

ASSESSMENT OF HEAT RECOVERY AND RECOVERY EFFICIENCY OF A SEASONAL THERMAL ENERGY STORAGE IN A MOIST POROUS MEDIUM

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Résumé

Le stockage d'énergie thermique a reçu un grand intérêt par les chercheurs et les industriels dans le cadre de la conception de nouveaux systèmes capables de stocker et fournir de la chaleur d'une manière efficace et pendant de longues périodes. Le but de ce travail préliminaire est de simuler les performances d'un système de stockage thermique saisonnier prometteur, qui est un échangeur de chaleur enfouis dans le sol. Plusieurs études de cas ont été simulées en fonction de plusieurs types de fluide caloporteur et de taux d'humidité différents. Le logiciel Comsol Multiphysics a été utilisé pour modéliser les échanges de chaleur entre un support fluide circulant dans un GHX, et un milieu poreux partiellement saturé composé essentiellement de gravier et située à environ 0,5m du sol. La discrétisation du système d'équations différentielles a été réalisée à l'aide de la méthode des éléments finis. Les performances du système de stockage ont été évaluées pour une période d'une année afin d'obtenir une bonne estimation de stockage et de la récupération de chaleur sur le long terme. Les résultats ont montré que l'utilisation du gasoil comme un fluide de travail donnera des niveaux de température plus relativement élevés par rapport aux autres fluide pendant les mois de la saison froide; cependant, l'utilisation de l'eau permet le stockage et la récupération d'importantes quantités de chaleur, beaucoup plus que le gasoil ou le glycol pourra faire. En outre, la taux d'humidité du sols n'a exercé aucune influence sur l'ensemble du processus.

Mots clés : *stockage de chaleur, long terme, sous-sol, récupération de chaleur, efficacité de la récupération*

Abstract

Thermal energy storage has received a great interest by researchers and industrials as part of designing new systems able to store and deliver thermal energy efficiently for long periods. The aim of this preliminary work is to simulate performances of a promising seasonal heat storage system, which is a heat exchanger buried underground in a moist porous medium. Several case studies have been simulated according to different types of hot fluid carrier and moisture content in a porous medium. Comsol Multiphysics software was used to model heat exchange between a fluid carrier flowing through a GHX, and a partially saturated porous medium composed essentially of gravel and situated at about 0.5m underground. Numerical discretization was realized by finite elements method. System performances were evaluated for a one-year period in order to get a good estimation of long-term heat storage and recovery. The results showed that the use of gasoline as a working fluid will yield higher temperature levels than the other fluids especially during cold season; however, use of water allowed for the storage and recovery of bigger heat energy than gasoline or glycol can do. Furthermore, soil moisture content did not seem to have any influence the whole process.

Keywords: *heat storage, long term, underground, heat recovery, recovery efficiency*

ملخص

لقي مجال تخزين الطاقة الحرارية اهتماما كبيرا من قبل الباحثين والصناعيين فيما يخص تصميم أنظمة جديدة قادرة على تخزين وتوفير الطاقة الحرارية بشكل فعال ولفترات طوال، والغرض من هذا العمل الأولي هو محاكاة أداء نظام حراري موسمي واعد لتخزين وتوفير الطاقة الحرارية، وهو بمثابة موزع حراري مدفون في الأرض. أجريت المحاكاة بناء على عدة أنواع من السوائل الناقلة للحرارة ومستويات رطوبة مختلفة لوسط التخزين. تم استخدام برنامج COMSOL Multiphysics لتصميم نموذج إنتقال الحرارة بين الموزع الحراري GHX، ووسط التخزين المكون من الحصى والذي يقع على بعد 0.5 متر تحت سطح الأرض. تم تقييم أداء النظام لمدة سنة من أجل تقدير جيد لتخزين واسترجاع الحرارة على المدى الطويل، وأظهرت النتائج أن استخدام الغازولين كسائل العمل يعطي درجات حرارة عالية نسبيا مقارنة مع السوائل الأخرى خلال أشهر الموسم البارد. ومع ذلك، فإن استخدام الماء يسمح بتخزين واسترجاع كميات كبيرة من الطاقة الحرارية، وأكثر بكثير مما يقدمه الغازولين أو الغليكول. بالإضافة إلى هذا، ليس لدى مستوى رطوبة وسط التخزين أي تأثير على العملية بأكملها.

