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A solar-driven ejector refrigeration system for Mediterranean climate: Experience improvement and new results performed

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Abstract

The need for air-conditioning in the Mediterranean countries is higher and higher due to the effects of global warming. This paper deals with an investigation of a high performance, solar-driven air-conditioning system, the project entitled "Mediterranean AIRCOND", is funded by the European Community under the 'Community Activities in the Field of the specific program for RTD and demonstration on "Energy, Environment and Sustainable Development".

"AIRCOND" aims to study and investigate performances of advanced solar driven air conditioning system; the field system is composed of three sub systems: the heating loop, the ejector cycle and the cold storage-air handling units: The heating loop is composed of a solar array of 60 square meters evacuated tube solar collectors; installed at a tilt angle of 45^{o} and facing to south, a 3000 L tank which is used as hot water storage in order to cover the required energy by the ejector cycle. The cold water produced by the ejector cycle will be then transferred in a 900L cold storage tank filled with 800L micro-encapsulated phase change material (MEPCM) for cold storage. It is designed to meet the dynamic cooling load.

The ejector was tested at the School of the Built Environment in the University of Nottingham in UK and then transferred to Tunisia for field evaluation.

Many previous theory studies have been fulfilled on this technology but never been performed experimentally at this level. This paper presents the research effort made and the experience gained during the implementation of the whole system: Different operation strategies were followed during more than one year to make the ejector cycle functional. The whole procedure has turned out to be very difficult; it was particularly difficult to obtain a deep vacuum and to ensure a good vacuum quality; this is a necessary working condition for the ejector cycle. Successful ejector tests

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were obtained during 8min, 15min and 40 min, after many investigations; later experiments led to 3 hours of continuous working. Results are very promising; the installation is still under tests in order to obtain a whole day permanent working of the ejector cycle and so of all the solar installation.

Keywords : Solar cooling; Ejector cycle; Vacuum process; Evacuated tubes solar collectors; AIRCOND Project

1. Introduction

Solar cooling technology is one of the most investigated researches in the solar applications field systems. The development, the dissemination and the evaluation of that area are subject to many studies; many solar cooling paths had been investigated, the required power for the operating temperature needed depends on the estimated cooling demand. For air conditioning, food and vaccine storage, solar thermal collectors provide the appropriate cooling system with the required power; meanwhile PV systems could also be another alternative for powering refrigeration systems. For air conditioning application, solar cooling systems using absorption cycle is one of the most used technologies thanks to its relatively good COP comparing to Dessicant, Ejector and Rankine cycles; COP can reach 0.6-0.7 [1], G.A. Florides et al [2] simulated and presented a total equivalent warming impact (TEWI) of a domestic-size absorption solar cooling system. the major disadvantage of this technology is that the absorption chiller cost is too high, which leads to a high total life cycle cost. Sergio colle et al [3] studied an analytical approach for the economical evaluation and optimization of absorption and an ejector cooling cycle.
The solar – driven refrigeration system using ejector cycle could constitute a compromise between cost and efficiency, although the ejector COP is low comparing to the other solar cooling paths that’s for many theoretical and numerical studies are made to optimize such a system, . The experiments conducted on this technology are very encouraging. Knowing that it works at low temperature ejector cooling cycle seems to be very promising since it can be easily driven by solar collectors and doesn’t require expensive equipments. A thermodynamics optimisation of a heat-driven refrigeration plant had been performed by Bejan.A et al [4] in order to maximise the refrigeration rate, while an experimental investigation of a steam ejector refrigerator was presented by Kanjanapon Chunnanond and Satha Aphornratana [5] in order to improve the ejector efficiency. All investigations that had been done on the solar driven ejector refrigeration system are mostly until now based on numerical modelling and simulation: Humberto Vidal et al [6] studied the hourly simulation of an ejector cooling cycle assisted by solar energy. The system was simulated using the TRNSYS program and the typical meteorological year (TMY) file. While G.K. Alexis et al [7] focused their research to investigate the performance of an ejector cooling system driven by solar energy and having R134a as working fluid, ejector performances had also represent the aim of many investigations, B.J. Huang and J.M. Chang [8] tested 15 ejectors in order to drive two empirical correlations to study the ejector performances using R141b as the working fluid, C.J. Korres et al [9] emphasise the relation between the the thermodynamic efficiency of jet compressors to the compression ratio of the corresponding cooling cycle, T. Sriveerakul et al [10]predicted the ejector performances using CFD and validated experimentally their numerical results.
Within the framework of the European research program, a solar-driven refrigeration system using ejector cooling cycle was installed in the National Engineering School of Tunis “ENIT” (Tunisia) in order to provide four offices in the school with solar cooling.
In our study, a 5kW single stage solar-driven ejector cooling system was assembled and tested, the working fluid is water. The ejector performance was evaluated for different operating conditions [11] by our partner from the University of Porto (Portugal) as well as a numerical assessment of the ejector

