AN ANALYSIS OF PHASE CHANGE HEAT TRANSFER IN A SOLAR THERMAL ENERGY STORE

Anica Trp, Bernard Frankovic and Kristian Lenic
Faculty of Engineering University of Rijeka, Vukovarska 58, HR-51000 Rijeka, Croatia, Europe, Phone: ++ 385 51 651 514, 675 801, Fax: ++ 385 51 675 801, E-mail: anicatrp@rijeka.riteh.hr

Abstract – In this paper, a numerical analysis of heat transfer in the latent heat store has been performed. Heat transfer in the latent heat store is the conjugate problem of the phase change of the phase change material and the transient forced convection between the heat transfer fluid and the wall. The differential equations of flow and heat transfer, with initial and boundary conditions, have been discretized by control volume approach and then solved using an iterative procedure. The set of algebraic equations has been solved by FORTRAN software. Velocity and temperature distributions of heat transfer fluid as well as temperature distributions of the wall and PCM inside the latent heat store have been obtained.

1. INTRODUCTION

Effective energy management is today one of the most actual problems. Because of that, interest in development of utilizing renewable energy sources has been growing. In this field solar energy has special significance but the radiated solar energy and the energy requirements are often at variance with time. To avoid this negative effect of periodic nature of solar energy, heat accumulation in heat storage tanks has been used. Latent heat storage system with solid-liquid phase change has some advantages like high storage density and short temperature interval of heat transfer.

Latent heat store analyzed in this paper is shell and tube heat exchanger with the phase change material (PCM) on the shell side. A representative element of the latent heat store is shown in Fig. 1.

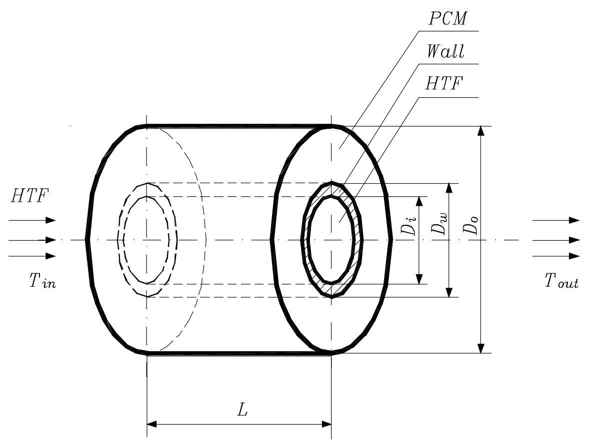

Fig. 1. Representative element of the latent heat store

A heat transfer fluid (HTF) flows through the inner polypropylene tube and exchanges heat with the PCM on the shell side. During the sunlight, i.e. active phase, hot fluid heats the PCM, the PCM melts and the heat is stored. During the eclipse phase, the PCM solidifies and the stored heat has been delivered to the cold fluid. Heat transfer in such latent heat store is the conjugate problem of the phase change of the PCM and the transient forced convective heat transfer between the heat transfer fluid and the adjacent wall. During melting of the PCM, heat transfer is performed primarily by natural convection, and during solidification heat transfer is controlled by heat conduction.

Some mathematical models that represent the numerical description of the heat transfer in the latent heat store use enthalpy method to describe heat transfer inside the PCM (Belleci and Conti, 1993) and some other use the temperature transforming model (Cao and Faghri, 1991). In this paper, a numerical analysis of transient phase change heat transfer problem combined with conjugate forced convection, has been performed. Mathematical model that describes flow and heat transfer of the heat transfer fluid, phase change material and wall has been formulated by studying heat transfer phenomena in the control volume of the latent heat store. To describe heat transfer inside the PCM the enthalpy method has been used. Differential equations, with initial and boundary conditions, have been solved numerically by FORTRAN software using an iterative procedure.

2. MATHEMATICAL MODEL OF FLOW AND HEAT TRANSFER IN THE LATENT HEAT STORE

The phase change heat transfer and fluid–wall convective heat transfer is an unsteady 2D problem. To establish a convenient mathematical model of flow and heat transfer, the following assumptions have been introduced:

- the heat transfer fluid is incompressible and viscous heating has been neglected,
- natural convection in the liquid phase of the PCM has been ignored,
- thermal losses and conduction through the outer wall of the store have been ignored,
- flow of the heat transfer fluid is laminar,
- the initial temperature of the latent heat store is uniform and the PCM is in the solid phase,
- inlet velocity and inlet temperature of the working fluid are constant.

