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Research progress of phase change materials (PCMs) embedded with metal foam (a review)

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Abstract

Latent heat storage using phase change materials (PCMs) attract more and more attention in recent years. But most of the PCMs present low thermal conductivity, which decrease the heat transfer rate and leads to low energy utilization efficiency of the storage system. Metal foam with high thermal conductivity, porosity, surface-area to volume ratio and strong mixing capability is considered as one of the most promising heat transfer enhancement materials. In this paper, the kinds of metal foam used in PCMs and the efficient thermal conductivity and convection heat transfer of the composite PCMs are reviewed. The research methods used in the investigation of conductive, convective and phase change heat transfer process in composite PCMs are also reviewed.

Keywords: phase change materials (PCMs); thermal conductivity; convection; heat transfer

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1. Introduction

CO_2-induced global warming has become a pressing issue and needs to be tackled. Efficient application of renewable energy is considered a promising solution to global warming and energy crisis. Most of the renewable energy is discrete and unstable. Due to extensive requirement in renewable energy applications (such as solar

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energy), thermal energy storage techniques have been paid great attention (Zalba et al. (2003) and Agyenim et al. (2010)). Latent heat storage using phase-change-materials (PCMs) is particularly attractive, since it provides benefits include reduction in temperature variability (thermal inertia) and high thermal energy storage density (Hoshi et al. (2005), Tian and Zhao (2013)).

Various PCMs are generally divided into two main groups from their compositions (i.e. organic and inorganic PCMs) or two categories from their melting points (i.e. high-temperature PCMs above 200 °C and low-temperature one below 200 °C). The high-temperature PCMs can be used in solar power plants, while the low-temperature PCMs are mainly used in waste heat recovery systems and buildings. Organic substances exhibit desirable properties at low temperature applications, such as limited supercooling, no phase segregation and non-corrosion. Inorganic PCMs have large latent heat and can be used in high temperature energy storage. But both of organic and inorganic PCMs present a low thermal conductivity (Zalba et al. (2003), Olives and Mauran (2001)).

In order to offset the heat storage/extraction rate during melting/solidification cycles, extensive investigations have been carried out to improve the thermal response of PCMs through adding various high thermal conductivity materials (Li et al. (2008)). The methods include dispersing high conductivity particles or fibers into PCMs, impregnating a porous metallic (or graphite) matrix with PCMs.

Metal foam is a cellular structure consisting of a solid metal, containing a large volume fraction of gas-filled pores. The pores can be sealed (closed-cell foam) or form an interconnected network (open-cell foam). Due to the high surface-area to volume ratio and strong mixing capability, high porosity open-cell light-metallic foams have emerged as one of the most promising emerging materials for thermal energy storage (Cui et al. (2010), Hong and Herling (2006), and Bugaje (1997)).

2. PCMs Embedded with Metal Foam

In many applications, thermal energy storage is required to receive, store and subsequently release heat. The major disadvantage of PCMs is their low thermal conductivities, which dramatically slows the phase change process and causes a wide temperature distribution within PCMs. Metal foams presents an order of magnitude higher thermal conductivity than PCMs. At the same time the random internal structure and high porosity of metal foam can enhance and accelerate the phase change process without significantly reducing PCMs' heat storage capacity. The distribution of foam ligaments in PCMs makes the melting and solidification processes more uniform.

There are many kinds of metal foams have been used in phase change materials, such as aluminum foam (Bauer and Wirtz (2000), Chintakrinda et al. (2011), Tong et al. (1995), Jiang et al. (2012)), copper foam (Chi et al. (2011), Sheng et al. (2013), Zhang and Yu (2007), and Cui (2012)) and Nickel foam (Shiina (2006), Weiqiang et al (2009), Xiao, (2013)).

