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Comparison between metal hydride pumps with and without phase change material

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***Abstract*—Metal hydrides (MHs) can react reversibly with a large amount of hydrogen under certain conditions. They are used not only as hydrogen storage carriers but also as energy conversion materials in many applications such as thermal sorption compressor [1], heat pumps [2-3-4], cooling system [5], and water pump systems. The present work is devoted to compare a metal hydride pump (MHP) to a metal hydride pump equipped with a phase change material (MHP-PCM). The governing equations describing the dynamic behaviour of these two pumps were established and a computer code was developed. Using this code, a comparison between MHP with and without PCM was carried for different heat transfer coefficient, total head, expansion gear ratio and absorption temperature.**

***Keywords*— Metal hydride pump, phase change material, pumping time, pump efficiency**

I. INTRODUCTION

Metal hydrides are promising materials for water pumping application. The metal hydride pump operates in autonomous mode without the consumption of electric power and fossil energies then it can be used in certain freestanding regions. Many alloys where used and compared for a water pumping system [6, 7, 8, 9, 10, 11]. Studies have shown that depending on the alloy used and depending on the operating condition, metal hydride pump (MHP) can pump an acceptable volume of water, but with a low efficiency and a long pumping time. So that, a new concept of pump has been studied to improve the pumping time and the pump efficiency. MHP requires an important amount of heat to desorb hydrogen for each cycle, then an enormous quantity of energy is lost and consequently a decrease in the pump efficiency. In contrast, for the new concept of pump: metal hydride pump equipped with a phase change material, the heat released during absorption of hydrogen is stored in the PCM and then released during desorption stage, thus an improvement in the pump efficiency. Then, this paper is devoted to compare theses two pump (MHP and MHP-PCM) using unsteady model. At first, a mathematical model is presented to predict the coupled heat and mass transfer within the MHP and MHP-PCM. Then, simulations were devoted to compare these two pumps for different: heat transfer coefficient, total head, expansion gear ration and absorption temperature.

II. OPERATING CONCEPT OF MHP AND MHP-PCM

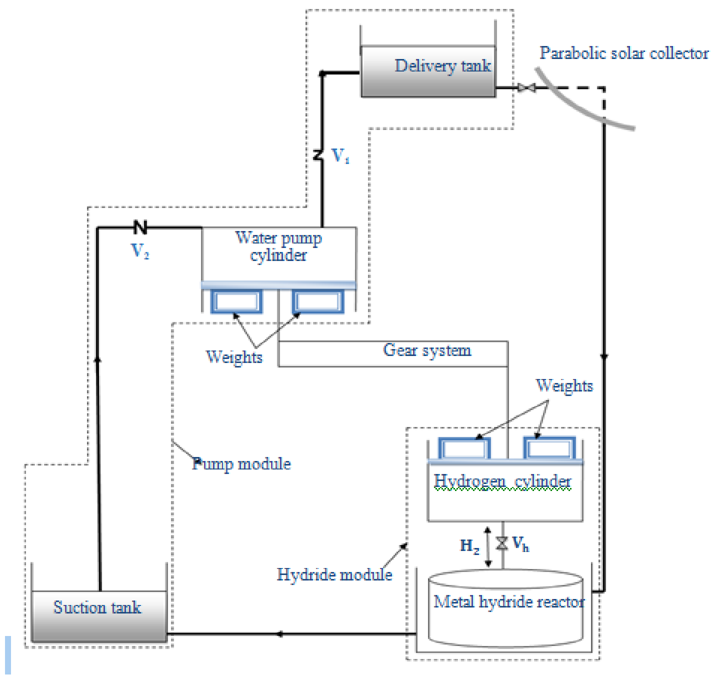

Fig. 1 Metal hydride pump

The MHP and MHP-PCM are composed both of two modules: Hydride module (metal hydride reactor, a frictionless piston cylinder arrangement with dead weights) and a pumping module (frictionless piston cylinder arrangement with dead weights, two tanks: one for suction and the other for delivery), these two modules are connected by a gear system. The difference between these two pumps resides in the metal hydride reactor. For the MHP, the reactor contains only a metal hydride, but for the MHP-PCM the reactor contains a metal hydride and a phase change material.

