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Research Paper

Study on heat transfer and cold storage characteristics of a falling film type of cold energy regenerator with PCM

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HIGHLIGHTS

- Peak temperature of phase change turning is about 20 °C in cold energy storage process.
- Hydrophilic treatment promotes the formation of stable liquid film during low liquid flow rate.
- Falling film heat transfer has better heat transfer performance with less pump power consumed.
- Film Reynolds number and tube row number decide the cold storage time and storage efficiency.
- Flexible cold storage quantity can be obtained by simply adjusting the tube bundle structure.

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ABSTRACT

The heat transfer and cold storage characteristics of a falling film type of cold energy regenerator were numerically and experimentally studied in cold energy storage process. Combined with falling film heat transfer and cold storage technology with solid-liquid phase change material, the test system was made up of three columns of horizontal tubes and each column vertically contained 36 copper tubes. Hydrophilic coating was sprayed on the outside surface of copper tubes to reduce the solid-liquid contact angle. The heat transfer fluid was water and the film Reynolds number range of liquid film was from 100 to 500. A mixture of decanoic acid, lauric acid and oleic acid was adopted as the PCM whose phase change temperature is around 20 °C. Study results show that the cold energy regenerator has good heat transfer performance and cold storage characteristics with small pumping power consumed. Lower film Reynolds number will strengthen the cold storage performance. At the same time, flexible cold storage quantity can be simply obtained through adjusting the column or row number of the tube bundle. The present study proposes a good choice for cold energy storage unit.

1. Introduction

As a major source of world energy, fossil fuel accounts for 85.5% of the global energy consumption. However, with the consumption of fossil fuels, a series of environmental issues such as climate changing and global warming will occur [1]. Under this circumstance, the utilization of new energy and renewable energy sources, as well as energy saving technology has become the focus of the world. In daily life, huge difference of energy supply between day and night exists and does harm to the stability of power transmission system. How to use the redundant electricity generated in night to release the electricity pressure in daytime is a critical problem now.

Cold storage technology, due to its unique effect on load shifting, is one of the solutions to this problem and has become an important measure to improve the situation of the shortage of electric power in the world. As an effective way to ease the imbalance between energy supply and demand, energy storage technology also accelerates the commercialization process of new energy and renewable energy. Hasnain [2] introduced the sustainable cool thermal storage technologies and their advantages and disadvantages. Charvát et al. [3] studied the PCM thermal energy storage in solar heating of ventilation air. Mankibi et al. [4] investigated the potential of using PCMs to improve the thermal performance of residential hot water tanks and to shift the peak power demand.

The medium and technology application are two main part of cold storage technology. Cold is stored in the medium in the form of sensible heat or latent heat. Compared with sensible heat cold storage, latent heat cold storage possesses the advantages of high energy density,

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Nomenclature

A	heat transfer area (m^2)
c_p	specific heat (J/kg/K)
H	enthalpy (J)
H	heat transfer coefficient ($W/m^2{\cdot}K$)
L	length of copper tube (m)
m	mass (kg)
P	power (W)
Q	heat (J)
q_v	volume flow rate of water (m^3/s)
R	external diameter of copper tube (m)
T	Temperature (°C)
ΔT	temperature difference (°C)

Greek letters

ρ	density (kg/m^3)
λ	heat conductivity coefficient of PCM (W/m·K)
θ	liquid rate of PCM
τ	time

Subscripts

i	inlet
l	liquid (water)
o	outlet
P	PCM
s	solid
w	wall

Abbreviations

DSC	differential scanning calorimeter
PCM	phase change material

extensive applicability and high system efficiency etc. Solid-liquid PCM is the main type in latent heat cold energy storage and can be classified as inorganic, organic and composite PCMs. For inorganic material, metal and alloy are used in high temperature system while hydrous salt is adopted for low temperature storage. Heckenkamp et al. [5] found a type of hydrous salt which holds low melting point and high latent heat. Besides, this hydrous salt is suitable for air conditioning system. Organic material includes paraffin, fatty acid and polyhydric alcohols. Apart from reversible melting and solidification process, the variation of phase change temperature and latent heat is also very small during these process [6]. The character of fatty acid is similar to that of paraffin. Furthermore, fatty acid has lower price and is an ideal choice for PCM. Composite PCMs usually have superior properties compared with original PCM and they can meet most demands in range of phase change temperature from 6 °C to 15 °C. He B et al. used Tetradecane and hexadecane binary mixtures as the PCMs and measured their thermos-physical properties [7,8]. Dimaano et al. investigated thermos-physical and heat transfer characteristics of the capric-lauric acid with some organic additives [9]. Up to now, various commercial composite phase change materials which possess outstanding performance have been developed while the high price limits their wide application. Also, the influence of adding nanoparticles to PCMs on the thermal conductivity was investigated [10].

