COMPARISON OF THERMAL DISPERSION EFFECTS FOR SINGLE AND TWO PHASE ANALYSIS OF HEAT TRANSFER IN POROUS MEDIA

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Abstract The present work involves numerical simulation of a steady, incompressible forced convection fluid flow through a matrix of porous media between two parallel plates at constant temperature. A Darcy model for the momentum equation was employed. The mathematical model for energy transport was based on single phase equation model which assumes local thermal equilibrium between fluid and solid phases. Single phase equation was derived by volume averaging on control volume. This model was modified by addition of dispersion terms.
The results of this investigation were compared with two phase simulation's results. Implementation of two phase model was expressed by separate energy equations of each solid and fluid phase. The results show that in many cases there are no significant differences between two approaches. However better compatibility of single phase model's results with empirical results and no possibility of determining the empirical parameters of two phase model, was observed.

Keyword Heat Transfer, Local Thermal Equilibrium, Porous Media, Thermal Dispersion

چکیده در این تحقیق دو دیدگاه تک فازی ودو فازی در انتقال حرارت درداخل یک کانال دو بعدی پر شده با ماده متخلخل با دمای دیواره ثابت بطور جداگانه بررسی شده اند. تحلیل انتقال حرارت در محیط متخلخل با در نظر گرفتن شرائط تعادل موضعی دمایی بر اساس معادلات انرژی تک فاز صورت می‌گیرد. این معادله بصورت متوسط گیری حجمی روی حجم کنترلی، که در آن شرط یکسان بودن دمای فاز جامد وسیال فرض شده است ، بیان می‌گردد. با افزایش عدد پکلت به مقادیر بیشتر از یک، به دلیل تأثیرات پراکندگی حرارتی، شرط تعادل موضعی دمایی صادق نخواهد بود. در دیدگاه اول مدل تک فاز، تنها با افزودن ترم پراکندگی حرارتی در معادله انرژی تصحیح می‌گردد و در دیدگاه دوم، معادلات انرژی بصورت مجزا برای هر یک از دو فاز بیان می‌گردد. نتایج عددی بدست آمده بر اساس هر دو دیدگاه ذکر شده، تحلیل و با یکدیگر مقایسه شده است. تطابق بهتر نتایج روش تک فاز با نتایج تجربی از یک سو وعدم امکان تعیین تجربی پارامترهای مدل دو فاز از سوی دیگر، بیانگر ارجحیت نسبی روش تک فاز نسبت به روش دو فاز، حداقل در محدوده مورد بررسی این تحقیق می‌باشد.

1. INTRODUCTION

The transport phenomena in porous media have been of continuing interest for the past five decades.
This interest stems from the complicated and interesting phenomena associated with transport processes in porous media. The wide applications available have led to numerous investigations in this area. Such applications can be found in solar receiver devices, building thermal insulation, heat exchangers, energy storage units, ceramic

processing and catalytic reactors to name a few. Our attention in this study focuses on packed beds of solid sphere particles in particular and porous media in general. Many aspects in this field are important to explore for a thorough understanding of fluid mechanics and heat transfer characteristic that are involved in the transport phenomena through porous beds. Some of the aspects related to transport phenomena were tackled in this literature.

An important topic in packed beds is related to the mixing and recirculation of local fluid streams as the fluid flows through tortuous paths offered by the solid particles. This secondary flow effect is classified as thermal dispersion. Extensive attention has been given to studies on determination of axial and radial effective thermal conductivities in cylindrical packed beds [1, 2]. Investigations by Cheng and Vortmeyer [3] and Hunt and Tien [4] provided some insight into the physics of the dispersion phenomena. Previous investigations [5, 6] have noted the small contribution from the axial dispersion to overall energy transport and the fact that its significance is confined to low Peclet or particle Reynolds numbers. This is because the convective heat transfer dominates the axial diffusion mode at high flow rates, therefore, the axial dispersion quantity can be neglected without causing significant impact on the heat transfer results. In above investigations, variations do exist among these models in terms of the Nusselt number predictions at various Peclet number due to incorporating different formulations for the porosity variations and the effective thermal conductivities. In all above mentioned investigations, a single phase model was adopted which assumes a state of local thermal equilibrium (LTE) between the fluid and solid phase at any location in the bed. This is a common practice for most of the investigations in this area where the temperature gradient at any location between two phases is assumed to be negligible. Vafai and Amiri [7] studied forced convection heat transfer with local thermal non equilibrium (LNTE) assumption and consideration of inertia and boundary effects with variable porosity in a channel filled by porous medium at constant walls temperature. Note that solid and fluid might be at the same temperature in some conditions especially in low Peclet numbers by implementation of two phase model but it is different from LTE assumption because the energy equations should solve separately.

