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Numerical investigation of a packed bed thermal energy storage system for solar cooking using encapsulated phase change material

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ABSTRACT

A numerical model for a packed bed thermal energy storage (TES) system using phase change material (PCM) is presented. The storage system is to be utilized for a solar cooking application. Sunflower Oil is the heat transfer fluid (HTF) during charging cycles. The packed bed TES consists of spherical capsules filled with erythritol, as the phase change material. The model uses dual-phase mathematical heat transfer equations while the phase change phenomena inside the PCM capsules is analyzed by using the effective heat capacity method. Results from the model are validated with experimental results from literature. Numerical and experimental results are reasonably comparable. The effects of inlet temperature and the flow rate of the HTF on the temperature profiles of the packed bed are presented.

1. INTRODUCTION

For livelihood, humans need food and the cooking of food is done on a daily basis. Thus, a huge amount of energy is expended daily for cooking purposes [1]. According to the World Health Organisation (WHO), about 2.5 billion people in developing countries rely on biomass for cooking and about 1.5 million deaths in developing countries can be attributed to indoor pollution caused by the combustion of biomass due the emission of carbon monoxide, hydrocarbons and particulate matter [2]. This heavy dependence on biomass for cooking needs may also lead to serious environmental degradation as the trees in forests could be depleted for the provision of fuelwood and charcoal.

Solar energy possesses the highest theoretical potential of about 120,000 TW, of the earth's renewable energy resources [3]. Solar cookers are safe, practical, potentially low-cost and effective application of solar energy with public and environmental health protection benefits, particularly in the developing countries [4]. Technically, cooking involves heating an amount of food to the boiling point of water and keeping the food at that boiling temperature for a desired period of time [5].

Direct solar cookers, which utilize direct or reflected solar radiation for solar cooking, have been in existence for years. These include solar panel cookers, solar box cookers and solar parabolic cookers [6]. They have the disadvantages of usefulness only during periods of good solar radiation, exposure of operators to the solar radiation and that cooking can only be done outdoors [7]. Indirect solar cookers utilize the heat transferred from a solar collector to the cooking unit by means of a heat transfer fluid (HTF) [5].

However, the supply of solar energy is time-dependent, as such, a discrepancy may arise between solar energy supply and demand. Thermal energy storage (TES) systems may cater for this time-discrepancy by storing solar thermal energy during sunshine hours for use later [8, 9]. TES systems can be classified as active or passive. The former can be direct or indirect. In the direct type, the storage medium is also the heat transfer fluid, whereas in the indirect type, a second fluid is used for storing the heat. In passive TES systems, a solid material is used as the storage medium (packed bed) while the HTF passes through the storage medium only during the charging and discharging phases [10].

Packed bed configurations have shown excellent heat transfer characteristics by providing a large surface area for heat exchange [11]. The spherical geometry of encapsulation of PCM is preferred because it presents a larger area of the encapsulated PCM for heat transfer than other geometries of encapsulation. It also makes the storage tank to have a greater packing density [12].

A latent heat thermal energy storage (LHTES) system operate on the principle that large amount of heat (latent heat of fusion) is stored in/released from a phase change material (PCM) as it changes its phase. The solid-liquid phase-change transformation is usually utilized for this purpose. The LHTES system is particularly attractive for domestic cooking applications due its high thermal energy storage density and its isothermal behaviour during heat retrieval process [13]. Various studies recommended that a LHTES system with operational temperature higher than 100 ℃ will achieve faster cooking and longer storage time [9, 14-15].

Erythritol is a natural occurring sugar alcohol present in various fruits and fermented foods. It is produced industrially by glucose fermentation. It has a solid-liquid phase change temperature of about 117 ℃, with a latent heat of 344 kJ/kg. It is widely used in the food industry as a low-calorie sweetener and also as an excipient in pharmaceutical formulations. It is cheap and readily available and can be encapsulated for use as phase change material in a TES system [16-18].