2.1. PCMs Embedded with Aluminum Foam

Bauer and Wirtz (2000) developed a plate like structure thermal energy storage composite consisting of a central core of foamed aluminum foam packed with PCM to store heat during peak power operation of variable power dissipating devices. Tong et al. (1995) inserted a matrix of continuously connected aluminum foam into phase change material (water) and investigated the solidification heat transfer of the water. Results show inserting metal-matrix into water provides a very effective way to enhance the solidification heat transfer.

Jiang et al. (2012) prepared a shape-stabilized PCMs using bulk porous Al foams impregnated with organic PCMs (paraffin and stearic acid). The thermal-/dynamic-mechanical properties of the shape-stabilized PCMs were studied. The filling fraction of PCMs was approximately more than 80%, the latent value of the paraffin/Al foam and stearic acid/Al foam composite is 72.9kJ/kg and 66.7kJ/kg.

2.2. PCMs Embedded with Copper Foam

Chi et al. (2011) made a new type of high efficiency energy storage devices consisted of cooper foam and water. The cold charging process of the new type energy storage devices was approved to be faster and more adequate due to the embedding of copper foam.

Sheng et al. (2013) prepared a salt hydrate/metal foam composite phase change material by using barium hydroxide octahydrate ($Ba(OH)_2 \cdot 8H_2O$) as latent heat storage PCM and copper foams as a supporting matrix. Thermal cycling and heat transfer performance was studied. Results show that high porosity copper foam not only enhance the heat transfer rate of $Ba(OH)_2 \cdot 8H_2O$ but also effectively reduce the supercooling of the PCM.

Zhang and Yu (2007) investigated the thermal performance of solid-liquid phase change thermal storage device with 98% pure Heneicosane ($C_{21}H_{44}$) filled in copper foam through a vacuuming procedure. Experimental results show that the thermal conductivity and performance of the thermal storage device is obviously improved using copper foam as a heat transfer enhancement.

Cui (2012) prepared a composite PCMs using paraffin as phase change materials and copper foam as filled materials. The results show that copper foam can not only lead to a more uniform temperature distribution within the thermal energy storage unit, but also extensively shorten the charging time.

2.3. PCMs Embedded with Nickel Foam

Shiina (2006) studied the application of latent heat storage technology using a composite PCM (a copper or nickel foam saturated by PCM). The results indicate that composite PCM had increased effective thermal conductivity and could augment temperature change reduction of the heat transfer fluid.

In order to improve the void distribution and thermal performance of phase change thermal storage devices, Xu et al (2009) designed and manufactured a thermal storage containers embedded with nickel foam cores. Embedding nickel foam into the PCMs enhanced both the void distribution and thermal performance of solid-liquid phase change process.

Xiao, (2013) prepared paraffin/nickel foam and paraffin/copper foam composite phase change materials (PCMs) using a vacuum impregnation method. Results show that the thermal conductivity of the composite PCMs were drastically enhanced, e.g., the thermal conductivity of the paraffin/nickel foam composite was nearly three times larger than that of pure paraffin.

3. Properties of PCMs Embedded with Metal Foam

3.1. Effective Thermal Conductivity

Due to the high thermal conductivity and porous structure, embedding metal foam into PCMs can enhance the heat transfer, thus improve the effective thermal conductivity of the composite PCMs.

It is very difficult to predict the thermal conductivity of the PCMs embedded with metal foam for the complicated pore structure of the metal foam. Xu et al (2009) proposed a new phase distribution model of metal foam matrix PCMs. Simplified heat transfer model with void sub model was established and the effective thermal conductivity formula was derived by the equivalent thermal resistance method.

Zhang et al (2010) investigated the thermal parameters (Effective thermal conductivity, thermal diffusivity and thermal capacity) of copper-foam/paraffin with four different porosities using transient plane source (TPS) method. The test results showed that the effective thermal conductivity is obviously improved by embedding the copper foam into paraffin and it reached 25 times compared to pure paraffin.