working using a CFD tool [12], other ejector results had been also performed by our partners from the University of Nottingham [13].
The system is driven by solar evacuated-tubes and includes a compact ejector refrigeration device and an ice-slurry using micro-encapsulated phase change material (MEPCM) for thermal energy storage, the implementation of the whole system was achieved by connecting the different subsystems: heat source loop, ejector cycle and cold storage-air handling units loop. The starting tests for the whole system had been conducted in ENIT.
This paper will present the experience gained during the system construction and will focus on the different strategies adopted to perform the ejector cooling cycle process and to make it experimentally performed by identifying experimentally the optimal operating conditions. Promising results had been obtained; the installation is still under tests for further investigations.

Nomenclature

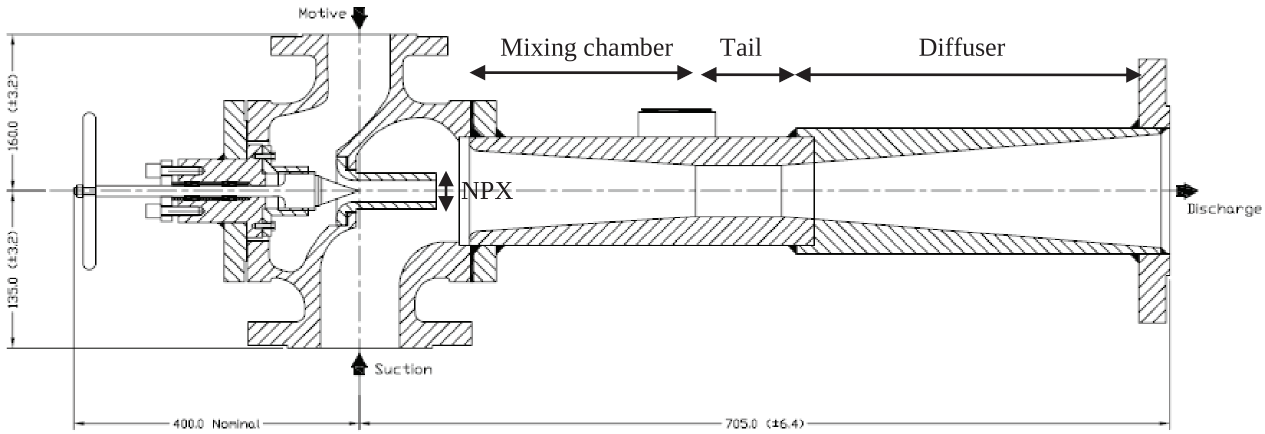
Abbreviation

COP coefficient of performance

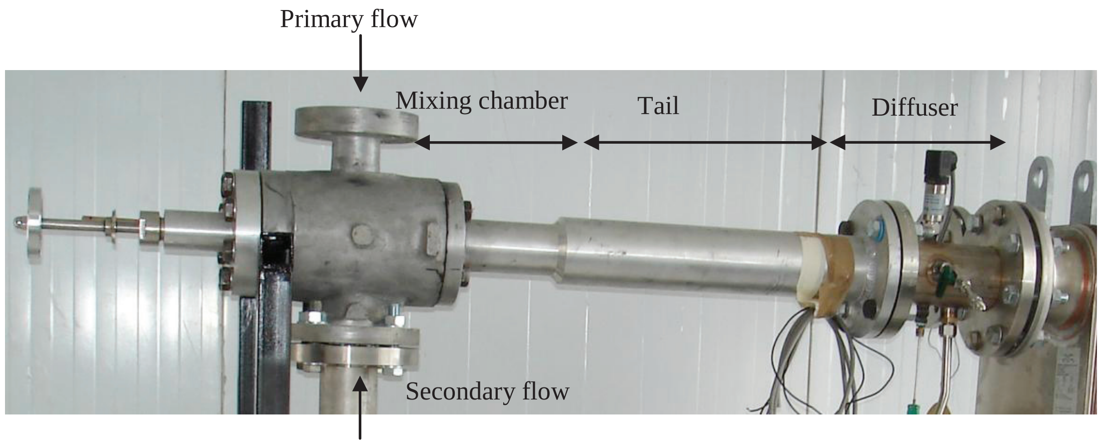
NPX nozzle exit plan

2. Ejector's geometry and flow structure

The ejector constitute the heart of the system since it keeps the refrigerant flowing, (which is the water vapour in our case), at fixed value of flow rate and at specific pressure. The ejector task in our system is comparable to the compressor function in a compression cooling system. The electrical power used to feed the compressor is replaced by the heat source in our case. The heat storage provides the ejector with a primary (or also named a motive) flow, in order to induce a secondary flow charged with calories to be discharged in the condenser. The ejector is composed of a primary nozzle, a mixing chamber, a throat and a diffuser as described in fig.1.(a). Fig.1.(b) shows the 5KW ejector used in this study before assembly. The primary flow enters the ejector at high temperature and high pressure, the superheated steam accelerates and expands through the primary nozzle, at the outlet of the NPX, this flow spreads out with a supersonic speed and creates a low pressure region, the secondary flow is then entrained into the mixing chamber. In the beginning the two fluids don't choke till the entrained flow rise to sonic value, once choked, the mixing process begins and causes the primary flow to be delayed whilst secondary flow is accelerated, at the end of the mixing chamber domain, the two flows are completely mixed, a shock wave takes place at the level of the throat due to the high pressure downstream of the mixing chamber throat. This shock causes a big compression effect in the diffuser where the compression of the flow to be discharged is achieved. [14]



(a) Ejector geometries [15]



(b) Ejector picture before assembly

Fig.1. Ejector schematic view and characteristics

3. Estimation of building air-conditioning load

An hourly TRNSYS [16] simulation has been conducted for the different offices of the laboratory, fig.2. shows the Trnsys model which has been used to calculate the cooling load of the building. The local metrological data of Tunis have been used. The hourly thermal load of each office has been calculated and sorted increasing ling. For each value of the thermal load, the number of corresponding hours has been calculated. A cumulative frequency curve has been plotted for each office as shown in fig.1. to fig.4.

the design load for each office has been selected as the value for which the building load is covered at least during 95% of the cooling period.