Sunflower Oil is widely used for industrial and domestic cooking in South Africa. It is locally manufactured in South Africa and reasonably priced at about R 12 (~USD 1.2) per litre. The choice of Sunflower Oil as the HTF borders on the following: (i) it is cheap, readily available and can be easily produced by extracting the oil from Sunflower seeds, (ii) it is edible and non-toxic (iii) its characteristics are comparable to other thermal oils used for domestic heat storage applications as reported in literature [19-20] and (iv) it has a flash point around 250 ℃, a temperature that is much higher than the operating temperature of the proposed TES.

Karthikeyan et al. [13] conducted a numerical investigation of a packed bed TES unit filled with spherically encapsulated PCM by comparing results from three mathematical models. The first model, a continuous solid phase model, considered all the PCM at the same height in the storage unit as being at the same temperature at a particular time. This model neglected axial thermal conduction. The second model included axial conduction in both the HTF and the PCM. The third model however, was a conduction-based, enthalpy model which considered thermal gradients inside the PCM capsules. The third model showed a closer agreement with experimental results than the first two models. Peng et al. [21] analyzed the behaviour of a packed bed LHTES system using concentric-dispersion equations and the phase change phenomena of the PCM in the capsules by the effective heat capacity method.

This paper presents a numerical investigation of the transient behaviour of a packed bed LHTES system, using encapsulated erythritol as the PCM and Sunflower Oil as the HTF. The aim is to investigate the TES system for domestic cooking needs, using a dual-phase mathematical model.

2. A SOLAR COOKING UNIT INTEGRATED WITH LHTES SYSTEM

Fig. 1 shows a schematic diagram of a indirect solar cooking unit integrated with a single, packed bed, TES tank. The cold HTF is pumped into the solar collector to be heated up and then back into the packed bed through the top of the tank during the charging cycle. As the HTF flows down through the PCM spheres, heat is transferred from the HTF to the PCM. The process is continued until the PCM spheres attain the inlet temperature of the HTF. During the discharging cycle, the hot HTF flows from the top of the TES tank into the cooking unit where it exchanges heat with the food to be cooked while the cold HTF is pumped back into the TES tank through the bottom.

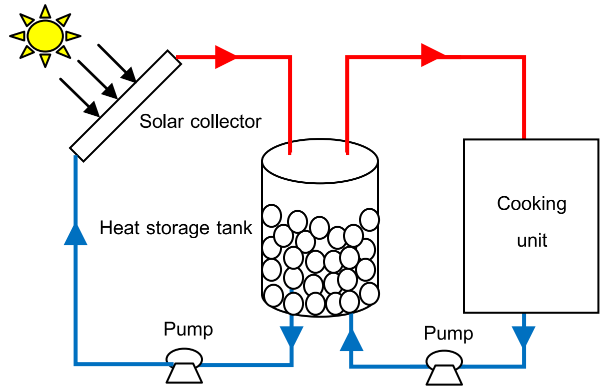

Fig. 1. The Schematic diagram of a solar cooker with a thermal storage.

NOMENCLATURE

ε	[-]	Porosity/Void fraction
ρ	[kg/m^3]	Density
c	[J/kg^{0}C]	Specific heat capacity
υ_f	[m/s]	Velocity of HTF
λ	[W/m^{0}C]	Thermal conductivity
T	[^{0}C]	Temperature
h_f	[W/m$^{2\,0}$C]	Volumetric heat transfer coefficient
r	[m]	Radius of PCM sphere
Re	[-]	Reynolds number
Pr	[-]	Prandtl number
μ_f	[kg/m s]	Dynamic viscosity of HTF
y	[m]	Axial distance
d_p	[m]	Diameter of PCM sphere
γ_{th}	[J/kg]	Latent heat
Subscipts		
f		Fluid/HTF
s		PCM
$m1$		solid-solid transition
$m2$		solid-liquid transition
$s1$		solid PCM
$s2$		liquid PCM
ini		initial

3. MATHEMATICAL MODEL

A schematic diagram of the packed bed LHTES system, consisting of a perfectly insulated vertical cylinder of length, H, diameter, D, with inlet and outlet manifolds at top and bottom ends, is shown in Fig. 2. The encapsulated spherical PCM spheres are randomly packed in the tank with porosity, e, through which the HTF flows. The HTF and the PCM are assumed to be initially at the same temperature.

