Jr. of Industrial Pollution Control 29(1)(2013) pp 127-132

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HEAT TRANSFER IN POROUS MEDIA: A REVIEW

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Key words : Convection heat transfer, Porous medium, Sintered medium, Magnetohydrodynamics (MHD) flow.

(Received 24 August, 2012; accepted 15 October, 2012)

ABSTRACT

Heat-transfer through porous media takes advantage of the fact that governing equations used for describing various flow and transport phenomena in porous media are all generally based on the same form of mass and/or energy conservation laws. The local distributions of the Nusselt number along the flow direction increase with the increase of the Reynolds number and thickness of the porous layer, but increase with the decreasing Darcy number. The wall temperature and concentration are constant and the medium is linearly stratified in the vertical direction with respect to the thermal conditions. When the fluid flows through porous media, pressure difference reduces with increasing porous parameter which implies a reduction in mass of the fluid that reduces the velocities of the fluid and the dust particles. The simulation model can predict the transient development of sheet temperature very accurately under the specified heating conditions. The theory of porous media for heat transfer in biological tissues is found to be most appropriate since it contains fewer assumptions as compared to different bioheat models.

INTRODUCTION

The flow of a binary mixture of viscous fluid and solid particles has been a subject of great interest to engineers and scientists because such flows occur in powder technology, transport of liquid, slurries in chemical and nuclear processing and in different geophysical situations. Such a binary mixture is called a dusty fluid. The study of dusty fluids has a significant role in the area of fluidization, combustion, use of dust in gas cooling systems, centrifugal separation of matter from fluid, petroleum industry, and purification of crude oil, polymer technology and fluid droplet sprays. Radiative heat transfer is important for systems such as a porous solid fuel bed.

Free convention flow due to thermal and mass diffusion has received widespread attention due to the importance of heat and mass transfer in engineering processes such as in petroleum and geothermal processes, drying, moisture migration in fibrous insulation, nuclear waste disposal and in the control of pollutant spread in ground water. Double diffusive convection driven by buoyancy due to temperature and concentration gradients has been studied by many researchers, among them Erickson *et al.* (1996) and Fox *et al.* (1968) who studied the effects of suction and injection on the problem of heat and mass transfer in the laminar boundary layer flow of moving flat sur-

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face with constant surface velocity and temperature.

Heat transfer in porous fibrous media is a very complex and classical problem which has been studied extensively. A thorough understanding of this problem is essential for many drying and thermal applications of such materials. One classical application is in the area of the production of paper and non woven materials where heat is applied to evaporate excess water. Similarly, many textile materials and now ovens which are used as thermal barrier materials are also subjects for such a study. The heat transfer and transport phenomena in the porous media are important processes in many engineering applications, e.g., heat exchanger, pack-sphere bed, electronic cooling, chemical catalytic reactors, heat pipe technology, etc. The objective of thermal management is to ensure that the temperature of each component in an electronic system remains within specified operating limits, or to ensure the enhancement of forced convection heat transfer in many engineering applications, such as nuclear cooling, heat exchangers, and solar collectors. Since the 1960s, significant progress has been made in mathematical modeling of flow and transport processes in fractured rock. Research efforts, driven by the increasing need to develop petroleum and geothermal energy in reservoirs, other natural underground resources, and to resolve concerns of subsurface contamination, have developed many numerical modeling approaches and techniques (Barenblatt *et al.*, 1960; Warren and Root, 1963; Kazemi, 1969; Pruess and Narasimhan, 1985).

A number of bioheat transfer equations for living tissue have been proposed since the landmark paper by Pennes appeared in 1948, in which the perfusion heat source was introduced. Although Pennes model is often adequate for roughly describing the effect of blood flow on the tissue temperature, some serious shortcomings exist in his model due to its inherent simplicity, as pointed out by Wulff, namely, assuming uniform perfusion rate without accounting for blood flow direction, neglecting the important anatomical features of the circulatory network system such as countercurrent arrangement of the system and choosing only the venous blood stream as the fluid stream equilibrated with the tissue. Coupled heat and mass transfer phenomenon in a liquid saturated porous medium is gaining attention due to its interesting applications.

The flow phenomenon in this case is relatively complex than that in pure thermal/solutal convection process. Processes involving heat and mass transfer in porous media are often encountered in the chemical industry, in reservoir engineering in connection with thermal recovery process, in the study of dynamics of hot and salty springs of a sea. The problem of dissipating high heat fluxes has received much attention due to its importance in applications such as micro-porous heat exchanger, cooling of electronic equipment (mirrors in powerful lasers, phased-array radar systems), industrial furnaces, fixed-bed nuclear propulsion systems and many others. The most effective way of cooling is pumping liquid inside these devices through micro channels or porous medium. (Hwang and Chao, 1994) analyzed the enhancement of heat transfer in sintered porous channels for both thermal entrance and thermally fully developed regions. The two channels of 5 x 5 x 1 cm were made of sintered bronze beads with two different mean diameters, d = 0.72 and 1.59 mm.