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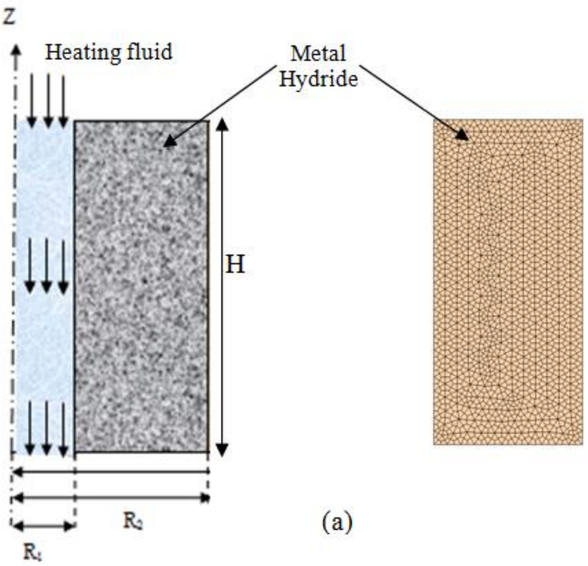
For the operating concept, the difference appears in the manner of providing the heat. For MHP, heat is provided by the concentric heat exchanger connected to the parabolic solar collector during the desorption process and during the absorption process heat released is lost for each cycle. In contrast, for the MHP-PCM heat is provided by the latent heat of solidification of the PCM and through the concentric heat exchanger during the hydrogen desorption. And during the absorption process, the heat generated by the hydride bed is stored in the PCM in order to be used in desorption stage. During these two process (absorption and desorption), the phase change material undergoes a phase transformation to store or release heat.

Initially, for the two pumps, the reactor is full of hydrogen and the gear system has an appropriate desorption gear ratio (G_{de}). Then, during hydrogen desorption, pressure inside the reactor increases. When this pressure exceeds the required pressure set by the gear ratio, the hydrogen and pump piston start moving causing the pump of water. At the end of desorption, the valve V_h is closed, heat is no longer provided and the gear ratio is reset to a lower ratio (Ge). Then less pressure in the hydrogen cylinder is sufficient to pump more water. At the end of expansion process, the gear system is disengaged, the valve V_h is opened and absorption process begins. During hydrogen absorption, the hydrogen and pump piston moves respectively inwards and outwards to suck water from suction tank through one-way valve-V2.

III. Configurations of MHP and MHP-PCM

Metal hydride reactors and unstructured meshes of MHP and MHP-PCM considered in the present paper are presented in figure 2. The first configuration (C1) presents the reactor of the metal hydride pump (MHP). It is composed of two coaxial cylinders (Fig. 2a). The inner one has a radius R1 and represents a convective heat exchanger. The external cylinder has a radius R2 and it is filled with one kg of hydride powder (LaNi5).



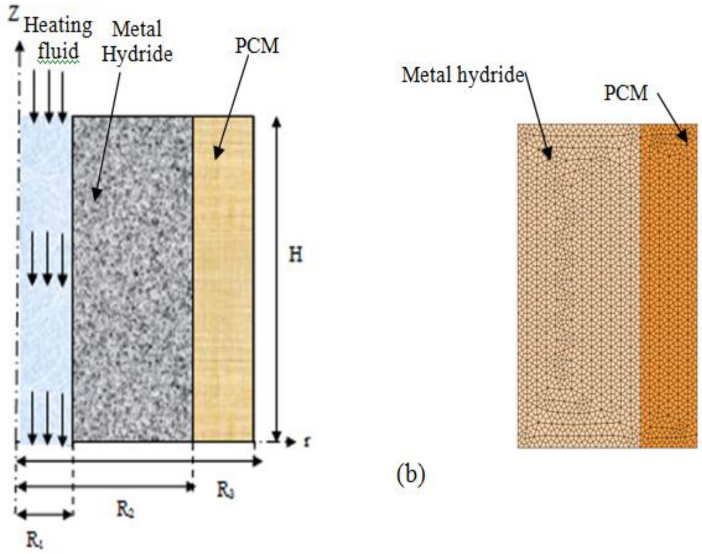


Fig. 2 Schematic diagram of the metal hydride reactor of (a) MHP (C1:without PCM) and (b) MHP-PCM (C2 :with PCM).