The mathematical model used in this work is similar to that used by [21], except that the radial dispersion in the PCM spheres was not considered.

The following assumptions were made in the formulation of the mathematical model used:

1) The tank is perfectly insulated with HTF flowing from the top when charging and from bottom when discharging.
2) The flow is axial and incompressible.
3) The temperature of the HTF is considered constant at entry into the storage tank.

4) The thermal resistance of the encapsulation material is neglected.
5) Radiant heat transfer in the storage is neglected.
6) The thermo-physical properties of the HTF are considered constant and calculated at an average temperature $T_{av} = (T_{in} + T_{out})/2$.
7) The PCM spheres are identical.
8) There is no internal heat generation in the bed.

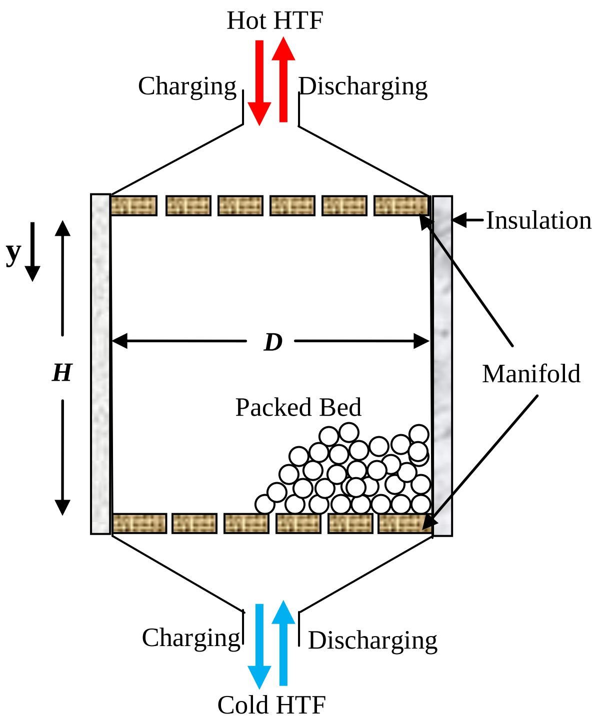

Fig.2. Schematic diagram of the packed bed LHTES system

The governing equations for the mathematical model for the HTF and PCM are respectively:

$$\varepsilon \rho_f c_f \frac{\partial T_f}{\partial t} + \varepsilon v_f \rho_f c_f \frac{\partial T_f}{\partial y} = \varepsilon \lambda_f \frac{\partial^2 T_f}{\partial y^2} - h_f (T_f - T_s) \quad (1)$$

$$(1-\varepsilon)\rho_s c_s \frac{\partial T_s}{\partial t} = (1-\varepsilon)\lambda_s \frac{\partial^2 T_s}{\partial y^2} + h_f (T_f - T_s) \quad (2)$$

The Reynolds number is calculated as: $Re = \frac{\rho_s d_p \varepsilon v_f}{\mu_f}$ (3)

The Prandtl number is calculated using: $Pr = \frac{c_f \mu_f}{\lambda_f}$ (4)

The volumetric heat transfer coefficient from [22] is calculated as:

$$h_f = \frac{6(1-e)\left[2+1.1Re^{0.6}Pr^{1/3}\right]\lambda_f}{d_p^2} \quad (5)$$

3.1. Phase change

The phase change within the encapsulated PCM is accounted for by the apparent heat capacity method. The PCM undergoes three stages during charging and discharging, namely: solid stage, solid-liquid phase change and liquid stage.