In present paper local thermal equilibrium (LTE) assumption was used and the error caused with this assumption was covered by adding thermal dispersion term to diffusion term. Temperature, local Nusselt number and heat flux diagrams are illustrated to height and length of channel and comparative tables based on results of single and two phase model are presented. The results show better accuracy and compatibility to experimental results for single phase model. Better prediction of thermal dispersion values in low Peclet number's range in this work is the major reason for better results of single phase model. The discrepancies between two phase models' results and experimental data are due to large Peclet or Reynolds numbers which is common in literature [7].

2. ANALYSIS

The problem under investigation is forced convection of incompressible fluid flow through a parallel plate channel filled by porous medium as illustrated in Figure (1).

The computational length and height is 50 and 2 cm, respectively. The extent of the packed bed in z-direction is assumed to be long enough that the problem will essentially be two dimensional.

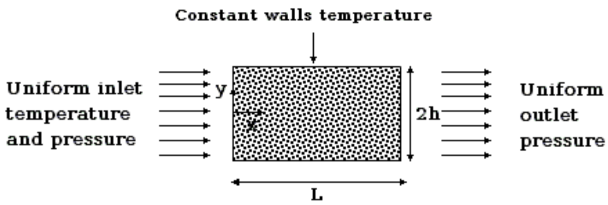


Figure 1. Schematic diagram of the problem

To summarize assumption on which established model is based:

(1) The medium is isotropic.

(2) The porous medium is of uniform spherical shape and incompressible particles.
(3) The porous medium is saturated.
(4) The forced convection dominates the packed bed, i.e. natural convection effects are negligible.
(5) The variation of thermophysical properties with temperature is ignored. This is a reasonable assumption for the operating temperature range applied (40 K) in the analysis.
(6) Due to the relatively low temperature considered in the present study, the inter-particle and intra-particle radiation heat transfer are neglected.
(7) The flow is one dimensional. The flow equation in x-direction is Darcy's equation. (Only x-direction component of velocity is non zero)
(8) The flow is fully developed, accordingly hydro-dynamically and thermally developing flows are not considered.
(9) Local thermal equilibrium exists between the fluid and solid phases.
(10) Heat transfer in x-direction is only convection and the conduction heat transfer is in x and y directions.

2.1. Governing Equations By assimilating the above points, the system of the governing equations can be presented in the following vector form based on the volume average technique [8, 9 and 10]:

Continuity equation

$$\nabla.\langle V\rangle = 0 \tag{1}$$

Momentum equation (Darcy's law)

$$-\frac{\mu}{K_p}\langle V\rangle - \nabla p = 0 \tag{2}$$

Energy equation of single phase model

$$\langle\rho_m\rangle c_{p_m}\frac{\partial\langle T\rangle}{\partial t} + \langle\rho_f\rangle c_{p_f}\langle\mathbf{v}\rangle.\nabla\langle T\rangle = \nabla.\ \{k_{eff}.\nabla\langle T\rangle\} \tag{3}$$

Energy equation of two phase model for solid phase

$$(1-\varepsilon)(\rho c_p)_s\frac{\partial\langle T_s\rangle}{\partial t} = \nabla.(k_{s_{eff}}\nabla\langle T_s\rangle) - h(\langle T_s\rangle - \langle T_f\rangle) \tag{4}$$

Energy equation of two phase model for fluid phase

$$\varepsilon(\langle\rho\rangle c_p)_f\frac{\partial\langle T_f\rangle}{\partial t} + (\langle\rho\rangle c_p)_f\langle\mathbf{v}\rangle.\nabla\langle T_f\rangle = \nabla.(k_{f_{eff}}\nabla\langle T_f\rangle) + h(\langle T_s\rangle - \langle T_f\rangle) \tag{5}$$

The physical aspects of various terms in the governing equations are discussed in references. [8, 9, 10] and the symbols are defined in the nomenclature. It should be noted that other mathematical models which include inertia term like Forchheimer model can be used. However, in this work, due to flow velocity ranges, Darcy's equation has been applied. It is important to know that the time interval within which steady-state condition is reached for the velocity field is of the order of few seconds for most practical cases [11]. Therefore, in the numerical analysis the steady-state forms of the continuity and momentum equations, equations (1) and (2), are considered.

The permeability of the packed bed is based on experimental results [12] and may be expressed as a function of particle diameter in the following form:

$$K_p = \frac{\varepsilon^3 d_p{}^2}{150(1-\varepsilon^2)} \tag{6}$$

where d_p is the particle diameter.

