Reaktor, Vol.6 No. 2, Desember 2002, Hal.: 48 - 55

THE EFFECT OF REYNOLDS NUMBER AT FLUID FLOW IN POROUS MEDIA

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Abstract

In packed bed catalytic reactor, the fluid flow phenomena are very complicated because of the fluid and solid particles interaction to dissipate the energy. The governing equations need to be developed to the forms of specific models. Flows modeling of fluid flow in porous media with the absence of the convection and viscous terms have been considerably developed such as Darcy, Brinkman, Forchheimer, Ergun, Liu, et al. and Liu and Masliyah models. These equations usually are called shear factor model. Shear factor is determined by the flow regime, porous media characteristics and fluid properties. It is true that these models are limited to conditions whether the models can be applied. Analytical solution for the model types above is available only for simple one-dimensional cases. For two or three-dimensional problem, numerical solution is the only solution. The present work is aimed to develop a two-dimensional numerical modeling of flow in porous media by including the convective and viscous terms. The momentum lost due to flow and porous material interaction is modeled using the available Brinkman-Forchheimer and Liu and Masliyah equations. Numerical method to be used is finite volume method. This method is suitable for the characteristic of fluid flow in porous media which is averaged by a volume base. The effect of the solid and fluid interaction in porous media is the basic principle of the flow model in porous media. The momentum and continuity equations are solved for two-dimensional cylindrical coordinate. The results were validated with the experimental data. The results show a good agreement in their trend between Brinkman-Forchheimer equation with the Stephenson and Stewart (1986) and Liu and Masliyah equation with Kufner and Hoffman (1990) experimental data.

Keyword: *finite volume method, porous media, Reynolds number, shear factor*

Introduction

Catalytic packed bed reactor is the type of reactor that is widely used in many chemical industries. In this reactor, flow maldistribution problem occurs frequently in the operation. Generally, the flow maldistribution is caused by inherent reactor design and operation problems. At present, the reactor is designed mostly using the simplification method of flow in which the complicated flow that may exist is assumed to become simple and known flow characteristics, such as resulting elementary reactor design procedures either perfectly mixed or plug flow reactor design concept. An improved reactor design method should be observed. If the flow field is predicted as realistically as to be, the flow maldistribution can be minimized or avoided in the design step.

The phenomena of flow distribution in packed bed have been formulated through several experiments. The measurement of flow inside packing has been done by McGreavy, *et al.*, (1986) and Stephenson and Stewart (1986). McGreavy, *et. al* using Doppler-laser anemometer while Stephenson and Stewart using a marker tracing method to observe the fluid motion with a video camera in a transparent packed bed. It was found that the local superficial velocity attained its global maximum and minimum at distance near 0.2 d_p and 0.5 d_p from the wall. McGreavy obtained the maximum velocity at 0.3 d_p from the wall.

Mathematical and numerical modelings of fluid flow in porous media have been widely developed. Among of them are models that are developed by Darcy (1856), Brinkman (1949), Forchheimer (1901) and Ergun (1952). However, those models are limited to one-dimensional flow and historically obtained through empirical approach. The original mathematical forms of the models absurd have not yet describe the complete components of momentum transfer. Some author extended directly one-dimensional models above to two and three-dimensional models. Giese, et al. (1998) and Liu and Masliyah (1999) have solved one-dimensional problem by neglecting convection terms and using finite difference method. Two-dimensional numerical investigation was developed by Stanek and Szekeley (1974) and Papageorgiu and Froment (1995). The momentum equations were simplified into two-dimensional mathematical model that correlate the pressure gradient and velocity component. The unknown

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pressure field was handled by transforming the equations into vorticity transfer equation. The solution was obtained numerically using finite difference method. However, their solution is not so much reliable method due to its limitation to two-dimensional laminar problem only. Its necessary to develop mathematical and numerical models to obtain a more realistic solution of fluid flow in porous media. The numerical and computational developments of fluid flow in porous media including the continuity and momentum equations have been established by Buchori, et al (2000) and Supardan, et al (2000).

The purpose of this research is to improve the continuity and momentum equation solution for two-dimensional of fluid flow in porous media that includes the diffusion and convection terms and to investigate the effect of flow regime at fluid flow in porous media. The Brinkman-Forchheimer and Liu and Masliyah equations are adopted to model the effect of fluid and solid interaction giving the momentum loss to the flow field equation.