(a) During the solid stage, $T_s < T_{m1}$

$$c_s = c_{s1};\ \rho_s = \rho_{s1};\ \lambda_s = \lambda_{s1} \quad (6)$$

(b) During solid-liquid phase change, $T_{m1} < T_s < T_{m2}$

$$c_s = \frac{c_{s1}+c_{s2}}{2} + \frac{\gamma_{th}}{T_{m2}-T_{m1}};\ \rho_s = \frac{\rho_{s1}+\rho_{s2}}{2};\ \lambda_s = \frac{\lambda_{s1}+\lambda_{s2}}{2} \quad (7)$$

(c) During the liquid stage, $T_p > T_{m2}$

$$c_s = c_{s2};\ \rho_s = \rho_{s2};\ \lambda_s = \lambda_{s2} \quad (8)$$

3.2. Initial and boundary conditions

At time $t = 0$,
$T_f = T_s = T_{ini}$ for $0 \le y \le H$

At time $t > 0$,
$T_f(0,t) = 70;\ \frac{dT_s}{dy} = 0$ for $y = 0$

$\frac{dT_f}{dy} = 0;\ \frac{dT_s}{dy} = 0$ for $y = H$

3.3. Method of solution

The two coupled, parabolic equations (eqn, (1) and (2)), were solved simultaneously for the new values of the temperatures of HTF and PCM at increasing time steps. A finite difference method was implemented by using the Matlab's pdepe solver [23].

3.4. Model validation

The dual-phase heat transfer model was validated using experimental data of Nallusamy et al. [24]. The temperature profile for the PCM at x/H=0.25 was compared to that obtained from the model during a charging cycle. The result is presented in Fig. 3.

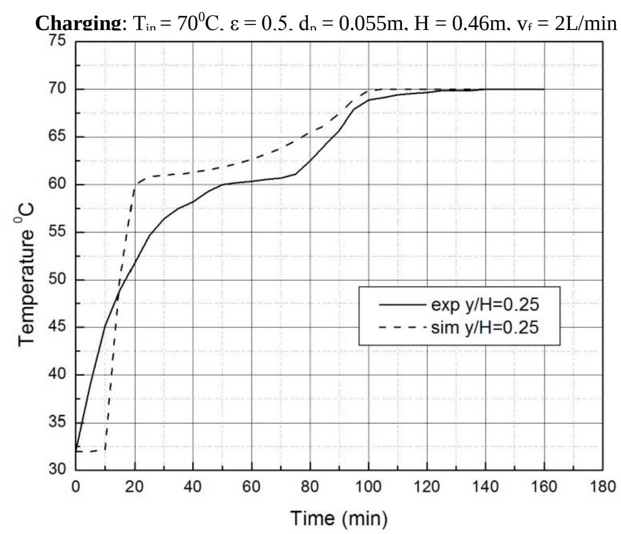

Fig. 3. A comparison between the numerical simulation results and experimental data for the temperature profile of the packed bed system.

There are some appreciable deviations from the experimental result, at some points, which may be attributed to (i) the effect of the encapsulation material, (ii) the radial thermal dispersion in the PCM spheres and (iii) heat losses from the walls, which was not accounted for in the model used for the simulation. Results obtained from the model showed acceptable agreement with the experimental results. The prediction of the model will suffice for the purpose of this study.

3.5 Quantity of heat stored

The quantity of heat, Q, stored in an elemental volume of the PCM is calculated by:

$$Q = \rho_{s1} c_{s1} (1-\varepsilon) V_{elem} (T_{m1} - T_{ini}) \quad (9)$$

for the sensible heat from initial temperature (T_{ini}) to the commencement of phase change. Where V_{elem} is the volume of the element of PCM at a height in the storage tank.

$$Q = \rho_{s1} (1-\varepsilon) V_{elem} \gamma_{th} \quad (10)$$

for phase change.

$$Q = \rho_{s2} c_{s2} (1-\varepsilon) V_{elem} (T_{final} - T_{m2}) \quad (11)$$

for the sensible heating from end of phase change to final temperature (T_{final}) of the PCM in the element.