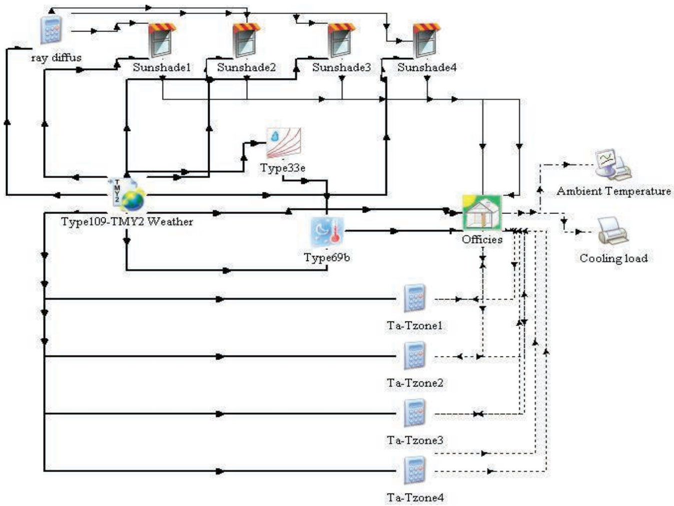
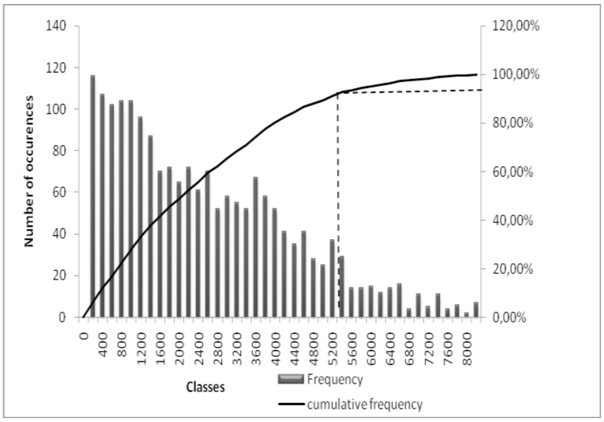
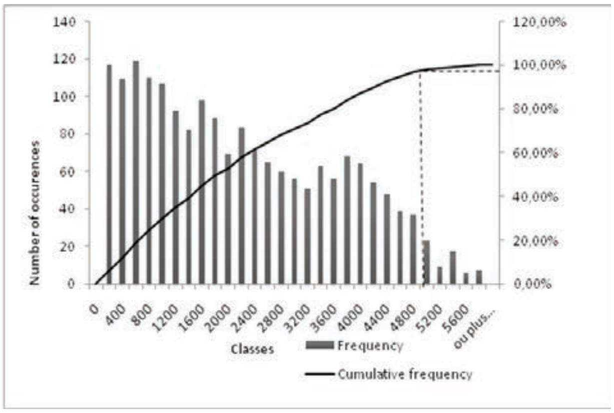


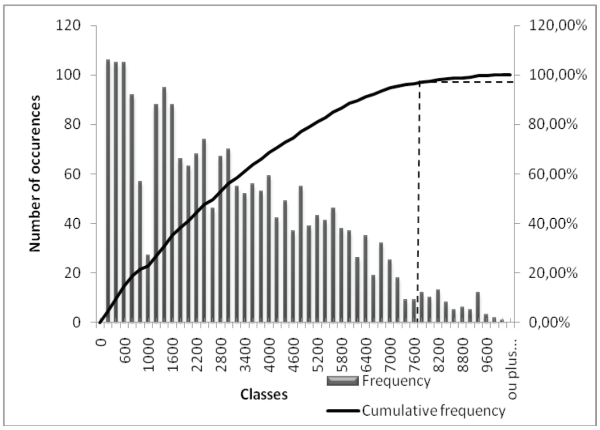
Fig.2. Trnsys model for cooling load estimation



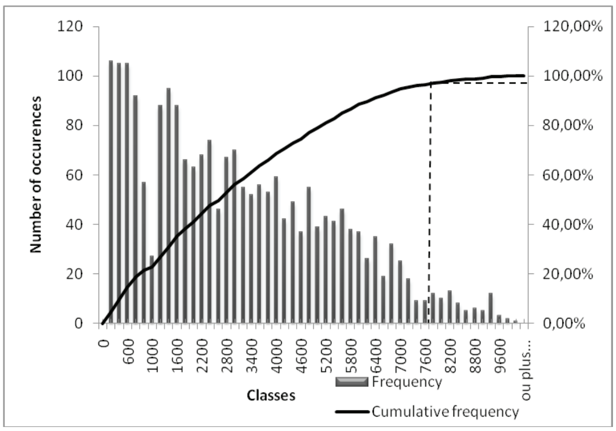
(a) Histogram of office N°1



(b) Histogram of office N°2



(c) Histogram of office N°3



(d) Histogram of office N°4

Fig.3. Cooling load required for each office

The cooling capacity needed for offices 1, 2, 3 and 4 are respectively 1.33KW, 1.72KW, 1.66KW and 1.66KW. Four cooling coils of 2.5 KW capacities each had been installed in the offices.

