JISSE
ISSN: 2636-4425

Journal of International Society for Science and Engineering

Vol. 1, No. 2, 41-47 (2019)

JISSE
E-ISSN:2682-3438

Numerical Analysis for the Effect of Porosity on Thermal Energy Storing and Releasing in The Spongy Porous Medium

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A R T I C L E I N F O

Article history:
Received:10-10-2019
Accepted:29-11-2019
Online:17-12-2019

Keywords:
Fluid flow,
Numerical analysis,
Porosity effect,
Porous medium,
Thermal energy storing and realizing

A B S T R A C T

Applications of heat transfer and fluid flow through porous media are very capacious, so they have drawn great attention and research. Acoustics, filtrations, and heat storage are examples of the wide application. The technique of the thermal energy storage (TES) to stock heat energy for later use is applied in many applications. Reliable stable low cost can be provided by storage solar thermal energy and undue heat from non-natural sources. A simple low-cost design that can fluently be constructed which uses the available porous media founded in nature is considered in the present study. The present study analytically investigated the effect of faction void of porous media (silicon rubber) on the process of heat transfer through heat storage and on the storage system. The study develops a numerical model to investigate the effect of several parameters, e.g. mass flow rate, bed length, particle diameter and different values of porosity during charging and discharge. The results depict that the amount of thermal energy stored, and the time of storage are affected by the working fluid, its porosity, and mass flow rate. The present model uses water as working fluid and the silicon rubber as storage medium. It is governed by two partial differential equations for these two substances. The conservation equations are applied on the present system for each of them separately. The storage medium and the working fluid are in case of heat exchange process all over.

Nomenclature

a interfacial surface area per unit volume.
Bd bed diameter, [m]
BL bed length, [m]
c_i inertial coefficient
c_f heat capacity of fluid, [W/kg K]
c_p specific heat, [kJ/kg K]
d_f solid strut diameter, [m]
dp particle diameter, [m]
F_i inertial variable with unit, [m^{-1}]
G mass flow rate per unit cross section, [kg/m^2sec]
h external heat transfer coefficient, [W/m^2K]
H height of the channel, [m]
k_f effective thermal conductivity of fluid, [kg/mK]
k_d thermal dispersion conductivity, [kg/mK]
k_s effective thermal conductivity of solid, [kg/mK]
K permeability of porous medium, [m^2]
L_c characteristic length
L Length of the channel, [m]
q_w wall heat flux
Q energy stored, [J]
T_c Temperature of cold plate, [^oC]
T_H Temperature of hot plate, [^oC]
T_w Temperature at the interface, [^oC]
T_o ambient temperature, [^oC]
t cooling or heating times, [h]
U average velocity, [m/sec]
U_{in} inflow velocity, [m/sec]
U_m average flow velocity, [m/sec]
V velocity vector
V_p pore velocity vector
X Horizontal direction
Z Axial direction

Geek Symbols

μ_f viscosity of fluid
ε porosity of the porous medium
μ_e effective viscosity
ρ_f density of fluid, [kg/m^3]
ã wetted area per volume
λ_ε effective thermal conductivity