4. Results and discussion

4.1. Effect of HTF inlet temperature on charge time

For the purpose of the simulation, the TES tank used is as depicted in Fig. 2, with a height of 0.46 m and a radius of 0.18 m. Spherically encapsulated erythritol PCM balls of radius 0.0275 m are randomly packed in the tank with a porosity of 0.5. Figs. 4 show the effect of varying the inlet temperature of Sunflower Oil (HTF) at a flow velocity of 1 L/min, on the charge time. With an increase in the HTF inlet temperature from 140 ^{0}C to 150 ^{0}C, the charging time for the TES unit (at y/H = 0.5) reduced by about 12.5 %. Fig. 5 shows the effect of variation of the inlet temperature on the charging time for the

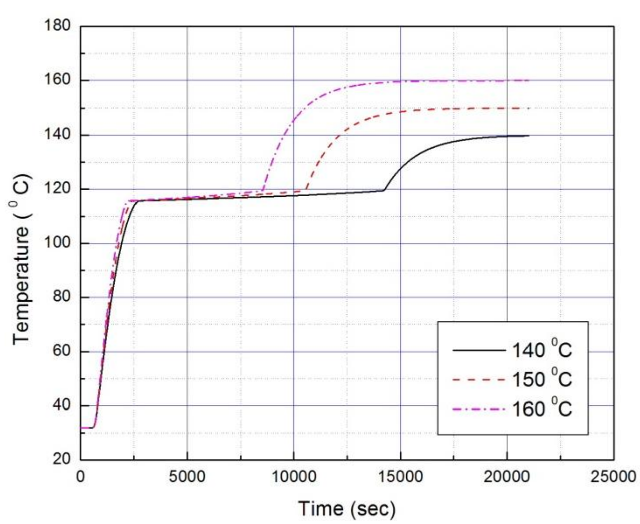

Fig. 4. Variation of charging time for the TES system at y/H = 0.5 with HTF flow velocity of 1 L/min.

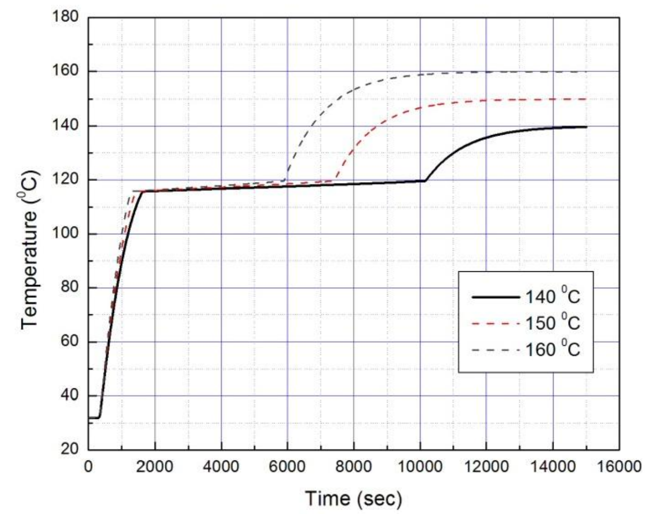

Fig. 5. Variation of charging time for the TES system at y/H = 0.5 with HTF flow velocity of 2 L/min.

TES at 2 L/min. The increment of inlet temperature from 150 ^{0}C to 160 ^{0}C also saw a 12.5 % reduction in the charging time for a flow velocity of 1 L/min. For a flow velocity of 2 L/min, the charging time reduced by 13.33 % for a temperature increase from 140 ^{0}C to 150 ^{0}C and 7.69 % for temperature increase from 150 ^{0}C to 160 ^{0}C. The rate of heat transfer is increased by an increase in the temperature of the HTF due to the increase in the thermal gradient between the HTF and PCM. Therefore, an increase in the inlet temperature of the sunflower oil will reduce the charging time of the TES unit.

