JP Journal of Heat and Mass Transfer
Volume 1, Number 3, 2007, Pages 331-342
Published online: February 25, 2008
This paper is available online at http://www.pphmj.com

EXPERIMENTAL STUDIES ON NATURAL CONVECTION IN A VERTICAL CIRCULAR CYLINDER EMBEDDED WITH POROUS MEDIA AT CONSTANT WALL TEMPERATURE

D. SUBRAMANYAM[1], K. RAVINDRANATH[1] and K. MALLIKARJUNA RAO[2]

[1]Department of Mechanical Engineering
S. V. University College of Engineering
Tirupati-517 502, A. P., India
e-mail: prasannadsm@yahoo.co.in

[2]Department of Civil Engineering
S. V. University College of Engineering
Tirupati-517 502, A. P., India

Abstract

An experimental study on natural convection heat transfer in vertical annular cylinders embedded with porous medium at constant wall temperature has been undertaken. Three stainless steel (301SS) test sections of different aspect ratios were employed. Nusselt number is found to increase with radius ratio and Rayleigh number but decrease with aspect ratio and viscous dissipation. Regression models were developed to predict Nusselt number in terms of aspect ratio, radius ratio, Rayleigh number and viscous dissipation parameter.

1. Introduction

The study of natural convection heat transfer in porous media finds importance in many applications like cryogenic containers, nuclear

Keywords and phrases: natural convection, vertical cylinder, aspect ratio, radius ratio, viscous dissipation, porous media.

Received November 7, 2007

reactors and buried pipe lines, etc. Many authors studied the effect of aspect ratio, radius ratio, Rayleigh number and viscous dissipation on natural convection in porous media. Ali [2] has studied numerically the effect of aspect ratio and Rayleigh number on natural convection in a rectangular porous medium. Choukairy et al. [5] have studied the phenomenon of transient laminar free convection in a vertical cylindrical annulus filled with air at $\mathrm{Pr} = 0.71$ numerically and analytically. Cheng [4] examined the effects of the modified Darcy number, the buoyancy ratio and the inner radius-gap ratio on the fully developed natural convection heat and mass transfer in a vertical annular non-Darcy porous medium with axisymmetric wall temperature and concentrations.

Havstad and Burns [7] have studied numerically the convective heat transfer in vertical cylindrical annuli filled with porous medium at low Rayleigh number. Hooper et al. [8] have studied buoyancy effect on convection adjacent to a vertical cylinder in porous media numerically.

Irfan et al. [9] have studied the effect of viscous dissipation and thermal radiation on natural convection in a porous medium embedded with in a vertical annular cylinder at constant temperature. Kumari et al. [10] have studied the effect of thermal dispersion on non-Darcy mixed convection flow in a vertical cylinder embedded with porous medium numerically. The effect of aspect ratio and radius ratio on natural convective heat transfer in a cylindrical annulus filled with porous media has been studied numerically by Nath and Satyamurthy [14]. Philip [15] has studied numerically on axisymmetric free convection at small Rayleigh number in porous cavities. Numerical studies were reported by Prasad and Kulacki [16] for steady free convection in a vertical annulus filled with saturated porous medium whose vertical walls are at constant temperatures and the horizontal walls are insulated. The curvature effects on temperature and velocity fields are found to be significant. Prasad et al. [17] have studied free convection in a vertical annulus filled with a saturated porous medium experimentally. The experimental results are reported for height to gap ratio of 1.46, 1 and 0.545 and radius ratio of 5.338 at constant wall temperature. The viscous dissipation effect has been studied considering the Darcy law by Nakayama and Pop [13], Magyari and Keller [11], Rees et al. [18], and Saied and Pop [19].

Al-Hadhrami et al. [1] have studied the combined free and forced convection in vertical channels of porous media. Murthy and Singh [12] have studied the effect of viscous dissipation on a non-Darcy natural convection regime. Tashtoush [20] reported an analytical solution for the effect of viscous dissipation on mixed convection in porous media.

It has been observed from the literature review that only few investigators studied the effect of viscous dissipation on natural convection in vertical annular cylinder embedded with porous media experimentally. So an attempt has been made in this paper to study the effect of viscous dissipation parameter on natural convection in vertical annular cylinder embedded with porous media.