Literature Review

1. Free convection heat transfer in porous medium

Prakesh *et al.* (2012) studied the present note deals with the effects of radiative heat transfer and free convection in MHD for a flow of an electrically conducting, incompressible, dusty viscous fluid past an impulsively started vertical non-conducting plate, under the influence of transversely applied magnetic field. The heat due to viscous dissipation and induced magnetic field is assumed to be negligible. The governing linear partial differential equations are solved by finite difference technique. The effects of various parameters (like radiation parameter N, Prandtl number Pr, porosity parameter K) entering into the MHD Stokes problem for flow of dusty conducting fluid have been examined on the temperature field and velocity profile for both the dusty fluid and dust particles.

Awad *et al.* (2011) analyzed the heat transfer characteristics in mixed convection along a semi-infinite plate in a fluid saturated porous medium with radiative heat transfer has been investigated. Diffusion-thermo and thermo-diffusion effects are assumed to be significant. Using a similarity transformation, the governing steady boundary layer equations for the momentum, heat and mass transfer were reduced to a set of ordinary differential equations and then solved using a recent novel linearization method and the Kellerbox method. The results were further confirmed by using the Matlab bvp 4c numerical routine. The effects of the Dufour and Soret parameters on the local skin friction and the local heat and mass transfer rates are investigated. Numerical results for the velocity and the temperature profiles are also presented.

Mahdy and Makinde (2010) numerically studied the mixed convection from a vertical isothermal surface embedded in a porous medium saturated with the Ostwald de-Waele type of non-Newtonian fluid under the influence of Soret and Dufour effects. Thermal radiation effects on heat and mass transfer over unsteady stretching surface was recently investigated by Shateyi and Motsa (2009) where a Chebyshev pseudo spectral collocation method was used to solve the governing equations. Studies by Hossain and Takhar (1996); Rapits and Perdikis (1998); Makinde and Ogulu (2008) and El-Aziz *et al.* (2009) are earlier investigations of the thermal radiation effects. Rapits (1998) studied the flow of a visco-elastic fluid and micropolar fluid past a stretching sheet in the presence of thermal radiation. Yu *et al.* (2007) have also shown that Soret mass flux and Dufour energy flux have appreciable and at times significant effect on heat and mass transfer rates. Atimay and Gill (1985) showed that an error as large as 30% in the wall mass flux could be expected if the Soret effect is neglected.

Nield *et al.* (2006) proposed the thermo-diffusion effect on free convection heat and mass transfer from a vertical surface embedded in a liquid saturated thermally stratified non - Darcy porous medium has been analyzed using a local non-similar procedure. The wall temperature and concentration are constant and the medium is linearly stratified in the vertical direction with respect to the thermal conditions. The fluid flow, temperature and concentration fields are affected by the complex interactions among the diffusion ratio Le, buoyancy ratio N, thermo-diffusion parameter Sr and stratification parameter e. Non-linear interactions of all these parameters on the convective transport has been analyzed and variation of heat and mass transfer coefficients with thermo-diffusion parameter in the thermally stratified non-Darcy porous media is presented through computer generated plots.

Ingham *et al.* (2004) studied the effects of radiative heat transfer on the fully developed free convection flow of a viscous incompressible fluid-saturated porous medium between two vertical walls in the presence of a uniform gravitational field have been studied. An exact solution of the governing equations has been obtained. Radiation is found to have significant effects on the velocity field and temperature distribution. It is observed that the fluid velocity decreases with an increase in either radiation parameter or porosity parameter. It is also observed that the velocity at any point in the flow region increases with an increase in Grashof number. The effect of thermal radiation on temperature field is also analyzed. The fluid temperature increases with an increase in either radiation parameter or temperature parameter.

2. Modeling Flow and Heat Transfer through Porous Media

Banerjee *et al.* (2010) proposed the modelling of the heat transfer process in a thin porous fibrous material such as a paper sheet when it is subjected to an incident heat flux introduced by a laser beam. A mathematical model based on the control volume principle is developed for numerical estimation of radial temperature distribution which is validated experimentally by infrared thermography. Here the heat flux is introduced by a CO2 laser beam of 10.6 μm wavelength and an infrared image sequence is recorded as a function of time with a high resolution infrared camera. The preliminary validation results indicate that the simulation model can predict the transient development of sheet temperature very accurately under the specified heating conditions.