الكلمات المفتاحية : *تخزين الطاقة الحرارية، المدى الطويل، تحت الأرض، استرجاع الطاقة الحرارية، فعالية الإسترجاع*

Underground thermal energy storage (UTES) is a sustainable technology destined to store and deliver energy at particular periods, such as winter, when heat demand is extremely high. This concept acquired a large focus because of society's energy need for heating or cooling (during winter), and to mitigate environmental issues dealing with energy production and supply. One of the UTES technology applications is seasonal storage in porous media, which can be defined as the process of storing heat in the ground for long periods, generally up to three or four months, then delivering it during the cold season. Seasonal storage systems can be designed particularly in hot sunny regions to collect and store solar heat energy loads for later use, and the most promising applications were found underground by means of borehole heat exchangers.

A lot of works have been carried out for studying ground heat exchangers (GHX), but only few have been dedicated for modelling heat recovery and heat recovery efficiency. Medjelled & al (2008) conducted a set of experiments to determine thermal parameters and overall heat transfer coefficient in a sandy unsaturated porous media. The scope this study was to evaluate thermal conductivity, heat capacity and global heat transfer coefficient variation with depth of the thermal storage medium. Chiasson & al (2010) led a simulation study for a horizontal GHX by taking into account varying thermal loading and weather conditions. The results provided a good insight for the design of their heat exchanger. Lanini & al (2014) investigated a 3D numerical model to simulate different type of U-tube borehole energy storage system. Their results were validated according to experimental data and numerical results. Rabin & al (1991) simulated a helical GHX for purpose of long-term thermal energy storage. Validation of the numerical model was carried out with experimental data and an analytical solution and the results were found to be in a good agreement.

In this preliminary work, Comsol Multiphysics was used to simulate heat transfer between a multiple pass GHX and a cubic storage medium for heat storage and recovery purposes, with time-varying boundary conditions of the working fluid at the inlet of the pipes, in addition to the introduction of the atmospheric conditions such as regional temperature and wind speed during the simulation. The main goal of this work is to make a forecasting on heat energy quantity that can be stored and recovered from the system described hereafter according to several case studies, as well as estimating heat recovery efficiency.

1. MODEL DESCRIPTION

a. Physical system

The UTES system studied in this work as depicted in figure 1 consists of a multiple pass GHX buried in soil at a depth of 8m. The GHX is a duct made of copper and has an internal diameter of 10 cm and a thickness of 4 mm. On the other hand, the heat storage media composed essentially of wet gravel is considered as a homogeneous and isotropic cubic porous medium having a size of 21m×20m×14m as

depicted. This storage domain is covered by a 50 cm-sandy layer to minimize heat loss to the atmosphere.

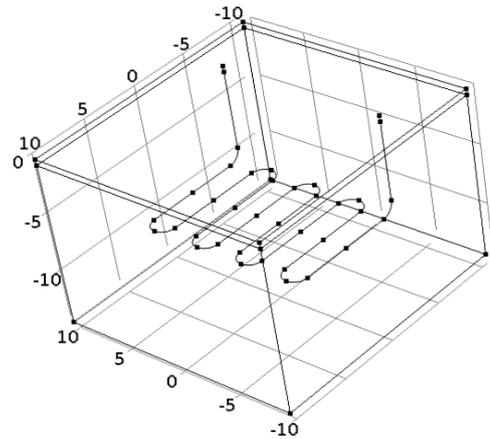


Figure 1 : Geometry of the underground thermal energy system

Heat storage and recovery are realized during the charging and discharging processes by a hot fluid carrier flowing along a GHX buried at 8m. Performances of this heat exchanger will be evaluated according to the use of water, gasoline (organic oil) and glycol which is also used as heat carrier as well as a corrosion inhibitor. Table 1 shows physical properties of gravel while table 2 shows thermal properties for the different fluids that will be under investigation.