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1. Introduction

An important branch of thermal power engineering that has enormous applications in practical life is heat transfer through porous media. Thermal energy storage (TES) is one of these applications, by using porous media such as sand, rock, or metal foam …etc to store thermal energy. Thermal energy stock for later use by thermal energy storage (TES) is commonly used with concentration power plants (CSP), to supply energy in case of interruption of concentration power plants (CSP). Thus, energy stock accommodates the energy demand. Another usage of TES is storing thermal energy dissipated from non-natural sources such as nuclear power plants and A/C units. Solar power plants are known for being a clean renewable energy source. The main trouble of solar power plants is that it is intermittent power supply due to its reliance on weather and sunshine. To manage these problems, efficient solar energy storage must be found. (Vafai and Tien, [1], [2]) presented a study heat transfer and convective flow in porous media. (Mahmud, I. Pop [3]), studied mixed convection, porous medium contained in a square vented enclosure. They found that Peclet number, Rayleigh number and the inlet width to the square enclosure height affect heat transfer and varying it. Porous heat exchangers performance and porous media characterization are permeated by (Boomsma and Poulikakos [4]) and (Boomsma et al. [5]). Using software based on the finite volume method to simulate the flow in the microscopic view by Krishnan et al. [6], the authors organized the open-cell structures, discussed the porosity and the permeability effect on Nusselt number and friction factor. Natural convection in finite porous enclosures with considerable non-Darcy is investigated by Lauriat [7] and Nithiarasu et al. [8]). Finite enclosures: such as vertical porous annulus with free convective heat transfer, were investigated by Chen et al. [9]. Using a finite element technique and approximate analysis for natural convection flow in a vertical annular enclosure at different values of radius and aspect ratios, to obtain the solution of the Nusselt number was studied for a high aspect ratio of the annulus, Hickox and Gartling [10]. Nivaskarthick designed a shell and spiral heat exchanger and experimentally studied it under various mass flow rates and inlet temperature of heat transfer fluid for low temperature industrial waste heat recovery using phase change material [11]. Naidu applied a Computational Fluid Dynamics (CFD) for thermal storage system keeping phase change material (PCM) in capsules [12]. The developed model was validated using experimental results. Alshaer, et al. [13]), discussed shapes of capsules to analyze thermal storage systems. Kanimozhi1, et al. [14], presented a study to predict electronic equipment thermal characteristics. Carbon foam matrix saturated with phase change material (PCM) was used. The authors employed Nano-Carbon tubes as thermal administration modules. Borah and Kumar) studied heat transfer enhancement in melting of PCM that had been analyzed by incorporating fins [15]. Fins had been placed and analyzed at different locations. It was observed that, if more fins are placed at bottom side melting is achieved more quickly.

2. Physical Model

The physical model of encapsulated carbon foam in a cylindrical casing; with water (in the liquid phase) as working fluid is studied. The flow of the working fluid (water) is passing from top to bottom as shown in Figure (1). The module is presented in the axial direction in one dimensional and steady state conditions. The system can be mathematically modeled using the appropriate conservation equations presented as two differential equations for the working fluid and the spongy-porous medium separately. The heat exchange process is occurring between working fluid (water) and spongy porous medium all over the cylinder. Water transient temperature distribution, spongy porous medium temperature distribution and the amount energy stored and realized within this system at any instant of time are provide with the model equations.

The microstructure of carbon foam is quite complex due to the manufacturing process. Therefore, the study of the relationship between its microstructure and bulk properties is a difficult problem. The solutions for geometrical and thermal-physical characteristic parameters, including the equivalent particle diameter, foam hydraulic diameter, pore window diameter, ligament diameter, internal surface area to volume ratio, effective thermal conductivity, permeability and Forchheimer coefficient can be derived utilizing the solid model.

3. Mathematical Modeling

The forced convection of incompressible fluid flow through open-celled metal foams is applied in the present system. Due to the complexity of the cellular structure precludes, a microscopic investigation of the transport phenomena at the pore level in porous medium is discussed. Also, the considering a representative elementary volume within the general transport equations which included the fluid and the solid phases are integrated. The two-equation model will be studied in the present analysis. The assumptions of the present model are drawn as follows:

- The medium is homogeneous and isotropic.
- The natural convection effects are negligible.
- The variation of the thermo physical properties with temperature is ignored.
- The radiation heat transfer is negligible, as the results of the relatively low operating temperature (<100ºC).
- The fluid flow and heat transfer reach steady state in the channel.

Based on these assumptions, the following governing equations are applied for the two phases.

3.1. Governing equations

- Continuity equation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \langle \rho V \rangle = 0.0 \qquad (1)$$

- *Momentum equation*

$$\frac{\partial}{\partial t}(\rho V) + \frac{\rho f}{\varepsilon}\langle(V\cdot\nabla)V\rangle = -\nabla\langle P\rangle_f + \frac{\mu_f}{\varepsilon}\nabla^2\langle V\rangle - \frac{\mu_f}{k}\langle V\rangle - \rho_f F_I[\langle V\rangle.\langle V\rangle]J \quad (2)$$

To explain the internal effect (non-Darcy flow), For chheime introduced the last term in Eq. (2), also Brinkman an interpret the boundary effects on the velocity distribution by the second term.