Characteristic of Porous Media

The characteristic of flow in porous media depend on properties and structure of itself. There are two important parameters to differentiate between the porous and empty media. The ratio between pore volume (fluid volume) and continuum medium volume (solid and fluid volumes) quantifies the space, which can be flown by the fluid. This ratio is recognized as porosity, ε. The other parameter for the fluid flow in porous media is tortuosity, τ. Tortuosity is the ratio between the global passage distance of the flow in a continuum volume (macroscopic distance) and that total passage distance of the flow in pore network straits (microscopic distance) in a continuum volume. From several experiments, it is obtained that a constant value of tortuosity does not depend on pore structure. Haring and Greenkorn (1970) got a value of τ equal 2.25 whereas Fatt (1956a) got 1.

The porosity is a quantitative that describes the fraction of the voids medium. In experiments have been done by researchers such as Roblee, *et al.* (1958), Benenati and Brosilow (1962), Ridgway and Tarbuck (1966), Thadani and Peebles (1966), Pillai (1977), Schuster and Vortmeyer (1980), porosity in packed bed is not uniform. Porosity at reactor wall is higher than bulk. The results show that maximum value of porosity is attained at wall with ε = 1. The porosity will be decreased and will attain constant value at fixed distance from wall. However, this decreased not linier but oscillated along reactor radius until distance 3 – 5 particle diameter.

The researchers made model to illustrate porosity profile along radial direction (Martin, 1978; Cohen and Metzner, 1981; Vortmeyer and Schuster, 1983; Mueller, 1990; Liu and Masliyah, 1999). This research using Liu and Masliyah model (1999) because their model is a better fit to the experimental data for packed beds of uniform spheres and cylinders. Their model is,

$$\varepsilon = \varepsilon_b + (1-\varepsilon_b)Er * \left[(1-0.3p_d)\cos\left(\frac{2\pi}{1+1.6Er^2}\,\frac{D/2-r}{p_d d_s}\right)+0.3p_d\right] \quad (1)$$

The exponential decaying function is given by

$$Er = \exp\left[-1.2p_d\left(\frac{D/2-r}{d_s}\right)^{3/4}\right] \quad (2)$$

For packed bed of uniform spheres, the period of oscillation is, $p_d = 0.94$

Flow Regime in Porous Media

Generally, flow regime is divided into two type, laminar flow regime and turbulent flow regime. Laminar flow regime is assumed to exist below Reynolds number of 2000 ($Re_p<350$) and turbulent flow regime above that number ($Re_p>=350$) (Blick, 1966). Liu, et al (1994) divided laminar flow regime to two region who Darcy flow regime region and Forchheimer flow regime region.

Darcy flow regime region is represented with Darcy's law. Darcy is the first man introduce one-dimensional empirical model for fluid flow in porous media with a simple linier relation between pressure gradient and flow rate that has a constant permeability. Darcy's law is considered valid for flow through porous media with viscous foece dominated inertia force. In application, Darcy's law lacks the flow diffusion effects. Darcy's law can be used to illustrate creeping flow in packed bed for particle Reynold number not more than 10 (Nguyen and Balakotaiah, 1994).

At the Forchheimer flow regime region, Darcy's law cannot be used because as a result of high velocity gas flow, Darcy's law gradually loses its predictive accuracy and ultimately becomes completely void. The empirical equation usually used for determining the pressure gradient for high speed flow through a porous medium is a velocity term squared that Forchheimer had developed (Blick, 1966; Firozabadi and Katz, 1979).

Shear Factor Model

Shear factor model is one of the forms to be introduced in momentum equation for covering the effect of flow and solid interaction in porous media. Shear factor can be determined experimentally or theoretically. Shear factor is determined by the flow regime, porous media characteristics and fluid properties. Ideally, one would like to use heuristic arguments to derive an expression for shear factor in terms of universal constants and easily measurable properties of the porous material and the flowing fluid. Some investigators focused their research on shear factor of momentum equation. Various shear factor models are shown in Table 1.