The continuity, momentum and energy equations governing the flow and heat transfer in latent heat store for the heat transfer fluid, the wall and the phase change material are

- HTF

$$\frac{\partial w_x}{\partial x} + \frac{1}{r} \cdot \frac{\partial (r \cdot w_r)}{\partial r} = 0 \tag{1}$$

$$\frac{\partial w_x}{\partial \tau} + w_x \cdot \frac{\partial w_x}{\partial x} + w_r \cdot \frac{\partial w_x}{\partial r} = -\frac{1}{\rho} \cdot \frac{\partial p}{\partial x} + + \upsilon \cdot \left[\frac{\partial^2 w_x}{\partial x^2} + \frac{1}{r} \cdot \frac{\partial}{\partial r}\left(r \cdot \frac{\partial w_x}{\partial r} \right) \right] \tag{2}$$

$$\frac{\partial w_r}{\partial \tau} + w_x \cdot \frac{\partial w_r}{\partial x} + w_r \cdot \frac{\partial w_r}{\partial r} = -\frac{1}{\rho} \cdot \frac{\partial p}{\partial r} + + \upsilon \cdot \left[\frac{\partial^2 w_r}{\partial x^2} + \frac{1}{r} \cdot \frac{\partial}{\partial r}\left(r \cdot \frac{\partial w_r}{\partial r} \right) - \frac{w_r}{r^2} \right] \tag{3}$$

$$\frac{\partial T_f}{\partial \tau} + w_x \cdot \frac{\partial T_f}{\partial x} + w_r \cdot \frac{\partial T_f}{\partial r} = = \frac{\lambda_f}{c_f \cdot \rho_f} \cdot \left[\frac{\partial^2 T_f}{\partial x^2} + \frac{1}{r} \cdot \frac{\partial}{\partial r}\left(r \cdot \frac{\partial T_f}{\partial r} \right) \right] \tag{4}$$

- Wall

$$\rho_w \cdot c_w \cdot \frac{\partial T_w}{\partial \tau} = \lambda_w \cdot \left[\frac{1}{r} \cdot \frac{\partial}{\partial r}\left(r \cdot \frac{\partial T_w}{\partial r} \right) + \frac{\partial^2 T_w}{\partial x^2} \right] \tag{5}$$

- PCM

$$\frac{\partial H_p}{\partial \tau} = \lambda_p \cdot \left[\frac{1}{r} \cdot \frac{\partial}{\partial r}\left(r \cdot \frac{\partial T_p}{\partial r} \right) + \frac{\partial^2 T_p}{\partial x^2} \right] \tag{6}$$

where H is the enthalpy related to the temperature with eguation $T = A \cdot H + B$ where the coefficients A and B are

$$A = \frac{1}{\rho_s \cdot c_s}, \quad B = 0 \quad \text{for} \quad H_p < \rho_s \cdot c_s \cdot T_m$$

$$A = 0, \quad B = T_m \quad \text{for} \quad 0 \le \frac{H_p - \rho_s \cdot c_s \cdot T_m}{\rho_L \cdot q} \le 1$$

$$A = \frac{1}{\rho_L \cdot c_L}, \quad B = T_m \cdot \left(1 - \frac{\rho_s \cdot c_s}{\rho_L \cdot c_L} \right) - \frac{q}{c_L}$$
$$\text{for} \quad \frac{H_p - \rho_s \cdot c_s \cdot T_m}{\rho_L \cdot q} > 1$$

The initial and boundary conditions are following:

- initial conditions $\tau = 0$

$$0 < r \le r_i, \quad 0 \le x \le L \quad \Rightarrow \quad w_x = w_r = 0$$
$$0 < r < r_o, \quad 0 \le x \le L \quad \Rightarrow \quad T_f = T_w = T_p = T_{init}$$