- *Working fluid phase energy equation*

$$\varepsilon\rho_f C_f\frac{\partial T_f}{\partial t} + \langle\rho\rangle_f C_f\langle V\rangle\cdot\nabla(T_f) = \nabla\cdot\{(k_{fe}+k_d)\cdot\nabla\langle T_f\rangle\} + h_{sf}a^{\sim}(\langle T_s\rangle - \langle T_f\rangle) \quad (3)$$

- *Porous media phase energy equation*

$$(1-\varepsilon)\,\rho sCs\frac{\partial Ts}{\partial t} = \nabla\cdot\{(k_{se}+k_d)\cdot\nabla\langle T_s\rangle\} + h\tilde{a}(\langle T_s\rangle - \langle T_f\rangle) \quad (4)$$

Where ⟨ ⟩ refers to the volume-averaged value and $J = V_P/|V_P|$ is the unit vector aligned along the pore velocity vector V_P.

If the Reynolds number is small such that laminar flow prevails, $F_I = C_I/\sqrt{K}$, where C_I is the inertial coefficient. The momentum boundary layer thickness is the order of $(\frac{K}{\epsilon})^{1/2}$ and the convective term $[\langle V\rangle.\langle V\rangle]$ responsible for boundary layer growth is significant only over a length of the order of (Ku_c/V), which depend on the magnitude analysis on the momentum equation, as found in Lauriat and Prasad [7].

The present model permits the appropriate conservation equations to be applied for the working fluid flow and the solid phase (porous medium), respectively, considering the thermal interaction between them and axial fluid flow. The energy equation for two phases can be calculated as:

$$\frac{\partial}{\partial t}(\rho u) = -\nabla P_f + \frac{\mu_f}{\varepsilon}\nabla^2 u - \frac{\mu_f}{\varepsilon}u - \rho_f F_1 u^2 \quad (5)$$

$$(1-\varepsilon)\rho_s C_s\frac{\partial Ts}{\partial t} = \frac{\partial}{\partial z}(k_{se}\frac{\partial Ts}{\partial z}) - h_{sf}\tilde{a}\,(T_s - T_f) \quad (6)$$

$$\varepsilon\rho_f C_f\frac{\partial Tf}{\partial t} + \rho C_f u\frac{\partial Tf}{\partial z} = \frac{\partial}{\partial z}(k_{fe}\frac{\partial Tf}{\partial z}) + h_{sf}\tilde{a}\,(T_s - T_f) \quad (7)$$

The boundary conditions are specified by the solid temperature satisfies the energy equation at the upstream and downstream boundaries, respectively, i.e.

At Z=0 for all t

$$(\mathbf{1}-\boldsymbol{\varepsilon})\,\boldsymbol{\rho_s C_s}\frac{\partial Ts(0,t)}{\partial t} = \boldsymbol{k_{se}}\frac{\partial^2 Ts(0,t)}{\partial Z^2} + [\boldsymbol{T_h} - T_s(\mathbf{0},t)] \quad (8)$$

At Z=L for all t

$$(\mathbf{1}-\boldsymbol{\varepsilon})\boldsymbol{\rho_s C_s}\frac{\partial Ts(l,t)}{\partial t} = \boldsymbol{k_{se}}\frac{\partial^2 Ts(L,t)}{\partial Z^2} + \boldsymbol{h}_{sf}\,[T_f(\boldsymbol{L},) - \boldsymbol{T_s}(\boldsymbol{L},\boldsymbol{t})] \quad (9)$$

3.2. Solution procedure

The two energy equations (6) and (7) that include the thermal behavior of the storage system are first applied to finite difference equations along with initial and boundary conditions. The finite difference equations are solved using the following numerical scheme.