In the present work, the effects of viscous dissipation, aspect ratio, radius ratio and Rayleigh number on natural convection in vertical annular cylinder inner walls heated at top and bottom portions embedded in porous medium at constant wall temperature have been studied experimentally.

2. Nomenclature

Ar : Aspect ratio $\left(\frac{H}{D}\right)$

C_p : Specific heat (J/kg K)

D : gap width of porous media, $r_0 - r_i$

e : Void ratio

g : Acceleration due to gravity $(\mathrm{m/sec}^2)$

$\overline{h}$: Average heat transfer coefficient

H : Height of cylinder (m)

K : Permeability of porous media (m^2)

Km : Effective thermal conductivity of saturated porous media $(\mathrm{w/mk})$

$\overline{\text{Nu}}$	:	Average Nusselt number
Pr	:	Prandtl number
Rr	:	Radius ratio $\left(\frac{D}{r_i}\right)$
Ra^*	:	Modified Rayleigh number
r_i	:	Radius of inner annular cylinder (m)
r_o	:	Radius of outer annular cylinder (m)
ΔT	:	Temperature differences $(T_i - T_o)$
α	:	Thermal diffusivity (m^2/sec)
β	:	Coefficient of thermal expansion of fluid (K^{-1})
μ	:	Coefficient of viscosity of fluid (N.S/m^2)
υ	:	Kinematic viscosity of fluid (m^2/sec)
ρ	:	Density of fluid (kg/m^3)
ϕ	:	Porosity of porous media
$\in$	:	Viscous dissipation parameter

Subscripts

i	:	inner cylinder
o	:	Outer cylinder
m	:	Porous medium

3. Experimental Apparatus and Procedure

The experimental setup consists of three sets of annular cylinders of two different diameters. The annular space between two cylinders is filled with porous medium of glass spheres of diameter 15.76 mm. The cylinders are fixed to the wooden plates both at top and bottom which act as insulating material. The entire assembly is fixed on iron stand. The cylinders are made up of 301SS grade stainless steel of thickness 2 mm and outer diameters of 5, 6 and 6 cm. The heights of the cylinders are 20, 30.5 and 45.1 cm. The inner diameter of the outer cylinders is 18.4 cm, thickness being 2 mm and made up of iron. The required heat is generated by fixing heating coils on the inner surface of the cylinder at top and bottom as shown in the line sketch of physical model in Figure 1a. An A.C. power supply is the available source to heat the vertical cylinders to pre-set temperature values. The power supply is varied with the help of thermistor. The voltage and current are measured with voltmeter (0-300 V) and ammeter (0-5 A). Four thermocouples are fixed on the surface of the cylinder and connected to the temperature indicator to measure the temperature.

The experiments have been conducted for all three sets of cylinders at average constant temperatures 45, 50, 55, 60 and 65°C with corresponding voltages being 80, 100, 120, 140 and 160 volts, respectively. For all voltages, the delivering surface temperatures stayed within the range of 38-78°C.

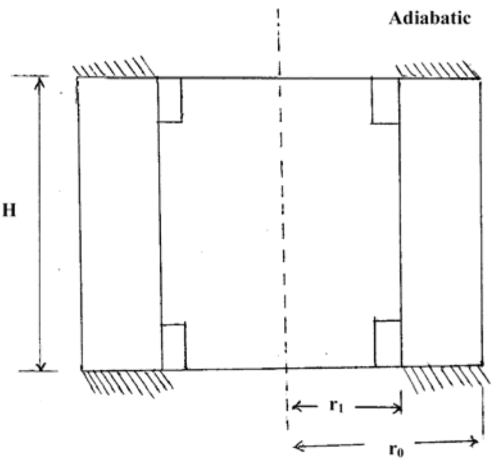

Figure 1a. Physical model.

The porosity of the porous medium is calculated making use of the following interrelationship developed for porous media and can be found in any standard text book on particulate mechanics or Geotechnical

Engineering (Das [6])

$$\gamma_d = \frac{G \cdot \gamma_w}{1 + e}, \quad (1)$$

$$\phi = \frac{e}{1 + e}, \quad (2)$$

where G is the specific gravity of the solid phase, γ_d is the dry unit weight given by the ratio of dry weight of porous media to its volume, γ_w is the unit weight of water, e is the void ratio defined as ratio of volume of voids to volume of solid in porous media and ϕ is the porosity of the porous medium defined as ratio of volume of voids to total volume of the porous media. The permeability of the porous media is determined by the following expression given by Bejan [3]

$$K = \frac{D_p^2 \phi^3}{180(1 - \phi)^2}, \quad (3)$$

where D_p is the diameter of the particle.

