Available online at www.sciencedirect.com

ScienceDirect

Procedia Manufacturing 35 (2019) 1303–1309

Procedia MANUFACTURING

www.elsevier.com/locate/procedia

2nd International Conference on Sustainable Materials Processing and Manufacturing (SMPM 2019)

The Characteristics of Heat Transfer in Plate Phase Change Energy Storage Unit

Changnian Chen[a]*, Zhen Xu [a], Hongxia Zhao [a], Zeting Yu[a], Jitian Han[a], Tien-Chien Jen[b]

[a]*School of Energy and Power Engineering, Shandong University, Jinan, 250061, China*
[b]*Mechanical Engineering Science, University of Johannesburg, Johannesburg, ZA-2006, South Africa*

Abstract

In order to study the heat transfer characteristics of the plate-type phase change energy storage unit, the Fluent Enthalpy method was used to simulate the heat storage and release process of the plate phase change materials (PCM) energy storage unit. The simulation results show that the main heat transfer zone will advance along the direction of the flat plate (air flow direction), and the speed of the main heat transfer zone is proportional to the air velocity with the continuous heat transfer process. In heat storage, the speed of the main heat transfer zone will accelerate with the increase of air velocities; while in the heat release process, the main heat transfer zone will accelerate with the increase of air velocities. Meanwhile, the liquid phase ratio of PCM material is also changing continuously which increases with time and is affected by the liquefaction or solidification speed. The faster the liquefaction and solidification speed are, the faster it will change. As the fluid inlet velocity increases, the heat storage exothermic efficiency also increases as the heat transfer fluid inlet velocity increases. Overall, the total heat transfer rate is gradually reduced compared with the initial heat transfer, and then tends to be consistent with the temperature of the heat transfer fluid.

Peer-review under responsibility of the organizing committee of SMPM 2019.

Keywords: Fluent; Heat transfer characteristics; PCM energy storage; Simulition;

1. Introduction

The application of phase change energy storage materials in energy storage has gradually attracted the attention of scholars all over the world. It has been widely used in water heaters, air conditioning, medical engineering, even military, aerospace engineering and other fields [1-5]. Phase change materials (PCMs) have the characteristics of

* Corresponding author. Tel.: +86-531-88395654; fax: +86-531-88395654.
E-mail address: chen.cn@sdu.edu.cn

2351-9789 © 2019 The Authors. Published by Elsevier B.V.
Peer-review under responsibility of the organizing committee of SMPM 2019.
10.1016/j.promfg.2019.05.031

small size, large energy storage per unit, friendly environment and easy control. Using PCMs, thermal energy can be stored in the material in the form of latent heat by phase change, and then converted into other forms of energy when used. The output temperature and energy are stable and the storage density is high. The storage heat per unit volume is 5-14 times that of sensible heat storage. The advantage is obvious [6-7]. But at the same time, the phase transition process is more complex and difficult to analyze [8-9].

Phase change energy storage technology is the use of materials to absorb or release heat to achieve energy storage and release purposes, it belongs to latent heat storage, energy storage density is high; phase change process is generally isothermal or approximate isothermal process, the temperature of phase change system is easier to control; phase change energy storage system uses simple devices, small size, flexible design, easy to use and easy to manage. It can be seen that energy storage technology has important application value in resolving the contradiction between energy supply and demand, improving energy utilization and protecting the environment.

However, the heat transfer process of phase change heat exchanger is more complex, especially for the composite phase change heat storage problem and the specific form of heat transfer unit, there is no more general formula reference, so it is necessary to study the relevant heat transfer characteristics. In this paper, the enthalpy method is used to analyze the heat transfer performance in PCM phase change energy storage unit, and the numerical simulation is carried out by the FLUENT software.

