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Theoretical and experimental studies on a latent heat thermal energy storage system (LHTES) containing flat slabs of phase change materials

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Abstract

Human growing need for energy, limited energy resources, pollution and global warming are all things that force us to be sensitive about rate of energy consumption. One of the leading options is saving the available energy in order to use when it is required. Saving the coldness of the night air for air-conditioning during the hot summer days in tropical regions to assist the common air-conditioning systems can be a proper opportunity to save energy. Phase change materials can be used on this field. For this purpose, a LHTES containing flat slabs of phase change materials (PEG 600 and PEG 1000) was used and a one-dimensional model in which axial conduction is considered was applied to analyze the experimental data. The results from the model and experiments were compared, and a good agreement was achieved. Moreover, for analyzing the performance of LHTES 8 experiments have been designed by factorial method.

Keywords: Phase change material, thermal energy storage, numerical model, LHTES, free cooling, heat recovery

1. Introduction

One of the oldest usages of Thermal Energy Storage (TES) goes back to the time when ice was provided from frozen lakes and rivers in the winter. The collected ice was then kept in well insulated warehouse to satisfy the needs for food conservation, air conditioning through the year. The air conditioning of Hungarian Parliament Building in Budapest is still done by ice harvested from Lake Balaton in the winter [1]. In order to condition the indoors air via changing the material phase, phase change material (PCM) can be embedded in a heat exchanger. During the night, PCM solidifies and the energy can be released (discharge cycle) and subsequently during the hot day, via a move through the heat exchanger, air is cooled and PCM melts (charge cycle). Medved and Arkar [2]-[5] used a cylindrical LHTES filled with spheres of encapsulated RT20 paraffin. They concluded that the ratio of the volumetric air flow to mass of the PCM has more influence upon the results than each individual parameter [2]. They also concluded that the greatest potential for free cooling exists in the areas with a higher temperature difference between the day and the night, i.e. variation of diurnal temperature is the major factor. Moreover, they showed that the most suitable PCM for each area is the one with a melting point of 2 °C higher than the average diurnal temperature [3]. In order to model the heat transfer in the LHTES under unsteady-state conditions, they used an adapted 2D continuous-solid-phase packed-bed model. The major assumption of this model is that the spheres behave as a continuous medium and not as a medium comprised of independent particles. Moreover fluid phase thermal dispersion, this model can consider the solid-phase heat conduction [2].

Nomenclature

Parameter	Description	Parameter	Description
a	Width of flat slabs (m)	Pr	Pranton number

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A	Area of cross section of duct= ab (m^2)	Q	Transferred heat (j)
b	Air gap between parallel slabs (m)	Re	Reynolds number
c_p	Heat capacity of PCM (J/kg°C)	T	Air temperature (°C)
c_{pg}	Heat capacity of Air (J/kg°C)	T_p	PCM temperature (°C)
Δx	Spatial length (m)	t	Time (sec)
Δt	Time step (sec)	U_p	Overall heat transfer coefficient (W/m^2°C)
E	Efficiency	x	Length variable (m)
h	Heat transfer coefficient between air and flat slabs (W/m^2°C)	τ	Process termination (sec)
i	Spatial step counter	ρ	Density of air (kg/m^3)
j	Time step counter	β	Thermal Expansion (K^{-1})
k_p	Thermal conduction of PCM (W/m^2°C)	α	Thermal diffusivity (m^2/s)
m_p	Mass of PCM (kg)	υ_L	Kinematic viscosity of melted parts of PCM (m^2/s)
m_g	Mass flow rate of air (kg/s)	δ	Thickness of slabs (m)
N_u	Nusselt number	Λ	Dimensionless parameter of Regenerator
P	Perimeter (m)	Π	Dimensionless parameter of Regenerator
Pe	Peclete number		

Vakilaltojjar and Saman [6] integrated a flat slab phase change thermal storage unit (PCTSU) employing two PCMs (calcium chloride hexahydrate and Potassium fluoride tetrahydrate) in different sections into conventional air conditioning. They proposed 3 models with different assumptions. The results of their investigation showed that decreasing the gaps between flat slabs enhances the efficiency.

