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A STUDY UPON FLOW AND HEAT TRANSFER IN POROUS MEDIA

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A Study upon Flow and Heat Transfer in Porous Media

Mr. Bagi

Research Scholar, Pacific University, Rajasthan

***Abstract* – Heat transfer to a fluid passing through a channel filled with porous materials is the subject of this investigation. It includes the derivation of the temperature solutions in channels having different cross sectional geometries. Primarily, consideration is given to a modified Graetz problem in parallel plate channels and circular tubes. This presentation includes numerical features of the exact series solution for these two ducts using the Brinkman's model. The results are compared to results from another numerical study based on the method of weighted residuals. Moreover, as a test case, the method of weighted residuals provided flow and heat transfer in elliptical passages. The results include the computation of heat transfer to fluid flowing through elliptical passages with different aspect ratios.**

Heat transfer through porous media in static saturated superfluid helium is investigated for porous media with different thickness, porosity and pore size. For large pore diameter, data are analyzed with the tortuosity concept in the pure Gorter-Mellink regime. It is shown that the tortuosity is constant over the temperature range investigated.

For smaller pore diameter, the analysis reveals that the permeability is temperature dependent in the Landau regime. In the intermediate regime, a model, including Landau and Gorter-Mellink regime, predicts a constant tortuosity within 10% but falls short predicting correctly the experimental data over the entire range of temperature.

The study of heat transfer and fluid flow through porous media has applications in a variety of engineering fields such as packed beds, perforated plates, tube banks, matrix heat exchangers, regenerators, electronic components etc.

The heat transfer coefficients of compact heat exchangers are estimated using transient testing methods. In this paper, numerical modeling of single blow transient testing method has been used on a porous body using FLUENTTM and then compared with experimental results. The flow friction characteristics were determined experimentally.

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INTRODUCTION

Heat transfer phenomena play a vital role in many problems which deals with transport of flow through a porous medium. One of the main applications of study the heat transport equations exist in the manufacturing process of polymer composites such as liquid composite molding. In such technologies, the composites are created by impregnation of a preform with resin injected into the mold's inlet. Some thermoset resins may undergo the cross-linking polymerization, called curing reaction, during and after the mold-filling stage. Thus, the heat transfer and exothermal polymerization reaction of resin may not be neglected in the mold-filling modeling of LCM. This shows the importance of heat transfer equations in the non-isothermal flow in porous media.

Generally, the energy balance equations can be derived using two different approaches: (1) two-phase or thermal non-equilibrium model and (2) local thermal equilibrium model. There are two different energy balance equations for two phases (such as resin and fiber in liquid composite molding process) separately in the two-phase model, and the heat transfer between these two equations occur via the heat transfer coefficient. In the thermal equilibrium model, we assume that the phases (such as resin and fiber) reach local thermodynamic equilibrium. Therefore, only one energy equation is needed as the thermal governing equation,. Firstly, we consider the heat transfer governing equation for the simple situation of isotropic porous media. Assume that radioactive effects, viscous dissipation, and the work done by pressure are negligible. We do further simplification by assuming the thermal local equilibrium that $T_s = T_f = T$ where T_s and T_f are the solid and fluid phase temperature, respectively. A further assumption is that there is a parallel conduction heat transfer taking place in solid and fluid phases.[1,2]

The multiphase flow in porous media has gained and is still gaining a lot of attention. This is due to the fact that problems involving the multiphase flow, heat transfer, and multi component mass transport in porous media arise in a broad spectrum of engineering disciplines. Important technological applications include the drying of porous solids and soils, subsurface contamination and remediation, thermally enhanced oil recovery, geothermal energy production, porous heat pipes, multiphase trickle bed reactors, nuclear reactor safety analysis, high-level radioactive waste repositories, paper machines.

However, due to the complicated transport phenomena involved, the multiphase flow and heat transport in porous media remain poorly understood and analytically intractable. Over the last decades a lot of efforts was made to create fundamental mathematical models for those phenomena. One of the purposes of this research is to review and to summarize the recent studies in this field and to compile the hierarchy of the models in order to provide a basis for further model developments and applications to specific problems.

Traditionally multiphase flow in porous media has been approached by so called Multiphase Flow Model (MFM), in which various phases are considered as distinct fluids with individual thermodynamic and transport properties and with different flow velocities. The transport phenomena are mathematically described by the basic principles of conservation for each phase separately and by appropriate interfacial conditions between various phases. The generalized Darcy's law is employed to represent momentum conservation in each phase, with the relative permeabilities of each phase introduced to account for a decrease in effective flow cross-section due to the presence of other fluids.[3]

In many applications, the Darcy’s law is inapplicable where the fluids flow in porous media bounded by an impermeable boundary. For these cases, the study of convective heat transfer should include inertia and boundary effects. A number of recent studies incorporated these effects by using the general flow model known as the Brinkman–Forschheimer-extended Darcy model. For example, Kaviany used the Brinkman extended Darcy model to obtain a numerical solution of laminar flow in a porous channel bounded by isothermal parallel plates. Vafai, using this model, studied forced convection for thermally fully developed flow between flat plates while Vafai reported a numerical study on the thermally developing condition. Also, for flow in parallel plate channels, Vafai used a two-equation model to study the effect of local thermal non-equilibrium condition. Vafai extended the earlier work by investigating different porous media transport models.

