International Journal of Advancements in Mechanical and Aeronautical Engineering – IJAMAE
Volume 1 : Issue 1

Publication Date : 09 January 2014

ANALYSIS OF FREE AIR COOLING-HEATING WITH THERMAL ENERGY STORAGE

M.R. Anisur, M.A. Kibria, M.H. Mahfuz, R.Saidur, I.H.S.C. Metselaar

***Abstract*— The present building energy consumption can be reduced by replacing the air conditioning system with Thermal Energy Storage (TES) system. In this present work, a semi-analytical model is applied to analyze the shell and tube type TES system for air cooling-heating application. The laminar forced convection heat transfer phenomena in between phase change material (PCM) inside a shell and air inside the tube are studied. The heptadecane PCM with 22°C melting temperature is used for this TES system. The melting front propagation is also analyzed. The outlet air temperatures are found 24°C to 26°C for the 32°C inlet air temperature.**

***Keywords*— Air heating and cooling; Thermal energy storage; Phase change material.**

I. Introduction

The energy demand for heating and cooling in building sector is rapidly increasing [1]. In this context, alternative solutions with thermal energy storage systems to reduce this energy consumption have been appeared [2]. The thermal energy storage system with phase change material (PCM) is quite effective for this application. Because, PCM can absorb or discharge a large amount of heat during its melting and solidification process [3]. Generally, low melting PCM is applicable in air-conditioning system to maintain human comfort temperature [4, 5]. Many researchers have been working on flat plate type thermal energy storage for air cooling-heating application [2, 6]. Zhang and Faghri [7] showed a conjugate analytical method to analyze the heat transfer phenomena in between PCM inside shell and heat transfer fluid (HTF) inside tube. They also reported that a significant error would be occurred if the fully developed nusselt correlation is used to calculate the laminar forced convection between a HTF of moderate prandtl number and PCM.

Hence, for laminar air flow, the same analytical model is applicable for a shell and tube type TES system for air cooling application. In this present study, different design parameters of the TES system with similar geometry for air cooling application through PCM melting has been examined.

II. System description

The TES system in Fig.1 consists of a copper tube inside an insulated shell. The shell is loaded with Heptadecane as PCM and the tube carries the air as HTF that flows with a constant inlet temperature higher than the melting point of the PCM. A constant air velocity is maintained by a fan. Thus, a laminar forced convection would be occurred in the system. The entire PCM is assumed to be at its fusion temperature (solid phase) initially. The TES system description is given in Table 1.

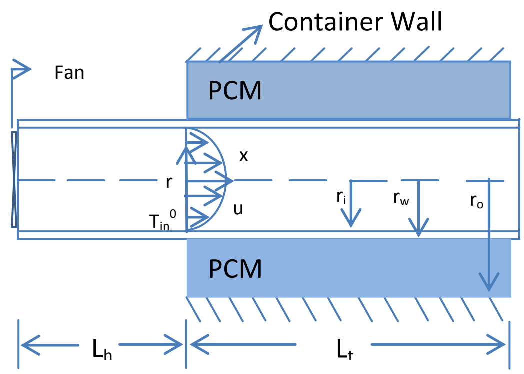

Figure 1. Schematic diagram of TES System for air cooling-heating

TABLE I. THE TES SYSTEM DESCRIPTION

Properties	Value	Ref.
Melting point of PCM , T_m^0 (°C)	22	[8]
PCM Latent heat , H (kJ/kg)	215	[8]
PCM density , ρ (kg/m^3)	778	[8]
PCM specific heat, C (kJ/kg/°C)	2.57	[9]
PCM thermal conductivity, k_p (W/m/°C)	0.21	[8]
Inlet air temperature , T_{in}^0 (°C)	32	n.a
Inner radius of the tube , r_i(m)	0.0038735	n.a
Outer radius of the tube , r_w (m)	0.0047625	n.a
Inner radius of the shell, , r_o (m)	0.015	n.a
Air velocity (m/s)	4.44	n.a
Air thermal conductivity k_f (W/m/°C)	0.0271	[10]
PCM mass (kg)	0.551	n.a
Copper tube thermal conductivity, k_w (W/m/°C)	401	[11]
Tube length,$(L_h + L_t)$, L(m)	1.9825	n.a
PCM container length, L_t (m)	1.115568	n.a

M.R. Anisur, M.A. Kibria, M.H. Mahfuz, R.Saidur, I.H.S.C. Metselaar

Department of Mechanical Engineering
University of Malaya
Malaysia
anis.me0259@gmail.com

III. Mathematical Formulation

The PCM melting and the convection in the tube-side is an unsteady 2D problem. In this solution, the axial conduction of the transfer fluid, the axial conduction in PCM, PCM subcooling effects, the heat capacity and axial conduction of the container wall are neglected. Further assumptions are that the thermophysical properties of the PCM are independent of temperature and PCM is assumed to be at the freezing temperature. On the other hand, Heat transfer happens only within the thermal entry length.