4.2. Effect of HTF flow velocity on the charging time

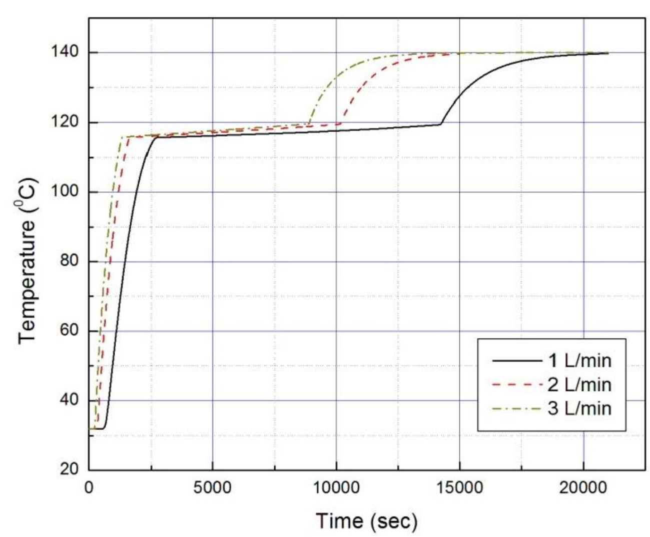

Fig. 6. Variation of charging time at y/H = 0.5 with varying flow rates at inlet temperature of 140 ^{0}C

Figs. 6 shows the variation in the charging time for varying flow rates at 140 ^{0}C. Fig. 7 also shows the variations in the charging time at the middle of the TES system for varying flow

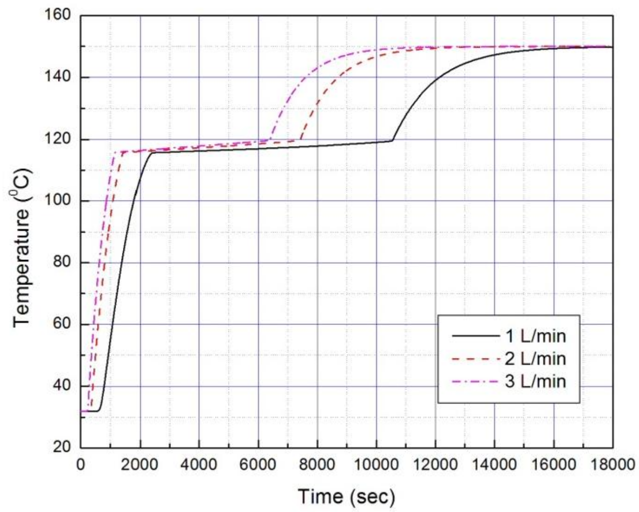

Fig. 7. Variation of charging time at y/H = 0.5 with varying flow rates at inlet temperature of 150 ^{0}C.

rates at 150 ^{0} C. With an increase in the HTF flow velocity from 1 L/min to 2 L/min, the charge time reduced by about 7.56 % and an increase of the flow velocity from 2 L/min to 3 L/min brought a 3.67 % reduction in the charging time of the TES system at y/H = 0.5. An increase in the flow velocity of Sunflower Oil through the packed bed will reduce the charging time. This is because an increase in the HTF flow velocity through the bed will cause an increase in the Reynolds number which will invariably increase the heat transfer coefficient of the HTF to the bed.

4.3. Sensitivity analysis

From Fig. 8, while keeping the flow rate constant, an increase in the HTF inlet temperature form 140 ^{0} C to 160 ^{0} C, shows an increasing trend in the quantity of heat stored. This is due to the