An extensive study of flow in porous media is available in. Angirasa discusses the history of development of transport equations in porous media and finite difference simulations. Nield et al. presented the effect of local thermal non-equilibrium on thermally developing forced convection in a porous medium. These references are valuable in this investigation of the accuracy and utility of the exact series solution presented here. The exact series solution requires the computation of a set of eigen values and the numerical computation of certain eigen values can become a formidable task. In practice, using, e.g., a 32 bitprocessor, it may not be possible to compute a large number of eigen values. To verify the accuracy of the series solution, the use of an alternative method of analysis becomes necessary. The closed-form solution that uses the method of weighted residuals is selected. It provides solutions with comparable accuracy over an extended range of variables. For a finite number of eigen values, the method of weighted residuals provides results with comparable accuracy at larger values of the axial coordinate. Because it is based on variational calculus and the minimization principle, it yields significantly higher accuracy near the thermal entrance region. In addition, standard-computing packages can produce all eigen values with ease instead of getting them one at a time.[4]

HEAT TRANSFER IN POROUS MEDIA

Several reviews and re-evaluations of modeling paradigms for saturated and unsaturated porous media have appeared during the past year. A unified streamline and heat and mass line method for the visualization of twodimensional heat and mass transfer in anisotropic media shows promise for convective diffusion problems of the type encountered in porous media. The method of asymptotes was applied to the Rayleigh–Be´nard problem to demonstrate the location of a state at which global resistance of heat transport is minimized. A comprehensive review nonlinear convection showed that not all predictions are experimentally validated.

Representation of a random porous medium with a universal dimension is shown to lead to significant errors in calculating total drag and heat transfer, and basic terminology describing Darcy’s law has been critically reviewed. The permeability of unsaturated media has been determined via a fractal model of the pore structure.

Two-equation modeling of the heat conduction problem is the focus of numerical work that compares results to a numerical solution at the microscopic level. A simplification of the mass balance equation is shown to reduce computational cost for numerical prediction of multidimensional convective heat and mass transfer. Modeling of heat transfer in unsaturated flow in dual scale fibrous media where fiber bundles and flow channels coexist shows a marked deviation from that predicted by single scale modeling. The mass transfer jump at the interface between a porous medium and fluid has been reformulated based on a non-local boundary region form of the volume averaged mass transfer equation.[5,6]

HEAT TRANSFER MODELING IN POROUS MEDIA

A porous medium is a heterogeneous system made of a solid matrix with its voids filled with fluids. Such a structure has the characteristic to possess various length scales of observation. In this study, we distinguish the two main length scales:

- The microscopic scale or pore scale where each solid grain is described individually, the associated lengthscale is the pore diameter l_c;
- The macroscopic scale corresponding to the lengthscale l_M of the observed phenomena.

At the macroscopic scale, the porous medium is represented by an equivalent homogeneous medium. The homogeneous medium is characterized by effective properties standing for the overall effects of the physical phenomena occurring at the pore scale. Different methods exist to obtain the description of the porous medium at the macroscopic scale. However, we present here only the methods used in the remainder of the manuscript to study heat transfer at a free-porous interface.

As with any technological problem, the treatment of fluid flow and heat transfer starts from direct empirical relations where the macroscopic laws are postulated and the medium properties are determined experimentally. Such a method is called heuristic and has the advantage of being generally intuitive.

In 1967, Whitaker introduces a method based on homogenization principles to change the scale of description of a porous medium from microscopic to macroscopic. This method is named the volume averaging method and can be decomposed into three steps. First the governing equations at the local scale of a given quantity, ψ_α, are integrated on a volume of averaging to derive the governing equations at the macroscopic scale. The averaged quantity is noted $\langle\psi_\alpha\rangle$. This spatial smoothing process makes appear non-closed terms in the averaged equations that involve a spatial deviation term, noted $\tilde{\psi}_\alpha$. This term is characteristic of the microscopic scale, and thus, the averaged equations are not closed. The second step closes the open terms with a closure relation for the spatial deviation term $\tilde{\psi}_\alpha$. The closure relation expresses the spatial deviation $\tilde{\psi}_\alpha$ as a function of macroscopic averaged quantities and closure coefficients. These closure variables are characteristic of the microscale and can be related to the effective transfer coefficients. In the third step one determines the closure variables through the resolution of closure problems using the length scale separation between the spatial deviation term, the representative volume of averaging and the averaged term. Following the three steps of the volume averaging method, the problem at the macroscopic scale is entirely closed and characterized. The advantage of this method is to derive the macroscopic model from the microscopic governing equations. However, in the context of the heat transfer study at a free-porous interface, this method cannot be directly used to characterize the transfers because the length scale separation is not verified at the interface.

