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UNIVERSITI PUTRA MALAYSIA

NUMERICAL AND EXPERIMENTAL HEAT TRANSFER CHARACTERISATION OF PARAFFIN WAX MATERIAL WITH DIFFERENT HEATED TUBE ARRANGEMENTS

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NUMERICAL AND EXPERIMENTAL HEAT TRANSFER CHARACTERISATION OF PARAFFIN WAX MATERIAL WITH DIFFERENT HEATED TUBE ARRANGEMENTS

By

SUDITAMA

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirement for the Degree of Doctor of Philosophy

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Abstract of the thesis is present to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

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Chairman: Associate Professor Megat Mohamad Hamdan Megat Ahmad, PhD

Faculty: Engineering

The aim of this study is to obtain the heat transfer characteristics of the heated tube inline and staggered arranged immersed in the thermal energy storage material (paraffin wax) as phase change material (PCM). The information about thermo-physical properties of phase change thermal storage material and heat transfer characteristic is very important for designing of thermal energy storage system. The Differential Scanning Calorymetery (DSC), density meter, thermal conductivity meter, and viscometer are used for measuring the thermo-physical properties of thermal energy storage material (paraffin wax).

Analysis of the heat transfer characteristics of heated tube inline and staggered arrangement immersed in the thermal energy storage material by experimental and numerical were used. These results would be helpful in

developing analyses and in their verification to design thermal energy storage system.

This study also presents an efficient and adequate of numerical technique for solving transient heat transfer problem of melting processes and then compare to the experimental result. The proposed technique comprises between the specific heat capacity and conduction/convection is heat transfer modes for solved the problem by a finite difference scheme. The temporal heat storage and the movement rate of solid-liquid interface in paraffin wax as phases change material (PCM) heated tube inline and staggered arrangement are studied.

Numerical scheme is suitable for solving phase change problem with boundary condition of constant heat flux. The result scheme is efficient and adequate. The numerical results agree fairly well with the experimental results, which show that the model is accurate enough to predict the solid PCM melting rate and the time needed to the melt of the solid PCM. The model also can be used to optimize the design and operation of thermal energy storage system with PCM outside the inline and staggered heated tube arrangement.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

KAJIAN CIRI PEMINDAHAN HABA PARAFIN WAX TERHADAP SUSUNAN TIUB PEMANAS YANG BERBEZA BERDASARKAN KAEDAH BERANGKA DAN UJIKAJI

Oleh

SUDITAMA

Ogos 2008

Pengerusi: Profesor Madya Megat Mohamad Hamdan Megat Ahmad, PhD

Fakulti: Kejuruteraan

Tujuan kajian ini adalah untuk mendapatkan ciri pemindahan haba bagi susunan tiub yang dipanaskan dan terbenam dalam bahan penyimpanan tenaga haba lilin pepejal sebagai bahan perubahan fasa. Maklumat tentang sifat fizikal termodinamik untuk bahan perubahan fasa dan ciri pemindahan habanya sangat diperlukan untuk merekabentuk sistem penyimpanan tenaga haba. Pada kajian ini penggunaan meter pembaca perbezaan haba, ketumpatan, meter aliran haba dan meter kelikatan diperlukan untuk mengukur sifat fizikal termodinamik bagi bahan penyimpan tenaga haba (lilin pepejal) dalam kajian ini.

Analisis ciri pemindahan haba bagi susunan tiub segaris dan selang seli yang dipanaskan terbenam di dalam bahan penyimpan tenaga haba adalah menggunakan kaedah berangka dan ujikaji. Keputusan kajian ini sangat

membantu dalam analisis selanjutnya dan pengesahan dalam rekabentuk sistem penyimpanan tenaga haba.

Kajian ini juga membentangkan teknik analisis kaedah berangka yang cukup memadai dan berkesan yang boleh digunakan untuk menyelesaikan masalah pemindahan haba tak malar terhadap masa pada proses perubahan fasa, hasilnya akan dibandingkan dengan keputusan ujikaji. Teknik yang digunakan mengandungi kaedah haba pendam dan mod pemindahan haba aliran dan olakan digunakan dalam rancangan beza terhad. Kadar penyimpanan tenaga haba dan kadar pergerakan sempadan padat/cecair bahan penyimpan haba berubah fasa yang dipanaskan oleh sejumlah tiub yang disusun secara segaris dan selang-seli dianalisis secara kaedah berangka.