The modified Rayleigh number and average Nusselt number were determined by the following expressions:

$$\mathrm{Ra}^* = \left(\frac{Kg\beta D \Delta T}{\nu\alpha}\right), \quad (4)$$

$$\overline{\mathrm{Nu}} = \left(\frac{\bar{h} D}{Km}\right). \quad (5)$$

4. Results and Discussion

The linear repression analysis is carried out using the MS-Excel software with statistical principles of curve fitting for three test sections.

Figure 1 shows the variation of Nusselt number with power supply and is found to increase with increasing power supply and hence temperature. The trend is observed to be linear for three test sections.

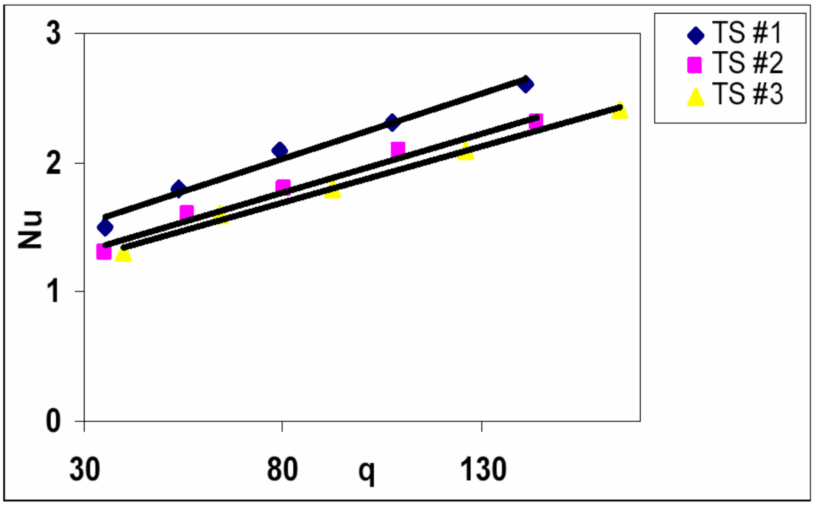

Figure 1. q vs Nu.

Figure 2 shows the variation of the Nusselt number (Nu) with coefficient of heat transfer. Nusselt number increases with increasing h and the trend is observed to be linear.

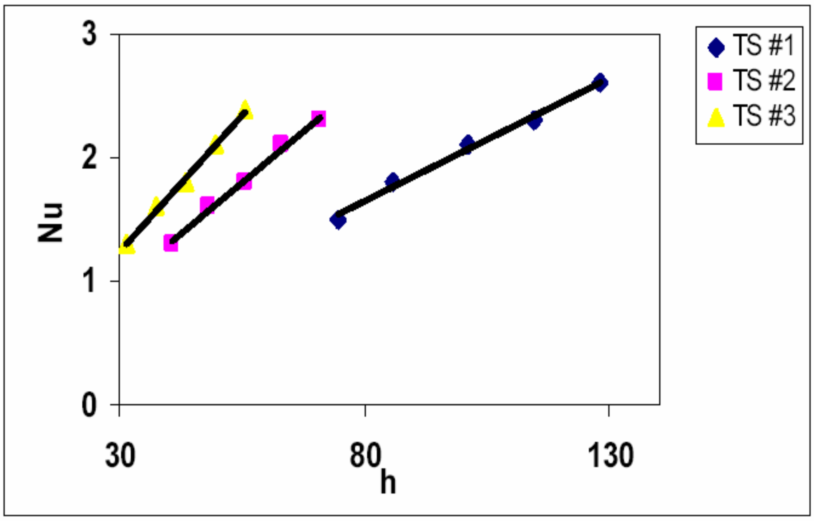

Figure 2. h vs Nu.

Figure 3 shows the variation of Nusselt number with Prandtl number Pr. Nusselt number increases with Prandtl number and trend is observed to be linear.

