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Numerical Model of Lab-Scale Packed-Bed Thermal Energy Storage System

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***Abstract*—This paper presents numerical modeling of lab-scale packed bed thermal energy storage (TES) system. In the packed-bed with 0.30 m diameter and 0.90 m height, monotype storage particles developed from demolition wastes are used. Synthetic thermal oil is be used as fluid phase between 80 – 180°C. Schumann and one-dimensional continuous phase models are compared. To perform the two different numerical models, it was assumed that the length of packed bed was divided into 90 equal layers. Both numerical models showed smooth temperature profiles. Comparison of numerical results with experimental data will be studied in the future work.**

***Keywords*—packed-bed, thermal energy storage, numerical modeling**

I. INTRODUCTION

Thermal energy storage (TES) systems are of great interest in industrial applications for replacing fossil fuels with renewable energy sources. High storage capacity and low cost systems are most preferred properties in industrial processes. For this reason, few existing industrial applications are focused on sensible thermal energy storage systems with sensible thermal energy storage materials (STESM), which have low cost and high energy density.

Water, molten salts, oil and air can be used as heat transfer fluid. Water is the most widely used heat transfer fluid. But integration of water storage systems in industrial processes are limited up to 100°C. For systems above 100°C, packed-bed TES systems with thermal oil and different particles are preferred [1]. On the other hand, air has low heat transfer coefficient and heat capacity.

TABLE I. DESING PARAMETRS FOR THERMOCLINE PACKED-BED [2]

Operational Parameters	*Thermophysical Parameters*
Mass flow Charging/discharging time Inlet temperature Charge/discharge pressure	Thermal conductivity Density Heat capacity Viscosity
Geometrical Parameters	***Performance Parameters***
TES (packed-bed) height Top/bottom radii Wall thickness Insulation thickness Particle diameter Packed-bed porosity	Outlet temperature changes Charged capacity Net discharged energy Supplied energy Efficiency Cost

There are many parameters that affect the performance of thermocline packed-bed TES systems. Marti et al [2] classifies these critical design parameters as operational, thermophysical, geometrical and performance parameters (Table I).

Effects of parameters on performance of TES can be investigated by mathematical models. Singh et al [3] developed 1-dimensional 2-phase model to investigate the performance of large-scale packed bed TES systems in Ait Baha, Morocco and Biasca, Switzerland. The results showed that at least 98% efficiency could be achieved with 30 mm rock diameter and 0.6 m insulation layer. Cardenas et al [4] evaluated packed-bed TES system by developing temperature dependent 1-dimensional 2-phase model. Packed bed with 4 mm rock diameter and 0.6 aspect ratio showed higher efficiency. Mawire et al [5] tested packed-bed TES system performance by comparing Schuman and modified Schuman models. As a result, Schumann model modified by considering dynamic temperature distributions was in more agreement with experimental results.

Erregueragui et al [6] developed 2-phase continuous model to compare performance of palm oil with two different synthetic oils in packed-bed filled with quartzite. Comparison study showed that energy transfer efficiency with palm oil is %16 higher than DowthermA and Therminol VP-1 synthetic heat transfer oils. Hoffman et al [7] compared 1-dimesional 1-phase model, 1-dimensional 2-phase model and experimental results at selected high levels of the storage tank. Lab-scale packed bed TES system was filled with rapeseed oil and quartzite rock. Results showed that 1-dimesional 2-phase model is more consistent with experimental data. Bruch et al [8] developed lab scale packed bed filled with thermal oil and rock. Experimental results were in good agreement with 1-dimensional 2-phase model.

In this study, performance of the packed-bed with Therminol 66 as heat transfer oil and particles from demolition wastes will be investigated by comparing Schumann model and 1-dimensional 2-Phase continuous solid phase models.

II. EXPERIMENTAL SET-UP

A lab-scale packed bed TES system was developed to evaluate its usability in industrial solar applications. Packed-bed thermal energy storage system is filled with spherical particles and heat transfer fluid (HTF). System parameters of the lab-scale packed bed is listed in Table II.