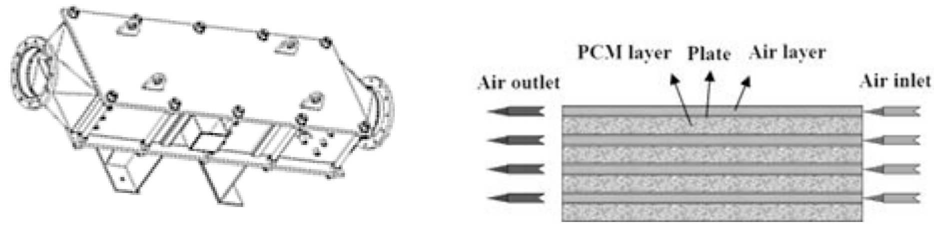
Nomenclature

$c_{p,s}$	Solid specific heat, J/(kg K)
$c_{p,s}$	Solid specific heat, J/(kg K)
h	Enthalpy, J/kg
L	Length of PCM unit, m
q	External heat flux, W/m^2
S	Cross-sectional area of PCM along air flow, K
T_a	Air temperature, K
Ts	Phase change material temperature, K
V	Velocity vector, m/s
ρ_s	Density, kg/m^3
λ_s	Thermal conductivity of PCM, W/(m K)
Subscripts	
M	Material
a	Air
0	Inlet state

2. Physical Model of PCM Storage Unit

The layout and physical model of the phase change energy storage device used is shown in Figure 1. The structure of the energy storage device is a kind of plate heat exchanger, in which the composite phase change material is encapsulated between staggered parallel plates. The heat transfer fluid (air) flows through the outer parallel channel and exchanges heat with the internal phase change material to achieve the purpose of thermal energy storage and release. In the heat storage process, the heat transfer fluid enters from the inlet above the device and flows out through the lower outlet; in the exothermic process, the flow direction of the heat transfer fluid is opposite to that of the heat storage process, and enters from the lower part and flows out from the upper part. The structure dimension of energy storage device is as follows: veneer area is 0.81 m^2, plate size is 1.6 m *0.505 m, steel plate is as thin as possible, i.e. about 1.0 mm, plate spacing is asymmetric channel, PCM channel is 0.010 mm, air channel is 0.003 mm, corresponding single channel cross-sectional area PCM channel is 0.00505 m, air channel is 0.001515 m^2. A summary of the unit structure parameters and material physical properties has been listed in Table 1 and Table 2.

In order to obtain more accurate simulation result, the following assumptions are made: 1) the heat conductivity and density of phase change media are constant and do not change with temperature; 2) the temperature of phase change is constant; 3) the heat transfer in phase change media is dominated by heat conduction, ignoring the effect of natural convection; 4) the initial temperature of phase change materials is close to the melting temperature.



(a) Layout of the PCM storage heat exchanger (b) Inner heat exchanger channels

Fig.1 Structure of the PCM thermal storage heat exchanger and channels

Table 1 The PCM unit structure parameters

No.	Structure parameters	Values
1	Air flow plate spacing/ m	0.003
2	PCM spacing/ m	0.01
3	Heat transfer area of veneer/ m^2	0.81
4	Cross section area of single channel/ m^2	0.001515
5	Section area of PCM in single channel/ m^2	0.00505
6	PCM channels number	39
7	Total heat transfer area/ m^2	63

Table 2 The PCM physical properties

No.	Performance parameters	Values
1	Phase change temperature/ ℃	138
2	Energy storage density of materials/ kJ/kg	300
3	Density / kg/m^3	~1000
4	Thermal conductivity/ W/(mK)	~1
5	Specific heat / J/(kgK)	1.9
6	PCM quantity/ kg	200
7	Heat storage capacity /kWh	16.7
8	PCM volume / m^3	0.200
9	Thermal resistance / mK/W	0.005

3. Mathematical Model of PCM Storage Unit

For the plate energy storage unit shown in the figure above, because the heat transfer along its thickness direction is very small compared with the flow direction, its internal heat storage and discharge area can be simplified to a two-dimensional structure for simulation calculation. In the process of simulation calculation, the average temperature of the PCM area and the outlet temperature of the heat transfer fluid are taken as the criteria, that is, when the average temperature of the PCM area is consistent with the temperature of the heat transfer fluid, or when the outlet temperature of the heat transfer fluid is consistent with the inlet temperature, the PCM inside the device is considered to be completely melted or solidified, other words, the heat energy storage or release are complete.

According to the air exothermic process, a coordinate system with the air inlet position as the origin and the x-axis direction parallel to the air flow direction has been established, as shown in Figure 2.