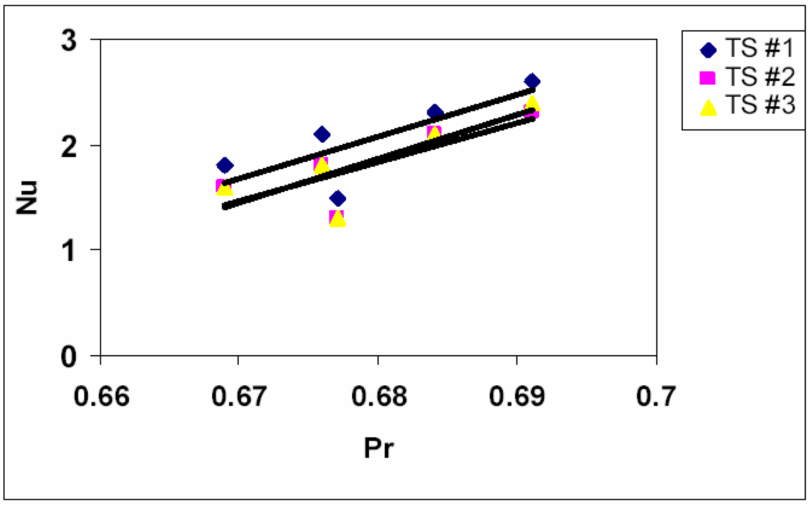

Figure 3. Pr vs Nu.

Figure 4 shows the variation of Nusselt number with modified Rayleigh number Ra. Nusselt number is found to increase with increasing Rayleigh number. The trend is observed to be linear. The relationship is given by the following equations:

$$\overline{\text{Nu}} = 0.1519\text{Ra}^{*0.7705} \qquad \text{for } TS\,\#1, \tag{6}$$

$$\overline{\text{Nu}} = 0.1268\text{Ra}^{*0.8056} \qquad \text{for } TS\,\#2, \tag{7}$$

$$\overline{\text{Nu}} = 0.1113\text{Ra}^{*0.8476} \qquad \text{for } TS\,\#3. \tag{8}$$

The correlation coefficient, R^2 for the above relationship is 0.99, indicating a very good fit.

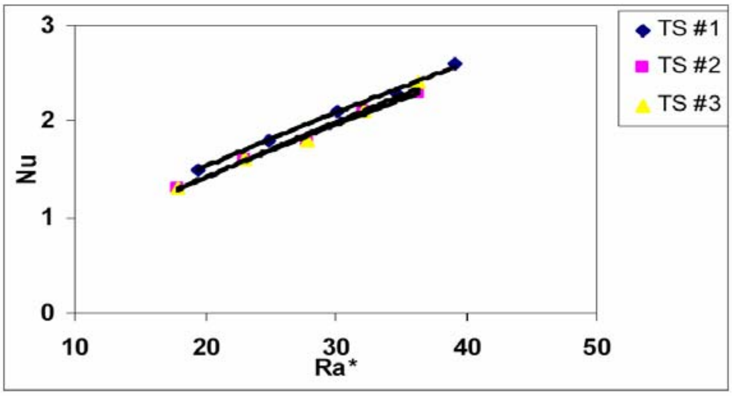

Figure 4. Ra^* vs Nu.

Figure 5 shows the variation of Nusselt number with viscous dissipation parameter $\in$. Nusselt number decreases with increasing viscous dissipation parameter $\in$ and trend is linear. The relationship is given by the following equations:

$$\overline{\text{Nu}} = -180.19 \in +3.3934 \quad \text{for } TS\#1, \tag{9}$$

$$\overline{\text{Nu}} = -166.98 \in +3.0557 \quad \text{for } TS\#2, \tag{10}$$

$$\overline{\text{Nu}} = -178.3 \in +3.1594 \quad \text{for } TS\#3. \tag{11}$$

The correlation coefficient for the above relationship $R^2 \geq 0.92$, indicating a good fit.