Pengunaan kaedah berangka dalam kajian ini adalah sangat sesuai untuk menyelesaikan perubahan fasa dengan kondisi fluks haba malar pada sempadan padat/cecair. Hasil analisis cekap dan sangat memadai dalam menentukan kedudukan sempadan padat/cecair bahan penyimpanan tenaga haba. Hasil kajian secara teoritikal munasabah dengan hasil ujikaji, yang mana menunjukkan model cukup tepat untuk meramalkan kadar pencairan bahan perubahan fasa pepejal dan masa yang diperlukan untuk mencairkannya. Model ini juga boleh digunakan untuk mengoptimumkan rekabentuk dan operasi sistem penyimpanan tenaga haba dengan bahan perubahan fasa yang berada di luar susunan tiub yang dipanaskan.

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Finally, I also wish to register my acknowledgement to all my colleagues and friends, who have contributed to success of this study, directly or indirectly.

I certificate that an Examination Committee has met on the 29 August 2008 to conduct the final examination of Suditama on his Doctor of Philosophy thesis entitled "Numerical and Experimental Heat Transfer Characterisation of Paraffin Wax Material with Different Heated Tube Arrangements" in accordance with Universiti Putra Malaysia (Higher Degree) Act 1981. The committee recommends that the student be awarded the Doctor Philosophy.

Members of the Examination Committee were as follows:

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This thesis was submitted to the senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy.
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Date, 18 December 2008

DECLARATION

I declare that the thesis is based on my original work except for quotations and citations, which have been duly acknowledged. I also declare that it has not been previously or and is not concurrently submitted for any other degree at UPM or at any other institution.

Suditama
Date: August 2008

LIST OF FIGURES

LIST OF NOTATIONS

C_p	specific heat
D	tube diameter
E	energy per unit volume
F	radiation Shape factor
Gr	Grashof number
h	convection heat transfer coefficient
h_{sf}	latent heat of melting
k	thermal conductivity
L	latent heat
N_{tu}	Number of heat transfer unit
Nu	Nusselt number
$\bar{n}$	normal
Pr	Prandl number
q	heat flux
R	tube radius
Ra	Rayleigh number
R_c	characteristic radius
r_o	radial distance
r_m	mean radius
$\dot{q}$	heat source per unit volume
Ste	Stefan number
t	time
T	temperature

U, U_*	Overall heat transfer coefficient
v	volume
x,y	Cartesian coordinate

Greek Symbol

α	thermal diffusivity
Δ	interval
ρ	density

Subscripts

i	calculated element
j	neighbor element to the *i* element
l	liquid
m	melting
s	solid
w	wall
o	initial

CHAPTER 1

INTRODUCTION

1.1 Energy Storage

Energy storage has only recently been developed to a point where it can have a significant impact on modern technology. Energy storage can be in the form of mechanical, chemical, biochemical, magnetically and thermal energy storage. It can contribute significantly in meeting society's need for more efficient, environmentally benign energy use in building for heating and cooling, aerospace power, and utility applications. The use of energy storage often result in such significant benefit such as reduction of energy cost, reduction of energy consumption, improved indoor air quality, increase flexibility of operation, and reduced initial and maintenance cost (Dincer, 2002).

Energy storage also has an enormous potential to increase the effectiveness of energy conversion equipment used and for facilitating large-scale fuel substitution in the world's economy. Energy storage not only plays an important role in conserving the energy but also improve the performance and reliability of a wide range of energy system. Energy storage leads to saving of premium fuels and makes the system more cost effective by reducing the wastage of energy. In most system, there is a mismatch between the energy supply and energy demand. The energy storage can overcome this imbalance and therefore help in saving of capital cost.

Energy storage becomes more important where the energy source is intermittent such as solar energy. The use of intermittent energy source is likely to grow, if more and more solar energy is use for domestic purposes. If no storage is use in solar energy system then the major part of the energy demand will met by the back up or auxiliary energy and therefore so called annual solar load fraction will be very low. In case of solar energy, both short and long term energy storage can used and this can adjust the phase difference between solar energy supply and energy demand and can match seasonal demand to the solar availability respectively (Garg 1985).

Generally, industrial civilizations are base upon abundant and reliable supplies of energy. To be useful, raw energy forms must converted into energy currencies commonly through heat release. For example steam, which is widely used for heating in industrial processes, is normally obtain through converting fuel energies into heat, and transferring the heat into water. Electricity, increasingly favoured as a power source is generating predominately with steam-driven generator, fuelled by fossil or nuclear energy. Power demand, in general whether thermal or electrical, is not steady. Moreover, some thermal and electrical energy sources, such as solar energy, are not steady in supply. In case where either supply or demand is highly variable, reliable power availability has in the past has generally been required. The results are high and partially inefficient capital investments, since the system operate at less than capacity most of the time.