4. Experimental setup and field testing system

The field system is composed of three subsystems as described in fig.4. : a heat loop, an ejector cooling cycle that have to be vacuumed, a cold storage and an air handling unit to provide the offices with coolness.

The heat storage is continuously loaded with hot water during the days' hours, stored water subsequently feeds the generator with heat in order to produce saturated vapor which becomes superheated vapor once crossing the super heater. This vapor constitutes the motive flow also called primary flow at the ejector inlet; the heat extracted from the water contained in the evaporator is released in a condenser. For our prototype a 15KW chiller is used to cool the condenser. It is intended to substitute this system by a ground heat exchanger and a cooling tower, the condensed water is divided between the evaporator and the generator to feed them again.

4.1. The heat source loop

The heat source loop is composed mainly of 60 m^2 evacuated tubes solar collectors and 3000L heat storage tank and A 7 KW resistance acting as an auxiliary heater; the solar collectors are installed in six sub arrays of four collectors each. Each collector is made of 24 Deward evacuated tubes facing to south and having a tilt angle of 45°. A second 200 L tank can be connected either in series or in parallel to boost the heating process and provide instantaneously the ejector loop with hot water when needed.
A 3 speed double circulator pump ensures the water circulation between the solar collector and the water storage tank. A second similar pump is installed for the circulation of the thermal fluid between the hot storage tank and the boiler.
Total incident solar radiation on the collectors' surface is measured by a pyranometer having a sensivity of 13.92 ×10-06 V per W/m^2, it is connected to a data acquisition program driving a data logger which measures the most significant data every time step. The different measurements (Pressures, temperatures and flow rates) are recorded every 1 minute: Temperature is recorded at 28 different points of the solar heating system; at the inlet and outlet of the collectors' sub arrays, as well as at the inlet and outlet of hot storage tank. Temperature sensors are also located at the inlet and outlet of the cold storage tank and air handling units.

4.2. The ejector cooling cycle

This loop is mainly composed of:

- A generator to provide saturated vapor. At its top is connected a steam drum to produce super heated vapor to avoid water droplets at the ejector inlet. The temperature difference between the super heater vapor and the saturated vapor is 10°C, the vapor flow has to be controlled and stabilized in such way to keep a temperature difference of 10°C between the vapor temperature and the superheated vapor temperature.
- A 5 KW ejector described previously
- A 10KW condenser to discharge the extracted calories.

• An evaporator which constitutes the cold production core; the cold water produced at the evaporator outlet will be transferred to the cold storage tank.

4.3. Cold storage and air handling units

A 900 L cold storage tank has been installed, filled with 800 L of micro-encapsulated phase change material MEPCM (Ruitherm RT6 and Linpar 14) that has been prepared by Ciba Chemicals [17] PCMs has been tested experimentally and its thermophysical properties have been measured for use in the proposed cooling system [13] , the cold storage tank provides air handling unit with cold water to cool the ambiance.