Table 1 : Physical properties of gravel

Porosity	0,15
Density (kg/m3)	2702
Thermal conductivity (W/m*K)	2
Specific heat (J/kg*K)	990

Table 2 : Thermal properties of different working fluids

Fluid	Density (kg/m3)	Thermal conductivity (W/m*K)	Specific heat (J/kg*K)
Gasoline	650-750	0.08-0.13	2100-3000
Water	1000	0.6	4180
Glycol	1060-1130	0.252	2300-2700

b. finite element meshing

The system described above was meshed using 3D tetrahedral finite elements as illustrated in Figure 2, and finer grids were obtained by the aid of the meshing tool of Comsol. We did not choose to model half the geometry of the system even if the domain of interest reflects an excellent symmetry because the temperature profile along the storing domain was not expected to show any similarities above and below the GHX. However and to gain much time, pipe flow module of Comsol was used. It

is a useful tool which has the tendency to resolve heat transfer and fluid flow equations in ducts using 1D curvilinear coordinate system, thereby reducing huge time and power usually allocated for 3D geometries simulation.

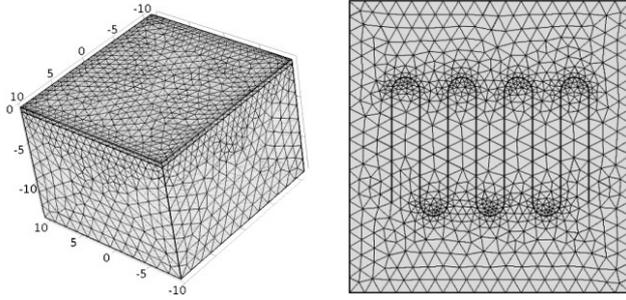


Figure 2 : Meshing of the ducts and the heat storage media

The meshed domain illustrated by the sketches in figure 2 is composed of 21354 tetrahedral elements for the cubic domain and 278 edge elements for the ducts.

c. Governing equations

The governing equations describing the physics of heat storage and recovery process will be derived according to an unsteady mode.

For the GHX, assuming a fully developed velocity profile for the working fluid and pressure drop due to viscous stress along the duct, the equations that describe heat transport and fluid flow along the duct are the following:

$$\rho \frac{\partial \bar{u}}{\partial t} = -\nabla P - f_d \frac{\rho}{2D_h} \bar{u} |\bar{u}| + \rho \bar{g} \quad (1)$$

$$\rho AC_p \frac{\partial T}{\partial t} + \rho AC_p u \nabla T = \nabla A k \nabla T + f_d \frac{\rho A}{2D_h} |\bar{u}|^3 - Q_{wall} \quad (2)$$

- u : Fluid velocity inside the duct;
- d_h : Hydraulic diameter;
- f_d : Friction factor;
- T : Temperature profile inside the duct;
- A : Cross sectional area of the duct.

The first term on the right hand-side of equation (1) represents fluid loss due to pressure drop whereas the second term denotes losses due to viscous stresses. The third term pertains to gravity forces.

In equation (2), the second term in the right hand-side represents heat generated by viscous stresses, and the third term denotes heat dissipation through duct wall.

For the storage domain, we have considered that the system is composed of gravel - with moist air filling the void space - overlain by a sandy layer. If we consider that heat transfer inside the storage domain is solely governed by thermal conduction, and the moist air is immobile and non-reactive with the soil particles, the equation that represents transient heat transfer in a porous medium is:

$$(\rho C_p)_{eq} \frac{\partial T_2}{\partial t} = \nabla k_{eq} \nabla T_2 + Q_{wall} \quad (3)$$

- T_2 : Field temperature of the porous media;
- C_{eq} : Equivalent heat capacity of the porous medium;
- k_{eq} : Equivalent thermal conductivity of the porous medium.