In the present study, the dispersion phenomenon is treated as an additional diffusive term added to the stagnant component [4] . The stagnant component is expressed in terms of the phase porosities and the individual thermal conductivities of the phases based on series model. The empirical correlation developed by Shahnazari an Abbasi [13] is employed in single phase approach to model the effective conductivity.

$$k_{eff} = k_m + k_d \tag{7}$$

$$\frac{1}{k_m} = \frac{\varepsilon}{k_f} + \frac{1-\varepsilon}{k_s} \tag{8}$$

$$k_d = \left(0.23Pe - 0.035\right) \times k_f \tag{9}$$

In fact k_d is the additional diffusive term due to thermal dispersion phenomenon that added to the stagnant diffusion component. Peclet number was calculated by Reynolds number based on particle diameter.

$$Pe = \Pr.\mathrm{Re} \tag{10}$$

$$\mathrm{Re} = \frac{\rho V d_p}{\mu} \tag{11}$$

The Nusselt number is defined as follow:

$$Nu = -\frac{2H}{T_w - T_m}\left(\frac{\partial \ \langle T \rangle}{\partial \ \ y}\right)_{Y=h} \tag{12}$$

Where T_m is the mixed mean temperature and is defined as follow:

$$T_m = \frac{\int_{-h}^{h} uT \ \ dy}{U_m H} \tag{13}$$

2.2. Boundary Conditions In this investigation, no slip condition is imposed at the walls and the walls are kept at constant temperature. The boundary conditions are, therefore, as follows:

$$u(x, y = h) = u(x, y = -h) = 0 \tag{14}$$

$$T(x, y = -h) = T_w \tag{15}$$

$$T(x, y = h) = T_w \tag{16}$$

$$T(x = 0, y) = T_{in} \tag{17}$$

Inlet and outlet velocity at boundaries are calculated from equation (2) where pressure gradient is considered known constant parameter.

In the numerical computations, inlet temperature (T_{in}) and boundary temperature (T_w) were taken as $27^\circ C$ and $67^\circ C$, respectively.

Particle diameter and porosity of bed characteristics values were used 0.294 mm and 0.69 respectively in computations to be closed data to experimental results of [14]. The Reynolds and Peclet numbers were varied by applying different axial pressure gradients. The physical data for fluid and solid phases which were considered in the numerical computations are calculated at the average film temperature and are shown in Table 1.

TABLE 1. Physical Data.

	Resin (90% Glycerin & 10% Diethylen glycol)	Fiber (Eglass 1)
$\rho \ \left(kgm^{-3}\right)$	1230	2550
$c_p \ \left(Jkg^{-1}K^{-1}\right)$	2495	670
$k \ \left(Wm^{-1}K^{-1}\right)$	0.282	0.421
$\mu \ \left(kgm^{-1}s^{-1}\right)$	0.2260125	-
Pr	2000	-

3. SOLUTION METHODOLOGY

A finite volume scheme was employed to solve the system of the governing equations subject to the cited boundary conditions. The numerical scheme was based on the discretized finite volume versions of equations (1) - (3). The steady state solutions of these equations were obtained. Grid generation of domain was implemented by use of uniform square grid with 10000 meshes. Heat transfer in y-direction was more essential. Therefore, the grid size in this direction was considered much smaller than x-direction. Momentum and energy equations are not coupled since forced convection was assumed.

Since Darcy's law was used as momentum equation, values of pressure gradient leads to velocity distributions.

The spatial derivatives in energy equation were discretized by the central differencing except for the convective term which is approximated by an upwind differencing scheme. Equation (3) was solved also in second order discretization. Due to high quantity for mesh number, no significant discrepancies were observed between first and second order solutions.

The accuracy of the numerical results was rigorously examined as temperature values in two consecutive iteration differed by less than the convergence criterion of 10^{-10}.

By neglecting x-direction diffusion in steady state condition, equation (3) can be solved analytically by separation of variable (S.O.V) method as follows.

$$\frac{T(x,y)-T_w}{T_{in}-T_w} = \frac{4}{\pi}\sum_{n=1}^{\infty}\frac{(-1)^{n+1}}{2n-1}\exp\left(\frac{-(2n-1)^2 k_{eff}}{(\rho C_p)_f u}(\frac{\pi}{H})^2 x\right) Cos\left[(2n-1)\pi\frac{y}{H}\right] \quad (18)$$