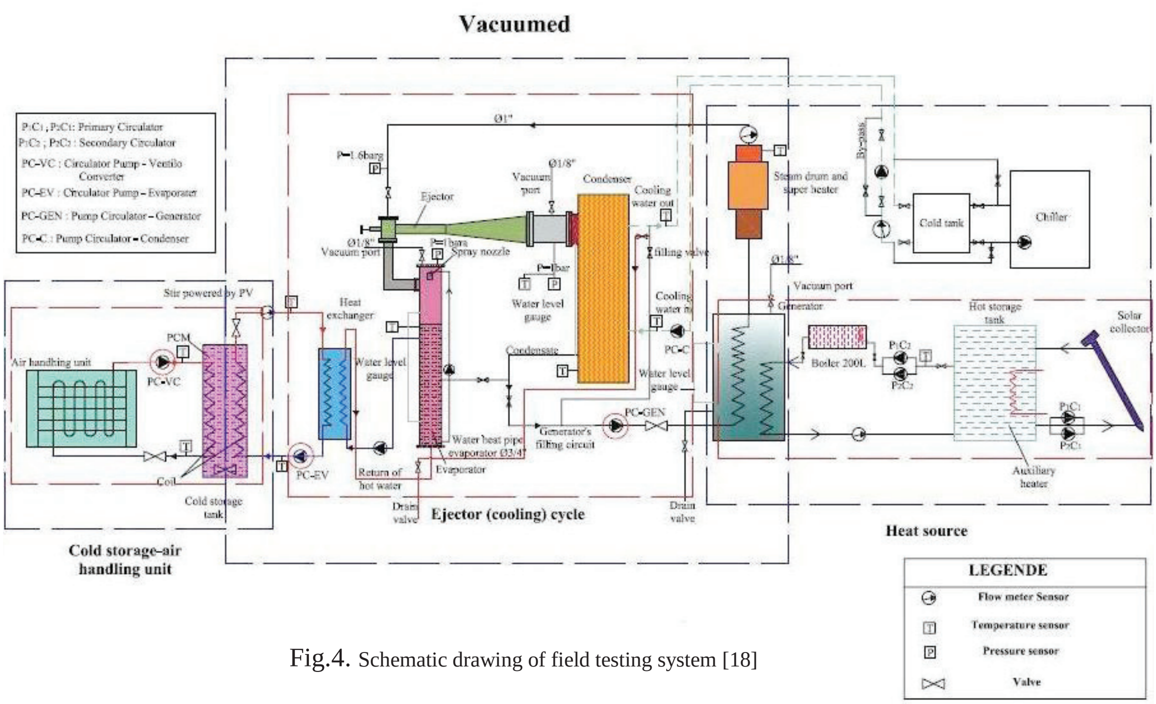
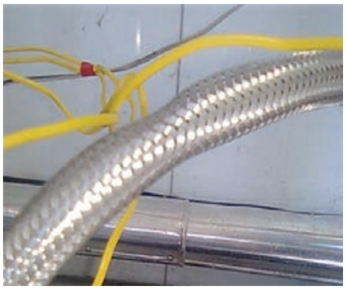


Fig.4. Schematic drawing of field testing system [18]

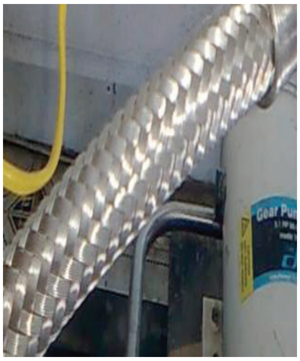
5. Vacuum process

The vacuum in the ejector cycle allows the liquid inside the ejector cycle to evaporate at low temperature. Therefore this part needs to be vacuumed before it starts to work. The connections and the welding should not have any leakages in order to keep the vacuum. The leakages are controlled by pressure sensors located along the circuit. The vacuum is tested using the pressure sensor to measure how low the pressure can be and how long it can be kept; pressure rise should not exceed 4 mbar/hr.