Table 1. Various shear factor models

Shear Factor Model	Equation
Darcy (1856)	$F = -\frac{\mu}{k}$ (3)
Brinkman-Forchheimer (1949)	$F = \alpha + \beta u \quad \alpha = -\frac{\mu}{k}$ (4)
Ergun (1952)	$F = 150\frac{\mu(1-\varepsilon)^2}{d_p{}^2\varepsilon^3} + 1.75\frac{(1-\varepsilon)\rho u}{d_p\varepsilon^3}$ (5)
Modified Ergun (Mc. Donald, et al., 1979)	$F = \frac{\mu}{r^2}\frac{(1-\varepsilon)^2}{\varepsilon^3 d_p{}^2}\left\{37.5\left[1+\frac{\pi d_p}{6(1-\varepsilon)}\right]^2 + 0.4375\left[1-\frac{\pi^2 d_p}{24}(1-0.5d_p)\right]\frac{\varepsilon^{1/6}Re_m}{1+(1-\varepsilon^{1/2})^{1/2}}\right\}$ (6)
Liu, et al., (1994)	$F = \left(\frac{\mu u(1-\varepsilon)^2}{4R^2 d_p{}^2\varepsilon^{11/3}}\right)\left\{A\left(1+\frac{\pi d_p}{6(1-\varepsilon)}\right)^2 + 0.69\left(1-\frac{\pi^2 d_p}{24}(1-0.5d_p)\right)Re_m\frac{Re_m{}^2}{16^2+Re_m{}^2}\right\}$ (7)
Liu and Masliyah (1999)	$F = \left(0.048\frac{1+0.46s_\Phi(1-\varepsilon^{1/2})^{1/2}}{s_\Phi}\left(\frac{Re^2}{36+Re^2}\right)(Re-3)+0.637+\frac{0.363}{s_\Phi}\right)\frac{18(1-\varepsilon)}{\varepsilon^{29/6}d_p{}^2}$ (8)

Mathematical Modeling of Fluid Flow in Porous Media

The fluid flow distribution in porous media can be represented completely and realistic in continuity and momentum equations. The momentum and continuity equations in porous media should be derived to cover the effect of solid porous media to the fluid flow.

In porous media, usually the number of holes or pores is sufficiently large that a volume average is needed to calculate its pertinent properties. This method is called REV (*Representative Elementary Volume*) (Slattery, 1969; Liu and Masliyah, 1999). The volume average of a point quantity associated with the fluid quantities (velocity, density, concentration or other) is

$$\Phi = \frac{1}{\Delta\upsilon}\int \Phi' d\upsilon \qquad (9)$$

Volume average quantities for fluid flow are usually referred as superficial velocities. Consequently, the superficial velocities are also spatially distributed. Spatial distribution of superficial velocities provides the information of fluid velocity. Other quantities, such as fluid and solid properties are also presented as volume average quantities.

The continuity equation for porous media is written in a control volume average, $\Delta\upsilon$, results

$$\frac{1}{\Delta\upsilon}\int\frac{\partial}{\partial t}(\varepsilon\rho)d\upsilon + \frac{1}{\Delta\upsilon}\int(\rho\vartheta_i)d\upsilon = 0 \qquad (10)$$

That equation can be written,

$$\frac{\partial\rho}{\partial t} + \frac{1}{\varepsilon}(\nabla \bullet \rho\vartheta_i) = 0 \qquad (11)$$

At steady state condition and two-dimensional direction, axial and radial position, Eq. (11) leads to

$$\frac{1}{\varepsilon}\frac{\partial}{\partial z}(\rho u) + \frac{1}{\varepsilon}\frac{1}{r}\frac{\partial}{\partial r}(r\rho v) = 0 \qquad (12)$$

The general momentum equations of fluid flow in porous media in a control volume υ constitute rate of increase of momentum, rate of momentum gain by convection, rate of momentum gain by viscous transfer (diffusion), pressure force, gravitational force or external force, and rate of momentum loss due to fluid and solid interaction in porous media. The momentum equations in porous media are averaged in a control volume as the following

$$\frac{1}{\Delta\upsilon}\int\frac{\partial}{\partial t}(\varepsilon\rho\bar{\vartheta}_i)d\upsilon + \frac{1}{\Delta\upsilon}\int\left(\rho\bar{\vartheta}_i\vartheta_j\right)d\upsilon =$$
$$\frac{1}{\Delta\upsilon}\int\varepsilon\rho f\, d\upsilon + \frac{1}{\Delta\upsilon}\int\varepsilon\left(\tau_{ij}\right)_j d\upsilon - \frac{1}{\Delta\upsilon}\int\varepsilon\nabla P\, d\upsilon \qquad (13)$$