3.2. Convection

Metal foam with high thermal conductivity is generally considered to have high potential to enhance the heat transfer performance for PCMs. In an attempt to enhance the convective thermal transport, metal foam can be used for making advanced compact heat exchangers because of the high surface area to volume ratio as well as enhanced flow mixing due to the tortuosity of the pass ways. But in the study of Tian and Zhao (2011), the natural convection in liquid region of the PCMs is suppressed by the metal foam. Buoyancy-driven velocities are too weak to produce dominant convection due to high viscosity and low thermal expansion ratio of the PCM and the large flow resistance of metal foam.

4. Research Methods of Heat Transfer in PCMs

In order to study the heat transfer and thermal storage capacity of the PCMs, extensive research methods have been developed, such as experimental study, theoretical analysis and numerical simulation.

4.1. Experimental Method

Lafdi et al (2007) built an experimental setup to measure the temperature profiles and capture the melting evolution of the PCM (low melting temperature paraffin wax) inside aluminum foam. Effects of porosity and pore size of the aluminum foam on the heat transfer performance were studied. For the higher porosity aluminum foam the steady-state temperature was reached faster as compared to the lower porosity foam. By using bigger pore size foam, the steady-state temperature was reached faster as compared to the foams with smaller pore size.

Wu and Zhao (2011) investigated heat transfer enhancement performance of metal foam (copper foam) in high temperature thermal energy storage system using $NaNO_3$ as phase change material. Effect of natural convection on the heat transfer rate was investigated under bottom and top heating conditions. The heat transfer rate can be enhanced by copper foam to 2.1 times compare to pure $NaNO_3$. However, in the liquid PCM, the heat transfer rate was no longer better that of the pure $NaNO_3$ because metal foam suppressed the natural convection severely. Under the top heating condition, the heat transfer rate was enhanced by 1.2 times.

Shi et al (2010) studied phase change heat transfer in ice ball with porous metal foam experimentally. The results show that porous metal foams can enhance the phase change heat transfer in ice ball, lead to starting phase change earlier and shorten the whole phase change time.

4.2. Theoretical Analysis Method

Krishnan et al (2004) employed a two-temperature model to account for the local thermal non-equilibrium. Separate energy equations for the solid and fluid respectively are written and closed using a steady-state interphase heat transfer coefficient between the two phases. A general momentum equation that includes the Brikman-forchheimer extension to Darcy flow is employed. Natural convection inside the fluid was analyzed using a two-temperature formulation. Results show that local thermal equilibrium is not ensured either during the transient or at steady state in the system.

Peng et al (2009) investigated the phase change heat transfer in PCM (wax) embedded in high porosity aluminum foam. A two-temperature model was established according to the difference of the heat transfer between wax and Al foam. The temperature distributions and flow fields of the PMCs were simulated by apparent heat capacity method. The results showed that the heat transfer of the PCMs in Al foam was effectively improved compared to pure PCMs without Al foam. Chen et al (2010) studied the melting process of paraffin in high porosity aluminum foam using a similar two-temperature model. The simulation results indicate that aluminum foam makes the temperature distribution of the paraffin more even. There is big temperature difference between metal frame and PCM during phase change process. Local thermal non-equilibrium is obvious. Melting speed of the paraffin increases with the decreasing of metal foam porosity.

4.3. Numerical Simulation Method

Based on local thermal non-equilibrium between the metal matrix and PCMs, Gao and Chen (2012) and Zhang et al (2013) developed a Lattice Boltzmann model to characterize the melting processes and heating conduction of PCMs in metal foams and the temperature filed of metal foams framework. An equation based on density distribution function was constructed to characterize the velocity field of melt fluid. An enthalpy-based method is employed to account the phase change problem. The melting front location as the function of time and the temperature distribution in metallic framework and the PCMs is simulated by Lattice-Boltzmann model. The effects of the porosity and pore size on the melting are also investigated and discussed. The results indicate that the effects of foam porosity play important roles in the overall heat transfer. For the lower porosity foams, the melting rate is comparatively greater than the higher porosity foams, due to greater heat conduction from metal foam with high heat conductivity. The foam pore size has a limited effect on the melting rate due to two counteracting effects between conduction and convection heat transfer. Increasing of the pore density leads to increasing conduction heat transfer, decreasing convection heat transfer and decreasing heat storage capacity. Therefore, it is suggested to consider engineering requirements to determine porosity in the design of foam metal heat storage device.