- *Finite difference grid and integration domain*

The employed method exhibits grid nodes in the axial direction. There is one grid point on each of the two boundaries. The other internal points around each of them in a control volume are shown in Fig.1, the solution is obtained by marching in time from the given initial distribution of temperature using the forward differencing through 60 time steps, and adopting a fully implicit scheme to avoid limiting the time step. Denoting the space index by (i) and time index by (τ), the fluid energy equation is discredited as:

$$\varepsilon\rho_f C_f\frac{T_{f\,i,\tau+1} - T_{f\,i,\tau}}{\Delta t} + \rho_f C_f V\frac{T_{f\,i,\tau+1} - T_{f\,i-1,\tau+1}}{\Delta Z} = h_{sf}\,\tilde{a}\,(T_{s\,i,\tau} - T_{f\,i,\tau+1}) \quad (10)$$

Where

Δt is the time step

ΔZ is the space mesh size

The following equation is the marching equation for solving the fluid temperature field which is yield by the above equation.

$$[\frac{\varepsilon\rho_f C_p}{\Delta t} + \frac{\rho_f c_p V}{\Delta Z} + h_{sf}\tilde{a}]T_{fi,+1} = \frac{\rho_f c_f V}{\Delta Z}T_{fi-1,K+1} + \frac{\varepsilon\rho_f c_f}{\Delta t}T_{fi,} + h_{sf}\tilde{a}T_{si,\tau} \quad (11)$$

In the following, the solid energy equation, forward and central differencing is used the transient and conductive terms:

$$(1-\varepsilon)\rho_s C_s\frac{T_{si,\tau+1} - T_{si,\tau}}{\Delta t} = \frac{K_{se}(T_{si+1,\tau+1} - 2T_{si,\tau+1} + T_{si-1,\tau+1})}{(\Delta Z)^2} - h_{sf}\tilde{a}(T_{si,+1} - T_{fi,\tau+1}) \quad (12)$$

The above equation can be arranged to give the following equation:

$$-\frac{Kse}{(\Delta Z)^2}T_{si+1,\tau+1} + [\frac{(1-\varepsilon)\,\rho sCs}{\Delta t} + \frac{2\,Kse}{(\Delta Z)^2} + h_{sf}\tilde{a}]T_{si,+1} - \frac{Kse}{(\Delta Z)^2}T_{si-1,\tau+1} = \frac{(1-\varepsilon)\,\rho sCs}{\Delta t}T_{si,\tau} + h_{sf}\tilde{a}T_{fi,+\tau 1} \quad (13)$$

The tri-diagonal matrix solver is used to solve the equations combination to get the temperature field through the solid phase at (τ+1) time step, to get the repeated and so on.

Integrating the following integral numerically give the energy stored in the solid phase at each time step.

$$E = (1-\varepsilon)\,\rho_s C_s\int_0^L\int_0^{2\pi}\int_0^{D/2}(T_s - T_f)\,r\,dr\,d\theta\,dZ \quad (14)$$

This yields as follows:

$$E = (1-\varepsilon)\,\rho_s C_s A\,(\int_0^L T_s dZ - T_o L) \quad (15)$$

The numerical solution of the governing equations, initial and boundary conditions yielded the temporal and spatial temperature distributions for the liquid phase (water) and the solid phase (silicon rubber) as spongy-porous medium inside the channel is considered.

Having obtained the working fluid and porous media temperature fields with time, the amount of heating or realizing energy can be obtained at the same time.

4. Results and Discussions

The numerical results will be presented and discussed to illustrate the performance of heat transfer and fluid flow and thermal behavior of spongy-porous media system during charging and discharging modes. The time is extended until saturation mode of the medium occurs, then, the amount of energy stored or released inside or from the medium, respectively. The present model has suitably selected numerical values of constant parameters and matrix variables to cover the numerical analysis of the heat transfer, fluid flow, and thermal behavior of spongy-porous media system, given in Figure (1). These parameters are length, inlet temperature of the working fluid, mass flow rate, porous material, particle diameter of the porous media, and porosity. Study the variation of the amount of the energy released or stored (from or in) the Silicon foam at different values of the important variables and high values of porosity that affected the thermal behavior and performance of the present system during cooling and storing modes. From the results, it is interesting to notice that the chosen variables and parameters of the present system affect the thermal performance and behavior of cooling and storing processes in many applications such as modern heat exchangers.