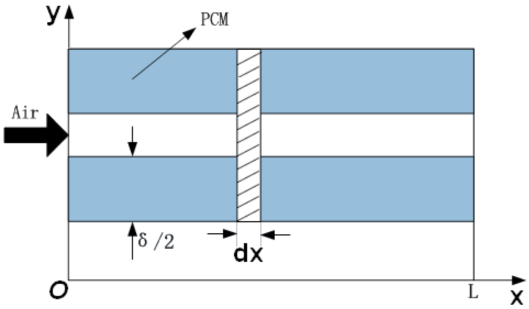


Fig. 2 Coordinate system and infinitesimal analysis for the PCM unit

Therefore, the following heat conduction equation can be established by analyzing the energy balance of d*x* volume from the origin of *x*.

$$S\rho_s c_{p,s}\partial T_s / \partial\tau = S\lambda_s \partial^2 T_s / \partial x^2 + KU\left(T_a - T_s\right) \tag{1}$$

The ideal gas equation of state is described as follows:

$$p = \rho_a R_M T_a \tag{2}$$

And the mass conservation equation is:

$$\rho_a u_a = \rho_{a,0} u_{a,0} \tag{3}$$

Energy equation:

$$\frac{\partial(\rho h)}{\partial t} + div(\rho u h) = div(\alpha\, grad h) + S_h \tag{4}$$

$$\frac{\partial(\rho h)}{\partial \mathrm{t}} = \lambda\nabla^2 \mathrm{T} = \frac{\partial}{\partial \mathrm{t}}\left(\lambda\frac{\partial \mathrm{T}}{\partial \mathrm{x}}\right) + \frac{\partial}{\partial \mathrm{t}}\left(\lambda\frac{\partial \mathrm{T}}{\partial \mathrm{y}}\right) \tag{5}$$

The boundary and initial conditions are listed as bellows:

For boundary conditions,

$$T_a(0,\tau) = T_{a,0} \tag{6}$$

$$\partial T_s(0,\tau) / \partial x = \partial T_s(L,\tau) / \partial x = 0 \tag{7}$$

For initial conditions,

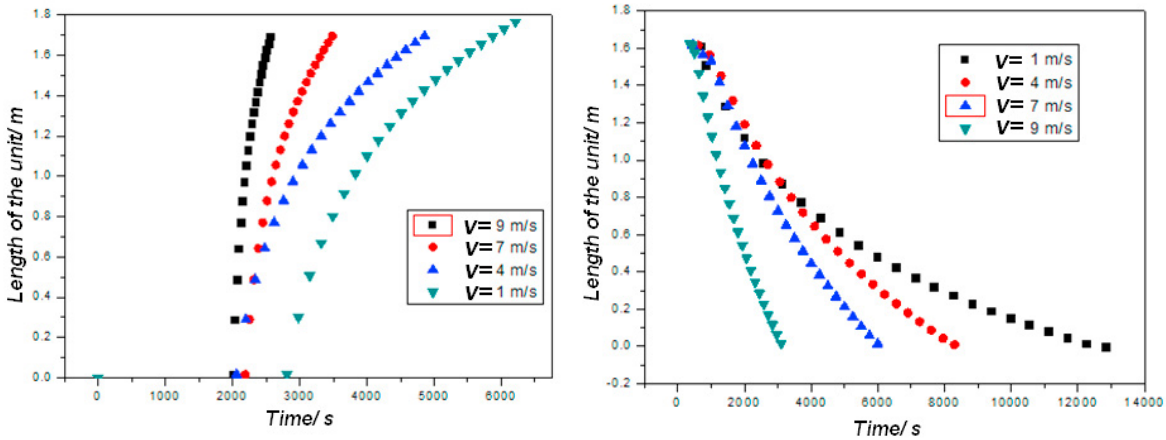
$$T_s(x,0) = f(x) \tag{8}$$

Considering the non-steady phase change process for heat storage and discharge in device, it is difficult to obtain the analytical solution under this problem. Therefore, numerical method is used to simulate the heat storage and discharge process of heat storage device, time and space are discretized in the solution area, and partial differential mathematical model equation is approximated by forward difference.