The equivalent heat capacity of the medium (C_{eq}) and the equivalent heat conductivity (k_{eq}) are evaluated according to the next formula:

$$(\rho C_p)_{eq} = \theta_s (\rho C_p)_s + (1 - \theta_s) (\rho C_p)_f \quad (4)$$

$$k_{eq} = \theta_s k_s + (1 - \theta_s) k_f \quad (5)$$

Here, θ_s represents solid volume fraction. Fluid parameters identified by the subscript (f) are taken as the arithmetic mean of air and moisture content.

d. Initial an boundary conditions

1.4.1. Ducts

The fluid carrier being initially at rest starts to flow during all the process with a mass flow rate of 0.11 kg/s. It was noticed after carrying out several simulations that this value is more suitable to achieve optimal rates for heat exchange and recovery.

The temperature of the working fluid at the inlet of the duct during the charging period (May to October) and the recovery period (November to April) follows the profile shown below (figure 3):

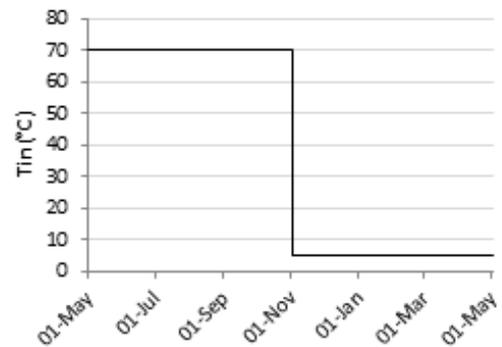


Figure 3 : Temperature of the working fluid at the duct inlet

1.4.2. Storing domain

The initial temperature of the storage domain was set to 5°C. The bottom and the four vertical boundaries of the storage domain were thermally isolated from the underground. Hence, Neumann boundary condition was set ($q=0$ W/m²). The upper surface exposed to varying atmospheric conditions was modeled by the following equation which takes into account heat transfer by convection (effect of wind speed) and radiation [5].

$$q_{top} = q_{conv} + q_{rad} = \left[h_c (T_{sky} - T_2) \right] + \left[q_{solar} + \epsilon \sigma (T_{sky}^4 - T_2^4) \right] \quad (6)$$

Where:

$$h_c = 6,2 + (1,4 \times u_{wind})$$

Here:

- u_{wind} : Wind speed near to the ground surface;
- ϵ : Sand emissivity;
- σ : Boltzmann constant.

Sky Temperature, wind speed and solar irradiation data had been collected from 2014 monthly measures in the region of Laghouat (Algeria).

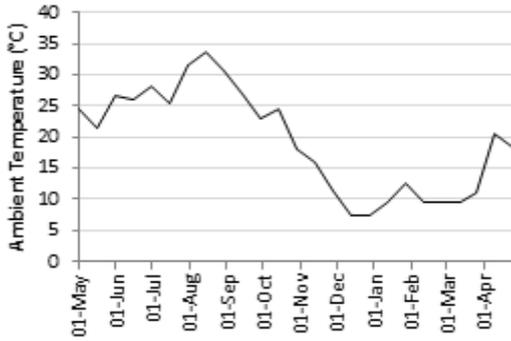


Figure 4 : Temperature history in the region of Laghouat

e. Initial an boundary conditions

The unsteady simulation was carried out for a twelve-month period, six months of heat charging (heat storage) and six months of heat discharging (heat recovery). The temperature of working fluid employed at the inlet of the pipes follows the initial and boundary conditions described above. The output of the simulation includes temperature of the circulating fluid and the temperature of the storing domain. Heat quantities during the charging and discharging process will be estimated by analytical formulas derived from the application of the thermodynamic equilibrium principle.

First of all, we will display temperature distribution for a basic case in order to get a primary insight on the behavior of heat exchange between the fluid carrier and the storing domain. Then, we will show the benefit of insulating the storing domain on its top for the sake of minimizing heat loss to the atmosphere especially during the recovery period.

After that, we will carry out some sensitivity cases on different fluid carrier and moisture content of the storing medium. Here, we will try to find out which fluid will be more efficient in delivering hot temperatures in cold season at high recovery efficiency.