As shown Figures (2) and (3) illustrate transient temperature for the working fluid (water) and the solid phase (silicon rubber) during storing at high porosity,$\mathcal{E}$=0.9, different axial location and at special condition. Also, Figures (4) and (5) show the temperature distribution with axial location for the working fluid (water) and the solid phase (silicon rubber) at different time intervals, high porosity, $\mathcal{E}$=0.9, and at special condition.

It notices that, the temperature distribution between the working fluid (water) and the solid phase (silicon rubber) decreases with the time and with the axial location. Therefore, as the time goes on, the cold working fluid (water) fills the system that the heat transfer occurs between the water and the silicon rubber until obtained the saturation.

In the present study, the porosity is considered which has an important variable and presented significant effect on the thermal behavior of this study. Therefore, Figures (6) and (7) show the variation of total value of energy stored or existed (in/from) the porous medium at different values of porosity, ($\mathcal{E}$= 0.3,0.5,0.6,0.7,0.8,0.9) and at special variables (G=0.15Kg/s, BL=0.8m, D_P=0.004m, T_o=25ºC, T_{in}=80ºC). It is noticed that, the porosity affects the amount of energy stored or released in the porous medium at all times, as the decreasing of the porosity, the capacity of the porous medium was increased that, the porosity affects the value of energy stored or existed (in/ from) the porous medium.

The variation of energy stored or released (in/from) the spongy porous medium at low porosity ($\mathcal{E}$=0.3), high porosity ($\mathcal{E}$=0.9) and at special parameters (G= 0.15Kg/s, BL= 0.8m, D_P= 0.004m, T_o= 25ºC, T_{in}= 80ºC) is shown in Figure (8). In this Figure, the value of energy stored or existed (in/from) solid medium is higher with low porosity and that's lower with the porosity is higher. Therefore, the low values of porosity is became an efficient chosen for energy storage or released system (in/ from) porous medium.

5. Conclusion

1. A numerical technique of the module is presented to predicate the transient heat transfer performance and fluid flow through the silicon rubber (porous medium).
2. The porosity is the most effective governing parameter.
3. Increasing the porosity leads to decreases the heat transfer rate between working fluid and silicon rubber as porous medium and noticed that the time increases for fully heating or cooling the system.
4. The higher porosity of the model needs a longer time to reach the steady state. On other hand, the capacity of heating or cooling for the system is lowered for the smaller volume of the absorbing material and the energy stored or released (in/from) the porous medium is decreasing.
5. The lower values of porosity are efficient than the higher values of porosity for stored or released energy.

Figures

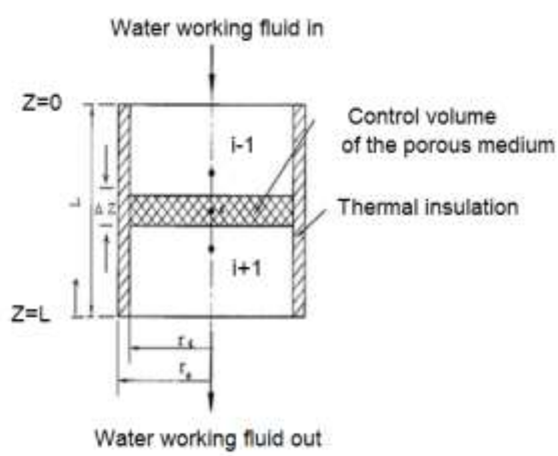

Figure 1: Schematic Diagram of the Present Model

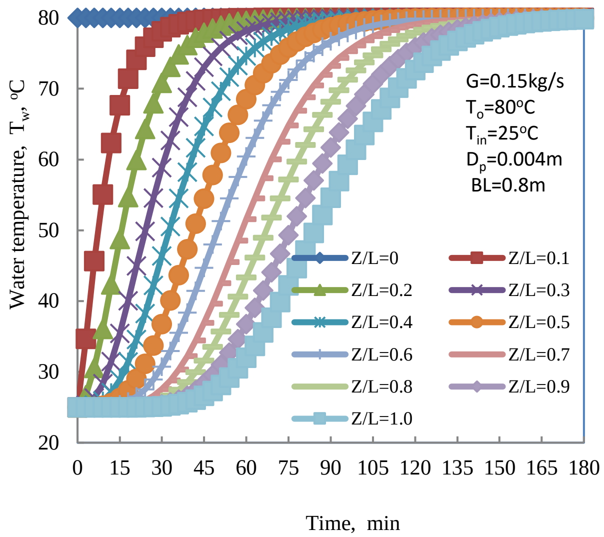

Figure 2: Water Temperature Distribution with Time at Different Axial Location during Storing Mode and High Porosity, Ɛ=0.9

