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NON-ISOTHERMAL FLOW MODELS WITH MASS DIFFUSION FOR A STATIONARY POROUS MEDIA BY EMPLOYING REPRESENTATIVE ELEMENTARY VOLUME

Bayram ALAKUŞ

Dumlupinar University, Department of Mechanical Engineering, Kütahya, alakusb@dpu.edu.tr

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ABSTRACT

Nowadays, in many industrial applications, porous materials play an important role in the design and development processes. For instance, in alloy solidification, between the solid and the fluid phases there is a region called mushy zone which contains both fluid and solid. Its structure is very complicated but can be handled as an anisotropic porous medium with directional variation in permeability. Other industrial applications such as flow over heat exchanger matrices, flow through turbo-machines, primary and secondary oil recoveries etc. can very well be approximated as porous media. Finally, it seems appropriate to mention that cooling of electronic micro systems is becoming more and more important as much of our modern day equipment contains more and more electronic circuits. In order to increase their performance and life, it is essential to have proper cooling arrangement. A reliable flow and heat transfer prediction in these arrangements is always difficult due to the complexity of flow structure. However, a porous medium approximation to such problems can be efficient. The generalized procedure described in this study is a good approximation for these structures.

Keywords: *Non-isothermal Porous media flow, Mathematical modelling; Representative Elementary Volume (REV).*

İZOTERMAL OLMAYAN VE KÜTLESEL DİFÜZYONUN MEVCUT OLDUĞU DURGUN BİR GÖZENEKLİ ORTAM İÇERİSİNDEKİ AKIŞKAN AKIŞININ TEMSİLİ BİR TEMEL HACİM KULLANILARAK MODELLENMESİ

ÖZET

Günümüz teknolojisinde, birçok endüstriyel uygulamada gözenekli materyaller dizayn ve geliştirmede önemli bir rol oynar. Örneğin, katılaşma problemindeki katılaşma esnasında oluşan katı ve akışkan bölgeleri bu ortama bir örnektir. Bu problem çok zor bir problem olmakla birlikte, gözenekli ortam akış modeli kullanılarak çözülebilir. Birkaç diğer uygulama örnekleri ise ısı değiştirgeçleri, termik-turbu makinalardaki akışlar, petrol çıkarılması ve proseslere tabi tutulması sayılabilir. Son bir örnek olarak, performans ve ömürlerinin arttırılması için, elektronik mikro sistemlerin soğutulması bu akış modeli kullanılarak yapılabilir. Bu çalışmada tanımlanan prosedüre ve model, bu türlü problemlerin çözümünde iyi ve güvenilir sonuçlar verir.

Anahtar Kelimeler: *İzotermal olmayan gözenekli ortam akışı, matematiksel modelleme, REV.*

1. Introduction

Scientific approach to the study of porous media flow began during the second half of the last century even though a solution to this type of problem was needed long before. In fact many of the materials employed in ancient time were basically porous in nature. As technology became more “sophisticated”, a practical solution to the problem became necessary. The first attempt was made in 1856 by Henry Darcy [1], who presented the results of his experiments on water flow through sand filters. He summarized his findings in the form of a mathematical relation, in which the flow rate through a porous filter is inversely proportional to the length of filter and proportional to the constant cross-sectional area times the difference in piezometric head across the medium. The proportionality coefficient used by Darcy is called “permeability” of the medium.

Darcy’s equation was the only one available to describe fluid flow through porous media for almost half of a century. Due to the lack of applications and facilities, very little was done to understand flow through porous media until the beginning of the last century. Later, the discovery and development of new technologies greatly influenced the study of flow and heat transfer through porous media. Nuclear energy, geothermal energy, as well as petroleum and water reservoir exploitation are just a few of the porous medium applications The demands of new technologies were met quickly, but as it often happens, most of the work was done to solve specific problems, and the results were therefore difficult to be synthesized in a general theory. Different extensions of Darcy’s law were introduced and some mathematical tools were developed in order to obtain a more rigorous formulation of the porous medium equations.

2. Mathematical flow models

A porous medium is usually considered to be composed of a solid matrix and voids. The so called saturated porous media, with which this work is concerned, present voids that are interconnected and completely filled with one or more fluids. Unsaturated porous media are in general partially filled with liquid, and since not all the voids are connected, the fluid can not flow everywhere in the pores.