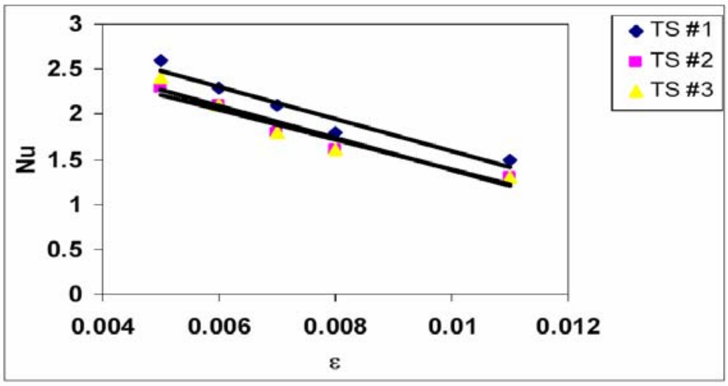

Figure 5. ε vs Nu.

From Figures 6-8, it can be observed that the Nusselt number increases with increasing modified Rayleigh number and radius ratio and decreases with increasing aspect ratio. The trend is linear. The relationship of Nusselt number, aspect ratio, radius ratio and modified Rayleigh number are given below:

$$\overline{\text{Nu}} = -0.0454\text{Ar} + 2.3934, \tag{12}$$

$$\overline{\text{Nu}} = 0.3333\text{Rr} + 1.4, \tag{13}$$

$$\overline{\text{Nu}} = 0.0741\text{Ra}^{*} - 0.2852. \tag{14}$$

Based upon the heat transfer results, the following correlation is developed by the method of least squares.

$$\overline{\text{Nu}} = 0.584\text{Ra}^{*0.5}\text{Ar}^{-0.25}. \tag{15}$$

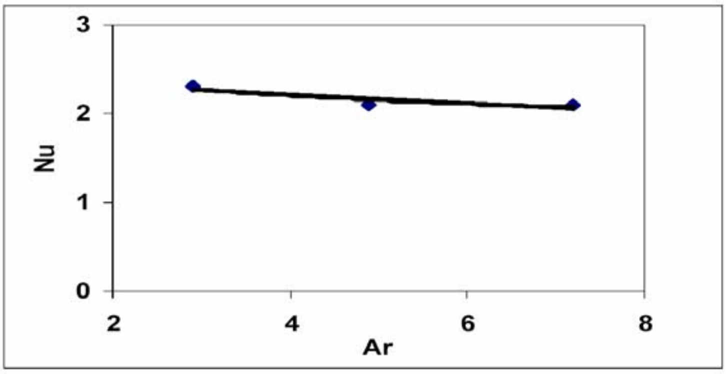

Figure 6. Ar vs Nu.

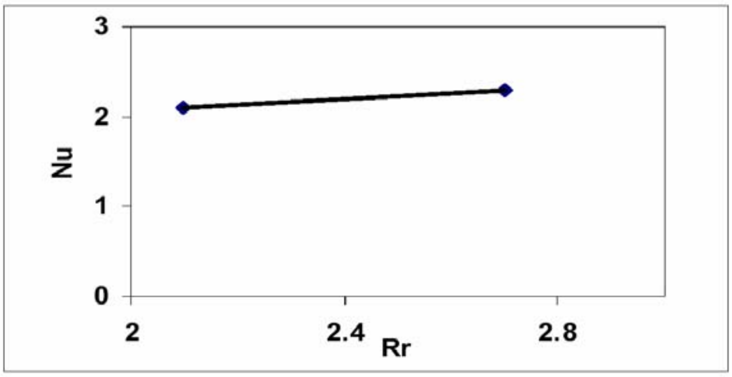

Figure 7. Rr vs Nu.

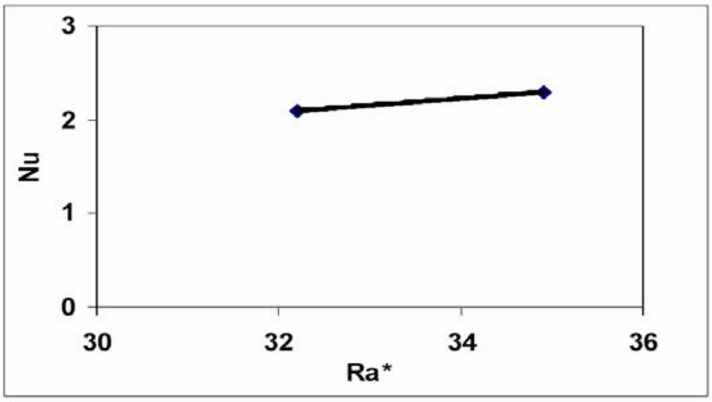

Figure 8. Ra* vs Nu.