In the present research work a one-dimensional model including axial conduction for a LHTES containing flat slabs of PCM has been presented. The modeling data have been validated by the experimental results. Our goal is to investigate the accuracy of the proposed model for describing the LHTES and also to investigate the dependency of LHTES efficiency on the operational parameters i.e. velocity and temperature of the heat transfer fluid.

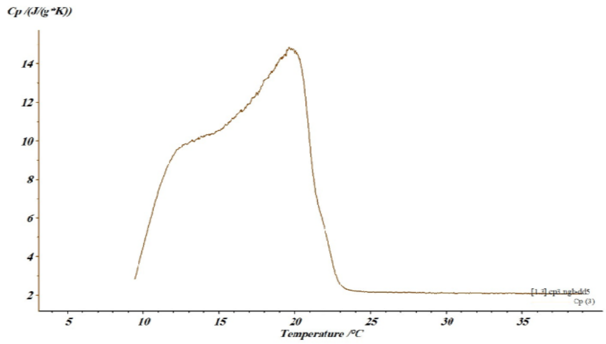

Fig. 1. DSC analysis of PEG 600.

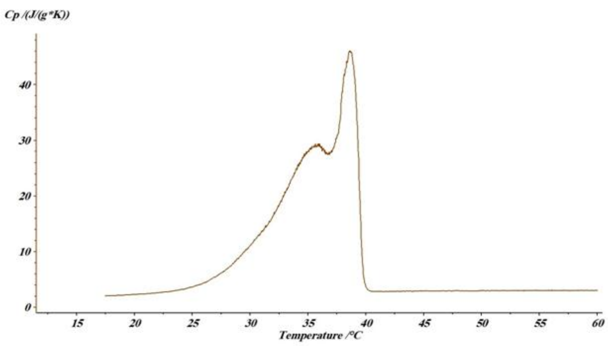

Fig. 2. DSC analysis of PEG 1000 .

2. Materials and Method

2.1. Properties of PCM

Poly Ethylene Glycol 600 (PEG 600), a product of Fluka Corporation, and Poly Ethylene Glycol 1000 (PEG 1000) have been used as PCM. In order to find out the temperature span for the phase change of PEG 600 and PEG 1000, DSC analysis was done by "Netzsch DSC 200 F3". Results of this analysis are shown in Fig. 1 and Fig. 2. Other properties of PEG 600 and PEG 1000 are listed in Table 1.

Table 1. Properties of PEG 600 and PEG 1000

Properties	PEG 600	PEG 1000
ρ_{liq}(kg/lit)	1.1258[7]	NA
ρ_{solid} (kg/lit)	1.232[7]	1.0927
k_{liq}(W/m°C)	0.189[7]	NA
ΔH_m(J/kg)	146440	158992
ΔT_m(°C)	17-23	33-40

2.2. Mathematical model

In this model the major assumption is that all the existing PCM in each control volume behave simultaneously. The mathematical model is based on the following assumptions:

1- Axial conduction in the air is neglected in the direction of the flow. For justifying this assumption *Peclet* number can be used [8]:

P_e > 100 axial conduction in the air can be neglected in the flow direction
P_e < 100 axial conduction in the air can NOT be neglected in the flow direction

$$P_e = R_e P_r \tag{1}$$

2- Temperature variations of the air normal to the flow are not considered.
3- No super cooling happens in the PCM.
4- Thermophysical properties of Air and PCM are constant and are the same for both phases, except the heat capacity of the PCM which is a function of temperature. This assumption is possible, because temperature variations are limited.
5- Heat transfer coefficient is the same for all slabs.
6- Heat loss to the surrounding is negligible.
7- Air residence time in the bed is small relative to the period.
8- The air inlet temperature assumes to be time dependant for discharge cycle (This assumption is related to the inlet temperature oscillations).
9- Heat transfer by radiation is neglected.
10- Heat capacity and thermal resistance of PCM containers have been ignored.
11- Natural convection in the melted parts of the PCM has been ignored.

