Implementation and Experimental Results of the New Thermo-Hydraulic CAPILI Pilot

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***Abstract*—After modeling and evaluating performances of the new thermo-hydraulic process "CAPILI" in the previous work, we are proposing the implementation of the first CAPILI experimental pilot in order to check the real behavior of the new patented process for a specific residential application. The obtained experimental results are extremely useful and will be harnessed in future works for analytical development of hydraulic motor resistance. Then, the validation and the calibration of the simulation method, which has been used to evaluate CAPILI performance for OTEC application, are checked. So, the CAPILI pilot will be described first. Then, experimental results will be presented and discussed.**

***Index Terms*—thermo-hydraulic process, liquid piston, residential application**

I. Introduction

The development of the human activities is inducing a growth of the energy consumption especially electricity. It is the second form of consumed energy after oil. The world electrical consumption have been passed from 6000TWh to 2000TWH during the period of 1973 to 2009 [1]. Unfortunately, the electrical production is mainly based on fossil resources at rate of 68%. Subconsciously, this has led to emission of high quantities of polluted particles causing the global warming and so, the climate change.

Nowadays, the awareness about the pollution impact on our life, our planet and our development is changing our behavior. Henceforth, to meet fossil fuel scarcity and respond to the demand of energy; we should streamline energy consumption by a widespread use of recovering heat systems [2] and improvement of systems performances [3]. Resulting issues gave birth to new thermo-hydraulic process using Liquid Piston. In reality, the concept of the liquid piston is not new. Its first application has been carried out in 1906 [4] on an internal combustion pump so called Humphrey pump wherein the force issued from the combustion acts directly on the first side of the liquid-gaz interface. This allows the displacement of the liquid on the other side corresponding to the outlet of the pump. Since, the increasing interest on liquid piston advantages for the energy conversion systems and coupling of Stirling engine systems has been crowned by different patents [5]-[8]. Among the thermo-hydraulic liquid piston systems recently patented we note; CHV3T [9] and CAPILI [10]. The first one has been designed for solar cooling [11] while the second one has been implemented either for residential [12] or for OTEC (Ocean Thermal Energy Conversion) electrical productions [13], [14]. In our previous work, the performance of CAPILI engine for an OTEC application has been studied first by considering the state energy balance for the selection of the suitable working fluid. The second step consisted on the dynamic modeling which was based in the concept of equivalent Gibbs system in order to appreciate the dynamic behavior of the CAPILI conversion process for the same OTEC application.

After the successful results obtained for the OTEC application, we are proposing in this paper the implementation of the first CAPILI experimental pilot designed for another area which is residential application. The aim is to bring out the real feasibility of the new CAPILI engine. Firstly, the experimental CAPILI pilot it described with its different component. After that, we discuss the modification that have been operated comparing to the basic configuration. Finally, we present the first experimental results obtained with the experimental CAPILI pilot.

II. Selection of the Suitable Working Fluid

A. First Step (αβ)

Characterized by a constant pressure difference applied to the hydraulic motor and corresponds to the following simultaneous transformations:

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a→b: compression of the condensed liquid by the feed pump WFP.

b→c: heating and evaporation of the working fluid in the evaporator connected to the gas inlet of the cylinder CT'.

d→e: partial condensation of the vapor flowing from the gas outlet of CT to the condenser.

B. *Second Step (βγ)*

Where the pressure difference decreases, this step corresponds to transformations:

c→d: isentropic expansion of the vapor in cylinder CT'.

e→a: end of condensation of the vapor flowing from CT to the condenser.

One should note that the process has not reached the beginning state even if the working fluid has performed a complete cycle. Therefore two complementary steps are required. These complementary steps are respectively identical to steps (**αβ**) and (**βγ**). For more details concerning the operating mode of CAPILI engine, readers are invited to consult our antecedent works [12]-[14].