5. Conclusions

In this paper, an experimental study of natural convection heat transfer in vertical cylinders embedded with porous medium at constant wall temperature has been presented. The outcome of the study is summarized with practical correlation equations linking to the average Nusselt number to the modified Rayleigh number, aspect ratio, radius ratio and viscous dissipation parameter. The result of the analysis may be useful to the heat transfer Engineers for design of heat transfer through porous media. Further, the analysis can be extended to the cases of different aspect ratios, radius ratios and with different porous media.

References

[1] A. K. Al-Hadhrami, L. Elliot and D. B. Ingham, Combined free and forced convection in vertical channels of porous media, Transport Porous Media 49 (2002), 265-289.

[2] Bahlul Ali, Boundary layer and stability analysis of natural convection in a porous cavity, Int. J. Thermal Sci. 45 (2005), 656-663.

[3] A. Bejan, Convective Heat Transfer, 2nd ed., John Wiley & Sons, New York, 1995.

[4] Ching-Yang Cheng, Fully developed natural convection heat and mass transfer in a vertical annular porous medium with asymmetric wall temperatures and concentrations, Appl. Thermal Engrg. 26 (2006), 2442-2447.

[5] K. Choukairy, R. Bennacer, H. Beji and S. Jaballab, Transient behaviour inside a vertical cylindrical enclosure heated from the side walls, Numer. Heat Transfer Part A 50 (2006), 773-785.

[6] Braja M. Das, Principles of Geotechnical Engineering, 5th ed., Thomson-Brooks/Cole, India, 2002.

[7] P. J. Havstad and M. A. Burns, Convective heat transfer in vertical cylindrical annuli filled with a porous medium, Int. J. Heat Mass Transfer 25 (1982), 1755-1766.

[8] W. B. Hooper, T. S. Chen and B. F. Armaly, Mixed convection along an isothermal vertical cylinder in porous media, J. Thermophysics Heat Transfer 8(1) (1994), 92-99.

[9] Anjum Badroddin Irfan, Z. A. Zainal, Zahid A. Khan and Zuiquernain Mallick, Effect of viscous dissipation and radiation on natural convection in a porous medium embedded with in vertical annulus, Internat. J. Thermal Sci. 46 (2007), 221-227.

[10] M. Kumari, G. Nath and I. Pop, Non-Darcy natural convection flow with thermal dispersion on vertical cylinder in a saturated porous medium, J. Acta Mech. 100(1-2) (1993), 69-77.

[11] E. Magyari and B. Keller, Buoyancy sustained viscous dissipation, Transport Porous Media 53 (2003), 105-115.

[12] P. V. S. N. Murthy and P. Singh, Effect of viscous dissipation on a non-Darcy natural convection regime, Internat. J. Heat Mass Transfer 40 (1997), 1251-1260.

[13] A. Nakayama and I. Pop, Free convection over a non-isothermal body in a porous medium with viscous dissipation, Internat. Commun. Heat Mass Transfer 16 (1989), 173-180.

[14] S. K. Nath and V. V. Satyamurthy, Effect of aspect ratio and radius ratio on free convection heat transfer in a cylindrical annulus filled with porous media, Proc. of 8th National Heat Mass Transfer Conference (1985), pp. 189-193.

[15] J. R. Philip, Axisymmetric free convection at small Rayleigh number in porous cavities, Int. J. Heat Mass Transfer 25 (1982), 1689-1699.

[16] V. Prasad and F. A. Kulacki, Natural connection in porous media bounded by short concentric vertical cylinders, ASME J. Heat Transfer 107 (1985), 147-154.

[17] V. Prasad, F. A. Kulacki and M. Keyhari, Natural convection in porous media, J. Fluid Mechanics 150 (1985), 89-119.

[18] D. A. S. Rees, E. Magyari and B. Keller, The development of the asymptotic viscous dissipation profile in a vertical free convective boundary layer flow in a porous medium, Transport Porous Media 53 (2003), 347-355.

[19] N. H. Saied and I. Pop, Viscous dissipation effects on free convection in porous cavity, Internat. Commun. Heat Mass Transfer 32 (2004), 723-732.

[20] B. Tashtoush, Analytical solution for the effect of viscous dissipation on mixed convection in porous media, Transport Porous Media 41 (2000), 197-209.