4. Simulation and Analysis

4.1. Process Analysis in Main Heat Exchange Zone

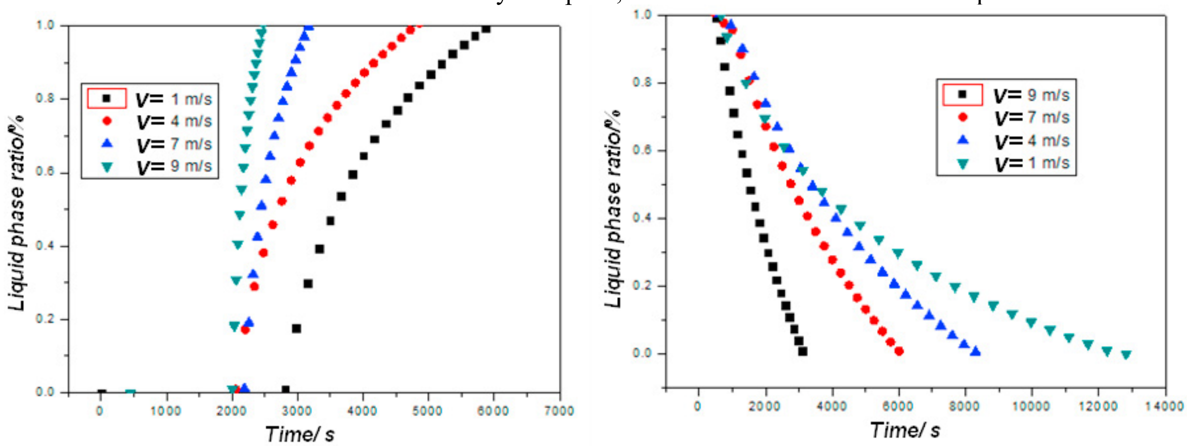
The process of the main heat transfer zone in phase change heat transfer unit has been analyzed. With the continuous heat transfer process, the main heat transfer zone will advance along the direction of flat plate (air flow). From Figure 3, it can be seen that the speed of the main heat transfer zone is proportional to the air velocity, and the speed of the main heat transfer zone (forward heat storage) will accelerate with the increase of the air velocity while the heat release. The main heat transfer zone also accelerates with the increase of the rate (reverse exothermic).



(a) thermal storage conditions (b) thermal discharge conditions

Fig. 3 Phase change heat transfer process in the main heat transfer zone

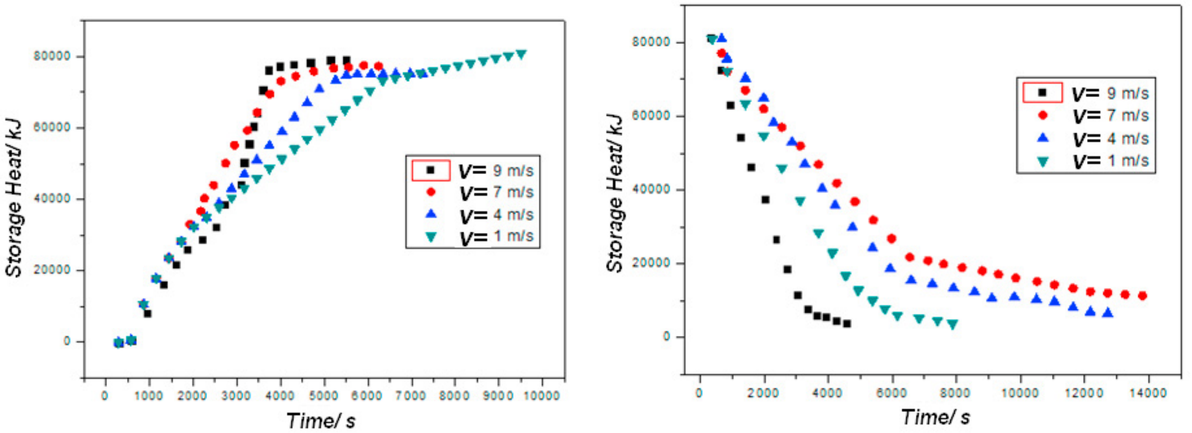
PCM material exists in two-phase state (liquid phase and solid phase) during exothermic process, the ratio of the mass of PCM material in liquid phase state to the mass of PCM material in general is defined as the liquid phase ratio of PCM material. With the continuous heat transfer process, the liquid phase ratio of PCM material is also changing continuously, that is, from 0% to 100%. From Figure 4, it can be seen that the change trend of liquid phase ratio is consistent with that of the propulsion degree of the main heat transfer zone. The liquid phase ratio of PCM increases with time and is affected by the speed. The faster the liquefaction speed is, the faster the liquid phase ratio of PCM decreases with time and is also affected by the speed, and the faster the solidification speed is.