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TABLE II. SYTEM PARAMETERS OF THE LAB-SCALE PACKED-BED

Parameter	Value	Unit
Height of storage tank; h_t	0.90	m
Diameter of storage tank; D_t	0.30	m
Inlet temperature range of HTF	80 – 180	°C
Diameter of particle, D_s	10	mm
Fluid velocity range; V_0	0 – 4	mm/s
Density of Therminol 66, ρ_f	Given by eq. 1	kg/m^3
Specific heat of Therminol 66, Cp_f	Given by eq.2	Jkg^{-1}K^{-1}
Thermal conductivity of HTF, k_f	Given by eq.3	Wm^{-1}K^{-1}
Density of particle, ρ_b,	2190	kg/m^3
Specific heat of particle, Cp_p	1340	Jkg^{-1}K^{-1}

The packed bed used in mathematical model has height of 900 mm and diameter of 300 mm. In the packed bed, 10 mm spherical particles from demolition waste are used as STESM. Demolition waste has storage capacity 1340 J/kg°C between 80-180 °C.

Figure 1 shows the lab-scale packed bed TES system filled with particles. During the storage cycle, hot HTF enters top of the packed bed tank. Solid phase absorbs heat from the hot heat transfer oil and thus heat is stored in particles. During the discharging process, cold HTF enters through bottom of the storage tank and hot particles are releasing heat to the cold HTF.

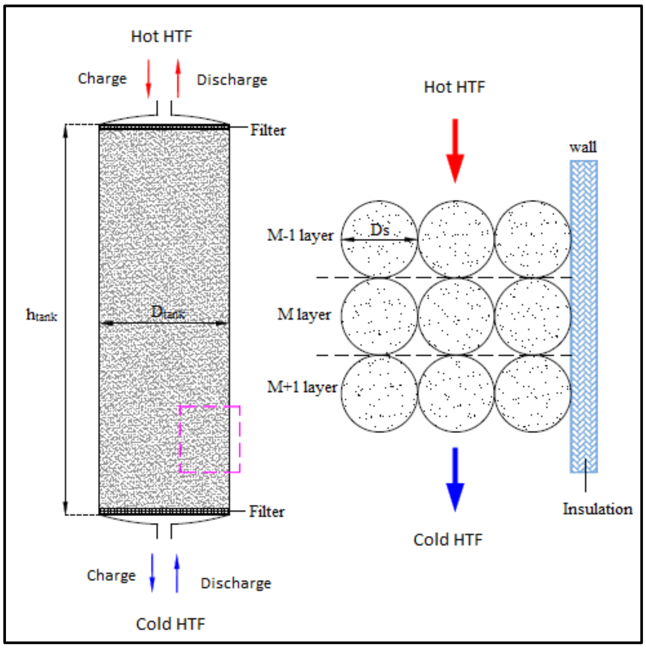

Fig. 1. Sketch of the packed bed sensible thermal energy storage system

To perform the numerical models, it is assumed that the length of packed bed is divided into equal layers. Each of the layers is 10 mm thick. So, the packed bed consists of 90 layers of demolition waste spheres. The single layer is assumed to be at same temperature level. So, temperature of particles and HTF are constant in given layer.

In this system, Therminol 66 heat transfer oil is used as HTF. HTF can flow through particles during charge for storing heat between 80 – 180°C. The density and the specific heat of the HTF vary with temperature, so density and specific heat is constant in given layer but changes between layers. Also, it is assumed that volumetric flow is constant in each layer.

Temperature dependent correlations are given in Equation (1), Equation (2), and Equation (3).

$$\rho_f = -0.614254\,T - 0.000321\,T^2 + 1020.62 \quad (1)$$

$$Cp_f = 0.003313\,T + 0.0000008970785\,T^2 + 1.496005 \quad (2)$$

$$k_f = -0.000033\,T - 0.00000015\,T^2 + 1.496005 \quad (3)$$

III. NUMERICAL MODELS

The performance of the storage systems can be described with different numerical models. There are four basic numerical models on packed beds such as Schuman's model, the continuous phase model, single phase model and thermal diffusion model. The first numerical model on packed bed system was improved by Schumann. Many studies still use models based on Schuman's model [9].