Base on the foregoing assumptions, and considering the heat balance equation (Fig. 3) for the passing air and the PCM, following equations can be derived as:

$$T(i+1,j) = T_{PCM}(i,j) + (T(i,j) - T_{PCM}(i,j))\exp\left(-\frac{PU_p\Delta x}{\nu A\rho C_{pg}}\right) \tag{2}$$

In equation (2) a dimensionless parameter can be introduced:

$$\Lambda = \frac{PU_P\Delta x}{\nu A\rho c_{pg}} \tag{3}$$

$$T_{PCM}(i,j+1) = T_{PCM}(i,j) + \frac{\Pi(T_{PCM}(i,j))}{\Lambda}(1-e^{-\Lambda})(T(i,j) - T_{PCM}(i,j)) + \frac{k_p a\delta dt}{C_p(T_{PCM}(i,j))m_p dx}[T_{PCM}(i+1,j) - 2T_{PCM}(i,j) + T_{PCM}(i-1,j)] \tag{4}$$

where

$$\Pi = \frac{PU_p \Delta x \Delta t}{m_p c_p (T_{PCM}(i,j))} \tag{5}$$

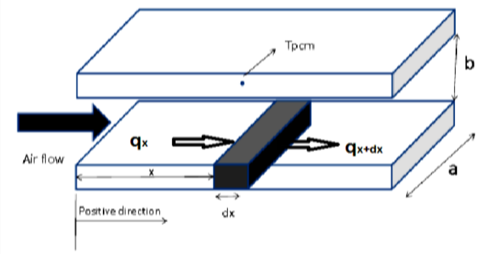

Fig. 3. Slab layout for establishing the heat balance equation.

2.3. LHTES prototype

For the experimental analysis, a small-scale prototype regenerator, containing about 200 gram of PEG packed in aluminium pouches has been set up. The schematic diagram of the built LHTES is shown in Fig. 4. The pouches made of aluminium coated with polyethylene films are embedded in bed parallel to each other with 13 mm gap between them. Because of the circular cross-section of the bed, several containers with different dimensions have been made. The specifications and numbers of the flat slabs are reported in the Table 2. The bed container is a PVC tube 85 mm in ID, five mm in wall thickness and 300 mm in length. Two K-type thermocouples were affixed to measure the inlet and outlet temperatures.

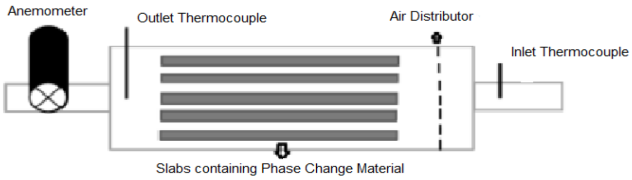

Fig. 4. The schematic diagram of the built LHTES.

In order to eliminate natural convection in the melted parts of the PCM for modelling, (since in melting cycle on contrary to solidifying cycle, free convection in the melted parts of the PCM can be the dominant mechanism of heat transfer) thickness of the pouches were chosen as [1]:

$$\delta_{\max} \le \left(\frac{5000\upsilon_L \alpha_L}{g\beta \Delta T}\right)^{1/3} \tag{6}$$

Table 2. Specifications of the flat slabs

Dimensions of flat slabs (mm)	Mass of the injected PCM in each container (gram)	Numbers of each container
3×38×210	26	2
3×53×210	38	2
3×75×210	53	1

3. 3. Results

3.1. Results of simulation of LHTES

3.1.1. Varying Temperature and Velocity for inlet air

Simulations are carried out at different inlet temperatures and for a range of mass flow rates. Effects of the inlet temperature and mass flow rate on the discharge (cold) and charge (hot) cycles are shown in figures (5) to (8). As shown in the figures, temperature of the inlet air plays an important role in the time needed for process termination. In the hot cycle higher temperatures and in the cold cycle lower temperatures reduce the time needed for process termination. Effect of inlet air velocity is definitely shown in Fig. 7 and Fig. 8. Higher velocities for inlet air make the needed time for process termination shorter. But as shown in the foregoing plots, in higher velocities this effect becomes weaker. Calculations are done using PEG 600 properties.