- boundary conditions $\tau > 0$

inlet plane $x = 0$

$$0 < r < r_i \quad \Rightarrow \quad w_x = w_{in}, \quad w_r = 0, \quad T_f = T_{in}$$
$$r_i \le r \le r_w \quad \Rightarrow \quad \frac{\partial T_w}{\partial x} = 0$$
$$r_w < r < r_o \quad \Rightarrow \quad \frac{\partial T_p}{\partial x} = 0$$

outlet plane $x = L$

$$0 < r < r_i \quad \Rightarrow \quad \frac{\partial w_x}{\partial x} = 0, \quad \frac{\partial T_f}{\partial x} = 0$$
$$r_i \le r \le r_w \quad \Rightarrow \quad \frac{\partial T_w}{\partial x} = 0$$
$$r_w < r < r_o \quad \Rightarrow \quad \frac{\partial T_p}{\partial x} = 0$$

fluid – wall interface $r = r_i$

$$0 < x < L \quad \Rightarrow \quad w_x = w_r = 0, \quad \lambda_f \frac{\partial T_f}{\partial r} = \lambda_w \frac{\partial T_w}{\partial r}$$

wall – PCM interface $r = r_w$

$$0 < x < L \quad \Rightarrow \quad \lambda_w \frac{\partial T_w}{\partial r} = \lambda_p \frac{\partial T_p}{\partial r}$$

outer wall $r = r_o$

$$0 < x < L \quad \Rightarrow \quad \frac{\partial T_p}{\partial r} = 0 .$$

3. NUMERICAL SOLUTION OF MATHEMATICAL MODEL

Differential equations, with initial and boundary conditions, have been discretized using control volume method. The resulting algebraic eguations are solved simultaneously using Gauss-Seidel iterative procedure. Due to nonlinearity of the problem iterations are needed during each time step. Convergence criteria is set on 0.01% for all variables of the system. System of discretization equations has been solved using FORTRAN software. As a result of calculation, velocity and temperature distributons of heat transfer fluid and temperature distributions of the wall and PCM inside the latent heat store have been obtained.

4. NUMERICAL RESULTS

Described numerical analysis has been applied on the latent heat store with water as the HTF and calcium chloride hexahydrate $CaCl_2 \cdot 6H_2O$ as PCM.

Thermophysical properties of $CaCl_2 \cdot 6H_2O$ are following:

- melting temperature T_m = 29.9 °C
- latent heat q = 187 kJ/kg
- thermal conductivity
  - solid phase λ = 1.09 W/mK
  - liquid phase λ = 0.53 W/mK
- specific heat
  - solid phase c = 1.4 kJ/kgK
  - liquid phase c = 2.2 kJ/kgK
- density
  - solid phase ρ = 1710 kg/m^3
  - liquid phase ρ = 1530 kg/m^3

The system is initially at the temperature 25 °C that is less then the melting temperature of the PCM. Inlet velocity of the water is 1 m/s and the inlet temperature is 50 °C.

Obtained numerical results show that steady state of the fluid velocity inside the tube has been reached quickly, while the temperature field has not reached fully developed state. Temperature field is changing as the melting interface progresses. Because of small Prandtl numbers, thermal conductivity is large, and heat transfer to the PCM is large.

Fig. 2 shows the radial temperature distribution in cross section of the tube x/L = 0.4 for different time periods. Regions of the HTF, wall and the PCM are indicated in diagram.
Dimensionless temperature is defined as

$$\vartheta = \frac{T - T_{\text{init}}}{T_{\text{in}} - T_{\text{init}}}\,, \qquad (7)$$