4. RESULTS AND DISCUSSION

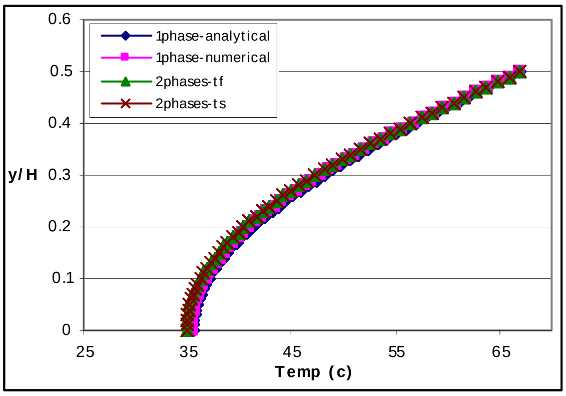
To examine validity of the numerical scheme, numerical results were compared with analytical results in steady state condition, neglecting x-direction diffusion.

As may be seen in Figure (2a) for $\frac{dp}{dx}=1.8\times10^5\,Nm^{-3}$ and Figure (2b) for $\frac{dp}{dx}=3.5\times10^5\,Nm^{-3}$ the comparison between numerical and analytical results showed an excellent agreement.

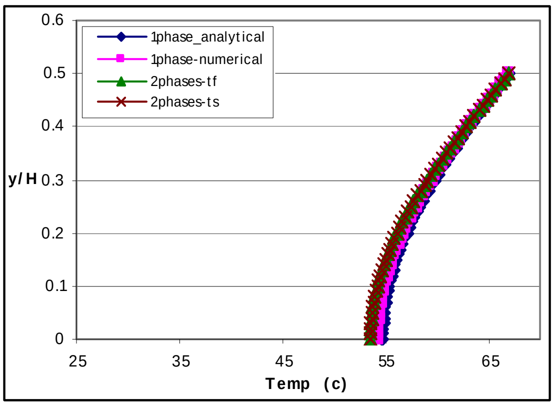
Temperature distributions were depicted to dimensionless length and height of channel those defined as follow:

$$\xi=\frac{x}{L} \qquad \eta=\frac{y}{H} \qquad (19)$$

Where H is total height of channel and equal to 2h.



(a)



(b)

Figure 2. Comparison of numerical and analytical temperature distribution results. (a) $\xi=0.1$, $Pe=1$. (b) $\xi=0.3$, $Pe=1$

Also, the local Nusselt number, channel center line temperature, cross section mean temperature and local heat flux from each plate of channel was depicted to ξ.

4.1. Longitudinal Effects Figure (3) illustrates development of temperature distribution in length of channel. It is clear that temperature increases due to effects of walls temperature and incoming heat flux to channel.

Figure (4) shows cross section mean temperature and center line temperature of channel those were confirmed increasing of temperature in length of channel.

Figure (5) depicts Nusselt number versus length of channel.

This diagram represents temperature gradient decreases in length of channel to an asymptotic value and stays constant at the end. Asymptotic value of Nusselt number is 10 in these physical

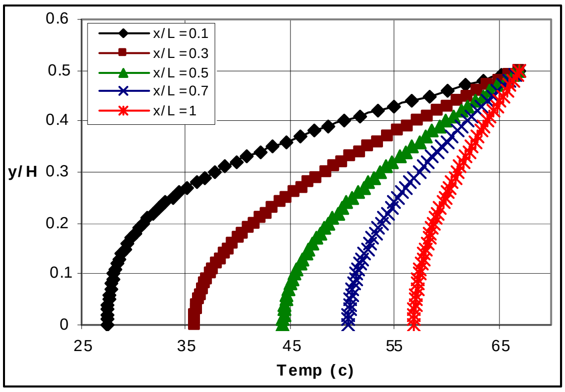


Figure 3. Comparison of temperature distribution in various dimensionless length of channel at constant Peclet number. $Pe = 5$

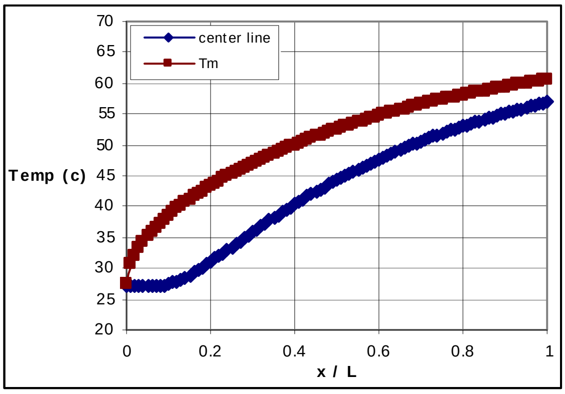


Figure 4. Center line and cross section mean temperature to dimensionless length of channel at constant Peclet number. $Pe = 5$