2. RESULTS AND DISCUSSION

a. Validation

In order to validate our model, we have compared our results to those obtained by the results obtained by Diersch *et al* (2011).

These latter developed an analytical solution to analyse the performance of heat storage and recovery by means of a heat exchanger buried at 100m below the ground.

For the laminar and turbulent regimes, our simulation results depicted in figure 5 show similar trends as for the analytical model of Diersch *et al* (2011); as well as results convergence which indicates that our model reproduces perfectly the phenomenon of heat and recovery.

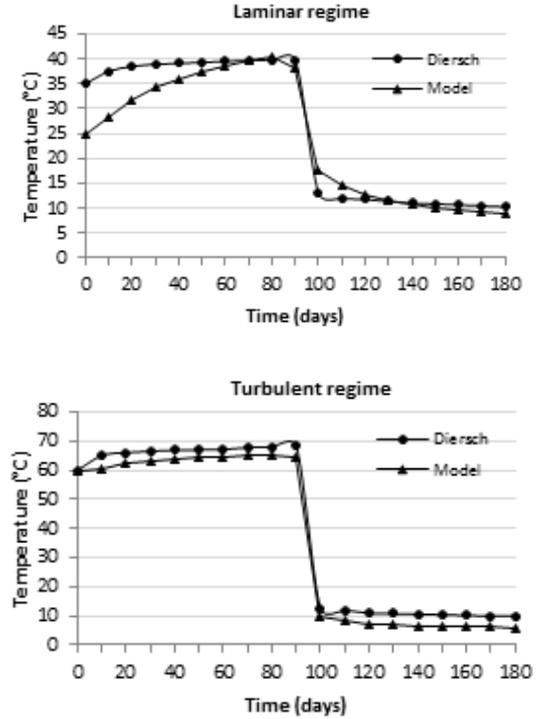


Figure 5 : Results validation – Laminar regime (left) and Turbulent regime (right)

b. Temperature distribution in the storing domain

Figures 6 and 7 illustrate several slices of the temperature profile inside the porous medium during the charging and discharging periods. Most of the heat energy yielded by the hot fluid carrier stays concentrated around the GHX while a small amount reaches the storing domain boundaries. At the end of this charging period, the maximum temperature reaches 60°C around the GHX and approximately 30°C at the boundaries of the porous medium.

On the other hand, the temperature change during the discharging period is extremely fast during the first days of recovery. Until the 20th day of the beginning of this process, heat transfer between the working fluid flowing across the GHX and the storing medium is performed at a high rate where the temperature around the heat exchanger declines from 60°C to 25°C.

At the end of discharging period, heat transfer to the fluid carrier declines, and the temperature profile inside the porous medium ranges between 8°C and 18°C approximately.