Once the installation is ready we couldn't reach a deep vacuum, serious problem with leakage were detected: pressure couldn't go under 30 mbarg, and the pressure loss was too high. After long investigations we realized that some of the installed valves were leaking; these values are not appropriate since their tightness is ensured if a continuous fluid flow is occurring. In our case, vacuum is performed and hence, the tightness clap is aspired inducing a leakage. Those values have been replaced by appropriate stainless steel values designed for vacuumed circuits. Some imperfections in welding stainless steel valves with copper pipes have been observed as well as a problem detected with some flexible hoses (as shown in fig. 5. (a)) which collapsed because these were made of plastic, all these problems caused leakage too. The vacuum problems took a lot of time to be solved, because of the complexity of the cycle and the difficulty to detect the leakage; the solution proposed was to change the existing valves with others especially made for vacuum application. We managed to replace the copper vacuum circuit by stainless steel one and the plastic flexible hoses by metallic one as shown in fig.5. (b). A 10KW flat plate heat exchanger had been added between the cold storage and the evaporator to avoid leakage due to the long distance separating them. The ejector cooling cycle had been thermally insulated using 50 mm glass wool layer around the heat generator, steam drum and primary flow pipes. The cold parts had been covered with 50 mm polyurethane layer.



(a) Plastic flexible hoses collapsed at vacuum



(b) Metallic flexible hoses unharmed at vacuum

Fig.5. Flexible hoses before and after alteration

Fig.6. shows the experimental setup of the ejector cooling cycle once all modification done, the vacuum tests' were successful. The pressure went down to 12 mbar, fig.7. shows the pressure rise versus time during 24 hours, sealing is ensured in the ejector cycle, the pressure rise was about 1.9 mbar/hr, comparing to vacuum test done at the laboratory of the university of Nottingham [7] and knowing that those tests were made at a small-scale in order to establish only the ejector performance, vacuum results of the ejector cycle connected to the whole system predicted the implementation of the solar ejector cooling cycle .