The averaged volume viscous term, the second term in the right hand side of Eq. (13), should be very complex to be derived resulting a well defined term. This term can be contributed also the momentum loss due to the fluid and solid interaction. Intuitively, the viscous term is defined by the diffusion rate of momentum and the new term for momentum loss due to the fluid and solid interaction is added to Eq. (13), specific flow models are resulted. At last, specific flow model is obtained as the following

$$\frac{\partial}{\partial t}\left(\rho\vartheta_i\right)+\frac{1}{\langle\varepsilon\rangle}\frac{\partial}{\partial x_j}\left(\rho\vartheta_i\vartheta_j\right)=\rho g_i + \frac{\partial}{\partial x_j}\left(\mu\frac{\partial\vartheta_i}{\partial x_j}\right)-\frac{\partial P}{\partial x_i}+F\vartheta_i \qquad (14)$$

Based on the volume average above, Liu and Masliyah (1999) derived momentum equations of flow in porous media to give more general equations as follows:

$$\frac{\partial}{\partial t}\frac{\rho\vartheta_i}{\tau}+\nabla\bullet\left(\frac{\rho\vartheta_i\vartheta_j}{\varepsilon\tau}\right)=\nabla\bullet\tau\mu\left[\left(\nabla\vartheta_i\right)+\left(\nabla\vartheta_j\right)^T\right] +\nabla\bullet\left(\tau\varepsilon\underline{\underline{K}}\bullet\nabla\frac{\rho\vartheta_i}{\tau\varepsilon}\right)-\tau\left(\nabla p-\rho g\right)+\tau\mu F\vartheta_i \qquad (15)$$

One cans overview the momentum equations above as mathematical modeling equations for fluid flow in porous media. The second term in the right hand side of Eq. (15) was a postulated closure form as an extra term for interaction flux within the fluid, which can be simplified into a similar form to diffusion. The first term in the right hand side of Eq. (15) is a pure diffusion term. Both of these terms can be combined to give a total diffusion term. The quantity $\underline{\underline{K}}$ was defined as a tensor of dispersion coefficients by Liu and Masliyah (1999),

$$\underline{\underline{K}}=d_p\left|\vartheta_i\right|D_T\begin{vmatrix}\delta_L & 0 & 0\\ 0 & 1 & 0\\ 0 & 0 & 1\end{vmatrix} \qquad (16)$$

Where d_p, D_T and δ_L are particle diameter, transverse dispersion coefficient and normalized longitudinal dispersion factor.

The last term in the right hand side of Eq. (15) represents the total flux from fluid to solid. Moreover, the form used by these authors was a specific proposed model for flux exchange between fluid and solid. The factor F was termed as the shear factor and considered to be a function of its local Reynolds number. The shear factor in a momentum transfer indicates the momentum loss due to a fluid and solid interaction.

For the moment, Eq. (15) is the most comprehensive momentum equation for fluid flow in porous media. This equation will be used to form a more specific mathematical model of fluid flow in porous media which will be evaluated in this work. Further simplification of Eq. (15) can lead to conventional mathematical models of flow in porous media, such as Darcy's, Brinkmam's, and Forchheimer's equations

Numerical Modeling and Computational Method

The momentum equations above can be further developed to the forms of specific models. Shear factor model is one of the forms to be introduced in momentum equation for covering the effect of fluid flow and solid interaction in porous media.

In this work research, the porous media flow is modeled by including the convection and the diffusion terms. Brinkman-Forchheimer and Liu and Masliyah models are adopted to model the momentum loss due to fluid and solid interaction which appears as ar additional term in the momentum equation. A specific mathematical modeling of fluid flows in porous Equation, Eq. (14,15), improves conventional models in term of the present of both convection and diffusion terms. Furthermore, this model can be developed to a numerical model.

A numerical modeling of fluid flow in the porous media is developed from Eq. (14). The momentum, Eq. (14) and continuity, Eq. (12), are presented for steady state, without gravitational force and two-dimensional cylindrical coordinate (axial and radial directions). The flow is incompressible and isothermal.

The continuity equation is written as

$$\frac{1}{\varepsilon}\frac{\partial}{\partial z}\left(\rho u\right)+\frac{1}{\varepsilon}\frac{1}{r}\frac{\partial}{\partial r}\left(\rho v r\right)=0 \qquad (17)$$

and two-dimensional momentum equations in axial and radial directions are written as

- Axial direction:

$$\frac{1}{\varepsilon}\frac{\partial}{\partial z}\left(\rho uu\right)+\frac{1}{\varepsilon}\frac{\partial}{\partial r}\left(\rho vu\right)=\frac{\partial}{\partial z}\left(\mu\frac{\partial u}{\partial z}\right) +\frac{1}{r}\frac{\partial}{\partial r}\left(r\mu\frac{\partial u}{\partial r}\right)-\frac{\partial p}{\partial z}+Fu \qquad (18)$$