and dimensionless time is defined as

$$\pi = \frac{w_{\text{in}} \cdot \tau}{D_{\text{i}} / 2}\,. \qquad (8)$$

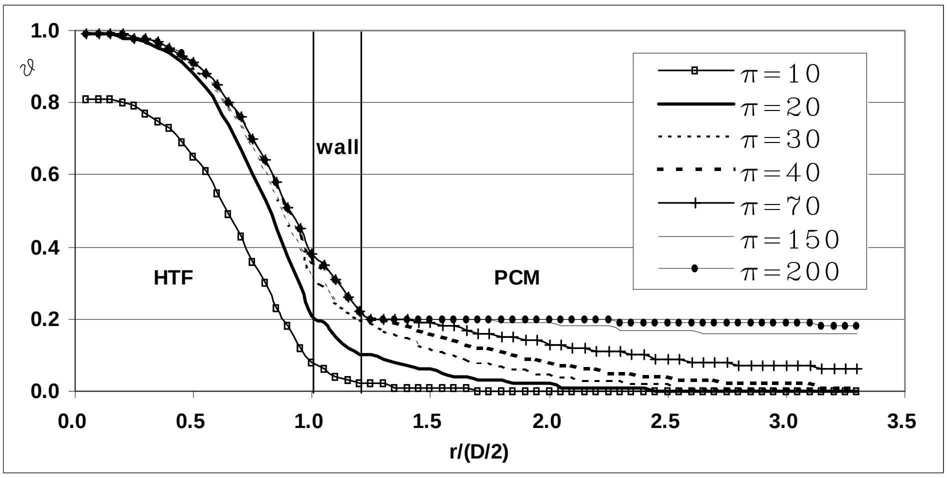

Fig. 2. Radial temperature distribution at x/L = 0.4 for different time periods

From the figure can be seen that the PCM temperature in specified cross section of the tube increases with time until the melting temperature is achieved. Then, melting of the PCM starts around the wall surface and the width of melting surface in the specified cross section becomes larger for longer time periods. During melting of the PCM the heat is delivered from the water and stored in the PCM. It can be also seen that heat transfer is high because of small Prandtl numbers of the water.

Temperature distributions of heat transfer fluid, wall and the PCM, in analyzed latent heat store, for different time periods are shown in Fig. 3.

It can be seen from the figure that at dimensionless time period π =200, melting surface of PCM has reached outer surface of the latent heat store in cross sections near to inlet surface of the heat transfer fluid, while in other cross sections some of the PCM remains unmelted. It can be concluded that heat transfer from the heat transfer fluid to PCM is fast because of large thermal conductivity of the water.

