# Bejan – Convection Heat Transfer

## 12.2 – Darcy Flow model

The darcy flow equation says that:

So:

The last equation is similar to the Hagen-Poiseuille result. This suggests that the Darcy flow is the macroscopic manifestation of a highly viscous flow through the pores of the permeable structure. represents a length-scale of the effective pore diameter.

The last length-scale is used to define the Reynolds number for the flow in porous media. We can discover also that Re\*f = 1. And in the limit O(Re) < 1, we can consider that the flow is laminar.

## 12.3 Energy equation

The basic idea is to divide the fluid flow region from the solid region and to apply the energy conservation equation for both regions.

Hipótese importante na dedução da equação da energia: o sólido e o fluido apresentam mesma temperatura

# Convection in Porous Media

## Chapter 1 - Introduction

“Momentum equation is the porous medium analog of Navier-Stokes equation”

“It should be noted in Darcy’s equation that “P” denotes an intrinsic quantity and that this equation isn’t a balance of forces averaged over a R.E.V”

Falar sobre o método de média sobre o volume (volume averaging technique)

“A distinction is made between an average taken with respect to a volume element of the medium and one taken with respect to a volume element consisting of fluid only. These two average velocities are related to each other by the Dupuit-Forchheimer relation”

“Brinkman did not just add another term to the momentum equation” (Search for Brinkman equation)

“The Brinkman equation may not be used in reservoir simulation because of the typical small values for porosities of the reservoir rock. Page 15, paragraph 2 cite some authors that verify this.”

“ A scale analysis by Lage (1993a) revealed the distinct regimes in which the various terms in the Brinkman-Forchheimer equation were important or not.” This can be used to justify the hypothesis used in the work.

Darcy’s law makes the assumption that all of the stress in the flow field is carried by the porous medium and the fluid is not subjected to any strain because of the viscous stresses. This is not valid in the case of very high permeability media. In this case, the Brinkman model considers the transition from Darcy Flow to a viscous free flow of a clean fluid

# The modeling of viscous dissipation in a saturated porous medium – Nield 2007

“The equality of the viscous dissipation and the power of the drag, when volume averages are taken is a fundamental principle (…) this argument involves a mathematical identity involving derivatives”

The Al-Hadhrami’s equation for viscous dissipation doesn’t follow the power of the drag principle at finite values for the Darcy Number.

An important practical consideration is the a priori estimation of whether or not viscous dissipation in a particular case. It is proved that this involves the comparison of the viscous dissipation term to the thermal diffusion term (in the case of sufficiently small Peclet numbers).

# Advanced Petroleum Reservoir Simulation

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# Handbook of Porous Media

## Chapter 3 - Dispersion in porous media

Dispersion causes fluid (velocity, molecules and temperature) to distribute evenly, which is directly analogous to mass diffusion and viscous stress.

Dispersion is caused due to fluctuations of bulk flow, whereas diffusion is caused due to random molecular motion (Brownian motion in fluids).

Either there is a velocity fluctuation (distribution) or there is flow stream splitting and rejoining along the path of the flow, it will cause dispersion to occur if a gradient exists. Dispersion is convection induced spreading or mixing

Because dispersion is an effective phenomenon occurring on a higher continuum level, where the velocity distributions or fluctuations on the continuum level of fluid are averaged out, averaging plays an important role in dispersion. For porous media, the continuum approach by default involves the averaging above the continuum level of the fluid saturating the medium. Therefore, dispersion is always associated with porous media.

Dispersion can be caused by flow and geometrical obstruction as well. Even if the velocity variation and diffusion were absent at the level of fluid continuum (truly inviscid flow), the porous matrix would cause constant splitting and rejoining of the flow streams and thus create spreading or dispersion.

The continuum hypothesis is valid under most conditions, but we would expect it to break down in the case that the free molecular path is of the same order of the magnitude as the flow channel dimension (the space between the pores) IMPROTANT: There’s a dimensionless number that describes it. Knudsen number tests the validity of fluid continua. Slip-flow can occur if the Knudsen number is of order greater than one.

“If one is willing to consider once again a continuum hypothesis, albeit on a much larger macroscopic scale whereby averaging is taken over a large enough volume that would embrace many pores and surfaces, then a second-order continuum hypothesis will provide a description of the fluid motion in a porous medium in an “average sense”.

An “REV” is a conceptual space unit, which is the minimum volume that can be located anywhere inside the porous medium within measurable characteristics of the porous medium become continuum quantities. An REV can be regarded as a macroscopic unit consisting of a large sum of microstructures.

Analogia entre hipótese do contínuo e volume averaging mostrada no texto é boa

Important observations about the difference of a pressure average and a velocity average.

## Chapter 2 – Dynamic modeling of convective Heat Transfer in Porous Media

Obtain a macroscopic energy conservation equation via a microscopic one. This is done by applying the volumetric average method in the last one.

Closure problem: The equations derived by volumetric averaging are less than the number of unknowns, these are associated with the momentum and thermal dispersions, the thermal tortuosity and the interfacial momentum and heat transfer.