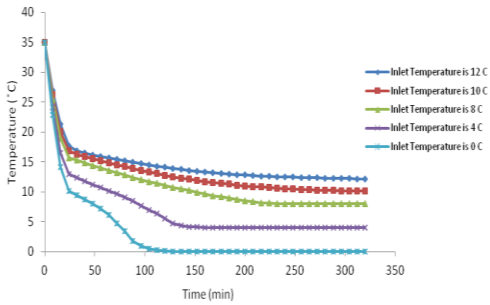

Fig. 5. Temperature distribution of a cold cycle at different inlet temperature.

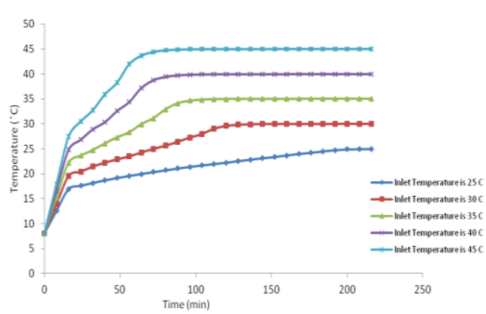

Fig. 6. Temperature distribution of a hot cycle at different inlet temperature.

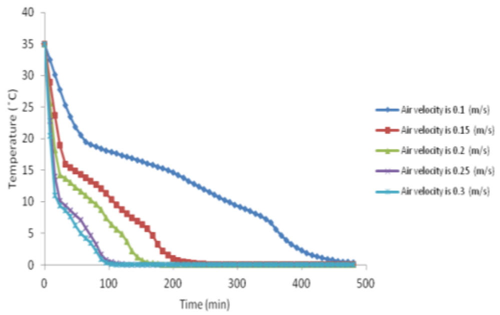

Fig. 7. Temperature distribution of a hot cycle at different inlet air flow rate.

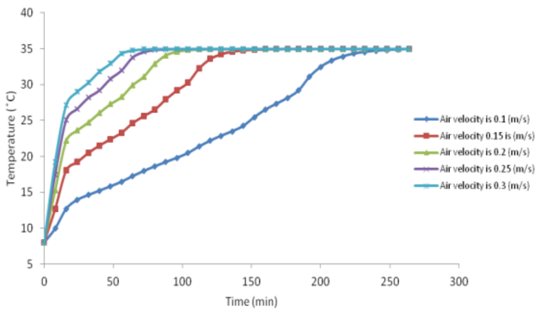

Fig. 8. Temperature distribution of a cold cycle at different inlet air flow rate.

3.1.2. Effects of Dimensionless parameter on LHTES efficiency

In order to evaluate the performance of the built LHTES the following correlation has been used for efficiency:

$$E = \frac{m_g c_{pg} \int_0^{\tau} (T_{hi} - T_{he}) dt}{m_g c_{pg} (T_{hi} - T_{ci}) \tau} \tag{7}$$

in which τ stands for the process duration. As shown in figure (9), with increasing Λ efficiency can be improved. It means that in the same length reducing the inlet air velocity is the solution to improve the performance of LHTES.

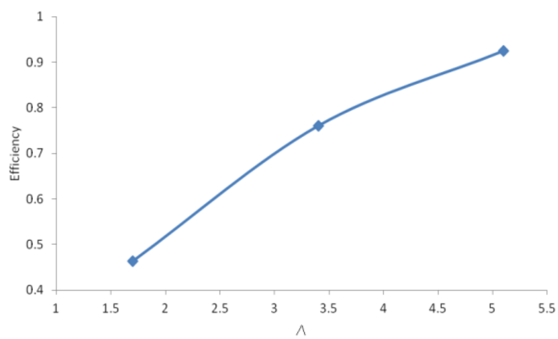

Fig. 9. Effect of Λ on efficiency.

3.2. Experimental results

Experiments are divided into two parts. For comparing theoretical and experimental results, experiments are done using PEG 600 as PCM. Secondly, 8 experiments have been designed with Factorial method in which effects of operational parameters such as inlet air temperature and velocity on the process duration and efficiency have been investigated. In the second part all the experiments are done using PEG 1000 as PCM.