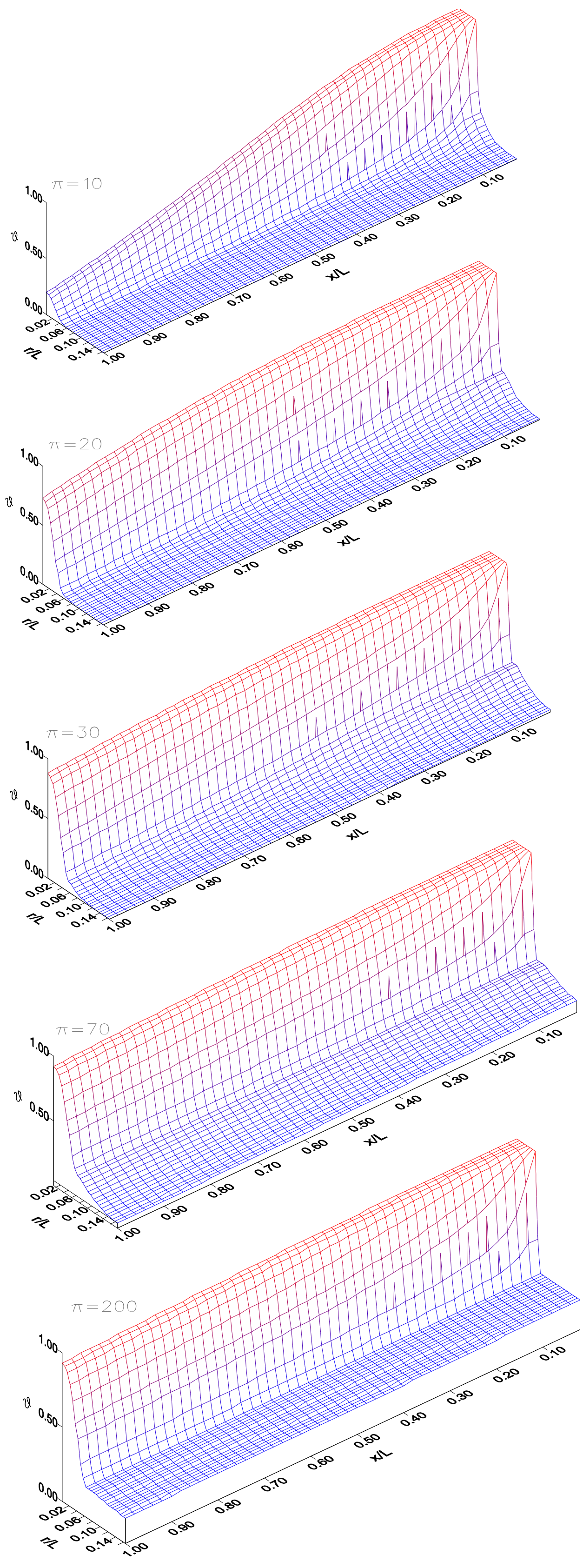

Fig. 3. Temperature distributions in latent heat store in different time periods

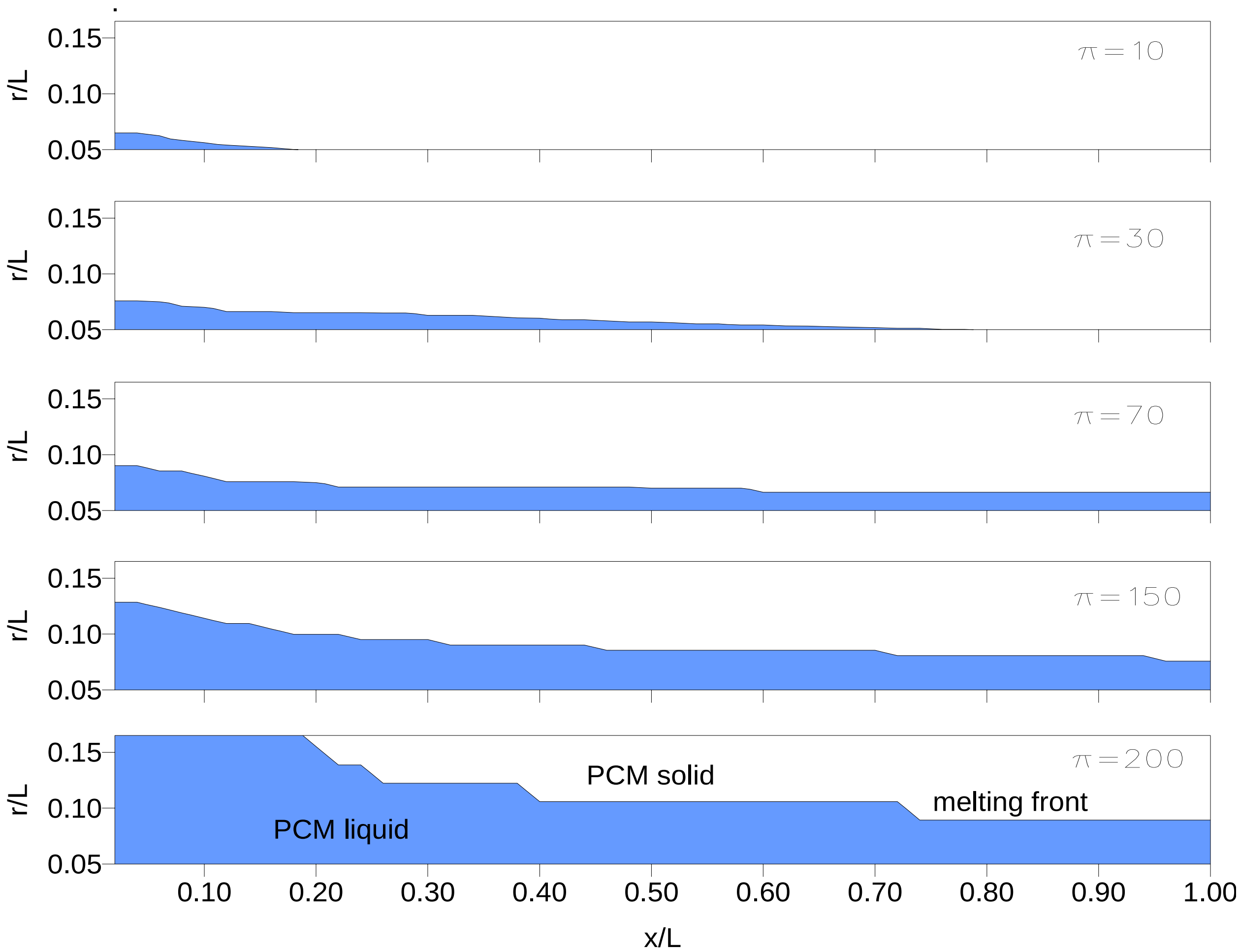

Fig. 4. Melting surfaces of PCM for different time periods

Melting surfaces of PCM for different time periods are shown in Fig. 4. From the figure it can be seen that melting of the PCM starts on the wall – PCM interface at the inlet surface of the heat storage tank. Melting front is then moving along the wall–PCM interface to the outlet surface of the heat store. Because of large thermal conductivity of the water, melting front reaches the outer surface of the tank in a cross sections of the store near the inlet surface before π = 200 i.e. for a relatively short time period.

5. CONCLUSIONS

Phase change heat transfer in solar thermal latent heat store has been analyzed in this paper. The results of numerical analysis show that fluid velocity field reaches steady state quickly, while temperature field changes with progressing of the melting interface. Heat transfer from the heat transfer fluid to the PCM is fast due to small Prandtl numbers of the HTF. Because of that melting surface reaches the outer surface of latent heat store in the cross sections near the inlet surface of the HTF after relatively short time. Exact temperature distribution in latent heat store obtained in the analysis is necessary for calculation of thermal efficiency of the heat storage tank. It is the basis for design optimization of the latent heat store.

NOMENCLATURE

c	J/kgK	specific heat
D	m	diameter of the tube
H	J/m^3	enthalpy per unit volume
L	m	length of tube
p	Pa	pressure
q	J/kg	latent heat of the PCM
r	m	radius of the tube
	m	radial coordinate
T	K	temperature
w	m/s	fluid velocity
x	m	axial coordinate

Greek symbols

λ	W/mK	thermal conductivity
υ	m^2/s	kinematic viscosity
π		dimensionless time
ρ	kg/m^3	density
τ	s	time
ϑ		dimensionless temperature

