International Journal of Technology and Emerging Sciences (IJTES)

www.mapscipub.com

Volume 02 || Issue 02 || April 2022 || pp. 01-05 E-ISSN: 2583-1925

Natural Convection Heat Transfer Within A Spherical Shaped Enclosure Filled With A Porous Medium – A Review

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Abstract - *Flow through porous medium has been a center of attention since last decade obviously due to its extensive applications in the field of engineering especially thermal insulations, contemporary building walls, safety of nuclear reactors, geophysical phenomes etc. Plethora of studies have been performed to understand the porous medium flow in rectangular and cylindrical shaped enclosure. However, numerous engineering applications involve spherical shaped porous media flow which cannot be, in any circumstances, ignored. Comparatively lesser number of studies are performed in spherical porous media flow. The current study is an effort in this direction to compile most of the relevant works performed in spherical porous enclosures and thereby comprehend the importance, extent of research and future scope in this domain of porous media flows.*

***Key Words*: Porous Medium, Thermal Insulation**

1. INTRODUCTION

Porous media flows have been an important vertical in thermal and fluids engineering since porous nature of a substance is inherent and unavoidable. Industrially, porous materials may be seen in soil mechanics, geophysics, drying, filtration, material science, solar collector, thermal insulations, acoustics etc. Table (1) enlists different type of porous media flows in various domains of engineering sciences. The importance of porous media in thermal applications have been crucial as well. This sort of applications can primarily be split into two categories; those based on enhancement heat transfer and those on suppression heat transfer. Thermal insulations, for example, is related to heat transfer suppression whereas grain storage, on other hand, is related to augmentation. Since many engineering applications have porous structure which may or may not be critical to the systems performance, the study of its thermal and fluid flow characteristics become increasingly important. The development of transport phenomena, particularly, in porous medium have flashed way back in mid-nineteenth century after Darcy [1] experimentally quantified the bulk resistance to flow of a liquid through porous bed and established a relationship between pressure difference across a porous media and discharge rate and is well-known today as Darcy's law.

Table -1: Applications of porous media flow

Sr. No.	Application Domain	Type of Porous Structure	Reference
1	Biomechanics	Bones, human lung and soft tissues modeling	[2,3]
2	Mechanical	Electronic cooling systems, fire safety, solar systems, heat exchangers, thermal insulators, sound, isolation, automobiles, refrigerators, combustion, capillary-assisted thermal technology, safety analysis of nuclear reactor	[4-8]
3	Material Science	Metal foams and polymers	[9]
4	Biological	Blood perfusion in tissues, Modeling of bio-heat transfer in tissues, photo thermal therapy	[10,11]
5	Production	Oil recovery, Oil production, drying and liquid composite molding, battery electrodes and other electrochemical systems	[12]
6	Chemical	Fuel cell membrane, Packed-bed reactor, bacterial	[13-15]
7	Geophysics	Aquifer's consolidation, melting of ice layers, or flow in magma chambers, disposal of waste, sub-surface contamination	[16,17]
8	Civil	Leakage through walls of water dams or reservoirs, protective casing for steel in building and construction	[18]

In later half of nineteenth century, the effective conductivity of porous medium eas experimentally calculated by Maxwell empirically and internal flow transition in porous media were extensively studied by Reynold performed. This gave a new stimulus of research in this field. The early half of twentieth century has seen the works of several fundamental yet important aspects of porous media flows in form of, Prandtl's external flow transition experiment, Carman-Kozeny permeability equation, Knudsen's slip-flow experiment. Nonetheless, most of the attention in porous media flow research was caught in the mid-twentieth century due to the expounding results reported by

Brinkman [19, 20] modification of Darcy's law, Ergun and Orning [21] model to constitute inertial effect, interfacial boundary condition by Beavers and Joseph [22] and study of multi-phase flow in porous media by Whitaker [23].

Depending upon the application, the study of porous media flow can be categorized, broadly, based upon the domain shape viz., rectangular, cylindrical and spherical porous enclosures. Moreover, some other shapes have also been studied in literature like, trapezoidal, triangular etc. Table (2) enlists the works reported based upon various porous enclosure shapes.

Table-2: Some significant works based upon various porous domain shapes.

Rectangular	Cylindrical	Spherical
[24-38]	[39-47]	[48-60]

MATHEMATICAL MODEL

Most of the works available in literature on spherical porous media are numerical simulation type. Hardly any work is found to be of experimental in nature. Following are the patterns of mathematical modelling that have been used to model spherical porous media flows.

