Latent Heat Energy Storage System with Continuously Varying Melting Temperature

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***Abstract*— Latent thermal storage systems are more efficient and more compact than the sensible type. The heat transfer fluid (HTF) temperature profile along the bed exists with higher temperature at the entrance and lower temperature at the exit section in charging process and the opposite in the discharging process. Recognizing the fact that the rate of heat transfer between HTF and the phase change material (PCM) depends on the temperature difference between the two, researchers recently proposed using multiple PCM's instead of single PCM in the bed to match the variation in the HTF temperature profile, thus maximizing the heat transfer rate. This new design is called cascaded PCM distribution. The question then rose how many stages the cascading should be. This work comes to answer this question by considering the limiting case of cascading that is the continuous linear cascading. Comparing the performance of the three cascaded stages with the linear continuous case, it is found that the three stages do approach the linear reference case with no need for more stages.**

***Index Terms*— cascaded thermal storage; multiple PCM's; cylindrical pellets; cross flow heat exchanger**

I. Introduction

Solar energy is intermittent in nature, like other renewable kind of energy resources. Thermal energy storage system becomes an essential part of such a system to manage harvesting the energy, store it when available, and reuse the stored energy back when the source of energy is out of reach. Two types of thermal energy storage systems are available, the sensible type, which depends on heating materials to a higher temperature without involving any phase change process. The other type is the latent thermal storage systems where the latent heat of the storage material is used. In the later type as the material is heated at its melting temperature, the material would store the added energy at constant temperature, but on the expense of changing its phase, from solid to liquid or liquid to vapor. In this case, the amount of the stored energy is proportional to the heat of fusion in the first type and the heat of vaporization in the second type. The second type (liquid/vapor) is not practical because of the large volume expansion involved. Latent thermal storage method is considered superior to the sensible thermal storage type; it is more compact and more economical. To protect the system from corrosion, chemical reactions, or agglomeration of the PCM material during solidification process, encapsulation of PCM is introduced. Containers in this case can take different shapes and are made of different materials.

The effectiveness of the thermal energy storage system is measured via the rate of charging and discharging processes. One essential limitation affecting the rate of charging and discharging process is the low thermal conductivity of the PCM. Most paraffin waxes thermal conductivity is around 0.2 W/m-K and that of most inorganic salts of 0.5 W/kg-K. [1]. One way of affecting such processes is by increasing the conductivity of the PCM material, using metal fins, metal beads, and metal powders [2, 3]. Heat transfer rate between HTF and bed PCM material is higher at the entrance section of the bed. Using one PCM at constant melting temperature will not enable maximizing the heat transfer process. Using different PCM's at different melting temperatures along the bed would maintain approximately same temperature difference between the HTF and the PCM which can lead to a higher heat transfer rate, thus improving the performance of the thermal energy storage system.

Thermal energy storage systems using multiple PCM's of different properties are called Cascaded Thermal Energy Storage System (CTES). Researchers implemented CTES technology and showed an improvement at different levels [4, 5]. The investigations covered both the quantity and the quality aspects of the stored energy use exergy analysis [6, 7]. One of the most affecting parameter is found to be the number of cascades or stages to use. Michels and Pitz-Paal [8] investigated a three-stage PCM's system, and Gong and Mujumdar [9] investigated five-stage PCM system. Sharma et al. [10] summarizes different types of PCM's that can potentially be used for TES. One can generate from the same type of PCM derivatives that have different properties. As an example, when changing the number of carbon atoms in Paraffin, one can change its melting temperature, latent heat, and other physiochemical properties. The same is true for other types of PCMs [10]. Selecting different composition of Eutectics of PCM thus can get the required PCM specifications that suit best the cascaded type of thermal energy storage system.

This paper considers a latent energy storage system with cylindrical PCM pellets with a continuously varying melting temperature distributed. The performance of such

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CTES is investigated numerically. Results in terms of charging and discharging time and the PCM and HTF temperature profiles are presented. The comparison of the CTES bed performance with a reference one stage bed using a single PCM at the average properties is performed to examine how effective the continuous cascading can be. Comparing the number of cascading stages with the reference linear continuous cascading case is also presented. The later exercise is meant to answer the question about how many stages is necessary to achieve the highest and most economical CTES performance. Verification of the present model is carried out and presented against the experimental works available in the literatures.