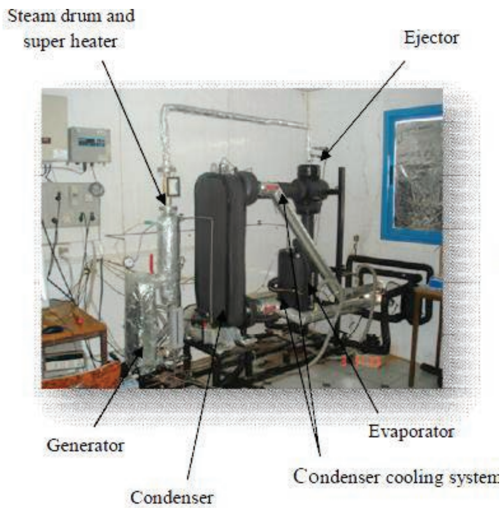


Fig.6. Experimental setup of the ejector cooling cycle

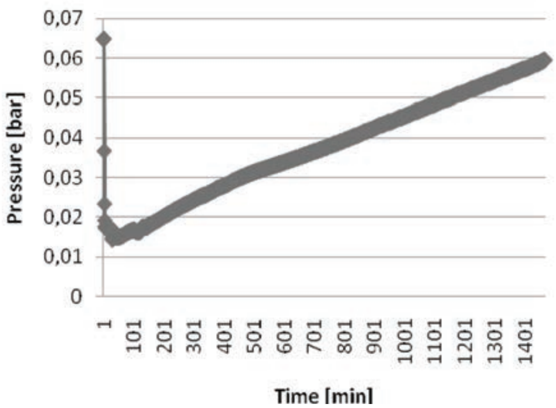


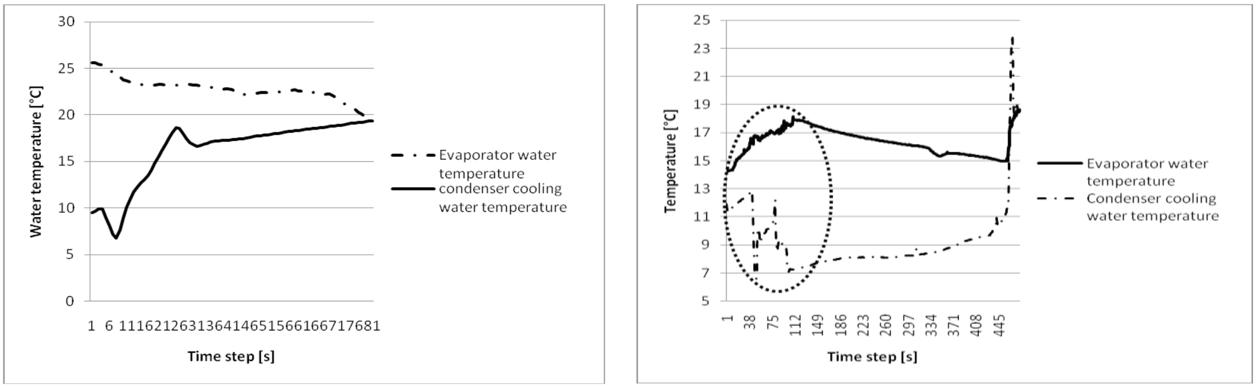
Fig.7. Vacuum test down to 12 mbar and pressure rise of 1.9 mbar/hr

6. Ejector cooling cycle tests

During the first test we did not succeed to keep a stable value of saturated vapor pressure whereas all operating conditions were suitable for a good test, we didn’t suspect a failure in the pressure sensor because it was a new one. After changing the pressure sensor, the second test was more successful, pressure drop in the condenser was about 14 mbar, the saturated water vapor varied from 0.5 to 0.6 barg, the “temperature-pressure” couple for saturated water production was continuous during 15 minutes and the water temperature decreased from 28°C to 15°C, to ensure a longer working period we need to keep a constant temperature at the inlet of the condenser cooling loop. This can be ensured by a powerful chiller.

The third test was successful for 35 minutes; the saturated water pressure was stable during the entire test’s time, since a deep vacuum has been reached (condenser pressure=2.5 mbar). Fig.8. (a) shows that the test stops when the condenser cooling temperature coming from the chiller reaches the cold water temperature produced in the evaporator; the chiller is no more able to cool the condenser. These three first tests permitted us to identify experimentally the operating conditions of the ejector cycle once assembled with the other loops of the installation, and to be aware about the importance of the condenser cooling cycle and so the chiller performance needed as well as the condenser pressure.

During the 4th test we managed to clean a component in the evaporator allowing spraying water, this component provides water droplets to make evaporation easier at the inlet of the ejector’s suction, this equipment maintenance had shown that the spray device was jammed with impurity contained in water. Once cleaned, the water spray function turns on again. A second 200 L tank was also