The second configuration (C2) presents the reactor of the metal hydride pump equipped with a phase change material (MHP-PCM), it is composed of three coaxial cylinders. The inner one has a radius R1 and represents a heat exchanger. The second cylinder has a radius R2 and it is filled with one kg of LaNi5 powder and the external cylinder has a radius R3 and it is filled with 0.6 Kg of Ba(OH)2-8H2O as a phase change material. During the hydrogen absorption, the heat released is stored by the PCM, then, it will be reused to desorb hydrogen during pumping process (Heat is absorbed or released when the PCM changes from solid to liquid and vice versa). The table 1 presents the geometrical parameters of the two reactors.

TABLE I
GEOMETRICAL PARAMETERS OF THE TWO REACTORS

Configuration	Parameter	Value
C1	Volume occupied by the hydride, (V_{LaNi5}) Height of reactor, H Inner radius of the reactor, R1 External radius of the reactor, R2	$2.439*10^{-4} m^3$ 6 cm 1cm 3.73 cm
C2	Volume occupied by the hydride,(V_{LaNi5}) Volume of PCM Height of reactor, H R1 R2 R3	$2.439*10^{-4} m^3$ $29.1*10^{-5} m^3$ 6 cm 1 cm 3.73 cm 5.4 cm

IV. Mathematical model

A. Metal hydride bed(MHP and MHP-PCM)

The energy equation in the metal is given by:

$$\left(\rho C_p\right)_e \frac{\partial T}{\partial t} = \lambda_e \frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) + \lambda_e \frac{\partial}{\partial z}\left(\frac{\partial T}{\partial z}\right) + \dot{m}[\Delta H + T\left(C_{pg} - C_{ps}\right)]$$

The mass conservation equations is expressed as:

- Hydrogen:

$$\varepsilon \frac{\partial \rho_g}{\partial t} = -\dot{m}$$

- Hydride:

$$(1-\varepsilon)\frac{\partial \rho_s}{\partial t} = \dot{m}$$

During hydrogen desorption , $\dot{m}$ is given by [12]:

$$\dot{m} = \rho_s C_d \exp\left(-\frac{E_d}{RT}\right)\left(\frac{P_g - P_{d,eq}}{P_{d,eq}}\right)$$

The desorption equilibrium pressure is expressed as:

$$P_{d,eq} = f\left(\frac{H}{M}\right) exp\left(\frac{\Delta H}{R_g}\left(\frac{1}{T} - \frac{1}{T_{ref}}\right)\right)$$

B. Phase-change material (**<u>specific to MHP-PCM</u>**)

The energy equation of the phase change material based is as follows [13]:

$$\left(\rho_{PCM}\, C_{p\,PCM}\right)\frac{\partial T}{\partial t} = \lambda_{PCM}\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) + \lambda_{PCM}\frac{\partial}{\partial z}\left(\frac{\partial T}{\partial z}\right) - \rho_{PCM}\, L\frac{\partial (f)}{\partial t}$$

The liquid fraction is expressed by:

$$f(T) = \frac{1}{1+e^{-2K(T-T_m)}}$$

Where:

$\lambda_{p,PCM}$, $\rho_{p,PCM}$, $C_{p,PCM}$ and L are respectively the thermal conductivity, the density, the specific, the latent heat of the PCM.

Tm is the melting temperature

K is the sharper transition at T = Tm.

C. Pumping system (MHP and MHP-PCM)

During desorption process, the pressure inside the reactor after any time interval (*dt*) is given as follows:

$$P(t) = \frac{(n(t)+n_0)R_g\, T_{moy}}{V_0}$$

Where:

n_0 is the initial number of hydrogen $n_0 = \frac{P_i\, A_h\, Z_0}{R_g T_i}$

n(t) is the number of moles of hydrogen desorbed, given by:

$$n(t) = \frac{HM_{max}\,(X_i - X(t))\, m_{métal}}{2\, M_H}$$

For the given set gear ratio (G_{de}) there exists a unique desorption pressure which decides the optimal operation of the water pumping system. it is given by:

$$P_{de} = P_i + \rho g h_t G_{de}\frac{A_p}{A_h}$$

The volume of water pumped as a function of time during desorption is as follows:

$$V_{pd}(t) = G_{de}\,\frac{n(t)R_g\, T_{moy}}{P_{de}}\,\frac{A_p}{A_h}$$

The volume of water pumped as a function of time during the expansion process is as follows:

$$V_{pe}(t) = G_e\,\frac{n(t)R_g\, T_{moy}}{P_{de}}\left(\left\{\frac{P_{de}}{P_{he}}\right\}^{\frac{1}{\gamma}} - 1\right)\frac{A_p}{A_h}$$

Where P_{he} is hydrogen pressure in the cylinder during expansion

$$P_{he} = P_i + \rho.g.h_t.G_e.\frac{A_p}{A_h}$$

The total amount of water pumped during desorption and expansion is given by:

$$V_t(t) = V_{pd}(t) + V_{pe}(t)$$

The pump efficiency is the ratio of energy required to pump water to the heat, Q_c, supplied to the system by convection.

$$\eta = \frac{\rho\, g\, V_t(t)\, h_t}{Q_c}$$

V. Results and Discussion

The aim of the present paper is to compare the performance (specific water discharge, pump efficiency, pumping time) of MHP and MHP-PCM. Two configurations C1 and C2 (Fig.2) are considered (C1: without PCM, C2: with Ba(OH)2-8H2O as a phase change material)

A. *Comparison between MHP (C1) and MHP-PCM (C2) for different heat transfer coefficient*

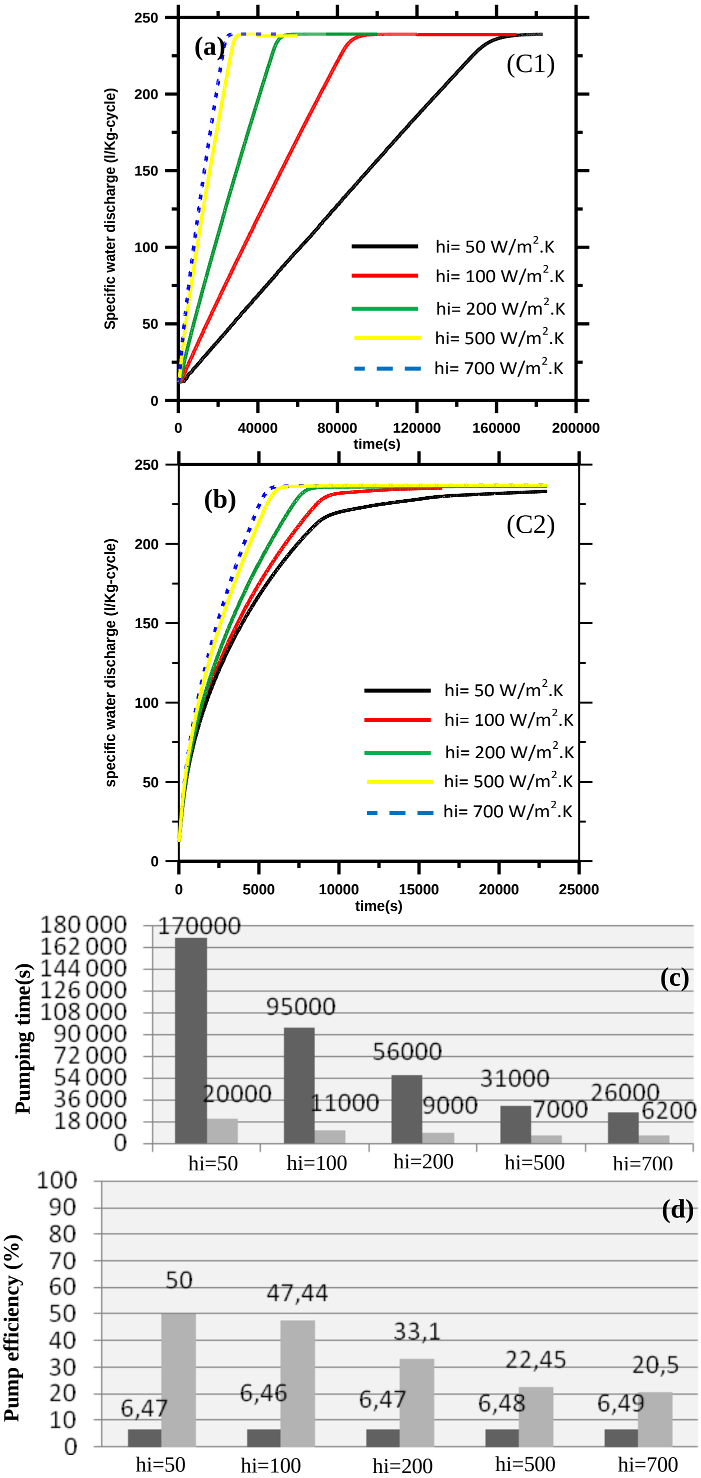
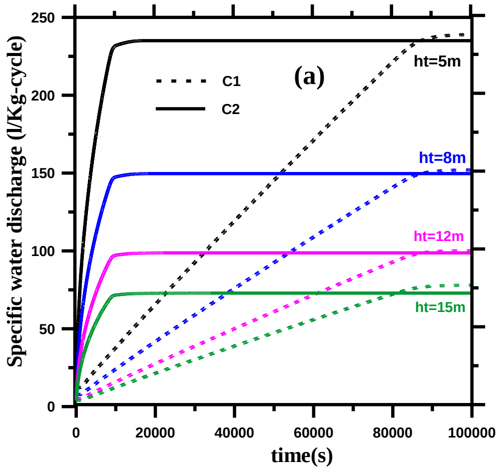