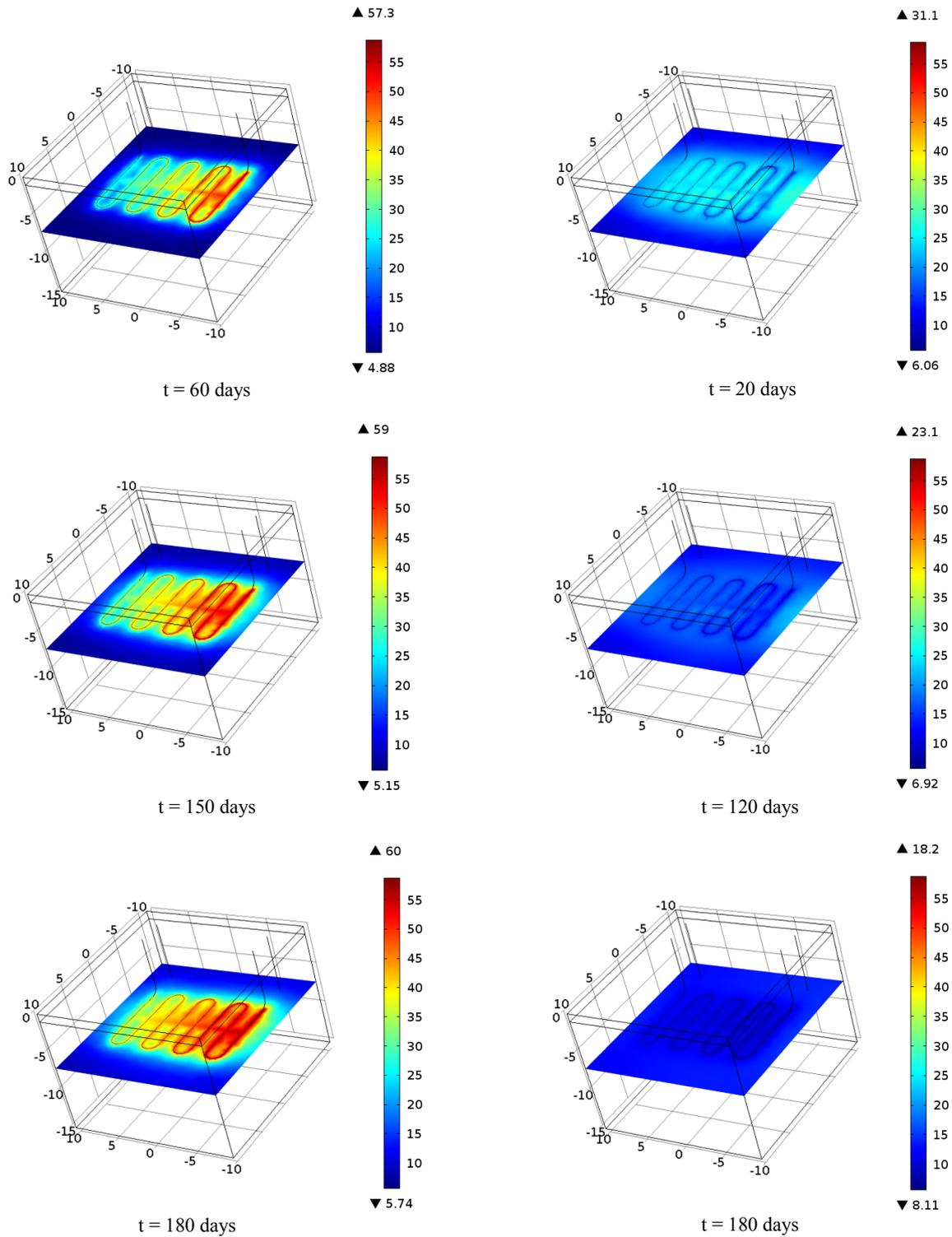


Figure 6 : Temperature evolution during the charging period

Figure 7 : Temperature evolution during the discharging period

During the two periods, heat transfer between the fluid carrier and the porous medium was stronger during the first days of charging than the last days. This is primarily due to the weakness of the thermal diffusivity of underground material, i.e gravel, which empeached an efficient diffusion and recovery of heat to and from the porous medium.

That's why a considerable amount of heat is still kept inside the domain as its temperature ranges between 8 and

18°C at the end of the recovery stage, while the temperature level at the outlet of GHX during this stage, see figure 8, is noticed at about 25°C which then falls to 5°C.

In addition, we have noticed from the simulation results that the stationary regime will be achieved at the day 144 of the discharging period where the recovered temperatures stay around 8°C.

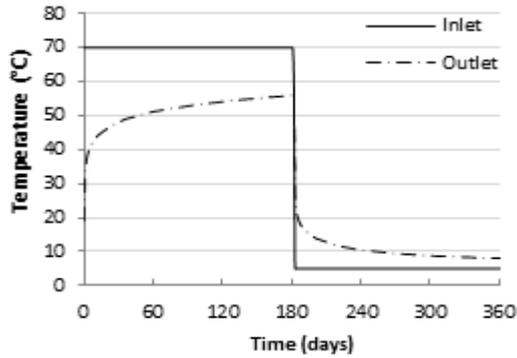


Figure 8 : Fluid carrier temperature at the inlet and outlet of the GHX

Figure 9 shows a general view of the storing domain at the end of the charging process where a total of 40 planes have been sketched. It easily seen that the temperature distribution around the GHX follows a parabolic trend and the temperature difference near the vertical boundaries of the storing domain is extremely small due to thermal insulation applied on those boundaries.