In Schumann's model, there is no heat conduction in radial direction and no heat conduction between particles and heat transfer fluids. In continuous phase model, solid particles filled in heat transfer fluid behave as continuous medium. As distinct from Schumann's model, in continuous phase model, there is heat conduction between particles and heat transfer fluid. Single phase model can be used if specific heat capacity and thermal conductivity of solid phase is higher than fluid media. Single phase model is generally preferred in rock/air systems. In thermal diffusion model, heat transfer occurs only between fluid and the bed [10, 11].

In this section, performance of the lab-scale packed bed TES system will be investigated by comparison of Schumann model and 1-dimensional continuous phase model.

A. Schumann Model

Schumann developed 1-dimensional 2-phase model to analyze heat transfer and temperature distribution in porous media [3, 5]. The assumptions for Schumann model are listed below:

- No heat conduction in radial direction
- No heat exchange between particles
- No heat exchange in fluid phase
- Heat exchange occurs between particles and HTF
- The fluid flow is incompressible

Within these assumptions, governing equations in Schumann's model can be written for solid and fluid phase as given in Equations (4) and (5) [11, 12]:

For fluid phase:

$$\varepsilon\,\rho_f Cp_f \frac{\partial T_f}{\partial t} + \varepsilon\, u_{sup}\,\rho_f Cp_f \frac{\partial T_f}{\partial x} = h_{pf}\alpha_{pf}\left(T_p - T_f\right) - U_w a_w\left(T_f - T_{env}\right) \quad (4)$$

For solid phase:

$$(1-\varepsilon)\ \rho_p\ Cp_p\ \frac{\partial T_p}{\partial t} = h_{pf}\alpha_{pf}\ (T_f - T_p) \qquad (5)$$

Where ρ_f and ρ_p are density of fluid and particle, respectively. Cp_f and Cp_p are specific heat of fluid and particle, respectively. x is the axial coordinate of packed-bed.

u_{sup} is superficial fluid velocity inside the packed bed, calculated as follows [13]:

$$u_{sup} = \frac{\dot{m}}{\rho_f\ \pi \frac{(D_T)^2}{4}} \qquad (6)$$

Uw is the overall heat loss coefficient from the storage tank to the surroundings. a_w is the area of the packed-bed per unit volume. In this study, it is assumed that system is well insulated and there is no heat loss from fluid to environment.

The specific surface area α_{pf} of packed bed was proposed by Cascetta et al [14].

$$\alpha_{pf} = \frac{6\ (1-\varepsilon)}{d_p} \qquad (7)$$

h_{pf} is the heat transfer coefficient between particle and HTF and can be calculated by Equation (8) [4]:

$$h_{pf} = \frac{Nu\ k_f}{d_p} \qquad (8)$$

Nusselt and Prandtl numbers are given by Equation (9) [4] and Equation (10) [8]:

$$Pr = \mu_f Cp_f / k_f \qquad (9)$$

Depending on system properties, there are different correlations for Nusselt number. According to Cascetta et al [14], equation (15) is the most appropriate correlation developed by Wakao between solid and fluid where particle Reynolds number is greater than 15.

$$Nu = 2.0 + 1.1 * Pr^{1/3} * Re_p^{\ 0.6} \qquad Re_p > 15 \qquad (10)$$

Reynolds number based on particle diameter (Re_p) indicates the flow regime in the packed-bed. Flow regimes based on Reynolds number are listed below [15]:

- $Re_p < 1$: Darcy or creeping flow regime
- $1–10 < Re_p < 150$: Forchheimer flow regime
- $150 < Re_p < 300$: Unsteady laminar flow
- $Re_p > 300$: fully turbulent flow regime

Re_p is a function of fluid density, fluid velocity, particle diameter (D_p), viscosity and bed void fraction (Ɛ). It is expressed by Equation (11) [1].

$$Re_p = \frac{\rho_f\ u_{sup}\ D_p}{\mu_f\ (1-\varepsilon)} \qquad (11)$$

B. One Dimensional Continuous Solid Phase Model

In continuous solid phase model, it is assumed that solid phase is a continuous media. In this solid media, particles are not independent. Governing equations can be written both in 1-dimesion and 2-dimensions, that is heat transfer can occur both in axial and radial directions.