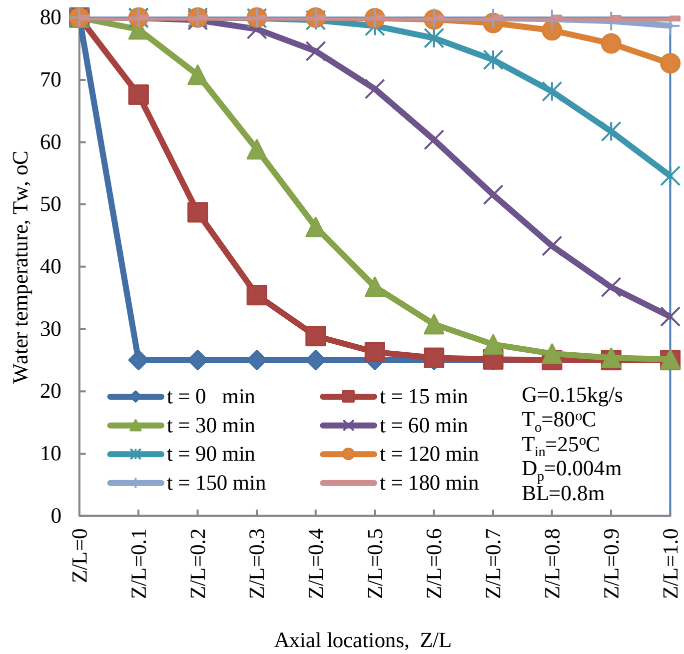

Figure 4: Water Temperature Distribution with Axial Location at Different Time during Storing mode and High Porosity, Ɛ=0.9

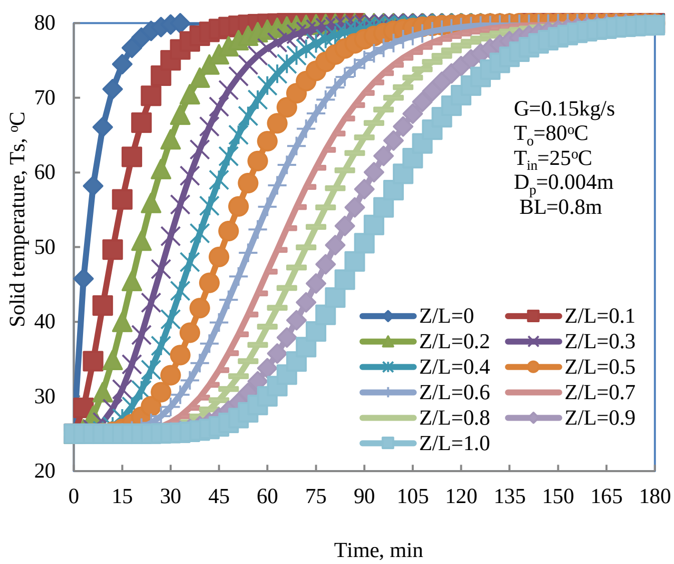

Figure 3: Solid Temperature Distribution with Time at Different Axial Location during Storing Mode and High Porosity, Ɛ= 0.9