In natural porous media, pore distribution is generally irregular, and so are quantities such as velocity, temperature, etc. However, in most practical engineering problems, the interest is focused on the spatial average values of these quantities, which from a macroscopic point of view, vary uniformly. Therefore, where not specified, we will be considering al l the variables in the sense of their mean spatial values over the so called representative elementary volume (REV). The concept of REV is fundamental in the volume averaging technique introduced by Bear [2] to study the porous media, which is still the basis of a large part of the work on porous media. The REV has to be so that the values of the quantities of interest are independent of the size of the volume itself, and its length scale should be larger than the pore scale, but smaller than the dimensions of the macroscopic domain [3], [14], [15].
In order to macroscopically describe the flow through a saturated porous medium, it is necessary to introduce variables that take into account the space left by the solid matrix to the fluid. One of them is the porosity, defined as the fraction of the total volume of the porous medium “occupied” by the voids.

When averaging over the REV (Fig. 1), it is possible to consider the whole volume of the porous medium, or the volume of the holes, which is entirely left to the fluid. Therefore it is possible to define two averages, the so called intrinsic average velocity *U*, obtained averaging over the pore volume in the REV, and the seepage or Darcy velocity *u*, averaged over the whole REV. The two velocities are not independent, but related by the Depuit-Forchheimer relation: $u=\varepsilon U$ [3].
A first use of these quantities may be represented by the derivation of the continuity equation, which can be shown to be described by the:

$$\varepsilon \frac{\partial \rho_f}{\partial t} + \nabla .\left(\rho_f u\right) = 0 \tag{1}$$

where ρ_f is the fluid density. The above equation balances the rate of increase of the fluid within the REV and the net mass flux through the surface contour of the REV, assuming that the porosity is constant. The derivation of the momentum conservation equation is not obvious, and is still a matter of discussion [11], [16], [17].

2.1 Darcy's model

During the last century researchers have derived generalized forms of the Darcy equation using either deterministic or statistical models [3], [18]. The well known original form of the equation has been re-written as:

$$u = -\frac{K}{\mu}\nabla p \tag{2}$$

for an isotropic medium, where K is the so-called intrinsic permeability, and p is the pressure gradient. Although Darcy's law can describe the flow through many natural occurring porous media, it is not valid for all types of situations. In fact, defined for a porous medium the Reynolds number based on the permeability of the porous medium as $\mathrm{Re}_K = \rho\sqrt{K}\frac{u}{\mu}$ has been proved that Darcy's equation is not adequate for flows where is Re grater than unity[5]. Even before, many researchers had already noticed the inappropriateness of Darcy's law and had started to propose new models.

2.2 Forchheimer extension of Darcy's Law

Quite a larger agreement can be found in the scientific community about the need to modify the Darcy equation to take into account the effect of non-linear terms in the momentum equation, as supported by experimental evidence [4]. The physical explanation for non-linear terms is still not completely understood. Some researchers have explained that even if the average of microscopic inertial terms are negligible in typical practical circumstances, the averaging of microscopic drag forces on the fluid due to the solid matrix leads to a macroscopic non linear theory for flow. Independently from their physical explanation, non-linear terms are usually introduced through the so called Forchheimer's equation:

$$\nabla p = -\frac{\mu}{K}u - \rho_f \frac{c_F \varepsilon}{\sqrt{K}} u \left|\bar{u}\right| \tag{3}$$

where the c_F is a non-dimensional form-drag constant. In the last ten years different expressions have been proposed for the Forchheimer's equation. Another form of the equation was derived by Irmay [3] and in this particular form:

$$\frac{\nabla p}{L} = 150\frac{(1-\varepsilon)^2}{\varepsilon^3}\frac{\mu\left|\bar{u}\right|}{d_s^2} + 1.75\frac{(1-\varepsilon)}{\varepsilon^3}\frac{\rho_f u\left|\bar{u}\right|}{d_s} \tag{4}$$

is known as Ergun's equation [19]. The linear term in equation (4) is equal to that in equation (3) if we assume:

$K = \frac{d_s^2\varepsilon^3}{150(1-\varepsilon)^2}$ which is the so called Carman-Kozeny equation, and where d_s is the average size of the solid particles [4], [19].

2.3 Brinkman extension of Darcy's Law

In 1947 Brinkman [6,7] presented a new model, derived for an assembly of spheres, in which he obtained a relationship between the permeability and the porosity. Furthermore, Brinkman presented an equation that is often referred to as "Brinkman's extension of Darcy's law" [3], or Brinkman's equation:

$$\nabla p = -\frac{\mu}{K}u + \frac{\mu_\varepsilon}{\varepsilon}\nabla^2 u \tag{5}$$

in which the effective viscosity μ_ε was introduced for the first time, along with the Laplacian of the velocity, to take into account the viscous effect that becomes greater as the porosity and the permeability of the medium become larger. The effective viscosity was initially assumed by Brinkman to b e equal to the fluid viscosity. The first drawback usually pointed out about this equation is related to the procedure used by Brinkman to derive it. In fact this makes it valid only for media with very large porosity (greater than 0.6). The second problem associated with the use of equation (2.6) is related to the value of the effective viscosity, which is known to be dependent on the geometry of the medium, but is not experimentally well documented [4], and is still subject to investigation [20,21]. Even though the validity of the Brinkman equation has not been proved, it has still been used for the solution of several problems, such as, for instance, the interaction between a viscous fluid and a saturated porous medium, and it has given accurate results [5,9,13,12,22].