Fig. 3. Comparison between the two configurations C1 and C2 for different heat transfer coefficient (a) specific water discharge for C1, (b) specific water discharge for C2, (c) pumping time and (d) pump efficiency.

It is observed from figures 3-a and 3-b that the same specific water is pumped for the two configurations. In fact, the heat required for the total desorption is provided, either only through the heating fluid (C1), or through both the phase change material and the convective heat exchanger (C2). So, the same quantity of hydrogen desorbed and consequently, the same volume is pumped. It is seen, from figure 3-c, that for a fixed heat transfer coefficient, the second configuration has the best pumping time. In fact, from the first configuration heat is provided only by the heating fluid. Contrary to the second configuration in which heat is provided from both the convective heat exchanger and the PCM solidification.Therefore, an acceleration of hydrogen desorption process and then an acceleration of the pumping process for the second configuration is obtained. For example, for hi = 50 W/m2.K, the integration of a PCM (C2) reduces the pumping time of about 88% compared to the case without PCM (C1). Also, it can be noted, from figure 3-c that the increase of heat transfer coefficient reduces the difference in the pumping time between the two configurations. Then, the integration of a phase change material has a great interest in the improvement of the pumping time, especially for low heat transfer coefficient. Figure (3d) shows that the integration of a PCM improves the efficiency of the pumping system regardless of the heat transfer coefficient. Indeed, for the first configuration, the heat released during hydrogen absorption is totally lost. Then, to desorb hydrogen, all of required heat is provided for each cycle only from the heating fluid. Then, a decrease in the pumping efficiency. In contrast, for the second configuration, the heat released during absorption process is stored by the phase change material in order to be reused during the subsequent desorption reaction Then, an increase of the pump efficiency. For example, for hi=50 W/m^2.K, the second configuration provides an efficiency 8 times higher than the efficiency of the first configuration.