The forced convection in the tube should be considered as an arbitrarily varied wall temperature problem because of TES system. However, the inlet velocity of HTF needs to be fully developed to solve this problem [12].

The hydrodynamic length for fully developed can be calculated by the following equation [13]:

$$\frac{L_h}{D} = C_h \operatorname{Re} \quad (1)$$

And the thermal entry length is considered as below [12]:

$$\frac{L_t}{D} = 0.1Pe \quad (2)$$

Considering dimensionless variable the main equations are obtained as follows [7]:

The local nusselt number and bulk temperature at the different location along the axial direction is measured from (1) and (2) respectively:

$$Nu(X) = \frac{\sum_{i=1}^{j} \Delta T_{w,i} \sum_{n=0}^{\infty} G_n \exp[-\frac{2\lambda^2}{Pe}(X-(i-1)\Delta X]}{2\sum_{i=1}^{j} \Delta T_{w,i} \sum_{n=0}^{\infty} \frac{G_n}{\lambda_n^2} \exp[-\frac{2\lambda^2}{Pe}(X-(i-1)\Delta X]} \quad (3)$$

$$T_b = T_w - 8\sum_{i=1}^{j} \Delta T_{w,i} \sum_{n=0}^{\infty} \frac{G_n}{\lambda_n^2} \exp[-\frac{2\lambda^2}{Pe}(X-(i-1)\Delta X] \quad (4)$$

Where $j = \operatorname{int}(\frac{X}{\Delta X}) + 1$. G_n and λ_n are Eigen value constants [12].

By balancing energy,

$$K_f Nu(T_b - T_w) = \frac{K_w(T_w - T_{wo})}{\ln R_w} \quad (5)$$

The dimensionless solid-liquid interface radius could be found from (4) as below:

$$S^2(\frac{1}{2} - \ln\frac{S}{R_w}) = 2(\frac{R_w^2}{4} - (\sqrt{1+2T_{wo}Ste} - 1))F_o \quad (6)$$

Melting front=$(S-R_w)/(R_o-R_w)$ (7)

Getting dimensionless solid-liquid interface the dimensionless temperature gradient at the outer tube wall surface is:

$$\frac{\partial T_p}{\partial R_{R=R_w}} = -\frac{1}{R_w \ln(\frac{S}{R_w})}(2T_{wo} - \frac{(\sqrt{1+2T_{wo}ste} - 1)}{ste}) \quad (8)$$

On the other hand, from the energy equation, the temperature gradient is observed as below:

$$\frac{\partial T_p}{\partial R} = \frac{(T_b - T_{wo})}{\frac{R_w}{K_f Nu} + \frac{R_w \ln R_w}{K_w}} \quad \text{at } R=R_w \quad (9)$$

A. *Calculation procedure*

To solve this problem, the computational domain has been considered with 100 x 170 grid size. Here wall temperature, T_w is guessed first. Then local nusselt number and bulk temperature is measured from (1) and (2) respectively. The outer wall temperature of the tube is determined by (3). So that dimensionless solid-liquid interface radius and temperature gradient can be calculated from (4) and (6) respectively. Solving (7) and (3) with this temperature gradient, a new wall temperature, T'_w would be found. Accordingly melting front also can be found from (5). If $T_w - T'_w \leq 10^{-5}$, then the next time step starts. Otherwise the steps are repeated with another T_w guessing.

IV. Results and Discussions

The present solution for air as HTF and Heptadecane PCM has been carried out for the dimensionless thermal entrance length, X=144. The figure 2. shows that the local nusselt numbers along the full thermal entrance length are remained in between the values for CWT and CHF boundary condition, although they increase with the fourier number. But after crossing the position X=100 it is almost constant. The nusselt numbers for CWT and CHF boundary conditions on the same thermal entrance position are tabulated in ref. [13]. Zhang and Faghri [7] also reported that the local nusselt number should be in between the values of nusselt number for CWT and CHF boundary condition in the thermal entrance region if X<100. Hence, this work has been validated for the same result as reported by them.

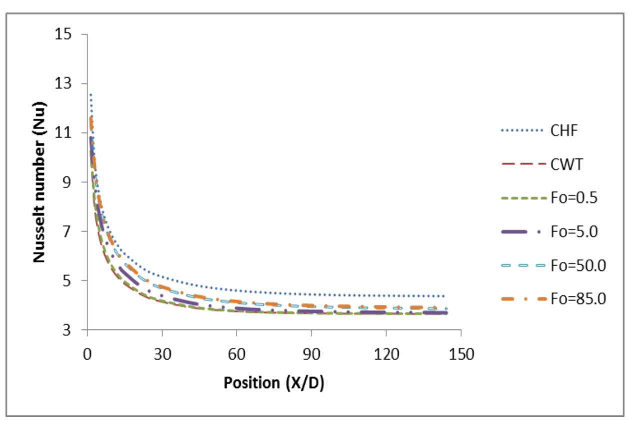

Figure 2. The local nusselt numbers for different positions and fourier numbers (Fo)

The figure 3 depicts the melting front propagation of the PCM as a function of time and distance from the entrance.