connected either in series or in parallel to boost the heating process and provide instantaneously the ejector loop with hot water in order to produce continuously saturated water vapor. Fig.8. (b) describes the successful ejector cooling cycle function during 3 hours; we observe an increase of water temperature during the first 45 minutes, this phenomenon coincides with an instability of the condenser cooling water temperature, than the cold water temperature produced was stable during 3 hours between 7°C and 13°C. This result shows the importance of condenser cooling cycle efficiency and its effect on condenser pressure.



(a) Schematic view of the 3rd test

(b) Schematic view of the 4th test

Fig.8. Cold water temperature produced Vs condenser cooling water temperature

7. conclusion

In the present study, a solar-driven refrigeration system providing 5KW of cooling load had been implemented and experimentally in the national engineering school of Tunis, the ejector test was performed in the University of Nottingham where its operating conditions had been determined, once in Tunisia (ENIT), the entire system tests were successful: the three subsystems were connected and tested, separately at a first time and assembled in a second time. The main challenges were to succeed to have a deep vacuum in the ejector cycle to make the whole system work as predicted by the theoretical studies. The important step that has been done in this series of experiments was to have a continuous ejector working at a real scale under real operational conditions.

Further investigations could improve these results; this will be the aim of the next studies, we propose to:

- Substitute the 15 KW water chiller by a cooling tower and to use a ground heat exchanger.
- Continue the experiences for different operating conditions and spindle positions of the ejector.
- Improve some equipments and the process in itself for a commercial exploitation of the system.
- PCM investigations in order to determine the appropriate solution for energy storage.

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