A phase filed model deals with free boundary problems without tracing their positions, and therefore provides potentials of being extended to consider more complicated mechanisms: multi-dimension and volume change. Han et al (2013) established a foam-PCM phase filed model to solve the phase change problem by introducing two phase files to deal with phase change and volume change. The coupled heat transfer between PCMs and metal foams is solved based on the non-equilibrium heat transfer theory. An effectiveness map distinguishing the conditions under which incorporating metal foam into the PCMs is sensitive, lowly sensitive or irrelevant is produced to guide the metal selection and structure design of metal foams when enhancing the heat transfer of PCMs.

5. Summary

In this paper the research progress of phase change materials (PCMs) embedded with metal foam is reviewed. The conduction, convection and phase change heat transfer process in the PCMs has been extensively investigated. Embedding metal foam into PCMs is an effective method to enhance the heat transfer in the PCMs. Due to the high thermal conductivity, surface area volume ratio, porosity and complicated three dimension network, metal foam in the composite PCMs increase the effective thermal conductivity of the composite PCMs, and thus improve the uniformity of the temperature distribution in the PCMs. Generally the metal foam embedded in the PCMs suppress the natural convection and reducing the convective heat transfer performance. Metal foam structure affects the heat transfer performance of the PCMs significantly. It is suggested to consider both the effects foam porosity and pore size on conduction and convection heat transfer as well as engineering requirements to determine porosity in the design of foam metal heat storage device.

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References

Agyenim, F., Hewitt, N., Eames, P., and Smyth, M., 2010, A review of materials, heat transfer and phase change problem formulation for latent heat thermal energy storage systems (LHTESS), Renewable and Sustainable Energy Reviews, 14, 615-628.

Akira, H., David, R.M., Antoine, B., Takeo, S.S., 2005, Screening of high melting point phase change materials (PCM) in solar thermal concentrating technology based on CLFR, Solar Energy Solar Energy, 79, 332-339.

Bauer, C.A., and Wirtz, R.A., 2000, Thermal characteristics of a compact, passive thermal energy storage device, ASME Heat Transfer Div. Publ. HTD, 366, 283-289.

Bugaje, M., 1997, Enhancing the thermal response of latent heat storage systems, Int. J. Energy Res., 21, 59-66.

Chi, P., Xie, Y., Yu, J., and Yang, X., 2011, Experiment and analysis for cold charging process of new energy storage device, Journal of Beijing University of Aeronautics and Astronautics, 37, 1070-1075.

Chintakrinda, K., Weinstein, R.D., and Fleischer, A.S., 2011, A direct comparison of three different material enhancement methods on the transient thermal response of paraffin phase change material exposed to high heat fluxes, International Journal of Thermal Sciences, 50, 39-47.

Cui, H.T., 2012, Experimental investigation on the heat charging process by paraffin filled with high porosity copper foam, Appl. Therm. Eng., 39, 26-28.

Gao, D., and Chen, Z., 2012, Influence of pore density on melting of phase change materials in metal foams-numerical simulation with Lattice Boltzmann method, Acta Energiae Solaris Sinica, 33, 1604-1609.

Hai-ting, C., Feng-qing, L., Jin-da, Z., and Wei, L., 2010, Enhancement of high porosity metal foam to phase change energy storage, J. Hebei Univ. Sci. Technol., 31, 3-6.

Han, X.X., Tian, Y., and Zhao, C.Y., 2013, An effectiveness study of enhanced heat transfer in phase change materials (PCMs), Int. J. Heat Mass Transfer, 60, 459-468.

Hong, S., and Herling, D.R., 2006, Open-cell aluminum foams filled with phase change materials as compact heat sinks, Scr. Mater., 55, 887-890.

