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The influence of the porous media permeability on the unsteady conjugate forced convection heat transfer from a porous sphere embedded in a porous medium

Gheorghe Juncu *

POLITEHNICA University Bucharest, Department of Chemical and Biochemical Engineering, Polizu 1, 011061 Bucharest, Romania

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ABSTRACT

The unsteady, conjugate, forced convection heat transfer from a porous sphere embedded in another porous medium has been analysed. Both porous media are fluid saturated. Local thermal equilibrium between the two phases is assumed. The fluid flow inside and outside the sphere was considered axisymmetric, steady and incompressible (Darcy and Brinkman flows). The heat balance equations were solved numerically in spherical coordinates system by an implicit alternating direction finite difference method. The influence of the porous media permeability and sphere Peclet numbers on the heat transfer mechanism and rate was analysed for different values of the physical properties ratios (thermal conductivity ratio and heat capacity ratio).

1. Introduction

The momentum, heat and mass transfer between a sphere and a surrounding medium is one of the classical benchmark problems for the analysis of transfer phenomena with broad applications in many environmental, industrial and life-science processes. The forced convection heat/mass transfer between a porous/non-porous sphere and a non-porous/porous surrounding medium is one of the particular cases of this problem.

Forced convection heat/mass transfer from a porous/non-porous sphere to a non-porous/porous surrounding medium was studied in [1–12]. Masliyah [1] investigated numerically the steady conjugate heat transfer from a composite sphere to a surrounding fluid flow for low Reynolds numbers values. The composite sphere has a solid, impermeable, isothermal core surrounded by a shell of homogeneous and isotropic porous medium. The flow in the porous shell is described by the Brinkman's equation. The effects of the porous shell thickness, permeability, and thermal conductivity on the heat transfer rate were studied.

The use of a porous wrapper on solid bodies is a new method to control the heat transfer. It also has applications in human clothing, [13]. Depending on its characteristics, the porous medium decreases/increases the heat transfer rate, [14].

The heat transfer from impervious spheres with constant temperature or prescribed surface flux distribution to a fluid saturated porous medium was studied in [2–7]. Paik et al. [8] analysed the unsteady mixed convection heat transfer from a solid sphere to a saturated porous medium. In [2–8], Darcy flow was assumed inside the fluid saturated porous medium. The impact of the Brinkman viscous term on the steady-state, forced convection mass transfer from a rigid sphere al low Peclet number, was investigated analytically in [9]. In this article, the boundary condition on the surface of the sphere is of Robin type.

The analysis of Romero [2] is motivated by the design of a groundwater velocimeter. Sano [4] mentions that the environmental impact of buried nuclear heat generating waste is one of the applications of his work. The underground contaminant transport and the contaminant leakage from storage underground cavities are the applications of the analysis made in [3,6,8]. The applications mentioned in [5,7] are the geothermal energy research and the cooling of the electronic devices.

Jain and Basu [10] solved numerically the case of forced convection heat transfer from a porous sphere with constant temperature to a surrounding fluid flow. Jain and Basu [10] consider that their work applies to: sedimentation of sludge flocs, motion of clusters in gas–solid fluidized-bed chemical reactors, settling flocs in liquid–solid chemical reactors and the microbiology of marine aggregates. Numerical simulations of the steady flow and heat transfer past and inside a porous sphere were made by Wittig

* Tel./fax: +40 21 345 0596.
E-mail addresses: juncu@easynet.ro, juncugh@netscape.net

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Nomenclature

List of symbols

a	radius of the sphere, m
c_P	heat capacity, J kg^{-1} K^{-1}
d	diameter of the sphere, $d = 2a$, m
k	thermal conductivity, W m^{-1} K^{-1}
K	permeability of the porous medium, m^2
Nu	instantaneous average Nusselt number, dimensionless
Nu_θ	instantaneous local Nusselt number, dimensionless
Pe	Peclet number, $Pe = U_0 d(\rho c_p)_f / k_{eff}$, dimensionless
r	dimensionless radial coordinate, r^*/a, in spherical coordinate system
r^*	radial coordinate in spherical coordinate system, m
t	time, s
T	temperature, K (Kelvin degree)
U_0	Darcy velocity far away from the sphere, m s^{-1}
V_R	dimensionless radial Darcy velocity component
V_θ	dimensionless tangential Darcy velocity component
Z	dimensionless temperature defined by the relation, $Z_{2(1)} = \frac{T_{2(1)} - T_{2,0}}{T_{1,0} - T_{2,0}}$