- Radial direction:

$$\frac{1}{\varepsilon}\frac{\partial}{\partial z}\left(\rho uv\right)+\frac{1}{\varepsilon}\frac{\partial}{\partial r}\left(\rho vv\right)=\frac{\partial}{\partial z}\left(\mu\frac{\partial v}{\partial z}\right) +\frac{\partial}{\partial r}\left(\frac{\mu}{r}\frac{\partial}{\partial r}\left(rv\right)\right)-\frac{\partial p}{\partial r}+Fv \qquad (19)$$

Equations (18) and (19) can be simplified in flux variables J, source term S and pressure gradient as follows:

$$J_{uz}=\frac{1}{\varepsilon}\rho uu-\left(\mu\frac{\partial u}{\partial z}\right) \qquad (20a)$$

$$J_{ur}=\frac{1}{\varepsilon}\rho vu-\left(\mu\frac{\partial u}{\partial r}\right) \qquad (20b)$$

$$J_{vz}=\frac{1}{\varepsilon}\rho uv-\left(\mu\frac{\partial v}{\partial z}\right) \qquad (21a)$$

$$J_{vr}=\frac{1}{\varepsilon}\rho vv-\left(\mu\frac{\partial v}{\partial r}\right) \qquad (21b)$$

$$S_u=Fu \qquad (22a)$$

$$S_v=Fv \qquad (22b)$$

Furthermore, Eq. (18) becomes

$$\frac{\partial}{\partial z}(J_{uz})+\frac{1}{r}\frac{\partial}{\partial r}(rJ_{ur})=-\frac{\partial P}{\partial z}+S_u \qquad (23)$$

and Eq. (19) becomes

$$\frac{\partial}{\partial z}(J_{vz}) + \frac{1}{r}\frac{\partial}{\partial r}(rJ_{vr}) = -\frac{\partial P}{\partial r} + S_v \qquad (24)$$

Fu and Fv terms in momentum equations are mathematical models for momentum loss due to a fluid and solid interaction in porous media. This term acts as a source term (S_u and S_v) in the momentum equation. Factor *F* is called shear factor.

Equations (17) to (24) are closure forms and numerically solvable. Well known finite volume method by Patankar (1980) is used in to model numerically. The computational domain is defined as the duct geometry of the flow to form a continuum volume. Subsequently, this computational domain is discretized in finite control volumes. Conservation laws must be valid at each control volume and so the whole computational domain. The discretization of momentum and continuity equations forms a set of linear algebraic equation. This set of linear algebraic equations is solved iteratively using a line-by-line method matrix solver. For each line, linear algebraic equations are solved using tridiagonal matrix direct solver, TDMA (Tridiagonal Matrix Algorithm). Unknown pressure field is handled using a standard SIMPLE procedure.

Discretization for momentum equation will have additional term namely source term. Special method used to solve this equation is by accomplishing initial predictive pressure field. Subsequently, this discrete equation is solved to obtain initial value from velocity filed value. The discretized pressure equation has been solved to obtain velocity correction equation and then actual pressure and velocity will be renewable.

Source term is an influential term in those equations solution. The source term must be linearized to avoid unrealistic computation result. The source term, Eq. (22), is linearized in the form of

$$S = S_C + S_P \vartheta_P \qquad (25)$$

The coefficient S_p is kept always less than or equal to zero. To meet with this criterion, this source is linearized following $S = S^* + \left(\frac{dS}{d\vartheta}\right)^* \left(\vartheta_P - \vartheta_P^{\ *}\right)$ (26) The symbol $\vartheta_P^{\ *}$ is used to denote the previous-iteration value of ϑ_P.

Results and Discussion

Comparison between Predicted Velocity Profile with Stephenson and Stewart Experimental Data

The computational parameters were set to be the same as experimental parameters of Stephenson and Stewart (1986). The pipe diameter D, particle diameter d_p, particle Reynold number Re_p, tube length L, bulk porosity ε_b are respectively 75.7 mm, 7.035 mm, 280, 144.9 mm, 0.354. These data in laminar flow regime. Experimental measurement of axial velocity was measured by averaging at distance 0.05 of pipe radius R. The grid size in the computation was set also to the length of 0.05 R. The porosity of the bed follows the profile of Eq. (4).