Jinghua, J., Yingying, Z., Aibin, M., Donghui, Y., Fumin, L., Jianqing, C., Jun, S., Song, D., 2012, Preparation and performances of bulk porous Al foams impregnated with phase-change-materials for thermal storage, PNSC Progress in Natural Science: Materials International, 22, 440-444.

Krishnan, S., Murthy, J.Y., and Garimella, S.V., 2004, A two-temperature model for the analysis of passive thermal control systems, Journal of Heat Transfer, 126, 28-37.

Lafdi, K., Mesalhy, O., and Shaikh, S., 2007, Experimental study on the influence of foam porosity and pore size on the melting of phase change materials, J. Appl. Phys., 102, 35-49.

Li, K., Guo, N., and Wang, H., 2008, Progress on the Study of Improving the Phase Change Materials Conductivity, 1-6.

Peng, D., Chen, Z., and Shi, M., 2009, Numerical simulations of phase change material thawing process in metallic foams, Journal of Engineering Thermophysics, 30, 1025-1028.

Py, X., Olives, R., Mauran, S., 2001, Paraffin/porous-graphite-matrix composite as a high and constant power thermal storage material, International journal of heat and mass transfer., 44, 2727-2737.

Sheng, Q., Xing, Y., and Wang, Z., 2013, Preparation and performance analysis of metal foam composite phase change material, Journal of Chemical Industry and Engineering, 64, 3565-3570.

Shi, J., Chen, Z., and Shi, M., 2010, Experimental study on the effect of the porous metal foams in ice ball on the freezing heat transfer of fluid, Journal of Engineering Thermophysics, 31, 1395-1397.

Shiina, Y., 2006, Reduction of temperature changes in heat transfer fluid by the use of latent heat storage technology, Transactions of the Atomic Energy Society of Japan, 5, 190-199.

Tian, Y., and Zhao, C.Y., 2011, Natural convection investigations in porous, Phase Change Materials, 3, 769-772.

Tian, Y., and Zhao, C.Y., 2013, A review of solar collectors and thermal energy storage in solar thermal applications, Appl. Energy, 104, 538-553.

Tong, X., Khan, J.A., and Amin, M.R., 1995, Enhancement of solidification heat transfer by inserting metal-matrix into phase change material, 8.

Weiqiang, X., Xiugan, Y., and Yuming, X., 2009, Effect of embedding nickel foam on solid-liquid phase change, Journal of Beijing University of Aeronautics and Astronautics, 35, 197-200.

Wu, Z.G., and Zhao, C.Y., 2011, Experimental investigations of porous materials in high temperature thermal energy storage systems, Solar Energy, 85, 71-80.

Xiao, X., Zhang, P., and Li, M., 2013, Preparation and thermal characterization of paraffin/metal foam composite phase change material, 112, 1357-1366.

Xu, W., Yuan, X., and Li, Z., 2009, Study on effective thermal conductivity of metal foam matrix composite phase change materials, Journal of Functional Materials, 40, 1329-1332.

Zalba, B., Marin, J. M., Cabeza, L. F., and Mehling, H., 2003, Review on thermal energy storage with phase change: Materials, heat transfer analysis and applications, Appl. Therm. Eng., 23, 251-283.

Zhang, T., and Yu, J., 2007, Experiment of solid-liquid phase change in copper foam, Journal of Beijing University of Aeronautics and Astronautics, 33, 1021-1024.

Zhang, T., Yu, J., and Gao, H., 2010, Measurement of thermal parameters of Copper-foam/paraffin composite PCM using transient plane source (TPS) method, Acta Energiae Solaris Sinica, 31, 604-609.

Zhang, Y., Gao, D., and Chen, Z., 2013, Influence of porosity on melting of phase change materials in metal foams with lattice Boltzmann method, Journal of Southeast University, 43, 94-98.

Zhen-qian, C., Ming-wei, G., and Ming-heng, S., 2010, Numerical simulation on phase change heat transfer of paraffin in metal foams, Journal of Thermal Science and Technology, 9, 6-11.