2.3 The generalized model

Most naturally occurring porous media have porosity less than 0.6 and generally Darcy's law can be used to solve flow in these media. However human influence in the last century, has created many things which are not "natural" any more, but still need to be studied. A similar example is represented by the most common refrigerant fluids, that are not found in nature, but should still be investigated. At the same time some very important porous materials, such as for instance polyurethane foam, fibre glass or some isolating materials, have a great number of practical applications, and therefore cannot be ignored. Since porous media can have porosity from 0.02 up to 0.99 [3,4], it should be possible to study all different situations using one single generalized model. In the present work incompressible viscous flows through porous media have been mathematically described using a generalized model, in which all the models described above are taken into account. Furthermore advective and temporal terms are included in the momentum equation in order to make the model more general. Even though some authors have argued about the inappropriateness of these terms [11,16], it is clear that they do have some effect during the development of boundary layer and transient solutions. Also regarding problems with porous medium and single phase fluid, these terms produce appropriate effects naturally [4,5].

The general form of the momentum equation for a medium of variable porosity saturated by an incompressible fluid can be derived by averaging the Navier-Stokes equations over the REV, using the well known procedure introduced by Whitaker [15,23] . The generalized momentum equation for a fluid saturated porous medium can be written as:

$$\rho_f\left[\frac{\partial u}{\partial t} + \nabla\left(\frac{u.u}{\varepsilon}\right)\right] = -\nabla\varepsilon p + \mu_\varepsilon\nabla^2 u - \left[\frac{\mu\varepsilon}{K}u - \rho_f\frac{c_F\varepsilon}{\sqrt{K}}u\left|\bar{u}\right|\right] + B \tag{6}$$

where all quantities are represented by their average values in the REV: u is the seepage (Darcy) velocity vector, p is the fluid pressure, ρ_f is the fluid density, c_F is the Forchheimer's coefficient, B represents the body forces acting on the system and μ_ε is the effective (or e Brinkman) viscosity that will be discussed extensively later. The hydrodynamic dispersion has been neglected in the above equation, for the sake of simplicity. Egrun's correlation (4), initially introduced for packed beds, is used to represent the total drag force of the solid matrix on the fluid. In this case the permeability K and the coefficient c can respectively be written as:

$$K = \frac{d_s^2\varepsilon^3}{b(1-\varepsilon)^2} \quad \text{and} \quad c_F = \frac{b}{\sqrt{a}\,\varepsilon^{3/2}} \tag{7}$$

With a and b being Egrun's constants ($a = 1.75, b = 150$), and d the particle size of the beds. The generalized momentum equation has been derived theoretically [10] and it has been extensively and successfully used in literature [16,8,9,10, 12,22]. There is no evidence that any of the terms of the momentum equation should be omitted. Furthermore, as will be shown later in this work, this model has the great advantage of allowing the solution of interface problems between a porous medium and a free fluid, considering a single domain. This approach is particularly convenient in the study of many applications, such as for instance alloy solidification [6, 24,25].

3. Heat and Mass Transfer models

3.1 Heat Transfer

This work is mainly concerned with the transport of heat, in addition to fluid flow, through porous media. There is a large number of applications, particularly in mechanical engineering, where the thermal aspect is fundamental: solidification of binary mixtures, dehumidification, insulation, and heat pipes are just a few examples [4]. In all these cases the temperature distribution inside the medium can be recovered from the solution of energy conservation equation, coupled to the momentum conservation and continuity equations.

The macroscopic energy equation for a saturated porous medium, derived using the volume averaging procedure, assuming local thermal equilibrium in the REV and neglecting thermal dispersion, can be written [10]:

$$\left[\varepsilon\left(\rho c_p\right)_f + (1-\varepsilon)\left(\rho c_p\right)_s\right]\frac{\partial T}{\partial t} + \left(\rho c_p\right)_f \nabla.(uT) = \nabla.\left(k_\eta \nabla T\right) \tag{8}$$

where T is the temperature in the REV, and the volumetric heat capacity (c_p) is considered for the fluid and the solid (subscripts f and s respectively). The effective conductivity k_ε of saturated porous media is calculated from conductive heat transfer through the medium (i.e. for the fluid in static conditions) [4].