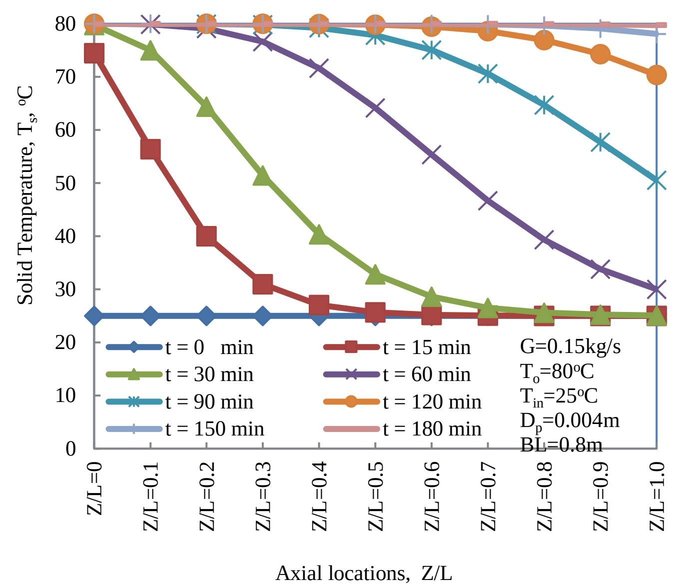

Figure 5: Solid Temperature Distribution with Axial Location at Different Time during Storing Mode and High Porosity, Ɛ=0.9

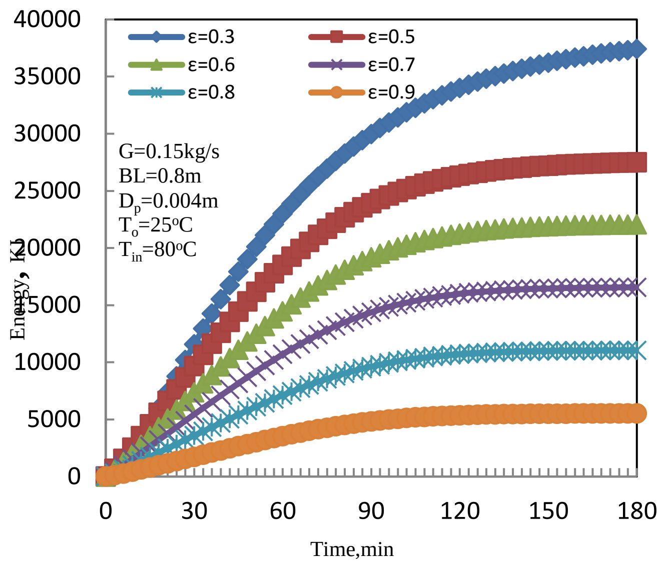

Figure 6: Variation of Energy Stored in Silicon Rubber at Different Values of Porosity

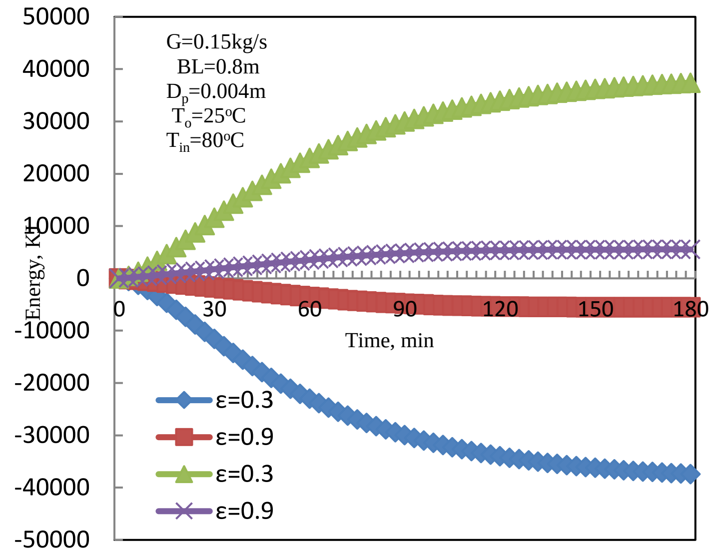

Figure 8: Variation of Energy Stored and Realized (in/ from) in the Spongy Porous Medium at Low and High Porosity (ε=0.3 & ε=0.9)