II. Analysis

In this work, a rectangular thermal energy storage tank of H x W x Z dimensions is considered as shown in Fig. 1. The tank is assumed to be filled with N number of cylindrical pellets of outer diameter D_{co} and Z is the length of the bed itself. These pellets are filled with PCM material of the right selected properties. The cylindrical pellets are arranged in rows and columns to fill the available volume in the storage tank. These pellets can be packed in-line or in staggered arrangement. Between these pellets an appropriate transverse and axial pitches, P, are allowed to enable the HTF to flow smoothly in between.

A well-insulated storage tank with no gradients in the velocity and temperature but in one direction along the height of the tank is assumed. Consider a control volume of width W and height (D_{co} + P) surrounding one row of the cylindrical pellets. Apply the energy balance over this control volume; thus, the energy transferred from the HTF is equal to that received by the row of pellets, and the pellets will store the energy transferred sensibly and latently. Mathematically this is presented as follows:

$$m_f \; C_{pf} (T_{f,x1} - T_{f,x2}) = \rho_f \, V_f \, C_{pf} (T_{f,t2} - T_{f,t1})/\Delta t + Q_{f\text{-}p} \tag{1}$$

$$Q_{f\text{-}p} = h_e \, A_{sp} (T_f - T_p) = \rho_p \, V_p \, C_{pp} (T_{p,t2} - T_{p,t1})/\Delta t \tag{2}$$

$$V_f = \varepsilon.H.W.Z \text{ and } V_p = (1 - \varepsilon).H.W.Z \tag{3}$$

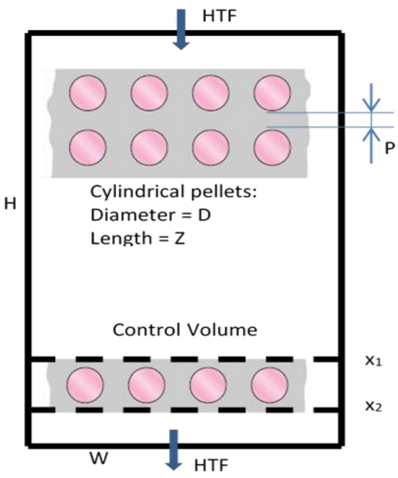

Figure 1. Schematic of thermal storage tank under investigation.

Here V_f and V_p are the volumes of the fluid and PCM in the control volume respectively and ε is the void fraction available between the pellets, and H.W.Z is the volume of the storage tank.

To incorporate the PCM latent effect in the analysis, enthalpy method is used, where the specific heat of the PCM assumes the regular C_p of material during the sensible heat transfer and an equivalent C_{pe} during the melting or solidification as follows:

$$\begin{aligned} C_{pe} &= C_{Ps} && \text{if} \quad T_p < T_{mS} \\ C_{pe} &= C_{pL} && \text{if} \quad T_p > T_{mL} \\ C_{pe} &= (C_{pS} + C_{pL})/2 + LH/(T_{mL} - T_{mS}) && \text{if} \quad T_{mS} \leqslant T_p \leqslant T_{mL} \end{aligned} \tag{4}$$

Here C_{pS} and C_{pL} are the specific heats of PCM in solid and liquid phases respectively. T_{mS} and T_{mL} are the solidus and liquidus PCM temperatures, and the difference between these two temperatures represent the temperature range over which the melting/solidification process occurs, the mushy zone. A correlation for Nusselt number (Nu) as a function of Reynolds number (Re) and Prandtl number (Pr) for forced convection across bundles of tubes is calculated as follows [11].

$$Nu = 0.8 \, Re^{0.4} \, Pr^{0.36}; \text{ and } h_e = Nu.k_f / D_{co} \tag{5}$$

When the PCM is in the melting process, the solid core is assumed at T_m of the PCM and a natural convection is assumed in the cylindrical annulus between the pellets container and the solid core. The heat transferred here is calculated using the equivalent thermal conductivity, k_{pe}, concept as described in [12].

$$K_{pe} = k_{pL}[0.386 \, (Pr/(0.861 + Pr)]^{0.25} \, [\log(D_{ci}/D_S)^4/\{(D_{ci} - D_S)^3(D_S\text{-}0.6 + D_{ci}\text{-}0.6)]^{0.25} Ra^{0.25} \tag{6}$$

$$Ra = g.\beta_p.L.(T_f - T_m).(R_{ci} - R_S)^3/\nu\alpha \tag{7}$$

where $D_S = D_{ci}$ (1 - LF_t)/2; and LF_t is the liquid fraction at time t.