Greek symbols

α	thermal diffusivity, m^2 s^{-1}
Φ	thermal conductivity ratio, $k_{eff,1}/k_{eff,2}$, dimensionless
μ	dynamic viscosity, kg m^{-1} s^{-1}
μ'	Brinkman viscosity, kg m^{-1} s^{-1}
θ	polar angle in spherical coordinate system, rad
ρ	density, kg m^{-3}
σ	porous medium parameter, $(\mu/\mu')\,\omega$-for Brinkman flow, ω-for Darcy flow
τ	dimensionless time or Fourier number, $\tau = 4t\alpha_{eff}/d^2$
ψ	dimensionless stream function
Ξ	thermodynamic ratio, $(\rho_1 c_{P,1})_{eff}/(\rho_2 c_{P,2})_{eff}$, dimensionless
ω	permeability dimensionless parameter, $a/\sqrt{K}$

Subscripts

eff	refers to effective physical property of the porous medium
f	refers to physical property of the fluid
1	refers to the interior of the sphere
2	refers to the exterior of the sphere
s	refers to the surface of the sphere
0	initial conditions

et al., [11]. Two different mathematical models (microscopic and macroscopic) for porosity were used. The analysis from [11] is focused on the modeling the fluid particle flows in fluidized-bed chemical reactors.

The unsteady conjugate heat transfer from a permeable sphere embedded in another porous medium was investigated numerically in [12]. Brinkman flow was considered in [12]. Numerical results for the internal/external problem were also presented. For the conjugate problem, the numerical results obtained for two boundary cases, $\sigma_1/\sigma_2 = 0.01$ and $\sigma_1/\sigma_2 = 100$, were analysed in detail. It was shown that the porous media permeability has a strong effect on the heat transfer rate.

The aim of the present work is to complete the analysis from [12] with a detailed investigation concerning the influence of the porous media permeability on the unsteady, forced convection, conjugate heat transfer from a porous sphere to a surrounding porous medium. This problem was not investigated until now. Darcy and Brinkman flows in both porous media were considered. The present computations are focused on the influence of the porous media permeability and sphere Peclet number on the heat transfer mechanism and rate for different values of the physical properties ratios (thermal conductivity ratio and heat capacity ratio) and $Pe \leqslant 10^3$. The results obtained in this work are of interest for any of the applications mentioned previously. Additionally, other related applications are the design of nuclear biological chemical filters and high performance electrochemical capacitors, [15,16], vascular and tissues flow and tumor growth.

This paper is organized as follows. In Section 2 we describe the mathematical model of the problem. Section 3 presents the numerical algorithm. The numerical experiments made and the results obtained are presented in Section 4. Finally, some concluding remarks are briefly mentioned in Section 5.

2. Model equations

Consider the steady, axisymmetric flow of a Newtonian incompressible fluid with a superficial velocity U_0 and initial temperature $T_{2,0}$ in a porous medium with permeability K_2. Inside the porous medium, a porous sphere with initial temperature $T_{1,0}$ and permeability K_1 is embedded (see Fig. 1). Both porous media are fluid saturated. The following assumptions are considered valid:

- locally, the temperatures of the solid and fluid phases are equal so that there is no net heat transfer from one phase to the other (*local thermal equilibrium, LTE*);
- during the heat transfer process, the volume and shape of the sphere remains constant;
- the effects of buoyancy, viscous dissipation and the work done by pressure changes are negligible;
- the physical properties of the sphere and the ambient porous medium are considered to be uniform, isotropic and constant;
- no emission or absorption of radiant energy;
- no phase change;
- no chemical reaction inside the sphere or in the surrounding porous medium.

For the scenario presented previously, the conjugate heat transfer is governed by the following dimensionless convection–diffusion equations:

$$\frac{\partial Z_i}{\partial \tau_i} + \frac{Pe_i}{2}\left(V_{R,i}\frac{\partial Z_i}{\partial r} + \frac{V_{\theta,i}}{r}\frac{\partial Z_i}{\partial \theta}\right) = \Delta Z_i, \qquad (1)$$

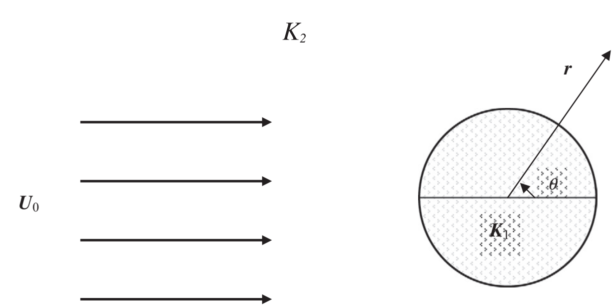

Fig. 1. Schematic of the problem.