# Principles of heat transfer in porous media – Kaviany

## Chapter 1 – Introduction

The rigorous volumetric average approach on transport phenomena in porous media is relatively new (second half of the last century)

Particle dimension is of order “d”, System dimension is of order “L”. If O(L/d) is of order one, then DNS is used to simulate the flow in the porous media.

When O(L/d) >> 1 and the thermal variation along the particle is negligible in comparison with the variation over “L”, we can assume local thermal equilibrium.

When the solid matrix structure can’t be fully described by the prescription of solid phase distribution over a distance of “d”, than a representative elementary volume with a dimension larger than “d” is needed. Here, the hypothesis of negligible temperature variation over the linear dimension of the REV is also assumed.

A forth length scale is also used in porous media, it’s called the Brinkman screening distance (analogous to the boundary layer-thickness), it’s smaller than “d” and is represented by the square root of the permeability .

Table 1.3 presents the scales of the quantities described above.

In general, in the presence of heat generation in the solid or fluid phases, the requirement for the local thermal equilibrium assumption is not satisfied.

## Chapter 2 – Fluid Mechanics

Bulk properties: properties assigned to the matrix/fluid system

Darcy’s experiment: the internal surface area (interstitial area) was many orders of magnitude larger than the area of the confining surfaces, so the bulk shear stress resistance was dominant in this flow. Darcy encountered that this bulk flow resistance can be characterized by the ratio between the permeability of the solid matrix and the viscosity of the fluid. The Darcy model isn’t closely followed for liquid flows at high velocities and for gas flows, even at low velocities.

For anisotropic media, the velocity vector and pressure gradient are not parallel, and a linear transformation via the permeability tensor is required.

Porosity is the volume fraction occupied by voids. The volume fraction of the interconnected pores is called the effective porosity. In nonconsolidated porous media, the effective porosity and porosity are equal. In some consolidated media, the difference between the two can be substantial. For rigid matrix, the porosity doesn’t change in the presence of a pressure gradient. In deformable media, it can change.

Voids are nonuniform in their size and in their distribution throughout the matrix.

The representative elementary volume is the smallest differential volume that results in statistically meaningful local average properties such as porosity, saturation and permeability. A graph that represents the local average versus a length scale could be showed. The length scale of a REV depends on the number of particles necessary to describe some portion of the porous media, if it has a lot of nonuniformities, than it’s necessary to use many particles to describe it.

As the filter velocity is increased, deviations from the Darcy law are observed. Based on the capillary models (the porous media is treated like a bunch of capillary tubes), these deviations are due to inertial (convective transport) contribution to the momentum balance.

It is recommended to write the Darcy-Forchheimer equation in terms of a single coordinate, i.e. not in the vector form. The author says that in the two-dimensional case, the Egun coefficient should be corrected.

The local volume-averaging technique, in principle, gives us the ability to relate the pore-level hydrodynamics to the macroscopic flow behavior

Use the material of the Handbook of Porous media to illustrate the results for the theorem.

## Chapter 3 – Conduction Heat Transfer

Heat conduction through fully saturated matrices as with heat conduction through any heterogeneous media depends on the structure of the matrix and the thermal conductivity of each phase. The structure of the porous media plays an important role in determining this process.

For the analysis of the macroscopic flow, local volume-averaged properties are used such as the effective thermal conductivity.

Some averaged properties are obtained through simple volume averaging, however, the effective thermal conductivity is expected to depend on the following:

* Thermal conductivity of each phase (liquid, gas or solid)
* The structure of the solid matrix
* The conductivity between nonconsolidated particles
* For gases, the thermal conductivity to be used is a function of Knudsen number

The application of the point energy equation to a point in the REV of the matrix and the integration over this volume gives rise to a temperature difference between a point in the fluid and in the solid. Similarly, across the REV, we have a maximum temperature difference. However, we assume that these temperature differences are much smaller than those occurring over the system dimension. Thus, it’s imposed the assumption of thermal equilibrium.

Important!!!! However the temperature differences at point and pore scale are negligible, their gradient are not and it can be deduced relations about the maximum time and length scales in order to this assumption be verified. The cases which the above relation is false are fast transients and when heat generation is not zero.

An assumption is made about the structure of the porous media by the Whitaker’s derivation, it has to be periodic

Talk about statistical treatments

## Chapter 4 – Convection Heat Transfer

Experiments have shown that the mere inclusion of darcean velocity times the average temperature gradient doesn’t account for all the hydrodynamic effect on the energy equation. The pore-level hydrodynamics also influences in the temperature field.

Inclusion of the effect of the pore-level velocity variation (non-uniformity) on the temperature distribution has to be taken into account in the thermal energy equation. This term is often modeled like the diffusion one.

The Dispersion in a tube paragraph fives a good idea about the dispersion concept.

Talk about the analogy between momentum dispersion tensor and Reynolds stress tensor.

Prove a reduced version of the average method theorem in appendix (Terencio’s notes).

Dispersion in porous media is different than that reviewed for the hydrodynamically fully-developed flow.

# Transport Phenomena in Multiphase Systems

## Chapter 3 – Generalized Governing Equations: Local Instance Formulations

Page 193 and 194 talks about the derivation of the energy equation. Each term on this equation is named and its contribution to the internal energy of the system is explained.