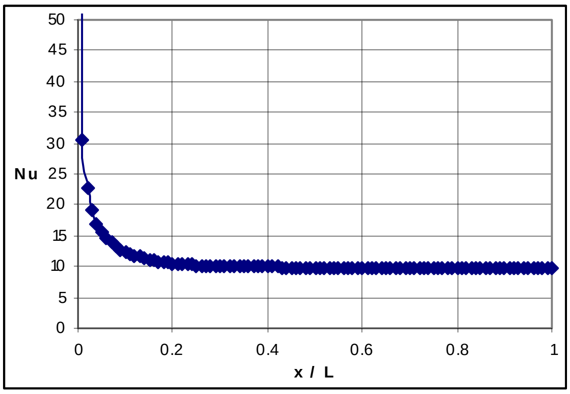
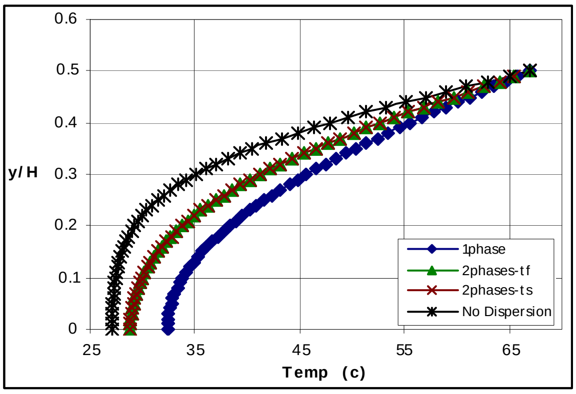
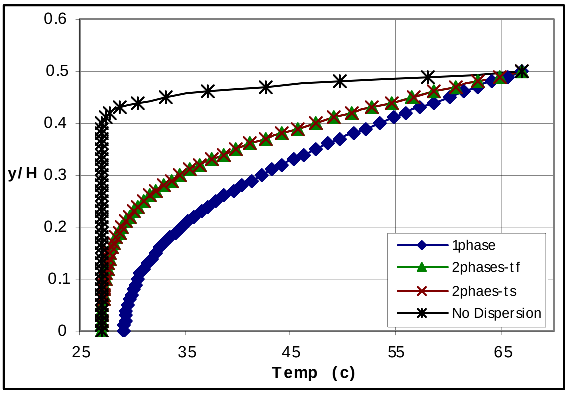


Figure 5. Local Nusselt number to dimensionless length of channel at constant Peclet number. $Pe = 5$

(a). $Pe = 5\ ,\ \xi = 0.3$



(b). $Pe = 10\ ,\ \xi = 0.3$



(c). $Pe = 200\ ,\ \xi = 0.3$

Figure 6. Thermal dispersion effects on temperature distribution in different models at different Peclet numbers when ξ is constant.

TABLE 2. Predicted values of transverse thermal dispersion by use of different correlations for various Peclet numbers.

k_d \ Pe	1	5	10
Shahnazari (empirical correlation)	0.055	0.314	0.639
Wakao&Kaguei (empirical correlation)	0.028	0.141	0.282
Baron (empirical correlation)	0.056	0.282	0.564
Koch & Brady (closed form solution)	0.022	0.109	0.218
Fried &Combarnous (Experimental Data)	0.225	0.366	0.648

conditions that occur almost in $\xi = 0.3$, also average Nusselt number is 12.8. Nusselt number at the entrance of channel is 202.

4.2. Thermal Dispersion Effects According to relation (9), value of additional diffusion term due to thermal dispersion effects is rigorously depend on Peclet number and the Peclet number is also depend on many parameters.

In this investigation all the parameters which can affect on Peclet number was kept constant except velocity. Therefore, variations of Peclet number represent velocity variations which will be discussed in section 4.3.

Figure (6) illustrated temperature distributions in $Pe = 5$, $Pe = 10$, $Pe = 200$ and $\xi = 0.3$ for single and two phase models. Temperature distribution without incorporating thermal dispersion effects was depicted for comparison.
All the relations for two phase model was based on reference [7]. The empirical correlation developed by Wakao and Kaguei [2] was employed in reference [7] to model the effective conductivity as follow:

$$k_d = 0.1 Pe \times k_f \qquad (20)$$

As illustrated in Figure (6), by adding thermal dispersion term to equations, both models predict higher temperatures.

An important point is the difference between predicted temperature by single and two phase models. This discrepancy is due to approximation of values of thermal dispersion on each model. This is clear that single phase model based on empirical relation (9) predicts higher value for thermal dispersion.