Young *et al.* (2009) investigated the numerical simulations have been carried out to investigate the turbulent heat transfer enhancement in the pipe filled with porous media. Two dimensional axisymmetric numerical simulations using the k–e turbulent model is used to calculate the fluid flow and heat transfer characteristics in a pipe filled with porous media. The parameters studied include the Reynolds number (Re = 5000–15,000), the Darcy number (Da = 10–1–10–6), and the porous radius ratio (e = 0.0–1.0). The numerical results show that the flow field can be adjusted and the thickness of boundary layer can be decreased by the inserted porous medium so that the heat transfer can be enhanced in the pipe. The local distributions of the Nusselt number along the flow direction increase with the increase of the Reynolds number and thickness of the porous layer, but increase with the decreasing Darcy number. For a porous radius ratio less than about 0.6, the effect of the Darcy number on the pressure drop is not that significant.

Kang *et al.* (2008) studied a physically based numerical approach is presented for modeling multiphase flow and transport processes in fractured rock. In particular, a general framework model is discussed for dealing with fracture-matrix interactions, which is applicable to both continuum and discrete fracture conceptualization. The numerical modeling approach is based on a general multiple-continuum concept, suitable for modeling any types of fractured reservoirs, including double-, triple and other multiple continuum conceptual models. In addition, a new, physically correct numerical scheme is discussed to calculate multiphase flow between fractures and the matrix, using continuity of capillary pressure at the fracture-matrix interface. The proposed general modeling methodology is verified in special cases using analytical solutions and laboratory experimental data and demonstrated for its application in modeling flow through fractured vuggy reservoirs.

Nakayama *et al.* (2007) analyzed a volume averaging theory (VAT) established in the field of fluid-saturated porous media has been successfully exploited to derive a general set of bioheat transfer equations for blood flows and its surrounding biological tissue. Firstly, two individual macroscopic energy equations are derived for the blood flow and its surrounding tissue under the thermal non-equilibrium condition. The blood perfusion term is identified and modeled in consideration of the transvascular flow in the extravascular region, while the dispersion and interfacial heat transfer terms are modeled according to conventional porous media treatments. It is shown that the resulting two-energy equation model reduces to Pennes model, Wulff model and their modifications, under appropriate conditions.

Hetsroni *et al.* (2005) proposed the heat transfer and pressure drop in a rectangular channel with sintered porous inserts, made of stainless steel of different porosity, were investigated experimentally. Heat flux up to 6 MW/m2 was removed experimentally by using porous samples with porosity 32% and average pore diameter 20 ?m. Under this experimental condition, the difference between the temperatures of the wall and the bulk water did not exceed of 55 K with a pressure drop of 4.5 bars. The generalization of data on heat transfer in a low porosity sintered stainless steel media, based on the permeability as scale of length and the effective thermal conductivity, was considered. An estimate of a heat sink efficiency using sintered porous material for cooling high-power mini-devices and comparing it with one for such modern porous media as compressed aluminum foams was done.

Khaled and Vafai (2003) investigated flow and heat transfer in biological tissues in their investigation. Pertinent works are reviewed in order to show how transport theories in porous media advance the progress in biology. The main concepts studied in this review are transport in porous media using mass diffusion and different convective flow models such as Darcy and those Brinkman models. Energy transport in tissues is also analyzed. Progress in development of the bioheat equation (heat transfer equation in biological tissues) and evaluation of the applications associated with the bioheat equation are analyzed. Prominent examples of diffusive applications and momentum transport by convection are discussed in this work. The theory of porous media for heat transfer in biological tissues is found to be most appropriate since it contains fewer assumptions as compared to different bioheat models. A concept that is related to flow instabilities caused by swimming of microorganisms is also discussed. This concept named bio convection is different from blood convection inside vessels. The works that consider the possibility of reducing these flow instabilities using porous media are reviewed.

CONCLUSION

When the fluid flows through porous media, pressure difference reduces with increasing porous parameter which implies a reduction in mass of the fluid that reduces the velocities of the fluid and the dust particles. The Dufour parameter increases the velocity and the temperature but has only a slight effect on the concentration profiles. The velocity increases by increasing the buoyancy parameter. The wall temperature and concentration are constant and the medium is linearly stratified in the vertical direction with respect to the thermal conditions. It is found that the critical wall temperature at the cold wall decreases with increase in either radiation parameter or porosity parameter .The transport theory in porous media involving various models such as Darcy and Brinkman models for momentum transport and local thermal equilibrium for energy transport were found to be quite useful in describing different biological applications. An efficiency of sintered porous heat sink and the comparison with an aluminum compressed foams one clearly show that such heat sink gives very high value of the heat transfer performance The blood perfusion heat source term is identified as the macroscopic energy equation by integrating the microscopic convection term within a local control volume.

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