3.2 Mass Transfer

Applications such as under-ground pollutant transport, nuclear waste disposal etc., involve a third component transport into a fluid saturated porous medium. In such situations, in addition to mass, momentum and energy, also a species conservation equation needs to be solved. The transport equation for the third component is similar to the convective heat transfer equation. The study of the component in the mixture can be performed in terms of its concentration in the medium or solutal mass fraction: $C = m/V$ .In particular the macroscopic equation for the calculation of concentration can be derived from the volume-averaging method, under the assumption of local chemical equilibrium in the REV, and represents the species conservation equation:

$$\varepsilon \frac{\partial C}{\partial t} + \nabla.(uC) = \nabla.\left(D_\eta \nabla C\right) \tag{10}$$

where D_ε is the effective mass diffusivity coefficient of the component. We should mention here that for both heat and mass transfer the case of "production" of energy or mass has not been considered in this work. It is well known that in these cases another term, the volume-averaged production rate, would appear in the energy equation or the mass equation, without introducing any particular difficulty to the problem.

3.3 Non-dimensionalization

It is very common, especially for complex fluid-dynamic problems which depend on several variables, to non-dimensionalize the governing equations before their solution. The non-dimensionalization process involves the choice of different normalizing factors and scales. As pointed out by Ostrach [26] the choice of these parameters is rather arbitrary, but the physical implication of this choice and its effects on the non-dimensional equations is very often underestimated. The present case is very peculiar since we are studying phenomena that have completely different scales: the macroscopic and microscopic fluid flow.

To give an example of this issue, we may think of natural convection in enclosures filled with porous media. This problem is governed by several parameters; scale analysis can considerably reduce their number. According to Bejan [27] the heat and fluid flow in such systems depend on two parameters: the geometric aspect ratio, H/L and the Rayleigh number based on the height of the cavity. Unfortunately, there is no homogeneous normalization procedure for this type of problem and therefore many authors propose the use of Rayleigh number based on the width of the cavity. The following scales and parameters have been employed to obtain the non-dimensional equations presented in the next section, which describe natural convection heat and mass transfer in a porous medium and are given as:

$$x^* = \frac{x}{L}, \qquad u^* = \frac{u}{\alpha_f / L}, \qquad p^* = \frac{p}{\rho\alpha_f^2 / L^2}, \qquad t^* = \frac{t}{L^2 / \alpha_f^2},$$

$$T^* = \frac{T - T_\varepsilon}{T_h - T_\varepsilon}, \qquad C^* = \frac{C - C_c}{C_h - C_c}, \qquad R_k = \frac{k_\varepsilon}{k_f}, \qquad R_\upsilon = \frac{\mu_\varepsilon}{\mu_f},$$

$$R_D = \frac{D_\varepsilon}{D_f}, \qquad R_\beta = \frac{\beta_C (C_h - C_c)}{\beta_T (T_h - T_\varepsilon)_\varepsilon}, \qquad R_C = \frac{(1-\varepsilon)(\rho c)_s + \varepsilon(\rho c_p)_f}{(\rho c_p)_f} \tag{11}$$

$$\Pr = \frac{\mu_f}{\rho_f \alpha_f}, \qquad Ra = \frac{g\beta_T (T_h - T_\varepsilon) L^3}{\upsilon\alpha_f}, \quad Da = \frac{K}{L^2}, \quad Le = \frac{D_f}{\upsilon_f}$$

with α_f thermal diffusivity, β_T and β_C coefficient of thermal and solutal expansion respectively, μ_f and υ_f dynamic and kinematic viscosity of the fluid respectively; x is the position vector and **g** represents the magnitude of the gravitational vector, T_h, T_c, C_h and C_c respectively are the hot and cold wall temperatures and concentrations while L is the characteristic length of the problem considered. In the above quantities, an asterisk is used for the non-dimensional variables, that will be used from now on, but for the sake of simplicity the asterisk will be dropped. This should not cause any misunderstanding, since it will always be specified when the equations are dimensional. Furthermore R_k is the ratio between the effective thermal conductivity of the porous medium and the fluid thermal conductivity, R_ε is the ratio between the effective (or Brinkman) viscosity and the fluid viscosity, R_D is the ration between the effective and the fluid mass diffusivity coefficient of the third component, R_β is the buoyancy ratio, and R_C is the non-dimensional overall heat capacity per unit volume. The parameters introduced are the Rayleigh number *Ra*, the Prandtl number *Pr*, the Lewis number *Le*, and the Darcy number, *Da*. For forced convection problems, where the buoyancy forces are negligible compared to the external (with respect to the domain under study) forces responsible for the fluid motion, another more adequate non-dimensional parameter is introduced, the Reynolds number as $\mathrm{Re} = \frac{\rho_f u L}{\mu_f}$. In this case the momentum equation is slightly different, since it does not present the buoyancy terms, and therefore the momentum equation is not strongly coupled to the energy equation.