The results of flow field velocity computation in packed bed catalytic reactor are compared to measured axial velocity profile given by Stephenson and Stewart (1986), which used optical measurement technique. Reactor configuration in this research is shown in Fig. 1. Comparing predicted velocity profile between Brinkman-Forchheimer model and Liu and Masliyah model is presented in Fig 2. The axial velocity component profile is shown in Fig. 3 and the radial is presented by Fig. 4. The vector of these velocity components is depicted in Fig. 5.

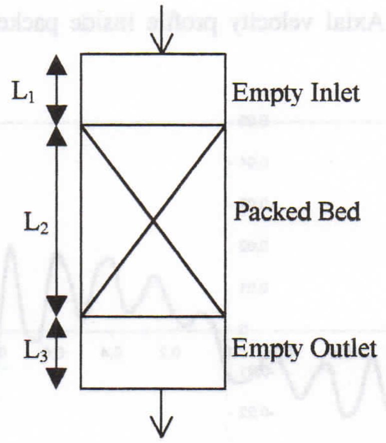

Figure 1. Reactor configuration

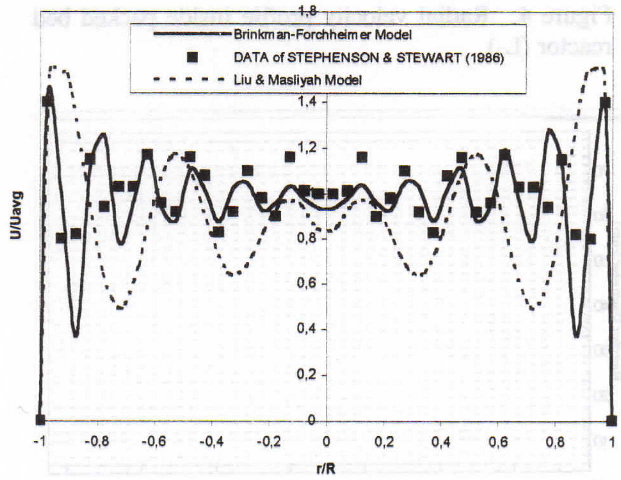

Figure 2. Comparing predicted axial velocity inside packed bed reactor between Brinkman-Forchheimer model and Liu and Masliyah model (L_2)

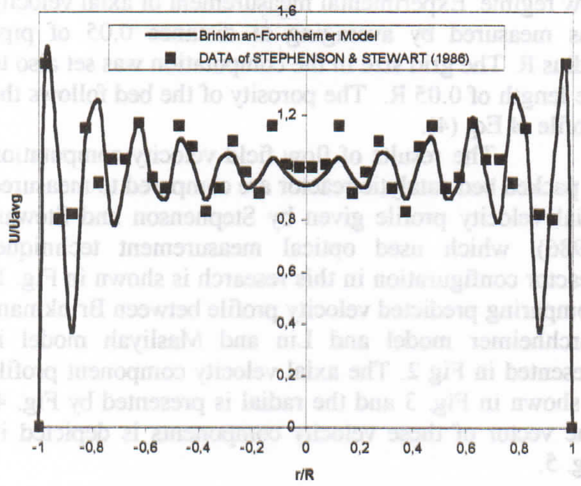

Figure 3. Axial velocity profile inside packed bed reactor (L_2)

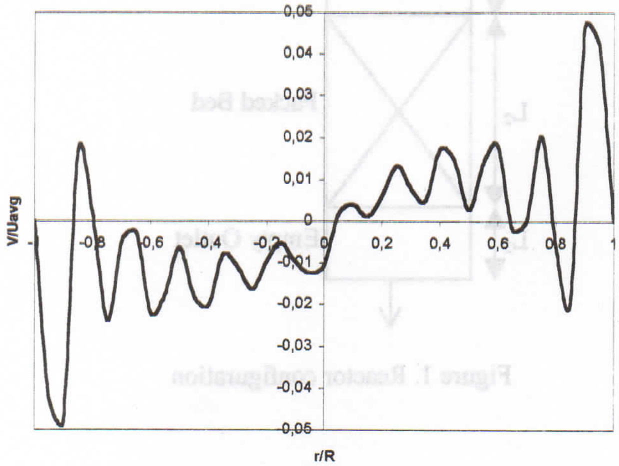

Figure 4. Radial velocity profile inside packed bed reactor (L_2)