Investigators have expressed many different relations for thermal dispersion approximation such as (9) and (20). Closed form correlation that was attained by Koch and Brady was used in this investigation as follow [15]:

$$k_d = \frac{63\ (2)^{1/2}}{320}\ (1-\varepsilon)^{1/2}\ \frac{Pe}{2} \times k_f \qquad (21)$$

Range of Peclet number in this work was selected between $1 \le Pe \le 20$ which is represented as $0.0005 \le \mathrm{Re} \le 0.01$.

The theoretically predicted values of effective diffusivity obtained from equation (17) have compared with the experimental values reported by Fried & Combarnous [16]. As it is noticeable in Figure (6), correlation (21) has not good accuracy for the range of Peclet number [14]. Values of experimental data are greater than those calculated by equation (21). Baron's results express thermal dispersion as follows [17]:

$$K_d = \frac{1}{(5 \propto 15)}\ Pe \times K_f \qquad (22)$$

Yagi et al. (1960) and also Schertz and Bischoff (1969) have expressed thermal dispersion as following relation [18]:

$$K_d = (0.1 \propto 0.3)\ Pe \times K_f \qquad (23)$$

Predicted values of transverse thermal dispersion using different correlations are shown in table 2 for various Peclet numbers.
As it appears from table 2, predicted values of thermal dispersion by Shahnazari empirical relation (9), was presented minimum discrepancies from experimental data reported by Fried &

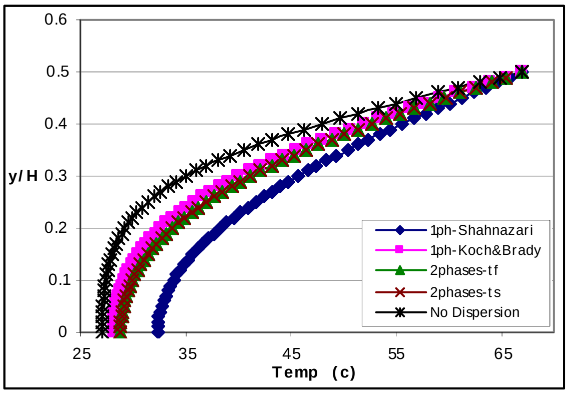


Figure 7. Comparison of temperature distributions for different correlations of thermal dispersion. $Pe = 10$, $\xi = 0.3$

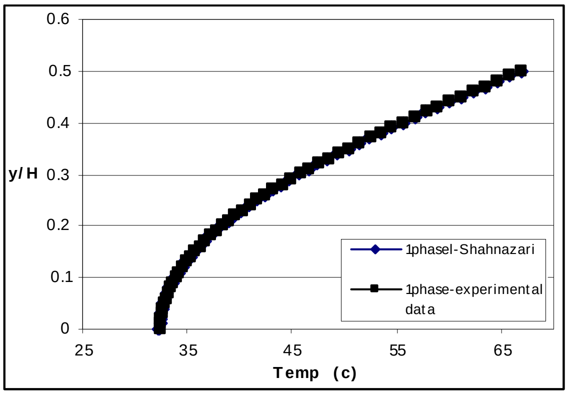


Figure 8. Comparison of temperature distributions considering Shahnazari's experimental correlation and Fried & Combarnous's experimental data for thermal dispersion. $Pe = 10$, $\xi = 0.3$

Combarnous and Baron's empirical correlation. Therefore, equation (20) that was applied in two phase model in reference [7] shows relative error in this present work's confine because of covering a wide range of Peclet number and this is a confirmation to the past investigations that governing relations for thermal dispersion are changed in Peclet numbers under 10 or 20. Therefore, considering different relations for different Peclet number ranges will cause more accurate results.

Figure (7) represents temperature distribution in single and two phase model considering different correlations of thermal dispersion.
As it appears temperature distribution of single

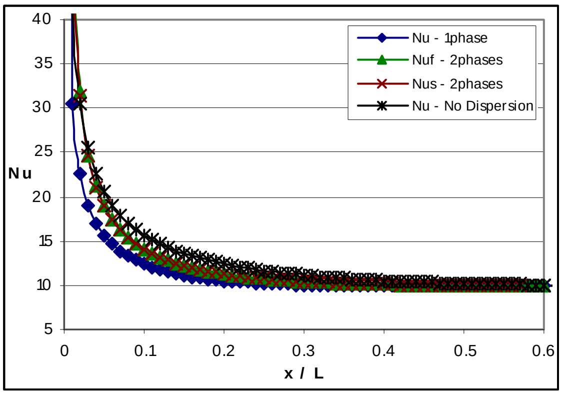


Figure 9. Thermal dispersion effects on local Nusselt number in different models at constant Peclet number. $Pe = 5$