4. The dimensionless mathematical model

The study of fluid flow, heat and mass transfer through porous media is based on the conservation of the various quantities, such as mass, momentum, energy and species. The related partial differential equations have been presented in their dimensional form. On the basis of what was written in the previous section, the equations can be written in non-dimensional form, with respect to fluid properties. For a piecewise homogeneous medium, with constant, uniform porosity and constant properties, except the fluid density, the system of non-dimensional governing equations is
mass conservation:

$$\nabla . u = 0 \tag{12}$$

momentum conservation:

$$\frac{1}{\varepsilon}\frac{\partial u}{\partial t} = -\frac{1}{\varepsilon^2} u . \nabla u - \nabla p + R_\upsilon \frac{\Pr}{\varepsilon}\nabla^2 u - Fu + Ra \Pr\left(T + R_\beta C\right) g \tag{13}$$

energy conservation:

$$R_c \frac{\partial T}{\partial t} = -\nabla .\left(uT\right) + \nabla .\left(R_k \nabla T\right) \tag{14}$$

species conservation:

$$\varepsilon \frac{\partial C}{\partial t} + \nabla .\left(uC\right) = \nabla .\left(\frac{R_D}{Le}\nabla C\right) \tag{15}$$

defined in the domain of interest. In the momentum equation **g** is the unit vector along the gravity direction, and

$F = \left(\frac{\Pr}{Da} + \frac{c_F}{\sqrt{Da}}\left|\bar{u}\right|\right)$ is the porous term that incorporates the Darcy term, proportional to the ratio Pr/Da, and the Forchheimer term, proportional to $c_F \left|\bar{u}\right| / \sqrt{Da}$. Furthermore, as mentioned, all the properties are assumed to be constant except density of the fluid. The density variation of the binary mixture is incorporated by invoking the Oberbeck-Boussinesq approximation, $\rho = \rho_0 \left[1 - \beta_T\left(T - T_0\right) - \beta_C\left(C - C_0\right)\right]$ with ρ_0 density of the mixture for the reference conditions T_0 and C_0 . As mentioned, dispersion in the porous medium has not been included and the Soret (mass flux due to temperature gradients) and Dufour (heat flux produced by concentration gradients) effects that have been considered negligible, for the sake of simplicity.

It seems appropriate to emphasize here that the presented model tends to the classical Navier-Stokes equations as the porosity of the medium goes to one and its permeability tends to infinity. Therefore the model is particularly suitable for the solution of interface problems.

5. Conclusion

In the present research, following a brief introduction on the available models for the study of fluid flow through porous media, the generalized model has been introduced. This model is presented in the form valid for a nondeforming porous medium fully saturated by an incompressible Newtonian fluid. The different contributions to the momentum equation, ob served by scientists over the years, are taken into account in this model, which can therefore be used for many types of media. The system of equations of the generalized model that describes the heat and mass transfer through the porous medium is presented in its non-dimensional form. Also the non-dimensional quantities and parameters introduced have been presented.

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FIGURES

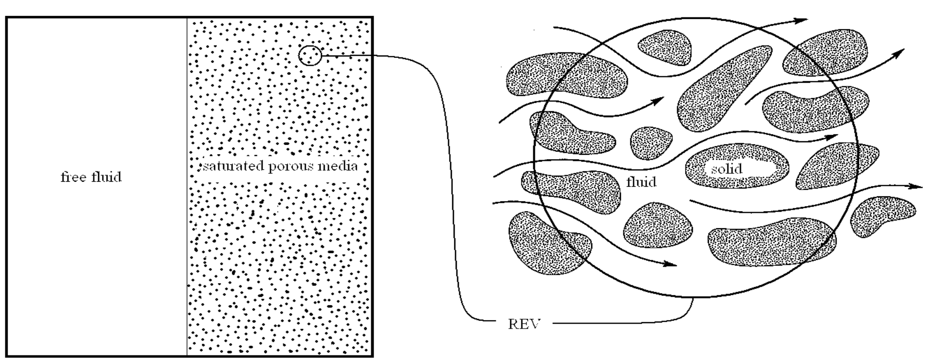

Figure 1: Representative Elementary Volume (REV)