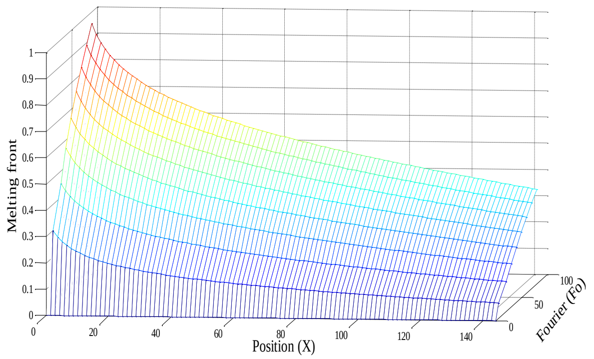

Figure 3. The melting front propagation for different position and fourier

The figure 4 shows the outlet air temperature from the tube. The outlet temperature also remains in the human comfort temperature range.

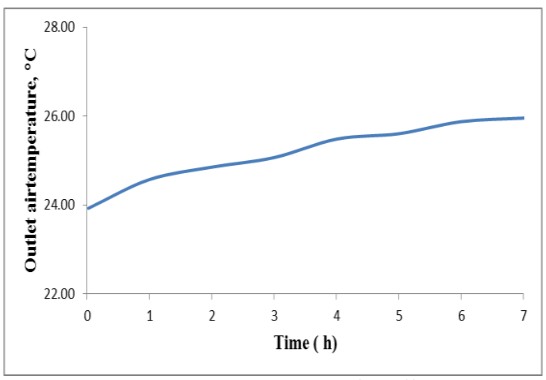

Figure 4. The outlet air temperature for different time

V. Conclusion

In the present study, thermal energy storage with Heptadecane PCM for air cooling application has been studied analytically. This analytical solution has been validated considering the varied wall temperature of the tube under the boundary condition of CWT and CHF. From the results presented above, it can be concluded that this method would be useful to design an air cooling-heating system. It is evident that the outlet air temperature remains within 24°C to 26°C.

Acknowledgment

This work was supported by one of the HIRG projects of University of Malaya, Malaysia. The project number is UM.C/HIR/MOHE/ENG/21.

References

[1] M.R. Anisur, M.H. Mahfuz, M.A. Kibria, R. Saidur, I.H.S.C. Metselaar, T.M.I. Mahlia. "Curbing global warming with phase change materials for energy storage", Renewable and Sustainable Energy Reviews, vol.18, pp.23-30, 2013.

[2] A.H. Mosaffa, C.A. Infante Ferreira, F. Talati, M.A. Rosen. "Thermal performance of a multiple PCM thermal storage unit for free cooling", Energy Conversion and Management, vol.67, pp.1-7, 2013.

[3] İ. Dinçer, M.A. Rosen. Thermal energy storage (TES) methods. John Wiley & Sons, Ltd2010.

[4] L.F. Cabeza, A. Castell, C. Barreneche, A. de Gracia, A.I. Fernández. "Materials used as PCM in thermal energy storage in buildings: A review", Renewable and Sustainable Energy Reviews, vol.15, pp.1675-95, 2011.

[5] A.A. Al-Abidi, S. Bin Mat, K. Sopian, M.Y. Sulaiman, C.H. Lim, A. Th. "Review of thermal energy storage for air conditioning systems", Renewable and Sustainable Energy Reviews, vol.16, pp.5802-19, 2012.

[6] S.M. Vakilaltojjar, W. Saman. "Analysis and modelling of a phase change storage system for air conditioning applications", Applied Thermal Engineering, vol.21, pp.249-63, 2001.

[7] Y. Zhang, A. Faghri. "Semi-analytical solution of thermal energy storage system with conjugate laminar forced convection", International Journal of Heat and Mass Transfer, vol.39, pp.717-24, 1996.

[8] S.D. Sharma, H. Kitano, K. Sagara. "Phase change materials for low temperature solar thermal applications", Res Rep Fac Eng Mie Univ, vol.29, pp.31-64, 2004.

[9] G.E. Totten, S.R. Westbrook, R.J. Shah. Fuels and lubricants handbook: technology, properties, performance, and testing. ASTM International2003.

[10] The Engineering ToolBox. Retrieved on 29 March, 2013, Available from: http://www.engineeringtoolbox.com/air-properties-d_156.html.

[11] Copper. Wikipedia. Retrieved on 29 March, 2013, Available from: http://en.wikipedia.org/wiki/Copper.

[12] W.M. Kays, M.E. Crawford. Convective Heat and Mass Transfer. McGraw-Hill1980.

[13] L.M. Jiji. Heat Convection. Springer London, Limited2007.

[14] R.K. Shah, A.L. London. Laminar flow forced convection in ducts: a source book for compact heat exchanger analytical data. Academic press New York1978.