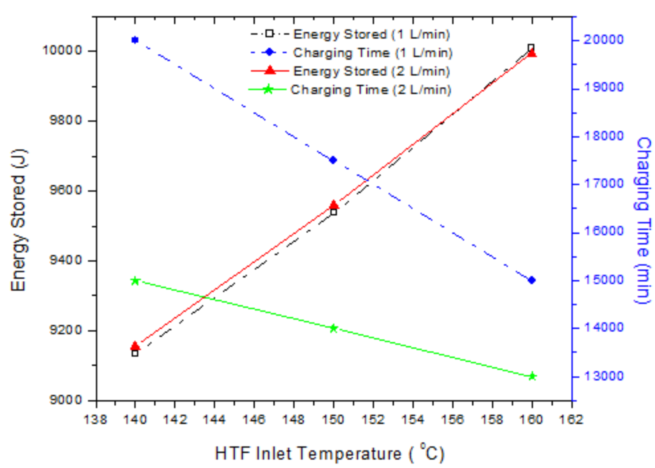

Fig. 8. Variation of energy stored and charging time with HTF flow rate at y/H = 0.5.

fact more thermal energy is available for storage at higher temperatures of the HTF. There was no significant difference in the quantity of heat stored in the PCM with flow rates 1 L/min and 2 L/min because the quantity of heat stored is not dependent on the flow rate. The charging time shows a decreasing trend with an increase in HTF inlet temperature in both flow rates as an account of greater rate of heat transfer, occasioned by the larger thermal gradients.

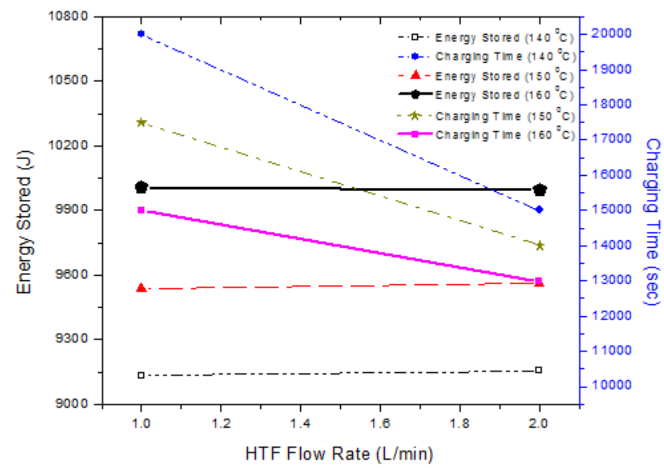

Fig. 9. Variation of energy stored and charging time with HTF flow rate at y/H = 0.5.

From Fig. 9, it is observed that there was very slight increase in the quantity of energy stored with constant temperature of HTF at 140 ^{0}C, 150 ^{0}C and 160 ^{0}C with increasing flow rate. The charging time shows a more noticeable decreasing trend with increasing flow rate, due to greater rate of heat transfer influenced by an increase in the Reynolds number.

5. Conclusion

The dual-phase model presented has been used to predict the performance of a packed bed TES unit, employing encapsulated erythritol as a packed bed and Sunflower Oil as the HTF. Results are given only for the charging cycles as a similar behaviour is expected, in the reverse pattern for discharging, within the assumptions employed in the study. An increase in the inlet temperature of the oil into the packed bed has shown to significantly decrease the charging time of the TES unit and also the maximum charge temperature. However, an increase in the operating temperature of erythritol will increase the risk of thermal degradation after several charging and discharging cycles. Thus, there is a trade-off between higher inlet temperature (consequently, lower charging time) and the possible durability (efficiency) of the TES unit over a period of time. An increase in the flow velocity also brought about a decrease in the charging time of the TES unit which, of course, will mean more pumping power which can increase the cost of the unit. The HTF inlet temperature has significant impact on both the charging time and quantity of heat stored in the TES system. The flow rate though has significant impact on the charging time, does not have significant impact on the quantity of heat stored in the TES system. Higher HTF inlet temperature means shorter charging time while more energy is available in the TES system for cooking. Higher flow rate means lower duration for charging the TES system. The results are useful to identify the optimal operational and design parameters of the packed bed TES system for practical operations. Further work will be done to develop the model to consider radial thermal dispersion in the PCM capsules, wall losses and the effect of the encapsulation material on the thermal conductivity of the PCM. Parametric studies will also be extended to include the effect of other parameters such as porosity/PCM capsule diameter.

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