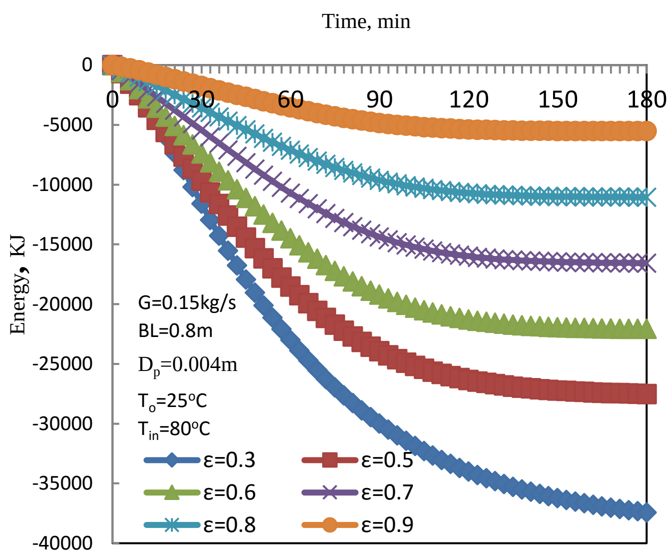

Figure 7: Variation of Energy Realized in the Present Model at Different Values of Porosity

References

(1) K.Vafai and C.L. Tien" Boundary and inertia effects on flow and heat transfer in porous media" Int. J. Heat Mass Transfer 24, 195-203, 1984

(2) K.Vafai" Convective flow and heat transfer in variable-porosity media" J. Fluid Mech. 147,233–259, 1984.

(3) S. Mahmud and I. Pop" Mixed convection in a square vented enclosure filled with a porous medium" Int. J. Heat and Mass Transfer 49(13), 2190–2206, 2006.

(4) K. Boomsma, and D. Poulikakos "The Effects of compression and pore size variations on the liquid flow characteristics in metal foams" *J. Fluids Eng* **124**, 263-272, 2002.

(5) K. Boomsma, D. Poulikakos and F. Zwick "Metal foams as compact high performance" Heat Exchangers Mechanics of Materials 35, 1161-1176, 2003.

(6) S. Krishnan, J. Murthy and S.V. Garimella" Direct simulation of transport in open-cell metal foam *J. heat transfer* 128, 793-799, 2006.

(7) G. Lauriat, and V. Prasad" Non-Darcian effects on natural convection in a vertical porous enclosure" Int. J. Heat Mass Transfer 32, 2135–2148, 1989.

(8) P.Nithiarasu, K.N. Seetharamu and T. Sundararajan "Natural convective heat transfer in a fluid saturated variable porosity medium" Int. J. Heat Mass Transfer 40 (16), 3955–3967, 1997.

(9) X.B.Chen, P. Yu, S.H. Winoto and H.T. Low" Free convection in a porous wavy cavity based on the Darcy–Brinkman–Forchheimer extended model" Numerical Heat Transfer Part A, 52, 377–397, 2007.

(10) C.E. Hickox and D.K. Gartling," Numerical study of natural convection in a vertical annular porous layer" Int. J. Heat and Mass Transfer 28, 720– 723,1985.

(11) R. Nivaskarthick," Analysis of thermal energy storage system using paraffin wax as phase change material Global Research and Development" in 2016 Journal for Engineering. International

Conference on innovation in Engineering and Technology, e-ISSN: 2455-5703, July 2016.

(12) N.Gali Chiranjeevi, KAruna, K. Dharma Reddy and P. V. Ramaiah," CFD Simulation for Charging and Discharging Process of Thermal Energy Storage System using Phase Change Material" International Journal of Engineering Research, Issue 4(5), 332-339, 2016
.

(13) W.G. Alshaer , S.A. Nada , M.A. Rady , Cedric Le Bot and Del Barrio," Numerical investigations of using carbon foam/PCM/Nano carbon tubes composites in thermal management of electronic equipment" Energy Conversion and Management 89, 873–884, 2015.

(14) B.Kanimozhi, Kasilanka Harish, Bellamkonda Sai Tarun and R. PogakuSatySainath" Charging and Discharging Processes of Thermal Energy Storage System Using Phase change materials" in 2017 IOP Conf. Series: Materials Science and Engineering **197**, 2017.

(15) B. Borah, Dr. Sudip Kumar," Numerical modeling of phase change material to enhance heat transfer using extended surfaces" International Research Journal of Engineering and Technology (IRJET), 05(03), 2018.

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