, with similar feeding temperatures, show comparable values of COP, between 0,2-0,32 for values of hot temperature inlet between 70- 80°C. The analysis of the performances show how, once the minimum feeding temperature of 67°C is exceeded, the COP of the machine decreases even if the refrigerating power increases. On the other hand, the variations in the feeding flow rate do not significantly affect the COP.

5 RESULTS FROM SIMULATION MODELS

Together with the measurements, a calculation model to simulate a single-stage refrigeration machine with H_2O – LiBr was developed. To develop this model, algorithms and empirical functions known from literature (Mc Neely, 1979) and (Uemura and Hasaba, 1964) were used and validated by comparing not only the data acquired experimentally but also data attained by using other models. Through this model, the concentrations of LiBr in the generator, in the absorber and the relative recycle factor (ratio between the solution and the refrigerant flow rates) for some of the measurements taken were calculated (table 5).

$T_{gen. (°C)}$	$T_{con. (°C)}$	$T_{abs (°C)}$	$T_{ev. (°C)}$	$X_{gen.}$	$X_{abs.}$	*f*
59.4	**29.2**	**31.8**	**10.5**	**53.7**	**47.9**	**9.3**
59.8	**29.7**	**32**	**10.8**	**53.4**	**48.0**	**9.8**
62.8	**30**	**31.5**	**11.2**	**54.4**	**48.4**	**9.0**

Table 5: values of LiBr concentrations in the generator and in the absorber and of the relative recycle factor calculated with the simulation model.

The recycle factor f can also be directly calculated from the experimental values of the solution temperature at the inlet and outlet of the absorber and generator, by applying the energy balance to the solution exchanger.
As can be seen from table 6, both approaches give the same value of f (about 9), thus validating the proposed simulation model.

$T_{gen.\ (°C)}$	$T_{con.\ (°C)}$	$T_{abs\ (°C)}$	$T_{ev.\ (°C)}$	$T_{sol,str.(°C)}$	$T_{sol,w.(°C)}$	*f*
59.4	**29.2**	**31.8**	**10.5**	**47,1**	**42,8**	**9,46**
59.8	**29.7**	**32**	**10.8**	**47**	**43,4**	**9,14**
62.8	**30**	**31.5**	**11.2**	**49,4**	**43,5**	**9,57**

Table 6: values of the recycle factor calculated from experimental measurements.

Thanks to the layout of the machine, the acquired data and the calculation model, it was understood how such low COP values were due to poor efficiency of the heat transfer of the evaporator, that allows only a small portion of the refrigerant to evaporate whereas the remaining refrigerant is brought to the absorber as a liquid without therefore having any cooling effect.

CONCLUSIONS

An experimental plant was created to study a single stage absorption refrigeration group with the pair Water – Lithium Bromide. Firstly, the plant, the measuring equipment and the acquisition system were set up and tested. An experimental campaign was begun which focused on analysing the plant behaviour as temperature and feeding flow rate of the hot water varied.
The results have shown how the machine shows the highest values of COP (equal to 0,40-0,45) at temperatures around 70°C, thus making it possible to work this machine with solar collectors.
The future developments of the research will therefore focus on the design and realization of a solar collector plant to supply the machine and the relative implementation of the calculation model.

NOMENCLATURE

COP	= Coefficient of performance	(-);
f	= recycle factor	(-);
G	= flow rate	(m^3/s);
Q	= heat power	(kW);
T	= temperature	(°C);
X	= concentration of LiBr	(%)
γ	= specific heat	(J/kg K);

Subscripts

in	= inlet;
out	=outlet;
h	= hot;
c	= cooling;
r	= refrigerated
ev	= evaporator;
con	= condenser
abs	= absorber;
gen	= generator;
sol	= solution;
str	= strong;
w	= weak.

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UNE INSTALLATION EXPERIMENTAL POUR EVALOUER LES PERFORMANCES D'UN REFRIGERATEUR A ABSORPTION

Une installation experimentale avec un refrigerateur a absorption a Eau-Bromide de Lithium a été realisé pre le Laboratoire de Tehrmodynamique de l'Université de Perouse, Italie. Les données experimentales sont examiné pour differentes conditions operationelles et les performances de la machine sont calculées.