When the PCM is in the solidification process, the thickness of the solid annulus is increasing with time. In this case the radius of the melted core, $R_m = R_{ci}.LF_t^{1/2}$; and the thermal resistance of the solid annulus, $T_R = \log(R_{ci}/R_m)/(2\pi L.k_{pS})$. The total thermal resistance between the HTF and the PCM inside the pellets is the combination of thermal resistances due to the external HTF film, pellet container wall and the equivalent thermal resistance of the melted or solid PCM inside the pellet respectively. The above equations are solved using finite difference method for the HTF and PCM temperatures as function of time and axial location along the bed. From these results, the charging and discharging times are calculated and presented as below.

III. Results and Validation

A rectangular bed of 500 x 250 x 250 mm dimensions is assumed. The pellets of cylindrical copper tubes of thickness 1 mm are assumed filled with the appropriate

PCM and packed in-linear or in staggered arrangement inside the storage bed. Properties of PCMs used in this study are summarized in Table I. To validate the mathematical model, calculations were run first using same dimensions and parameters as reported in the experimental work of Watanabe et al. [4]. The comparison between the charging/discharging time reported by [4] and the one calculated using the present model is presented in Table II. The model predicts the experimental results within 12.5 % in case of uniform PCM distribution and within 9 % in case of cascaded PCM distribution. The average liquid fraction (ALF) of the PCM, the HTF temperature at the exit section of the bed, and the exit temperature of the PCM in the last pellet row in the bed, all as functions of charging/discharging time are shown in Figs. 2, 3, and 4 respectively. The time for charging and discharging process is improved substantially when using cascading. The PCM melts and solidifies in shorter time as demonstrated in Fig. 2. This proves that higher rate of heat transfer between HTF and PCM in case of cascading. In Fig. 3, the exit HTF temperature approaches the HTF inlet temperature faster in case of cascading. Fig. 4, demonstrates that PCM melts in case of charging process and solidifies in case of discharging process significantly faster in cascading case. With cascading, the rate of heat transfer is increased and thus the dynamic performance of the thermal energy storage system is improved.

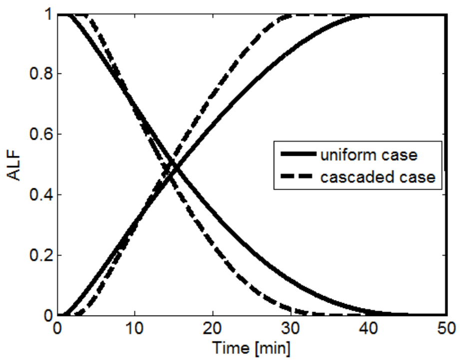

Figure 2. Average liquid fraction, the effect of cascading.

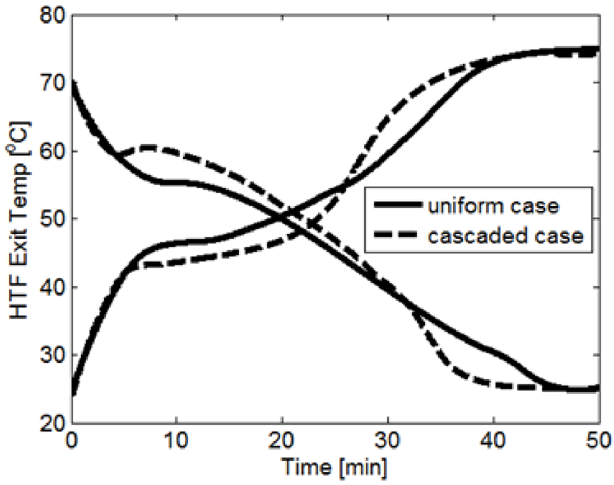

Figure 3. HTF exit temperature, the effect of cascading.