3.2.1. Comparison of simulation results and experimental results

For validating the written correlations for proposed LHTES several experiments with different inlet temperatures and inlet velocities have been done. Results are shown in figures (10) and (11) respectively.

Discrepancies between the modelling and experimental data are probably due to non ideal distribution of PCM and air gaps in pouches. Note that in this part PEG 600 have been used as PCM.

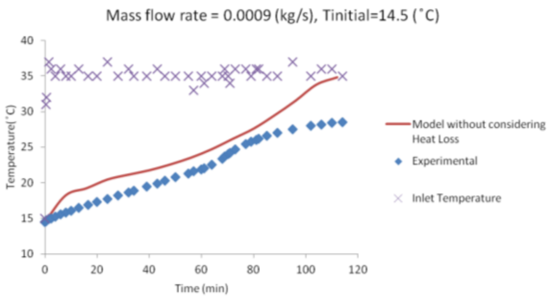

Fig. 10. Hot cycle-Low inlet temperature and low inlet velocity.

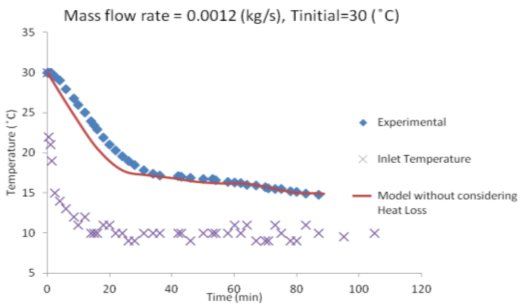

Fig. 11. Cold cycle-Low inlet temperature and low inlet velocity.

3.2.2. Performance Analysis

In this part 8 experiments have been designed with Factorial method, 4 experiments for the cold cycle and the other 4 experiments for the hot cycle, which are done using PEG 1000 as PCM. The following tables consist the related data and results for each experiment.

According to the results presented in Tables 3 and 4, following results can be concluded:

1) Increasing passing air velocity and temperature difference between inlet air and melting point of PCM, are two possible ways for shortening the process duration.

2) Increasing passing air velocity reduces the efficiency. It is probably related to the shortened residence time of the air in the bed.

Table 3. Cold cycle related data and results

Number of experiment	1	2	3	4
Inlet Air temperature (°C)	15	20	15	20
Inlet Air Velocity (m/s)	4	4	5	5
$Q_{\max} = m_g c_{pg} (T_{initial} - T_{inlet}(t))\tau$	265973	249123	262192	250229
$Q_{real} = m_g c_{pg} \int_0^{\tau} (T_{out}(t) - T_{inlet}(t)) d\theta$	97187	85728	95363	80249
Process termination (min)	117	130	92	103
Efficiency(%)	36.5	34.4	36.3	32.06

Table 4. Hot cycle related data and results

Number of experiment	1	2	3	4
Inlet Air temperature (°C)	50	55	50	55
Inlet Air Velocity (m/s)	4	4	5	5
$Q_{\max} = m_g c_{pg} (T_{initial} - T_{inlet}(t))\tau$	410010	374700	473088	415991
$Q_{real} = m_g c_{pg} \int_0^{\tau} (T_{out}(t) - T_{inlet}(t)) d\theta$	191687	187290	198437	193702
Process termination (min)	195	152	180	135
Efficiency (%)	46.7	49.98	41.94	46.56

3) In the hot cycle increasing the inlet air temperature, and in the cold cycle reducing inlet air temperature, increases the efficiency.

As can be seen there is a consistency between numerical and experimental results.

4. Conclusions

In this paper a one dimensional model for a LHTES containing flat slabs filled with PCM is presented. This model without considering the free convection in the melted parts of the PCM, calculates Air and PCM temperatures along the axial direction. For validating the model some experiments have been preformed. Moreover for finding the optimum operational conditions eight experiments were designed with Factorial method. It was observed that having a determined temperature difference in both cycles is very important due to its efficiency enhancement and process termination reduction.

5. Acknowledgement

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