Alternatively, capital investments can sometimes be reduce if load-management techniques are employed to smooth power demand, or if energy storage is used to permit the use of smaller power generating systems. The smaller systems operate at or near the peak capacity, irrespective of the instantaneous demand for power, by storing excess converted energy during reduced demand periods for subsequent use in meeting peak demand requirements. Although some energy generally is lost in the storage process, energy storage often permits fuel conservation by utilizing more plentiful but less flexible fuels such as coal and uranium in application now requiring scarce oil and natural gas. In some cases energy storage enable the waste heat accompanying conversion process to use for secondary purposes.

The opportunities for energy storage are not confining to industries and utilities. Storage at the point of energy consumption, as in residences and commercial building, will likely be essential to the future use of solar heating and cooling system, and may prove important in lessening the peak demand loads imposed by conventional electrical, space conditioning system. In the personal transportation sector, now dominated by gasoline-powered vehicles, adequate electrical storage systems might encourage the use of large number of electric vehicles, reducing the demand for petroleum.

1.2 Thermal Energy Storage

Thermal energy storage is a temporary storage of high or low temperature energy for later usage. Example of thermal energy storage is the storage of solar energy for overnight heating. This is because solar energy, unlike fossil fuels, is not available at all times. Even cooling loads, which nearly coincide with maximum levels of solar radiation, often are present after sunset. Thermal energy storage can be important means of offsetting the mismatch between thermal energy availability and demand.

Thermal energy may be stored by elevating or lowering the temperature of a substance (i.e. altering its sensible heat), by changing the phase of substance (i.e. altering its latent heat, or by a combination of the two. Both thermal energy storage forms are expect to see extended applications as new energy technologies are developed.

Energy demand in the commercial, industrial and utility sector varies on a daily and weekly basis. Ideally, these demands are match by various energy conversion systems that operate synergistically. Peak hours are most difficult and expensive to supply. Peak electrical demand generally met by conventional gas turbine or diesel generator, which is reliant, costly and relatively scarce oil or gas. Thermal energy storage provides an alternative method of supplying peak energy demand. Likewise, energy storage can improve the operation of cogeneration, solar, wind, and run-of-river hydro facilities.

A review by Zalba et al. (2003) on phase change energy storage materials, heat transfer analysis and applications, provide examples of energy storage applications such as,

i. Utility

Relatively inexpensive base load electricity can used to charge energy storage during evening or off-peak weekly. The electricity used during peak periods, reducing the reliance on conventional gas and oil peaking generator.

ii. Industry

High temperature waste heat from various industrial processes can stored for use in preheating and other heating operations.

iii. Cogeneration

Since the closely coupled production of thermal and electricity by a cogeneration system rarely matches demand exactly, excess electricity or heat can be stored for subsequent use.

iv. Wind and run-of river hydro

Conceivably the system can operate around the clock, charging an electrical storage system during low-demand hours and later using that electricity for peaking purposes. Energy storage increases the capacity factor for these devices, usually enhancing their economic value.

v. Solar system

By storing excess solar energy received on sunny days for use on cloudy days or night, energy storage can increase the capacity factor of solar energy systems.

Tomlinson et al. (1990) point out that industrial production uses about a third of total energy consumed in the USA, much of it is hydrocarbon fuels. Therefore, energy efficiency improvement in the industrial sector can have a substantial impact on national energy consumption level. Thermal energy storage (TES) represented an important option for improving industrial energy efficiency. By storing and then using thermal energy that would otherwise be discharge in flue gasses to the environment, less purchased fuel is used, plant thermal emission are reduced, and product cost associated with fuel use are decreased.

1.3 Problem Statements

It has been estimated that if the present rate of population growth and exploitation of readily available stored energy in fossil fuels continues, then the fossil fuel may depleted completely in a century or so (World Energy Council, 2005). As a result, scientists all over the world are in search of new and renewable energy sources. However, developing efficient and inexpensive energy storage devices is an important field as developing new sources of energy.

The global energy flow and storage of solar energy as a renewable energy source is shown in Figure 1.1 (Jensen 1980). The figure explains why it is important to store thermal energy. From the figure it shows that the terrestrial energy is divided into terrestrial absorption, and photosynthesis from the solar radiation and plus the position of the moon. The solar energy radiation