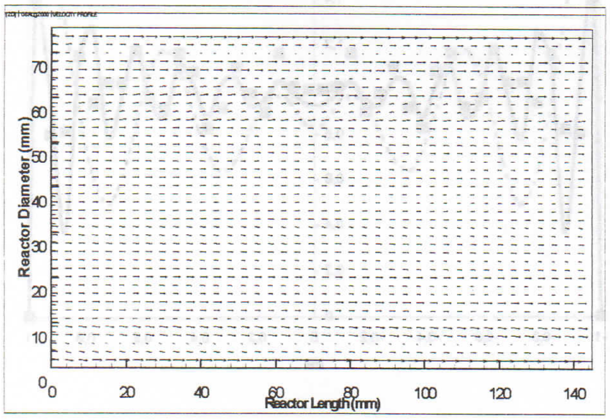

Figure 5. Profile of velocity along the inside packed bed reactor (L_2)

Those figures indicate that velocity profile produce the trend of having global maximum and minimum peaks at distance very close to the wall. The result of predicted velocity profile using Brinkman-Forchheimer model differs with Liu and Masliyah model. The predicted flow fields using Brinkman-Forchheimer model agree closely to measured velocity from Stephenson and Stewart's experiment.

In accordance with Staphenson and Stewart, the first maximum and minimum peak should occur at distance 0.2 d_p and 0.5 d_p from the wall. This value becomes a critical criterion in comparing the predicted results using various models and experimental results (Cheng and Yuan, 1997). These computational results from Brinkman-Forchheimer model give the first maximum peak at distance 0.201 d_p and the first minimum peak at 0.57 d_p. This means that in term of the quantity, these computational results are quite accurate.

A quasi-analytical solution for one dimensional at those experimental parameters above was obtained by Cheng and Yuan (1997). Their results indicate the second maximum peak to occur at 1.0 d_p from the wall. The second peak from the present results occurs at distance 1.07 d_p, that is almost the same value as Cheng and Yuan result above.

Comparison between Predicted Velocity Profile with Kufner and Hofmann Experimental Data

The computational parameters were set to be the same as experimental parameters of Kufner and Hofmann (1990). Brinkman-Forchheimer and Liu and Masliyah models will be introduced in momentum equation. The computation results of fluid flow field inside packed beds will be compared with the experimental data of Kufner and Hofmann.

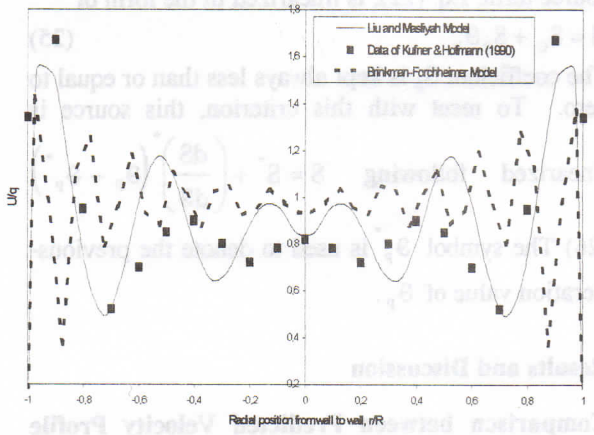

Fig. 6. Axial flow velocity distribution for flow through a packed bed

Fig. 6 shows the axial flow velocity profile for an airflows through the packed bed of spheres with d_p=4,5 mm; D=20 mm, average feed velocity (q)=1,883 m/s, ε_b=0,4167 and Re=2285 (Re_p=465). These data in turbulent flow regime. In accordance with Kufner and

Hofman's experiment, Liu and Masliyah model more agree closely to measured velocity than Brinkman-Forchheimer model.

The radial velocity component profile and interaction between axial and radial flow velocity from Liu and Masliyah model are shown in Fig. 7 and 8. Fig. 8 give fluid flow field in packed beds of spheres. These figures of Liu and Masliyah model indicate that velocity profile produce the trend of having global maximum and minimum peaks at distance very close to the wall. Generally, the numerical solution of all of shear factor models agrees with the experimental data.

In accordance with Kufner and Hofmann's data, the first maximum and minimum peak should occur at distance 0,22d_p and 0,66d_p from the wall. This value becomes a critical criterion in comparing the predicted results using various shear factor models and experimental results. This computation results from Liu and Masliyah model give the first maximum peak at distance 0,17-0.22d_p and the first minimum peak at 0,60-0.62d_p. This means that in term of the quantity, these computational results are quite accurate.