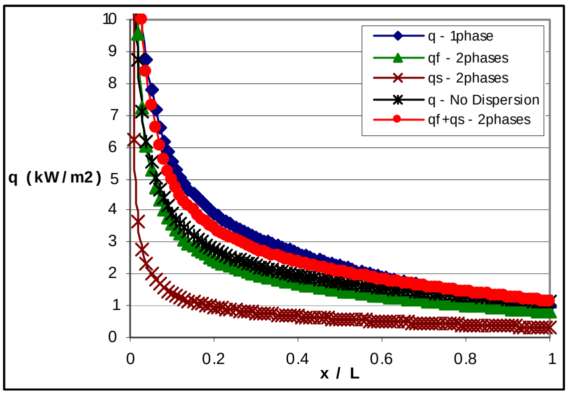


Figure 10. Thermal dispersion effects on heat flux in different models at constant Peclet number. $Pe = 5$

phase model with Koch & Brady's predicted values of thermal dispersion has a good compatibility to two phase model and discrepancies from single phase model with Shahnazari's predicted values. Figure (8) was presented a very good compatibility of Shahnazari correlation and Fried &Combarnous Experimental Data in prediction of temperature distribution.

Therefore, it sounds that accurate prediction of Shahnazari correlation for thermal dispersion in single phase model causes accurate prediction for temperature distribution compared two phase model.

Figure (9) depicts local Nusselt number to dimensionless length of channel.
Values of Nusselt number are greatest when thermal dispersion effects are excluded and also two phase model predicted greater values for

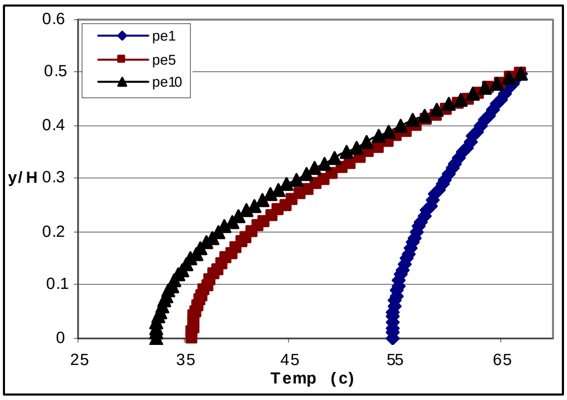


Figure 11. Peclet number effects on temperature distribution which shows temperature profile atdifferent Peclet number and constant dimensionless length. $\xi = 0.3$

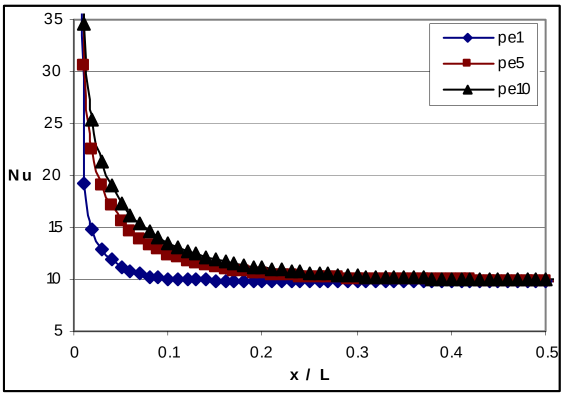


Figure (12). Peclet number effects on local Nusselt number which shows Nusselt number versus dimensionless length of channel at different Peclet number.

Nusselt number than single phase model. It should be mentioned that the definition of the Nusselt number (12) essentially represents the temperature gradient at the boundary and greater values for Nusselt number do not mean greater heat flux, because magnitude of heat flux also is dependent to k_{eff} that should be multiplied by Nusselt number. Then Figure (10) illustrates the heat flux from each plate of channel.

As expects, the least value of heat flux is related to no dispersion assumption, because of the least value of k_{eff}. Considering the prediction of the maximum value of additional diffusion term due to thermal dispersion effect by single phase model, k_{eff} has maximum value in this model. Then greater values of temperature gradient in single phase model were predicted greater values for heat flux than two phase model.

Average Nusselt number and total heat flux in different empirical models are presented in Table 3 and Table 4 for various Peclet numbers, respectively.

4.3. Velocity (Peclet) Effects

As mentioned in section 4.2. variations of Peclet number represent velocity variations in present work. Figure (11) shows temperature distribution on various Peclet numbers across height of channel when $\xi = 0.3$.