ASSUMPTION

The mathematical modelling of spherical porous medium is subject to following assumptions. Though not imperative, these assumptions have been commonly found in the literatures [47, 50, 51, 53, 57]. The mathematical model assumes Newtonian type of fluid, laminar flow, 2D and in-compressible flow. Viscous dissipation, compression effects and radiation are ignored. All the properties of fluid are maintained constant apart from density which is approximated by Boussinesq equation and also temperature dependent viscosity. The fluid and the solid matrix of the porous medium are supposed to be in local thermal equilibrium with each other. The porous medium is assumed to be isotropic and homogeneous. The fluid viscosity is same as the effective viscosity, while the effective thermal conductivity of the fluid-saturated porous medium is equivalent to the fluid's thermal conductivity.

GOVERNING EQUATIONS

If u, v, w are the components of the velocity field and T is the temperature, The governing equations consisting of conservation of mass, momentum and energy are given as,
Darcy Model [48, 49, 51, 53, 55]:

$$\frac{1}{r^2}\frac{\partial}{\partial r}(r^2 u) + \frac{1}{r \sin\emptyset}\frac{\partial}{\partial \emptyset}(v \sin\emptyset) = 0$$

$$\frac{\mu}{K}u = -\frac{\partial p}{\partial r} - \rho\, g \cos\emptyset$$

$$\frac{\mu}{K}v = -\frac{1}{r}\frac{\partial p}{\partial \emptyset} + \rho\, g \sin\emptyset$$

$$u\frac{\partial T}{\partial r} + \frac{v}{r}\frac{\partial T}{\partial \emptyset} = \alpha_e\left[\frac{\partial^2 T}{\partial r^2} + \frac{2}{r}\frac{\partial T}{\partial r} + \frac{1}{r^2}\frac{\partial^2 T}{\partial \emptyset^2} + \frac{\cot\emptyset}{r^2}\frac{\partial T}{\partial \emptyset}\right]$$

Density variation according to Boussinesq approximation is given by,

$$\rho = \rho_m\left[1 - \beta(T - T_m)\right]$$

Brinkman Model [50, 56, 58]:

$$\frac{\partial}{\partial r}(r^2 u)\sin\emptyset + \frac{\partial}{\partial \emptyset}(r\, v \sin\emptyset) = 0$$

$$\frac{\mu}{K}u = -\frac{\partial p}{\partial r} - \rho\, g \cos\emptyset +$$

$$\mu\left[\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial u}{\partial r}\right) + \frac{1}{r^2 \sin\emptyset}\frac{\partial}{\partial \emptyset}\left(\sin\emptyset\frac{\partial u}{\partial \emptyset}\right) - \frac{2u}{r^2} - \frac{2}{r^2}\frac{\partial v}{\partial \emptyset} - \frac{2v}{r^2}\cot\emptyset\right]$$

$$\frac{\mu}{K}v = -\frac{1}{r}\frac{\partial p}{\partial \emptyset} + \rho\, g \sin\emptyset$$

$$+\mu\left[\frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial v}{\partial r}\right) + \frac{1}{r^2 \sin\emptyset}\frac{\partial}{\partial \emptyset}\left(\sin\emptyset\frac{\partial v}{\partial \emptyset}\right) + \frac{2}{r^2}\frac{\partial u}{\partial \emptyset} - \frac{v}{r^2 \sin^2\emptyset}\right]$$

$$u\frac{\partial T}{\partial r} + \frac{v}{r}\frac{\partial T}{\partial \emptyset} = \alpha_e\left[\frac{\partial^2 T}{\partial r^2} + \frac{2}{r}\frac{\partial T}{\partial r} + \frac{1}{r^2}\frac{\partial^2 T}{\partial \emptyset^2} + \frac{\cot\emptyset}{r^2}\frac{\partial T}{\partial \emptyset}\right]$$

Some non-dimensional parameters used in this equations for converting it into dimensionless equations are,

$$\text{Rayleigh Number, } Ra = \frac{\rho K \beta\,(T_i - T_o)D}{\mu\alpha}$$

$$\text{Darcy Number, } Da = \frac{K}{D^2}$$

Local & average Nusselt numbers, to quantify the heat transfer rate may be defined as,

$$Nu_L = \frac{1}{rr}\frac{\partial\theta}{\partial R}$$

$$\overline{Nu} = \int_0^{\pi} Nu_L \frac{\sin\emptyset}{2}\, d\emptyset$$

Here, *rr* is the radius ratio defined as ratio of outer to inner radius of sphere, *R* is the dimensionless radial parameter.