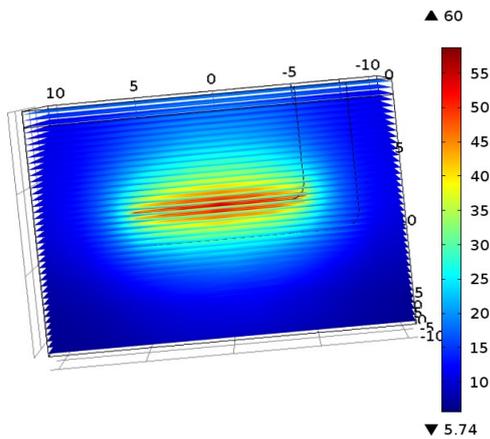


Figure 9 : Temperature distribution around the GHX

c. Effect of thermal insulation on the top layer

By adding a sandy layer as a means to reduce heat loss to the atmosphere, we noticed a significant decrease in the outward heat flux. This fact is shown by figure 10 where we can see that heat loss is tremendously reduced after insulating the top of storing domain.

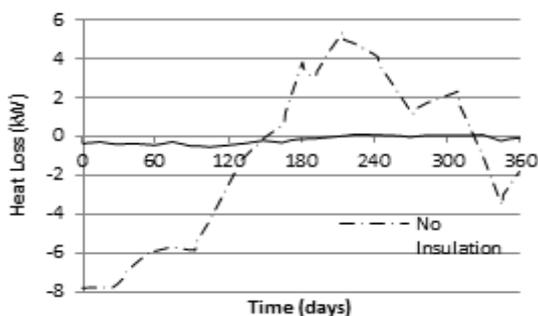


Figure 10 : Insulation of the top of the storing domain by a sandy layer

d. Moisture content sensitivities

In this part of work, a parametric study was run according to different moisture content “ ω ” (10%, 25% and 40%) that characterizes partially saturated media. From Figure 11, the temperature of water at the outlet of GHX followed the same trend whatever the moisture content was, and this fact was the same when using glycol or gasoline. After 30 days of the discharging process, the temperature of water 15°C at the outlet of the GHX, while at the end, it stabilizes at about 10°C. So, we can conclude that moisture content of the storing medium does not affect tremendously the yielded temperature during heat recovery.

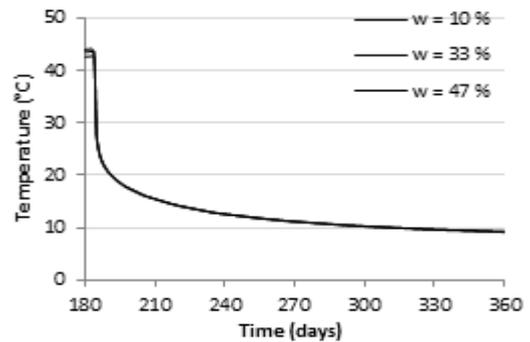


Figure 11 : Temperature of the fluid carrier at the outlet of the GHX

e. Fluid carrier sensitivities

In this sensitivity study, we wanted to find out which fluid carrier will deliver high temperature especially during cold season where heat demand is needed. We ran three simulation cases according to the three working fluids shown in table 1.

The results plotted in figure 11 show that gasoline delivers slightly high temperatures than water and ethylene glycol. After 30 days of the discharging process temperatures on the outlet of duct is respectively 26°C, 16°C and 14°C for gasoline, water and glycol. This trend continues to decline with time. At the end of this stage, the temperature at the outlet of duct reaches 12°C in case of using gasoline, whereas when we use glycol or water, the temperature will be approximately 8°C.