Present phase change cold storage technology can be classified as shape-unstable phase change technology, modular unit technology, large container storage technology and assistant heat pipe technology according to various conditions of PCM. Shape-unstable phase change technology is one type of direct contact cold storage technologies. It reduces the thermal resistance between heat transfer fluid and PCM through direct contact, and finally enhances the heat transfer character. Studies about shape-unstable technology are not many. Both Inaba et al. [11] and Martin et al. [12] chose liquid medium which hold density different from PCM as the heat transfer fluid to conduct experiments while Belusko et al. [13] adopted air as the heat transfer fluid. The PCM unit of modular unit technology holds the geometry of spherical, cylindrical, plate-like, ball-like and so on [14–16]. The specific shape can be flexibly adjusted according to the actual requirement. Navarro et al. [17] proposed an innovative constructive system that consisted of a prefabricated concrete slab with macro-encapsulated PCM inside its hollows. He found that this system could reduce effectively the total energy consumption of the building by experimental research. The application of commercial PCMs and the adoption of fins were also studied [18–20]. Groulx et al. [21] investigated the enhancement in the melting rate of PCM by addition of fins in rectangular enclosures. The influence of fin size and distribution on solid-liquid phase change in a rectangular enclosure was also studied [22].

Large container storage technology is also the hot spot. Avci et al. [23] and Ismail et al. [24] explored the heat transfer situation of a horizontal tube-in-shell storage unit. Other researchers [25–27] strengthened the heat transfer of tube-shell regenerator with different types of fins. By increasing heat transfer area, coiled pipe type improves large container storage technology. Rahimi et al. [28] intensified the heat transfer process by the utilization of coiled pipe and fins together. Besides, heat pipe is used in phase change cold storage technology due to its advantages of effective heat transfer, continuous temperature and simple structure etc. Fang et al. [29] and Turnpenny et al. [30,31] verified that the use of heat pipe could raise the cold storage efficiency through experimental researches. Studies [32,33] also adopted fins to strengthen the heat transfer effect of heat pipe type phase change regenerator. Moreover, Mankibi et al. [34] designed an experimental test bed to characterize PCM-water exchanger and the prototype would be used in the future for the experimental validation of a numerical model.

Although various heat transfer technologies are employed for present cold energy regenerator, the heat transfer ways between fluids and PCM are almost all the forced convection in various channels or tubes during cold energy storage process. Usually, PCM is stored in different types of containers and exchanges heat with fluids outside the container through the metal wall. The flow of fluid medium argues for the pumping power. Moreover, the bigger the heat transfer coefficient is, the greater the consumed pumping power is. The consumed pumping power is nearly the same as the heat released. Hence, it is essential to find a new phase change cold energy regenerator to reduce the consumed pumping power.

Falling film heat transfer is a passive heat transfer mode in which the heat transfer fluid flows through the tube surface with the help of gravity. No power is needed during the heat transfer process. The only energy required is to lift the liquid working medium to a higher place and the consumed energy mentioned is very small compared with that consumed in complex piping systems. At the same time, falling film heat transfer holds high heat transfer coefficient. Therefore, falling film type of heat exchanger is a suitable structure for cold energy storage. Under the circumstance of same heat transfer ability, the pump work needed for falling film regenerator is much less than that of forced convection regenerator.

Up to now, most of the industrial falling film heat exchangers are evaporative heat exchanger. Tube bundle contains horizontal tube type and the vertical tube type. Compared with the vertical type, horizontal tube type has simpler structure and better heat transfer performance. Therefore, most industrial devices choose horizontal tube type.

For the falling film flow outside horizontal tubes, the flow pattern of