Average Nusselt number is evaluated using numerical integration of local Nusselt number by Simpson's 1/3rd rule

BOUNDARY CONDITIONS

For annulus based geometry, generally, there are two surfaces on which boundary conditions are imposed. The thermal boundary conditions levied on the physical domain are uniform relative to angular coordinate. Thus, symmetrical plane may be assumed to exist at the plane which breaches the annulus into equal halves. The computational domain thus includes only half of the spherical domain. Usually, the inner surface may be considered as hot while outer surface as cold. In dimensionless terms for Darcy flow model, these boundary conditions are as follows,

$$\psi = 0 \text{ on all boundaries}$$
$$\theta = 1 \text{ or } \frac{\partial \theta}{\partial R} = -1, \text{ inner surface}$$
$$\theta = 0, \text{ outer surface}$$
$$\frac{\partial \theta}{\partial \emptyset} = 0, \text{ plane of symmetry surface}$$

In dimensionless terms for Darcy-Brinkman flow model, these boundary conditions are as follows,

$$\psi = 0 \text{ on all boundaries}$$
$$\theta = 1 \text{ or } \frac{\partial \theta}{\partial R} = -1, \text{ inner surface}$$
$$\theta = 0, \text{ outer surface}$$
$$\Omega = -\frac{1}{R \sin \emptyset} \frac{\partial^2 \psi}{\partial R^2}, \text{ inner \& outer surface}$$
$$\frac{\partial \theta}{\partial \emptyset} = 0, \text{ plane of symmetry surface}$$

Here, ψ and Ω is stream function and vorticity respectively given as,

$$U = \frac{1}{R^2 \sin \emptyset} \frac{\partial \psi}{\partial \emptyset}$$
$$V = -\frac{1}{R \sin \emptyset} \frac{\partial \psi}{\partial R}$$
$$\Omega = \frac{\partial V}{\partial R} + \frac{V}{R} - \frac{\partial U}{R \partial \emptyset}$$

In case of transient model, the initial conditions may be written as,

$$\psi = \theta = 0, \quad \tau < 0$$

Here, τ is non-dimensional time parameter.

NUMERICAL METHODS

The solution to above mentioned coupled partial differential equations have been solved in numerous ways be various authors. Perturbation expansion method [51], Successive Accelerated Replacement (SAR) scheme [49, 50], Least square Methods [48], Successive line over-relaxation method [47] have been utilized widely. For discretization of grid and governing equations, modified Sorenso's method have been used for generating orthogonal grid along the boundary [47]. Apart from this, Grid system and Weighing Function Scheme (WFS), finite difference method has been widely used. The range of Rayleigh number varies as per the problem statement. However, following are the range of parameters generally implemented in literature, Rayleigh number (20 - 80000), Darcy number (0.1 – 0.00001), Prandtl number (150 – 750), Radius Ratio (1 – 3).

HEAT TRANSFER RESULTS

Nusselt number is the most common quantitative parameter calculated to estimate the rate of heat transfer of the system. Apart from this, to evaluate the fluid flow, value of maximum absolute stream function is also noted.

Table-3: Various values of Nusselt number reported

Ra	***Nu***	**Ref.**
10	1.017 (rr = 2)	[61]
	1.06 (rr = 2)	[62]
	1.04 (rr = 2)	[63]
	1.04 (rr = 2)	[50]
30	1.36 (rr = 2)	[62]
	1.31 (rr = 2)	[63]
	1.26 (rr = 2)	[49]
50	1.74 (rr = 2)	[62]
	1.7 (rr = 2)	[63]
	1.57 (rr = 2)	[50]
75	2.10 (rr = 2)	[62]
	2.11 (rr = 2)	[63]
	1.94(rr = 2)	[49]
100	2.35 (Da = 0.01)	[50]
200	2.74 (rr = 2)	[61]
500	4.4 (rr = 3)	[49]
1000	6.1(rr = 3)	[50]

CONCLUSION

The current review paper has collected all the relevant details viz., governing equations, boundary conditions, numerical methods, heat transfer results, applications on study of spherical porous media flows whichever were available and it may not be a hyperbole to summarize that particularly this domain of porous media flow has a considerable hiatus in research. Although flow through porous media has widely been the focus of study since last two decades, its study in spherical domain is still very scarce. Applications involving spherical porous media are not limited. From food storage, spherical tanks, safety of nuclear reactors, geophysical application etc. are some of the applications where spherical porous media are frequently encountered. Almost all the studies reported in literature are of numerical and computational in nature. Experimental data have not been benchmarked as regards to spherical porous media flows. Thereby, a lot of scope is available to explore, analyze and experiment in porous media flow through spherical geometry.

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