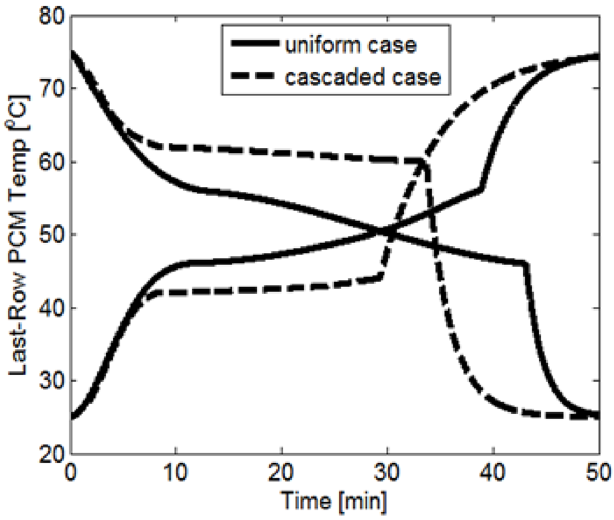

Figure 4. Last-row PCM temperature, the effect of cascading.

TABLE I. PROPERTIES OF THE PCMS USED IN THIS STUDY; PCMS PROPERTIES

PCM-type	ρ_S/ρ_L	C_{pS}/C_{pL}	K_S/k_L	T_m	LH	μ	β
	Kg/m^3	W/kg-C	W/m-C	C	kJ/kg	Pa.s	1/K
PCM40	844/760	2052/2411	0.4/0.15	42 – 44	168	4.9E-03	8.3E-04
PCM50	848/767	1650/1863	0.4/0.15	50 – 52	200	6.6E-03	7.7E-04
PCM60	861/778	1850/2384	0.4/0.15	60 – 62	209	6.3E-03	7.1E-04

TABLE II. VALIDATION OF THE PRESENT MODEL AGAINST THE EXPERIMENTAL RESULTS OF WATANABE ET AL [4]

	Experiment			Present model		
	Charging/discharging time [min]			Charging/discharging time [min]		
Flow rate [L/min]	0.5	1.0	1.5	0.5	1.0	1.5
Charging/uniform	40	22	17	35	25	20
Charging/cascaded	35	20	16	38	28	24
Discharging/uniform	41	22	18	34	24	20
Discharging/cascaded	36	18	16	34	24	23

TABLE III. PCMS AND OPERATING PARAMETERS FOR DIFFERENT RUN CASES

	PCMs used	HTF T_{inlet} [C] Charg./Disch..	T_{init} [C] Charg./Disch.	Pellets diameter [mm]	HTF flow rate, Q_f [L/min]	Pellets arrangement
Uniform case	PCM50	75/25	25/75	20	0.5	Inline
Cascaded case	PCMs 40/50/60	75/25	25/75	20	0.5	Inline
2-stage case	PCMs 40/60	75/25	25/75	20	0.5	Inline
3-stage case	PCMs 40/50/60	75/25	25/75	20	0.5	Inline
Linear case	PCM50 with varying T_m	70,**75***,80/20,**25***,30	**25*/75***	10,**20***,30	**0.5***,1.0,1.5	Inline & **Staggered***
• Reference operating conditions						

A similar thing is obvious from figure 5 which shows the variation of average liquid fraction in the bed as a function of charging/discharging time. From figure 5 it is clear that increasing the number of stages improves the dynamic performance of the bed. Comparing the three-stage case and the reference linear case the difference in performance is very minimal. This suggests that 3-stages is good enough and economical to achieve the best from the cascading technique.

The effect of other parameters such as pellet diameter, flow rate of HTF, HTF inlet temperature, and pellets arrangement on the performance of thermal energy storage system using cascading technique are studied and presented in Figs. 6-9. Decreasing the size of the pellets actually increases the surface area-volume ratio and thus increases the heat transfer rate, as shown by Fig. 6. Increasing the mass flow rate increases the heat transfer rate and thus decreases both charging and discharging time. This is quite clear from figure 6. Admitting the HTF at a higher inlet temperature reduces substantially the charging time, while using colder HTF reduces the discharging time, as demonstrated in Fig. 8. Figure 9 demonstrates the effect of pellets arrangement due to changes in the external heat transfer coefficient around the pellets.With cascading, the rate of heat transfer is increased and thus the dynamic performance of the thermal energy storage system is better. This is obvious from figure 10 which shows the variation of heat transfer rate in the bed as a function of charging/discharging time. Cases calculated and presented here are summarized in Table III.

IV. CONCLUSIONS

Latent Heat Thermal Energy Storage System with cascading arrangements, using different PCM's prove to have advantages over the uniform case. One expects to have more improvement as number of stages increases. Comparing with the limiting case of continuous linear cascading, the three stages case seems to approach the maximum limit. Further increase in stages thus is not required. Using smaller pellets size, at higher HTF mass flow rate and at higher inlet temperature in case of charging and at lower inlet temperature in case of discharging will improve the performance further. Using staggered arrangements also shows an improvement in the bed performance.