B. *Comparison between MHP (C1) and MHP-PCM (C2) for different total head*



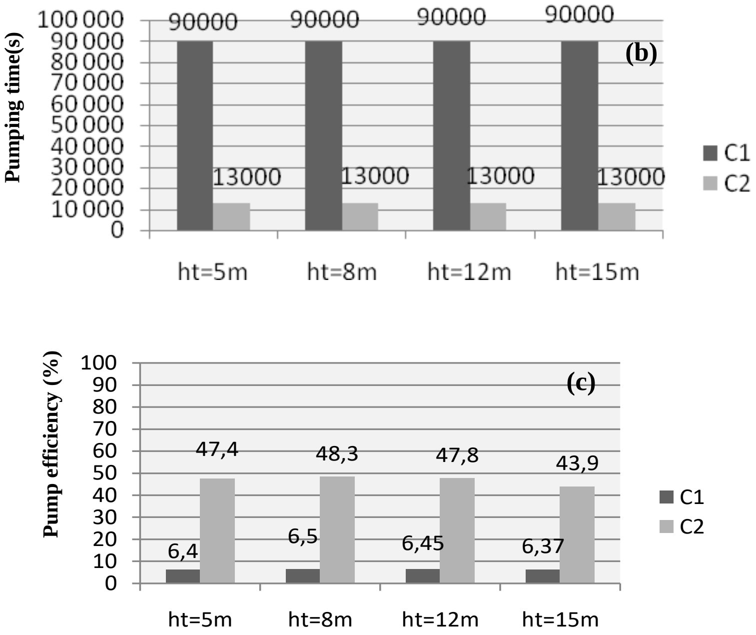


Fig. 4. Comparison between the two configurations C1 and C2 for different total head (a) specific water discharge (b) pumping time and (c) pump efficiency.

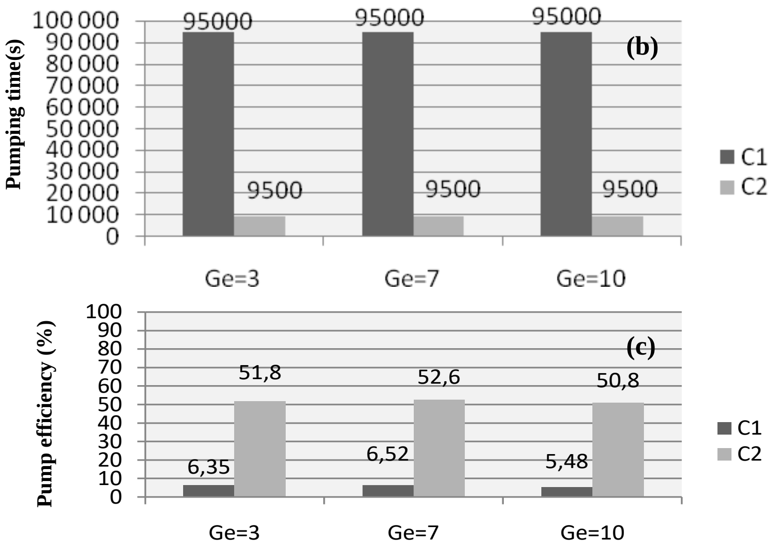
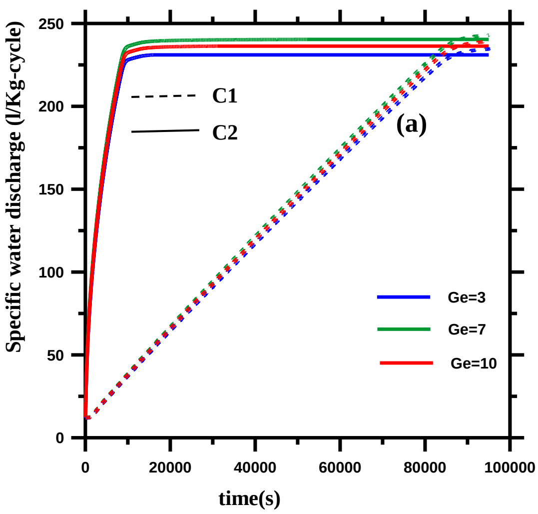


Fig. 5. Comparison between the two configurations C1 and C2 for different expansion gear ratio (a) specific water discharge (b) pumping time and (c) pump efficiency.