As it appears, less velocity magnitude causes higher walls temperature effects on fluid due to

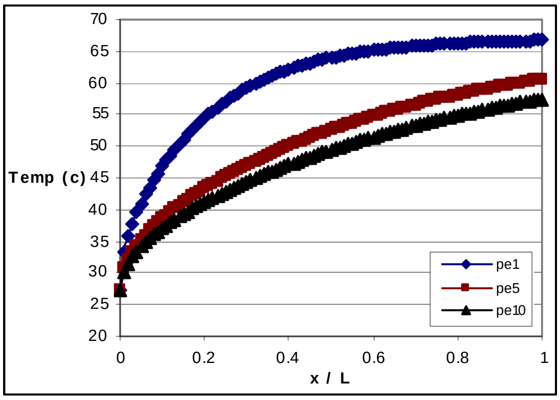


Figure 13. Peclet number effects on cross section mean temperature to dimensionless length of channel which shows cross section mean temperature at different Peclet number.

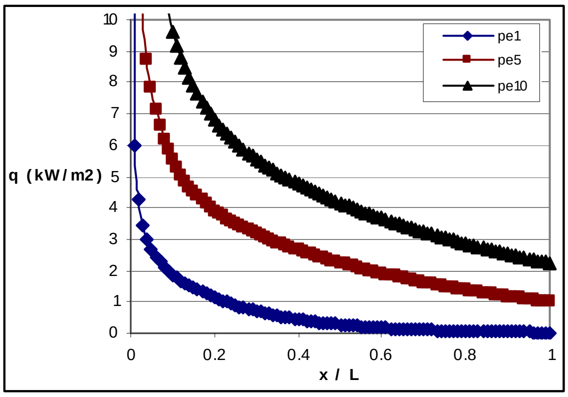


Figure 14. Peclet number effects on heat flux which shows heat transfer rate versus dimensionless length of channel at different Peclet number.

velocity term at right side of equation (3). Figure (12) was showed that cross section mean temperature of fluid at exhaust of channel is equal to walls temperature for $Pe = 1$.

But for $Pe = 5$ and $Pe = 10$ the fluid temperature is less than walls temperature. Figures (13) and (14) were depicted local Nusselt number and heat flux from each plate to non dimensional length of channel, respectively. Heat transfer is greater in higher Peclet numbers due to greater values of temperature gradient in boundaries and also greater values of k_{eff} due to thermal dispersion effects.

5. CONCLUSIONS

In this work, accurate simulation of heat transfer in packed beds has been accomplished. The analysis has been conducted for steady, incompressible forced convective fluid flow. In addition, the simulation was carried out using separate energy equations for the fluid and solid phases for two phase model and an energy equation with LTE assumption for single phase model. Furthermore, the investigation aimed at exploring the influence of a variety of effects such as length, thermal dispersion and velocity on the transport processes in porous media. Comparison of temperature distribution, heat transfer rate and Nusselt number between single and two phase model with different correlation of dispersion was represented. Results show that implementation of single phase model could provide a better prediction especially in low Peclet number range. Accurate prediction of Shahnazari correlation for thermal dispersion in single phase model at low Peclet number range ($1 \le Pe \le 20$) causes accurate prediction for temperature distribution compared with the two phase model. Due to compatibility of single phase model's results with empirical results and no possibility of determining the empirical parameters of two phase model, usage of single phase model relations for prediction of thermal behavior of fluid in porous medium is more reasonable at least in Peclet number range of this investigation.

6. NOMENCLATURE

Symbol	**description**
x, y, z	Coordinates
$\langle \ \rangle$	Volume averaging
Greek symbols	
ξ	Dimensionless length
η	Dimensionless height
ρ	Density (kg/m^3)
ε	Porosity
μ	Dynamic viscosity (kg/ms)
Subscripts	
f	Fluid
s	Solid
m	Fluid and solid
eff	Effective property
d	Dispersion
w	Wall
in	Inlet
C_p	Specific heat at constant pressure (J/kgK)
∇P	Pressure gradient (Pa)
H	Height of the packed bed (m)
h	Half height of the packed bed (m)
k	Thermal conductivity (W/mK)
K_p	Permeability (m^2)
L	Length of the packed bed (m)
T	Temperature $(^{\circ}C)$
u	Velocity component in the x-direction (m/s)
V	Velocity vector (m/s)
t	Time (sec)
d_p	Particle diameter (mm)
U_m	Mixed mean velocity (m/s)
Pr	Prandtl number
Pe	Peclet Number
Nu	Nusselt number

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