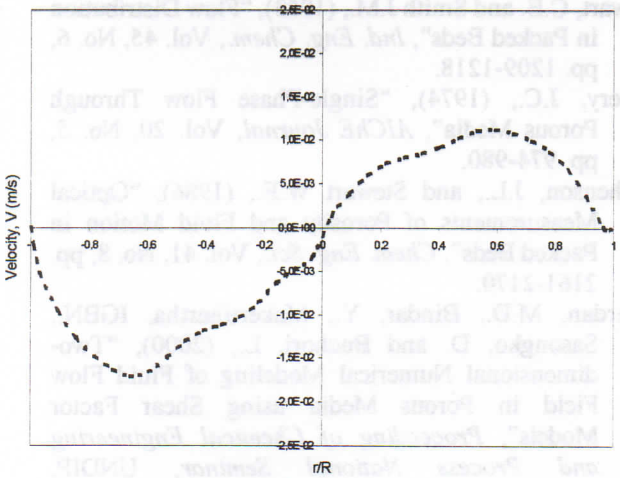

Fig. 7. Radial flow velocity distribution

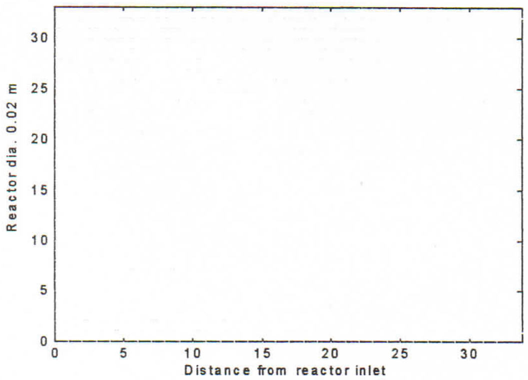

Fig. 8. Vector plot flow velocity distribution

Conclusion

A mathematical model of the fluid flow in porous media as an improvement of the conventional models has been developed. Two-dimensional numerical model to this mathematical model was established. The numerical modeling results agree very closely to the existing literature experimental data at various parameters.

The introduction of the Brinkman-Forchheimer model to the momentum equation is proven to be workable in the prediction of the flow in porous media limited in laminar flow regime. The computational results also indicate a good agreement with Stephenson and Stewart experimental data. Furthermore, these results are also considered to be accurate in which the predicted global velocity maximum and minimum occur at the distance close the experimental data, 0.201 d_p and 0.57 d_p.

The numerical results for the Liu and Masliyah model velocity distribution show a good agreement with the Kufner and Hofman experimental data. The flow field profiles on axial direction agree well with the existing literature experimental data. It is observed that the first maximum peak occurs at distance of 0,17-0.22d_p; the second maximum peak occurs at distance of 1.00-1.02d_p and the first minimum peak occurs at distance of 0.60-0.62d_p. However, this model can used limited in turbulent flow regime only.

From this results can be concluded that the comparison of present numerical modeling results with experimental and quasi-analytical results leads to some important findings. The convection and the diffusion terms in the mathematical modeling can be solved numerically and no need to be excluded. The effect of these terms to the flow field prediction exists especially to complex flow configuration that can be solved one-dimensional approach. It may be argued that these terms can be neglected. This practice may be valid for strong one-dimensional flow in porous media. This numerical model is considered to be accurate. Furthermore, the radial velocity profile can be predicted in which its importance is very clear for real flow, non one-dimensional flow. There are various non-ideal problems of the flow in porous media can be investigated using this numerical model. The established numerical model offers the mean for the investigation of the effects of various parameters.

Acknowledgement – The authors thank to Hibah Tim Project URGE Batch IV for financial support to this research

Nomenclature

p_d = oscillation period
D = reactor diameter, m
d_p = particle diameter, m
α = viscous resistance coefficient
β = inertia resistance coefficient
ε_b = bulk porosity
G = gravitation force, m/s^2
Er = exponential decaying function

k = permeability, m^{-2}
L = packing length, m
S = source term
p = pressure, $kg/m.s^2$
Re_p = particle Reynold number
r = reactor radius, m
u = superficial velocity x-direction, m/s
v = superficial velocity y-direction, m/s
ε = porosity
μ = fluid viscosity, kg/m.s
ρ = fluid density, kg/m^3
ρu_i = mass flux, $kg/m^2.s$
$\rho u_i u_j$ = momentum flux, $kg/m.s^2$
∇ = nabla, operator gradient
J = flux
Subscript: 0 = initial value

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