(a) thermal storage conditions (b) thermal discharge conditions

Fig. 4 Liquid phase ratio in the process of phase change heat transfer

The amount changes of thermal storage during heat storage and exothermic process is studied. It can be seen from Figure 5 that the growth rate of heat storage is relatively small at the beginning stage, because it is only the characteristic of sensible heat storage. When phase change occurs, the growth rate increases approximately linearly, and the change trend of heat storage decreases until the end of phase change heat storage stage, but the total heat storage increases. Under the conditions of 1 m/s, 4 m/s, 7 m/s and 9 m/s flow rates, the time period for the increase of storage heat is gradually shortened, which is about 3000s, 2600s, 1700s and 900s, respectively. It can be concluded that the phase change heat release process occurs at the beginning of heat release. The phase change heat release process lasts until the phase change is complete. The time period for the linear decrease of the heat storage capacity under the flow conditions of 1m/s, 4m/s, 7m/s and 9m/s is also gradually shortened, which is about 3200s, 2800s, 1900s and 1100s, respectively. Converting to sensible heat release, the rate is low and the storage heat decreases slowly.



(a) thermal storage condition (b) thermal discharge condition

Fig. 5 Thermal storage changes during heat storage and exothermic process

Conclusions

1) With the continuous heat transfer process, the main heat transfer zone will advance along the direction of the flat plate (air flow direction), and the speed of the main heat transfer zone is proportional to the speed. In heat storage, the speed of the main heat transfer zone (forward heat storage) accelerates with the increase of the rate, while in heat release, the main heat transfer zone accelerates with the increase of the rate (reverse heat release).

2) With the continuous heat transfer process, the liquid phase ratio of PCM material also changes continuously. The liquid phase ratio of PCM increases with time and is affected by velocity. The faster the liquefaction speed is, the faster the liquid phase ratio of PCM decreases with time and is also affected by velocity.

3) When heat storage occurs, the growth rate of heat storage is relatively small at the beginning stage. When phase change occurs, the growth rate increases approximately in a straight line, and the growth rate is larger. Until the end of phase change heat storage stage, the change trend of heat storage decreases, but the total heat storage increases. While heat release occurs, the decrease of heat storage basically shows a linear decrease at the beginning, so it can be concluded that the initial stage of heat exchanger heat release occurs. Phase change heat release process, which goes on until the phase change is complete, and then converts to sensible heat and exothermic, and the rate decreases.

Acknowledgements

This work is supported by the Natural Science Foundation of Shandong Province, China (ZR2014EEQ008) and the National Natural Science Foundation of China (51706124).

References

[1] Z. M. Jiang. Reflections on Energy Issues in China, Journal of Shanghai Jiaotong University, 2008, 42(3): 345-359.

[2] Y. L. Li, Y. Jin, Y. Huang, etc., Fundamentals of Heat Storage Technology (I) - Basic Principles of Heat Storage and New Trends of Research, Energy Storage Science and Technology, 2013 (01): 69-72.

[3] Kenisarin M, Mahkamov K. Solar energy storage using phase change materials [J]. Renewable and sustainable Energy Reviews, 2007,11(9): 1913-1965.

[4] Rudd A F. Phase-change material wallboard for distributed thermal storage in buildings [G]//ASHRAE Trans, 1993, 99(2):339-346.

[5] Hammond M J. Reversible Liquid/Solid Phase Change Compositions [P]. US Pat.: 5785884, 1998−07−28.

[6] Feldman D, Shapiro M M, Banu D. Organic Phase Change Materials for Thermal Energy Storage [J]. Sol. Energy Mater, 1986, 13(1): 1−10.

[7] Syed M T, Kumar S, Moallem I M K, et al. Thermal Storage Using Form Stable Phase Change Materials [J]. ASHRAE J., 1997, 39(5): 45−50.

[8] Akiyama T, Yagi J. Encapsulation of Phase Change Materials for Storage of High Temperature Waste Heat [J]. High Temp. Mater. P., 2000, 19(4): 219−222.

[9] Vigo T L, Frost C M. Temperature Adaptable Fibers [J]. Text. Res. J., 1986, 56(12): 737−740.

[10]Chen Xiao, Zhang Renyuan, Mao Lingbo. Progress in research and application of paraffin wax phase change material [J] .Materials Research and Application, 2008 (2):89-92.