The basic configuration as presented above targets residential application in European region. In this case, we planned that the CAPILI engine evaporator will be feed by a flat plat solar collector (T_{hs}=70 ℃) while the heat rejection will be performed using geothermal probe wherein the sink temperature can rises T_{cs}=13 ℃ especially during the winter seasons. Resulting heat source and cold sink temperatures allow the selection of the suitable working fluid for this specific residential application.

As mentioned in our previous work [12]-[14], This part of study is carried out with considering some simplifications, namely:

- Study state operating mode for all components
- Neglecting of kinetic and potential energies
- An ideal hydraulic motor, η_{HM}=1

The selection of the suitable working fluid has been performed by the application of the first thermodynamic law which led to express the specifics heat exchanges in evaporator (q_h) and condenser (q_l) by:

$$q_h = h_c - h_b \tag{1}$$

$$q_l = h_a - h_d \tag{2}$$

As CAPILI engine is a closed cycle system, its efficiency (η_{CPL}) can be write as:

$$\eta_{CPL} = 1 - \frac{|q_l|}{q_h} \tag{3}$$

Several fluids have been considered by the study: R21, R12, R114, R152a, R152, R600, R600a, RC318, R138, R134a, R134. So, the best working fluid for this application will be the one who gives a higher efficiency with a maximum of operating pressure applied on the hydraulic motor. In addition, criteria relating to low toxicity, safety, flammability are also took in count. The obtained results show that R134a is the best working fluid for this application. It allows getting a cycle efficiency of 13.03% with a pressure difference (ΔP) of 16.6bar and an exegetic performance of 78.46% as depicted in Fig. 1. Contrary to the OTEC application, the actual pressure difference for the residential application required rather a hydraulic motor which is more suitable for a higher ΔP and low flow rate comparing to hydraulic turbines that operate generally with low ΔP and a higher flow rate.

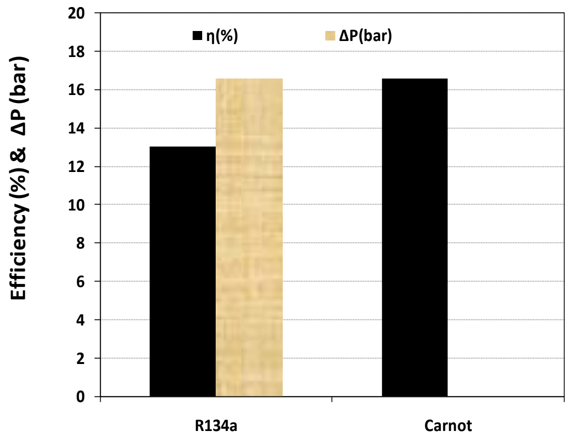

Figure 1. Efficiency and pressure difference of R134a.

III. Description of the CAPILI Pilot

The pilot has been designed for the first step experimental validation of the novel CAPILI process described below.

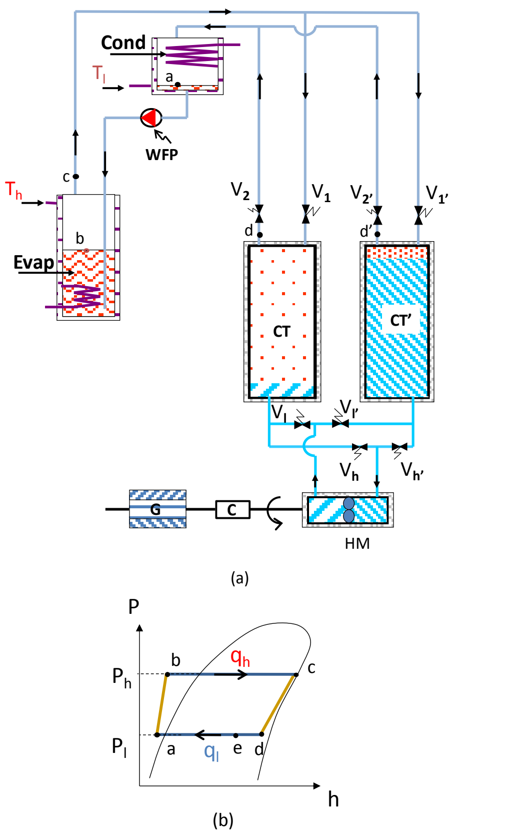

Figure 2. a) Basic configuration of 1st type CAPILI engine, b) 1st type CAPILI cycle.