In 1996, another approach is introduced in (Kuwahara et al., 2001) that we call the mixed method. This method uses the formalism and the first step of the volume averaging method to derive the non-closed macroscopic equations from the microscopic equations. However, the closed form of the governing macroscopic equations are postulated and not formally proved as in the volume averaging method. The expressions for the effective coefficients are determined analytically by identifying the terms in the postulated closed equations and the non-closed terms. Thanks to this identification, the effective coefficients are then computed with temperature and velocity fields solutions of numerical simulations. In this context, the numerical simulations correspond to experimentations with as many measuring points as mesh cells. The limits of this method are the postulation of the closed equations. Indeed, the postulated two-temperature model does not involve enough physical phenomena, that leads to incoherent results for the effective transfer coefficients. The advantage of this method is that it gives access to the determination of the effective transfer coefficients without consideration of length scale separation. Thus, this method of determination can be used in the transition zone where the length scale separation is not valid.[7]

MULTIPHASE FLOW AND POROUS MEDIA

Porous media modeling demands thorough explanation of rock and fluid properties. The tortuous structure of porous media naturally contributes to complicated fluid transport through the pores. Since there is no interaction between fluids, single phase flow is comparatively easy to visualize. In this kind of system, flow efficiency is a function of permeability which is a property of rock and independent of the fluid saturating it. Single phase fluid flow through a porous medium is well described by Darcy's law, and the primary elements of the subject have been well understood for 150 years.

Multiphase flow through porous media is important for a various applications such as CO2 sequestration, and enhanced oil recovery. These often involve the displacement of a nonwetting invading fluid from a porous medium by a wetting fluid, a physical phenomenon known as imbibition. Modeling of multiphase flow, on the other hand is still an enormous technical challenge. To capture the best model of multiphase flow, true description of fluid interaction such as capillary pressure and relative permeability is inevitable. Considering these parameters, the complexity of numerical calculation in reservoir simulation process will increase. In some cases, these two parameters will create instability in numerical simulation.

Numerical analysis of multiphase flow has long been a subject of interest, and there exists a growing body of literature addressing this subject. The modeling of such physical flow process mainly requires solving the mass and momentum conservation equations associated with equations of capillary pressure p_c, saturation S and relative permeability k_r.

HEAT TRANSFER OF A POROUS BODY USING MODIFIED MAXIMUM SLOPE METHOD

There has been an increased amount of research into the use of porous media for the purpose of enhancing the heat transfer rates in the last two decades. Using porous medium to enhance the rate of heat and mass transfer in energy systems has many advantages. Porous Media Heat Exchangers (PMHE) offer a large amount of heat transfer to occur within a small volume. The values of Nusselt number are approximately 50% higher than the values predicted for laminar flows in channels without porous materials. Moreover, the convective heat transfer coefficient is higher for systems filled with porous material than the systems without porous material due to the high thermal conductivity of the porous matrix compared with the fluid thermal conductivity, especially for gas flows.

Hayes have analyzed the thermal performance of compact heat exchangers numerically, assuming it as a porous body. The general method followed by these authors is to experimentally obtain the permeability and inertia coefficients of the porous media by using the Forcheimer equation, and provide these as inputs to the numerical method.

Mohamed used wire mesh heat exchanger for their study. Metallic wirescreen meshes have been widely used in refrigeration, chemical reaction, food processing, solar energy collection, heat dissipation, combustion, and other applications. To simulate fluid flow and heat transfer in cross wire screen meshes, many researchers have treated these structures as porous media.

General analytical models have been developed from the porous medium prototype. Depending on the efficiency of energy exchange between solid and fluid phases, these models can be catalogued as one-energy-equation models or Local Thermal Equilibrium model (LTE) and two-energy equation models or Local Thermal Non Equilibrium model (LTNE). The former assumes that a thermal equilibrium between the two phases is established locally due to efficient thermal communication, whilst the latter acknowledges the local temperature difference between the two phases and employs separate differential equations governing the energy transportation in the two phases. One equation accounts for the heat transfer due to convection, while the other equation accounts for the heat transfer due to conduction within the porous media.[8-10]

CONCLUSION

This study allows a better understanding of the heat transfer mechanisms at a free-porous interface. The models used to characterize the heat transfer are complex due to the number of effective transfer coefficients involved. However, only the total heat flux conservation plays an important part in the boundary conditions that must be applied at the free-porous interface. Such a result considerably simplifies the determination of the boundary conditions. Thus, using boundary conditions of continuity for the temperature, only the heat flux jump parameters must be computed to close the macroscopic model. For heating configurations, for which the solid heat source dominates the heat transfer, the macroscopic problem is easily solved for any interface location knowing the solid heat source in the transition zone.

In this study, combined heat and mass transfer effects on MHD free convection flow past an oscillating plate embedded in porous medium is presented. Results are presented graphically to illustrate the variation of velocity, temperature, concentration, skin-friction and Nusselt number with various parameters.

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