In this study, packed-bed system is evaluated with 1-dimesional model. Assumptions are given below:

- Fluid velocity and temperature distribution is only in axial direction.
- HTF flows through the packed-bed in laminar regime.
- Particle bed porosity in the tank is homogenous.
- Properties of particles are independent from temperature.
- Inlet temperature and velocity is constant.
- For solid, filler material is spherical with a very small contact surface, so that there is no heat conduction between particles.
- Heat conduction occurs in fluid phase in axial direction.

Governing equations are given for both particle and HTF with respect to time and axial distance [11] as follows:

For fluid phase:

$$\varepsilon\ \rho_f\ Cp_f \frac{\partial T_f}{\partial t} + u\ \rho_f\ Cp_f\ \frac{\partial T_f}{\partial x} = k_{fx}\ \frac{\partial^2 T_f}{\partial x^2} + h_{pf}\ \alpha_{pf}\ (T_p - T_f) - U_w a_w (T_f - T_{env}) \qquad (12)$$

For solid phase:

$$(1-\varepsilon)\ \rho_p\ Cp_p\ \frac{\partial T_p}{\partial t} = k_{px}\ \frac{\partial^2 T_p}{\partial x^2} + h_{pf}\ \alpha_{pf}\ (T_f - T_p) \qquad (13)$$

k_{fx} and k_{px} defines axial effective thermal conductivity for HTF and particle, respectively. Ismail and Stungisky [11] proposed correlations for axial effective thermal conductivities given in Equation (14).

$$k_{fx} = 0.5\ Pr\ Re_p\ k_f \qquad for \quad Re_p > 0.8 \qquad (14)$$

Axial effective thermal conductivity can be expressed as:

$$k_{px} = k_{efx} - k_{fx} \qquad (15)$$

It is assumed that, the packed-bed is well insulated and there is no heat loss between fluid phase and environment.

C. Boundary Conditions

The initial conditions for both of the models are that inlet temperature (T_{in}) and fluid velocity (u_{sup}) are constant during charging.

During charging process, initial temperature is always higher than working fluid in any M layer, $T_{in} > T_M$

The boundary conditions for both of the models are the same and given in Table III:

TABLE III. INITIAL AND BOUNDARY CONDITIONS

	Fluid phase	*Solid Phase*
Initial condition (t=0)	$T_f = T_{in}$	$T_p = T_0$
Boundary condition ($x=h_{tank}$)	$T_f = T_{in}$	$\frac{\partial T_p}{\partial x} = 0$
Boundary condition (x=0)	$\frac{\partial^2 T_f}{\partial x^2} = 0$	$\frac{\partial T_p}{\partial x} = 0$

IV. RESULTS

In this study, two numerical models are used to investigate performance of a packed bed TES system. Numerical models have been analyzed at constant mass flow rate of 1000 kg/h and inlet temperature of T_{in} 90°C. At these conditions, Re_p was 15, which provides forchheimer flow regime.

Solid phase was assumed as monotype spherical particles with 10 mm diameter. Bed void fraction was taken as 0.45. For the initial conditions of solid and fluid phase temperature, T_0, were taken as 24°C. Total charging time was 102 minutes in Continuous Phase Model and 106 minutes in Schumann model.

Schumann and 1-dimensional continuous phase models were used to obtain the thermocline profiles. Axial temperature profiles are presented by dimensionless variables for both numerical models as given in the Equations 16-18.

$$\theta = \frac{T - T_{min}}{T_{max} - T_{min}} \tag{16}$$

$$t^* = t/t_{max} \tag{17}$$

$$h^* = x/h_{tank} \tag{18}$$

Where t is time, h is the tank height.

As seen in Figure 2 and Figure 3, for both numerical models, there is no deviation in thermal gradient from top to bottom of storage tank. Thermocline profiles can be seen clearly.