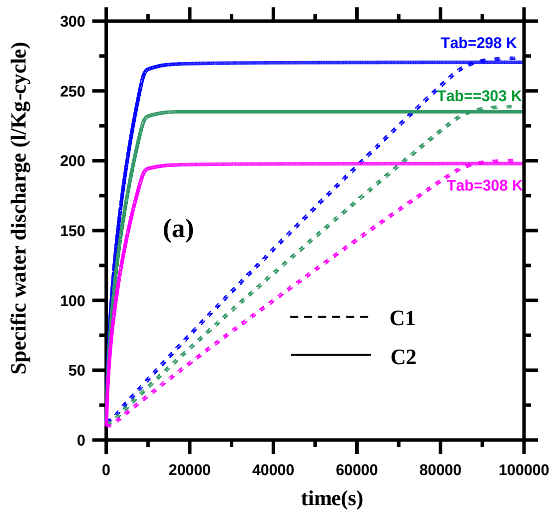
It is seen from figure 4-a, that the increase of pump head, causes a decrease in the specific water discharge, for the two configuration. Also, for a fixed total head, the same volume is pumped for both C1 and C2. It is observed, from figure 4-b, that the integration of PCM (C2) improves the pumping time of about 85%. For ht=5m, an improvement of about 86% in the pumping efficiency is observed by adding a phase change material (C2).

From figure 5-a, it is seen that for a fixed expansion gear ratio, the same specific water is pumped for the two configuration. Also, it is seen, for the two configurations, that there exist an optimal expansion gear ratio which allows to pump more water. From figure 5-b and 5-c, it is seen that adding a phase change material (C2) allows an improvement of about 90% in the pumping time and 87.6% in the pump efficiency comparing to the first configuration, for an expansion gear ration equal to 7.

C. *Comparison between MHP (C1) and MHP-PCM (C2) for different expansion gear ratio*



D. *Comparison between MHP (C1) and MHP-PCM (C2) for different absorption temperature*



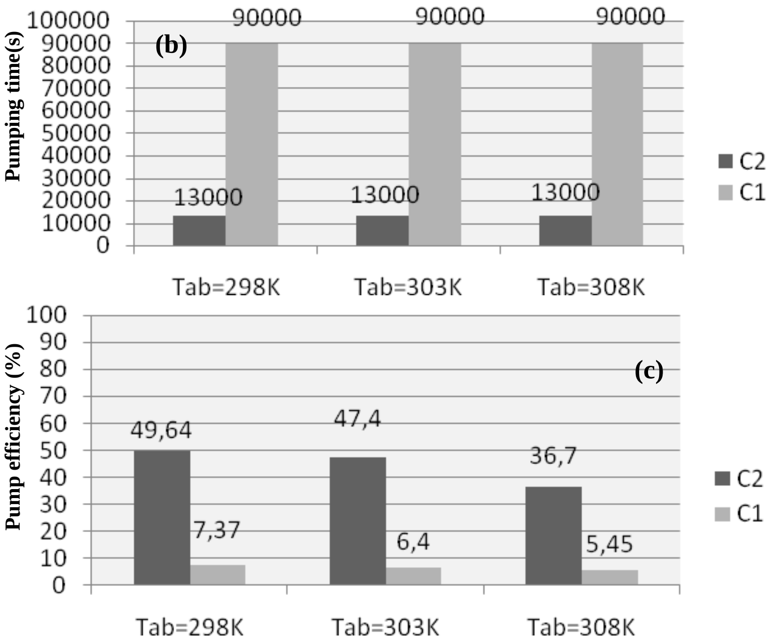


Fig 6. Comparison between the two configurations C1 and C2 for different absorption temperature (a) specific water discharge (b) pumping time and (c) pump efficiency.

Figure 6 shows that lower absorption temperature allows to pump more water with a maximum of pump efficiency, for the two configurations. It is seen, from figure 6-b, that adding a phase change material allows an improvement of about 85.5 % of the pumping time. Also, whatever the absorption temperature, the addition of a phase change material provides an efficiency nearly 8 times higher than the efficiency of a water pump system without PCM (C1).

VI. CONCLUSIONS

MHP and MHP-PCM using $LaNi_5$ as hydriding alloy were numerically investigated. An unsteady model and a numerical code were presented to predict the coupled heat and mass transfer within the MHP and MHP-PCM. Then, simulations were devoted to compare the performances of these two pumps for different: heat transfer coefficient, total head, expansion gear ratio and absorption temperature. Obtained results have shown that:

-For fixed parameters, the same specific water is pumped for the two configurations.

- Depending on parameters used, the integration of phase change material (C2) reduces the pumping time of about 90% comparing to the first configuration (without PCM).

- The MHP-PCM provides an efficiency almost 8 times higher than the MHP.

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