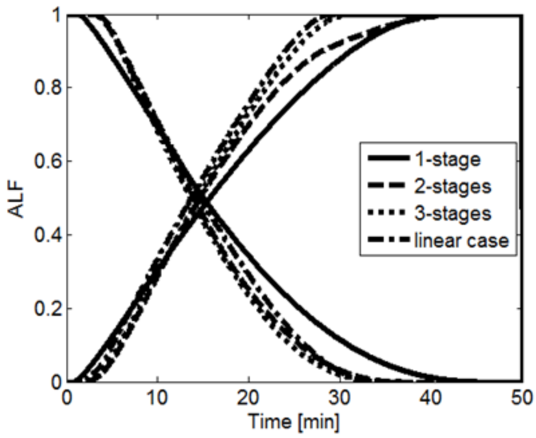

Figure 5. Average liquid fraction, the effect of number of cascading stages.

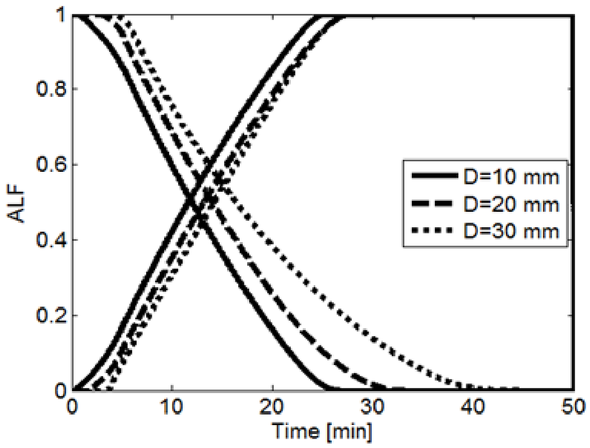

Figure 6. Average liquid fraction, the effect of pellet diameter.

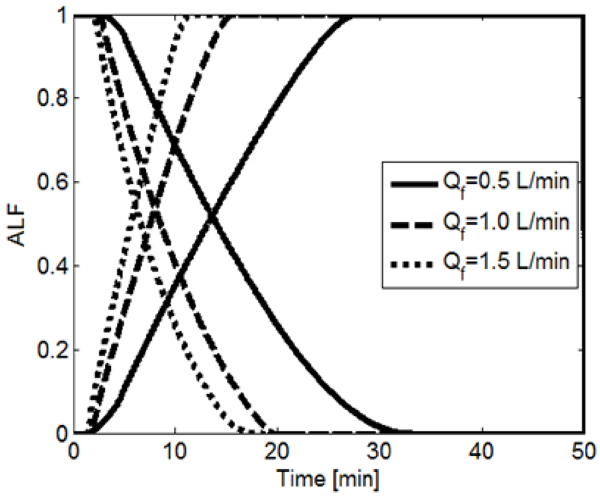

Figure 7. Average liquid fraction, the effect of HTF flow rate.

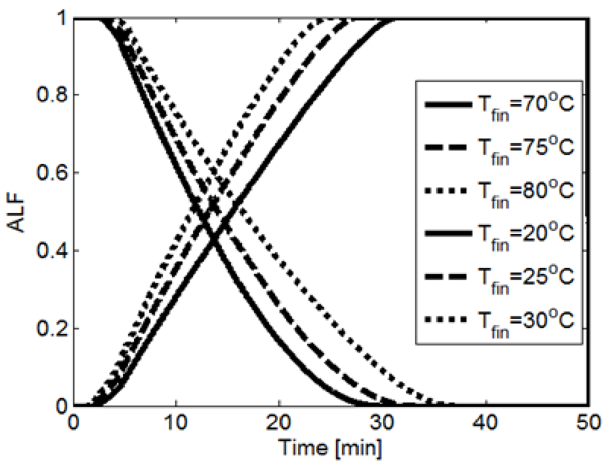

Figure 8. Average liquid fraction, the effect of HTF inlet temperature.