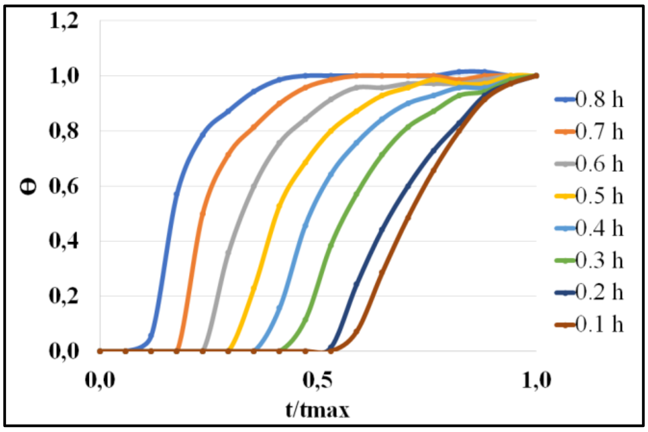

Fig. 2. Axial temperature distribution in 1-D Continuous Phase Model

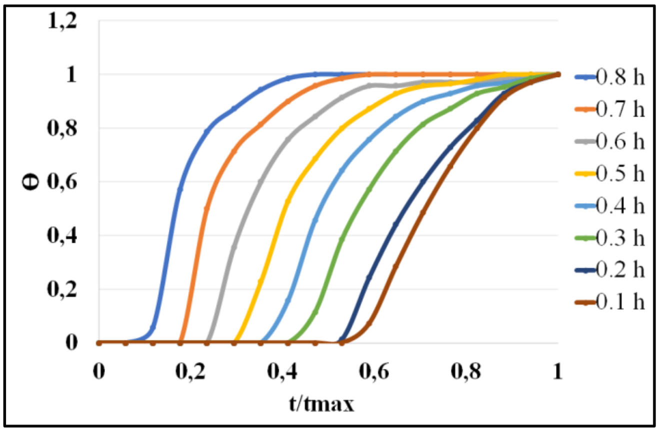

Fig. 3. Axial temperature distribution in Schumann Mmodel

Figure 4 shows the comparison of axial temperature profile of two different numerical models according to time scale. Comparing with 1-dimensional continuous phase model, in Schumann model, axial heat conduction through fluid phase is neglected. For this reason, temperature level decreases at lower tank levels. This increases total time to reach steady state in temperature distribution. Heat loss was neglected. However, cold wall of packed-bed had little effect on outlet temperature.

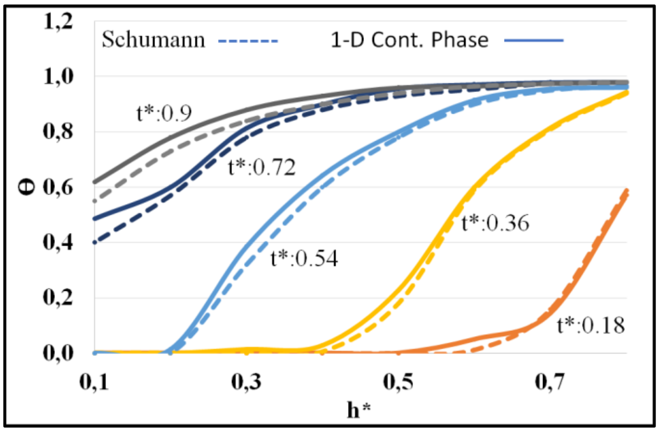

Fig. 4. Comparison of axial temperature profile at different time

As a result, TES unit showed good storage performance with the designated parameters such as packed-bed size, particle size and shape, flow rate of HTF etc.

V. CONCLUSION

This study analyzed two different models for the packed bed filled with particles and heat transfer oil. Mathematical models showed the basic energy balance during charging. Thermocline profile was seen very clearly for both Schumann model and 1-dimensional continuous phase model. Differentiations in two methods caused little deviations on charging time.

Temperature distribution and system performance can be analyzed better with 2-D models, which will be carried out in future studies. Also, if there is heat loss between fluid and environment, thermal stratification may be effected in real time applications.

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