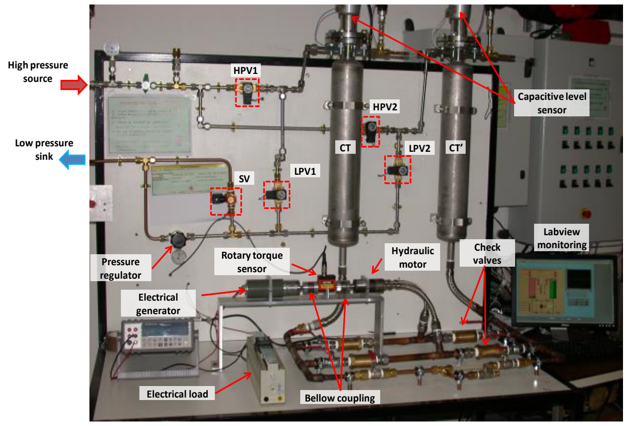

Figure 3. 1st type CAPILI experimental pilot.

So, for the implementation of the 1st type CAPILI engine experimental pilot two major modifications have been operated comparing to the basic configuration (Fig. 2). These modifications consist to replace respectively evaporator and condenser by a high pressure source (N2) and a low pressure. Resulting modifications have been performed firstly to focus on the hydraulic part for checking the behavior of the hydraulic motor and the different steps of the CAPILI cycle (**αβ** and **βγ**). Secondly, the technological development and dynamic modeling of both evaporator and condenser has been well controlled by Martins [15]. In fact, the whole experimental pilot as shown in Fig. 3 is composed of:

- 2 capacitive level sensors
- 4 electrical valves for working fluid monitoring
- 2 security valves
- An orbital hydraulic motor (OML8) to produce mechanical power
- A rotary torque sensor for the measurement of Hydraulic Motor (HM) rotary speed and generated torque
- 2 bellows coupling
- An electrical generator to convert mechanical power into electricity
- A pressure regulator to adjust the low pressure
- 4 check valves for the hydraulic part
- Mineral oil acting as liquid transfer fluid

The whole CAPILI pilot is monitored using Labview software. The chronological activating of the different valves during the operating CAPILI process is resumed in the following Table I.

TABLE I. CHRONOLOGICAL ACTIVATING OF VALVES (O: OPEN, C: CLOSE)

Cylinder	Phase	VHP2	VBP2	VHP1	VBP1
CT'	αβ	O	C	C	O
	βγ	C	C	C	O
CT	γδ	C	O	O	C
	δα	C	O	C	C

IV. RESULTS AND DISCUSSION

As well as, we are intending to show the feasibility of the novel CAPILI process. We are going to interest only on the qualitative discussion concerning the obtained results. The experimental results will be used to develop analytical approach; especially the hydraulic motor resistance in the case of residential application which consist to harness a hydraulic motor instead of hydraulic turbine for OTEC application.

For the residential application, we have adjusted the high pressure source (N2 gas cylinder) and low pressure sink in order to obtain the same condition if real evaporator and condenser have been used ie: $P_h \approx 21$ bar and $P_l \approx 5$ bar leading to a total pressure difference $\Delta P \approx 16$bar. Also, the electrical load (Rc) has been fixed at Rc=7Ω.

Under these operating conditions, the first obtained results allow to show the evolution of the hydraulic liquid flow rate (Q) and the ΔP operated on the hydraulic motor (Fig. 4). The different steps, αβ and βγ, can be easily distinguished. The former one is characterized by a constant difference of pressure that reach 15 bar while ΔP_{mot} is decreasing during the step βγ until a value of about 7bar. Therefore, the hydraulic flow rate (Q) moving alternatively between the cylinders CT' and CT is estimated from 7 to 8l/min during the first step, then it drops until 3.5l/min at the end of βγ step. We observe also that step αβ lasts only 13s however, βγ step is almost two times much longer about 24s.