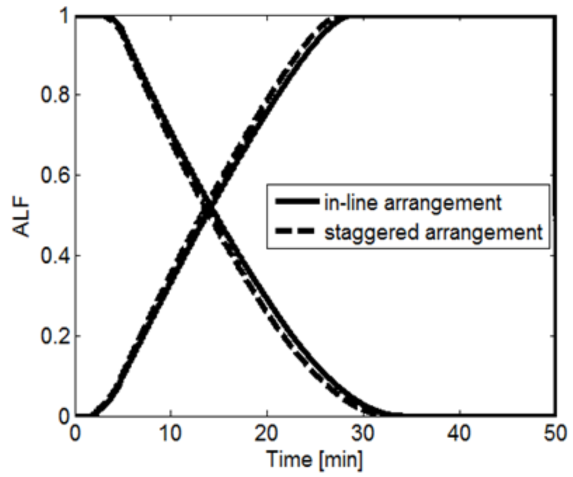

Figure 9. Average liquid fraction, the effect of pellets arrangement.

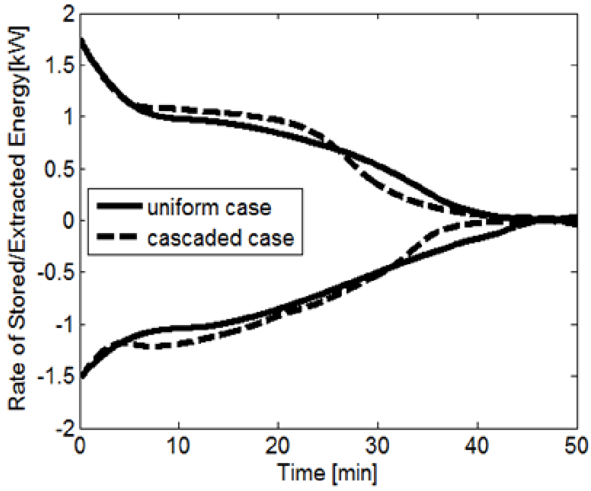

Figure 10. Rate of stored/extracted energy, the effect of cascading.

NOMENCLATURE

ALF	average liquid fraction
A_{sp}	outer surface area of the pellet, m^2
C_{pe}	equivalent specific heat of PCM, J/kg-K
C_{pf}	HTF specific heat, J/kg-K
C_{pS}	specific heat of PCM in solid state, J/kg-K
C_{pL}	specific heat of PCM in liquid state, J/kg-K
D	diameter, m
D_{co}	the pellet outer diameter, m
Dci	the pellet inside diameter, m
D_S	Diameter of the solidified portion of PCM, m
K	thermal conductivity, W/m-K
k_f	HTF thermal conductivity, W/m-K
k_p	thermal conductivity of PCM, W/m-C
k_{pe}	equivalent thermal conductivity, W/m-K
h	heat transfer coefficient, W/m^2-K
h_o	heat transfer coefficient, W/m^2-K
h_e	equivalent heat transfer coefficient, W/m^2-K
LH	Latent heat of fusion of PCM, J/kg

mof HTF mass flow rate, kg/s
N number of the cylindrical pellets
Nu Nusselt number, hD/k, dimensionless
Q_f flow rate of HTF, L/min
P pitch distance between pellets, m
Pr Prandtl number
R_c thermal resistance of the pellet cover, m-K/W
R_f thermal resistance of the fluid, m-K/W
R_p thermal resistance of PCM, m-K/W
Re Reynolds number, $\rho uD/\mu$, dimensionless
R_m radius of the melted portion PCM,ess, m
R_s radius of the solidified portion of PCM, m
T_{fin} HTF inlet temperature, ^oC
T_{init} tank initial temperature, ^oC
T_m PCM melting temperature, ^oC
T_{mS} solidus temperature of PCM, ^oC
T_{mL} liquidus temperature of PCM, ^oC
T_p temperature of PCM, ^oC
TRP total equivalent thermal resistant, m-K/W
V_f volume of the HTF, m^3
V_p volume of the pellets, m^3
u flow velocity, m/s

Greek Symbols
α thermal diffusivity, m^2/s
β thermal expansion coefficient, 1/K
Δt time interval, s
ε storage bed porosity
ρ density, kg/m^3
ρ_f HTF density, kg/m^3
ρ_p PCM density, kg/m^3
μ dynamic viscosity, Pa-s
ν kinematic viscosity, m^2/s

Subscripts
f HTF, heat transfer fluid
x location along the bed height, m
t time, s
p PCM

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1. T.K. Aldoss, M.M. Rahman, "Comparison between the single-PCM and multi-PCM thermal energy storage design," Energy Conversion and Management, vol. 83, pp. 79–87, 2014.
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