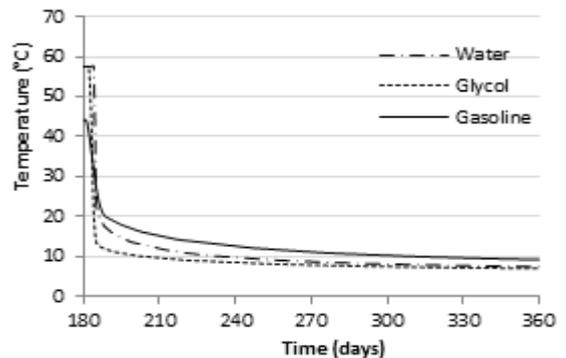


Figure 12 : 1 Temperature of the fluid carrier at the outlet of the GHX

2.5.1. Heat recovery efficiency

The amount of heat stored is simply determined from the difference between the temperature of working fluid at the inlet and at the outlet of the pipes during the charging period. The same approach is applied to estimate the amount of heat recovered during the discharging period. Formulas (7) and (8) will be used to calculate heat stored and recovered during the two processes. The results indicating the cumulative heat quantity during the charging and the discharging processes are shown in figure 12.

For the charging period:

$$Q_{\text{stored}} = \dot{m}C_p (T_{\text{in}} - T_{\text{out}})|_{\text{storage}} \quad (7)$$

For discharging process, the amount of heat recovered is the sum of heat yielded by the 2 ducts:

$$Q_{\text{recovered}} = \sum \dot{m}C_p (T_{\text{in}} - T_{\text{out}})|_{\text{Recovery}} \quad (8)$$

Hence, recovery efficiency “ η ” will be calculated by formulae (9):

$$\eta = \frac{Q_{\text{recovered}}}{Q_{\text{stored}}} \quad (9)$$

The results given by the amount of heat stored and recovered for this case are illustrated in the following plot.

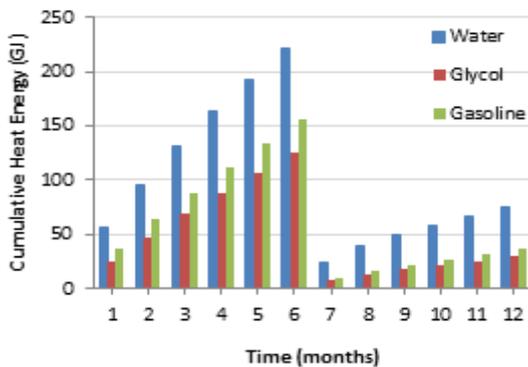


Figure 13 : Cumulative heat stored and recovered for the fluid carrier sensitivities

The main idea displayed by figure 13 is that water as a fluid carrier allows for the storage and recovery of a bigger amount of heat energy than gasoline or glycol even if gasoline yields a high level of temperature and better recovery efficiency as depicted by figure 12.

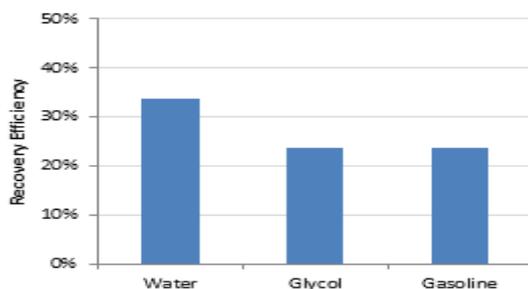


Figure 14 : Heat recovery efficiency

CONCLUSION

The aim of the work made along this paper was to make a forecasting on the performances of a UTES system and to get a good insight on the performance of our thermal energy storage system in term of heat recovery, recovery efficiency and temperature deliverability during cold season.

The study of different case studies gave us an idea of the capabilities of each fluid carrier to store and deliver heat energy in optimal conditions. In addition, the impact of the moisture content sensitivities was not found to yield any advantages.

This work will be improved in the future where we will try to find a solution to recover the amount of remaining heat underground during the discharging period, i.e., cold season, where energy demand is generally high.

Furthermore, we will try to optimize the energetic design of the UTES studied herein and adapt it for real situation in order to satisfy heat energy needs for a specific couple of buildings.

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