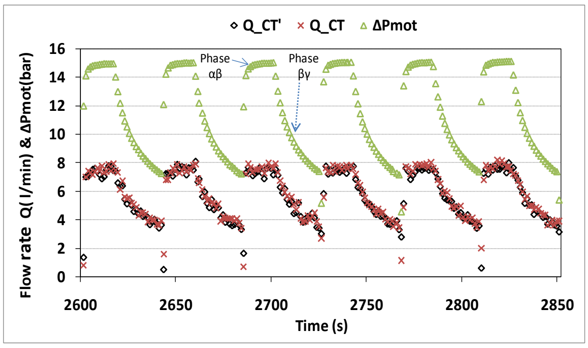

Figure 4. Evolution of flow rate and pressure difference during the CAPILI cycles steps.

At the same time, the maximum hydraulic power is generated during the step αβ but the conversion into mechanical power is seriously affected. We are estimating that only 40% of hydraulic power is converted which means a ratio of 60% of losses across the hydraulic part (Fig. 5). After that, the mechanical power is transformed into electricity by the electrical generator. The generated electrical current during the phase αβ is characterized by a voltage of 28V while the intensity is close to 2.8A (Fig. 6). That leads to a higher electrical power of 55W during the step αβ which still reducing until 15W at the ending of βγ (Fig. 5). We also denote the lost power due to mechanical conversion which is mainly caused by the bellows coupling and especially the speed increasers components integrated the electrical generator.

We have to highlight, here, that the conversion line of the hydraulic power into useful electrical power has seriously affected the whole efficiency of CAPILI pilot. Resulting issues can be mainly explained by the fact of even with ΔP_{mot} of 15 bar, the hydraulic motor still far from its design load. Consequently, its efficiency was only 40% conducting to lose 60% of hydraulic energy. Also, other energies lost have occurred in the coupling and speed increaser component. Nevertheless, the obtained results still of great interest because it allowed to highlight the feasibility the CAPILI process for a specific residential application. Next step consists in the development of the analytical hydraulic motor resistance in order to perform the dynamic modeling for this application.

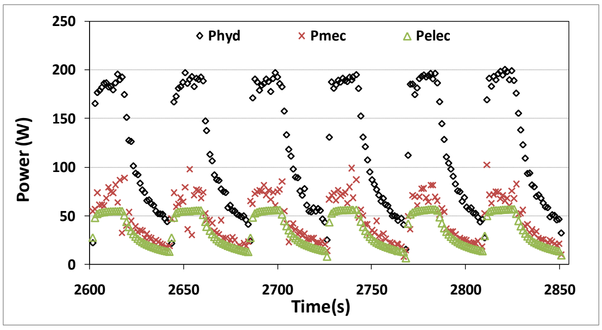

Figure 5. Powers evolution for the experimental CAPILI pilot, at ΔP_{mot}= 15 bar and Rc=7Ω.

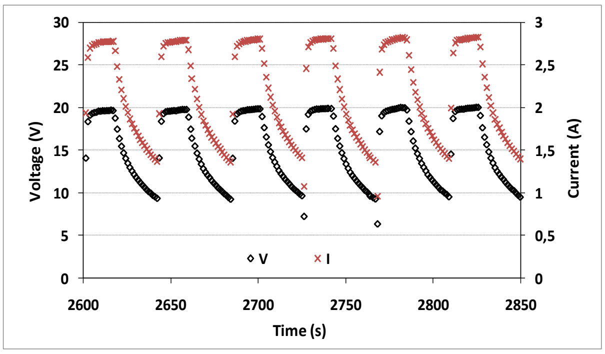

Figure 6. Characterization of generated electrical current.