Subscripts

f	heat transfer fluid
i	inside radius of the tube
in	inlet
init	initial
L	liquid phase of the PCM
m	melting
o	outer surface of the latent heat store
p	PCM
r	radial coordinate
s	solid phase of the PCM
w	wall
x	axial coordinate

REFERENCES

[1] Bellecci C. and Conti M. (1993). Transient behaviour analysis of a latent heat thermal storage module. *Int. J. Heat Mass Transfer* 36, 3851-3857.

[2] Bellecci C. and Conti M. (1993). Latent heat thermal storage for solar dynamic power generation, *J. Solar Energy* 51, 169-173.

[3] Cao Y. and Faghri A. (1991). Performance characteristics of a thermal energy storage module: a transient PCM/forced convection conjugate analysis. *Int. J. Heat Mass Transfer* 34, 93-101.

[4] Duffie J. A. and Beckman W. A. (1991) *Solar Engineering of Thermal Processes*, John Wiley & Sons Inc., New York.

[5] Esen M., Durmus Aydin and Durmus Ayla (1998). Geometric design of solar-aided latent heat store depending on various parameters and phase change materials, *J. Solar Energy* 62, 19-28.

[6] Hasan A. (1994). Phase change material energy storage system employing palmitic acid, *J. Solar Energy* 52,143-154.

[7] Minkowycz W. J., Sparrow E. M., Schneider G. E. and Pletcher R. H. (1988) *Handbook of Numerical Heat Transfer*, John Wiley & Sons Inc., New York.

[8] Patankar S. V. (1980) *Numerical Heat Transfer and Fluid Flow*, McGraw-Hill, New York.

[9] Voller V. and Cross M. (1981). Accurate solutions of moving boundary problems using the enthalpy method. *Int. J. Heat Mass Transfer* 24, 545-556.

[10] Watanabe T. and Kanzawa A. (1995). Second law optimization of a latent heat storage system with PCMs having different melting points. *J. Heat Recovery Systems* 15, 641-653.

[11] Zhang Y. and Faghri A. (1996). Semi-analytical solution of thermal energy storage system with conjugate laminar forced convection. *Int. J. Heat Mass Transfer* 39, 717-724.