V. Conclusions

The validation of the CAPILI process has been performed during this study. An experimental pilot corresponding to the 1st type CAPILI engine has been implemented. The experimental study targeted a residential application, which use a flat plat solar collector as hot source at 70 ℃ and a geothermal probe for the clod sink at 13 ℃. According to the selection criteria mentioned above, the energy balance at steady state has conduct to selected R134a as suitable working fluid for this specific application.

After that, the experimental study has been engaged. Based on the selection study of R134a, pressure operating conditions of the experimental pilot have been fixed at $P_h \approx 21$ bar and $P_l \approx 5$ bar leading to a total pressure difference $\Delta P \approx 16$bar. For an electrical load of Rc=7Ω, we were able to distinguish easily the different steps of CAPILI engine. It was observed that step αβ take 13s and deliver a maximum electrical power of about P_{elec}=55W. However, the step βγ is much longer (24s) and the generated power decreases continually until reaching 15W and the end of this respective phase. We have highlighted also an important lost of the conversion line from hydraulic power (P_{hyd}) into electrical power. The main lost has been located in the hydraulic motor where the conversion performance from hydraulic to mechanical (P_{mec}) power was 40%. Resulting issue is explained by the fact that hydraulic motor was far from its design load.

Even so, the experimental results present a great interest because its demonstrate the technical feasibility of the novel CAPILI engine for the specific residential application. The continuity of this work will focused on development of an analytical model for the hydraulic motor resistance. After than the experimental development can be extended to the implementation of a small size OTEC plant.

Acknowledgment

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References

[1] *Key World Energy Statistics*, International Energy Agency IEA, 2013.
[2] Z. Zsigraiova, G. Tavares, V. Semiao, and M. G. Carvalho, "Integrated waste-to-energy conversion and waste transportation within island communities," *Energy*, vol. 34, pp. 663-635, 2006.
[3] W. Fratzscher and K. Stephan, "Waste energy usage and entropy economy," *Energy*, vol. 28, pp. 1281-1302, 2003.
[4] H. A. Humphrey, "An internal-combustion pump, and other application of a new principle," *Proceedings of the Institution of Mechanical Engineers*, vol. 77, pp. 1075-1200, November 1909.
[5] J. Gerstmann and Y. Friedman, "Liquid piston heat-actuated heat pump and methods of operating same," US patent 4148195, 1979.
[6] D. R. Culter, "Liquid piston heat pump," US patent 4501122, 1985.
[7] D. L. Howard, "Liquid piston heat engine," US patent 5195321, 1993.
[8] R. Conde and D. Faroughy, "Fluidic-Piston engine," US patent 6568169, 2003.
[9] S. Mauran, N. Mazet, P. Neveu, and D. Stitou, "Plant for production cold, heat and/or work," WO2009144402, December 3, 2009.
[10] S. Mauran, N. Mazet, P. Neveu, and D. Stitou, "Installation and method for production of cold and/or heat," WO2010109143, September 30, 2010.
[11] M. Martins, S. Mauran, D. Stitou, and P. Neveu, "A new thermal-hydraulic process for solar cooling," *Energy*, vol. 41, pp. 104-112, 2012.
[12] S. Mauran, M. Martins, D. Stitou, and H. Semmari, "A novel process for engines or heat pumps based on thermal-hydraulic conversion," *Applied Thermal Engineering*, vol. 37, pp. 249-257, 2012.
[13] H. Semmari, S. Mauran, and D. Stitou, "A novel Carnot-based heat engine for OTEC application," in *Proc. Conf. CET-IEEE*, Shanghai, China, October 2011.
[14] H. Semmari, D. Stitou, and S. Mauran, "A novel Carnot-based cycle for ocean thermal energy conversion," *Energy*, vol. 43, pp. 361-375, 2012.
[15] M. Martins, "A thermody-hydraulic process applied for residential solar cooling: Thermodynamic analyse and optimization," Ph.D thesis, University of Perpignan, Via, Domitia, 2010.

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