# *Influence of Natural Convection on the Thermal Properties of Insulating Porous Medium with Air Cavity*

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## 1 Abstract

The influence of natural convection on the thermal properties of insulating porous medium with air cavity is studied. Here, the combined effect of air movement in the air cavity and the air movement inside the insulation is evaluated with the help of numerical analysis. The influence of total natural convection on the thermal properties of mineral wool, loose-fill insulation, insulation made of small and large polystyrene ball with air cavity are studied. The results are presented in terms of dimensionless numbers and the temperature distribution across the insulation.

## 2 Introduction

The knowledge of temperature distribution and the heat transfer flow rate within the conductive body are important. In the determination of the temperature distribution the boundary conditions can either be a specification of the surface temperature directly or the specification of heat flow rate to and from the surface. In case of insulating porous materials with low density and high permeability the convective conditions on the surface are often the controlling factors, i.e., the heat flow resistance in the conducting body is much smaller than the resistance due to convection at the surface, with the result that the conditions on the surface and not on those with in the body itself regulate the heat flow.

When the fluid particles that carry heat along in the form of internal energy and is influenced by the external forces to create its motion, this type of heat transfer is termed as forced convection. Where as, when the motion of the fluid is buoyancy induced, the same is refered to as natural convection.

## 3 Horizontal Insulating Medium with Air Cavity

The physical situation and coordinate system for horizontal medium with air cavity is shown in Fig. 1 The conservation equations for the porous layer, as mentioned earlier, are based on the fact that the Darcian law holds good and the effect due to buoyancy are taken in to consideration. The mean flow equations for two dimensional steady case for the air cavity can be formulated as follows.

a. Continuity:

$$\frac{\partial}{\partial x}(\rho U) + \frac{\partial}{\partial y}(\rho V) = 0 \tag{1}$$

b. Momentum:

$$\rho U \frac{\partial}{\partial x}(U) + \rho V \frac{\partial}{\partial y}(U) = -\frac{\partial}{\partial x}(P) + \frac{\partial}{\partial x}\left(\mu_f \frac{\partial}{\partial x} U\right) + \frac{\partial}{\partial y}\left(\mu_f \frac{\partial}{\partial x} U\right) \tag{2}$$

$$\rho U \frac{\partial}{\partial x}(U) + \rho V \frac{\partial}{\partial y}(U) = -\frac{\partial}{\partial y}(P) + \frac{\partial}{\partial x}\left(\mu_f \frac{\partial}{\partial x} V\right) + \frac{\partial}{\partial y}\left(\mu_f \frac{\partial}{\partial x} V\right) + \rho g \beta (T - T_c) \tag{3}$$

c. Energy:

$$\rho c_{pf} U \frac{\partial}{\partial x}(T) + \rho C_{pf} V \frac{\partial}{\partial y}(T) = \frac{\partial}{\partial x}\left(k_f \frac{\partial}{\partial x} T\right) + \frac{\partial}{\partial y}\left(k_f \frac{\partial}{\partial y} T\right) \tag{4}$$

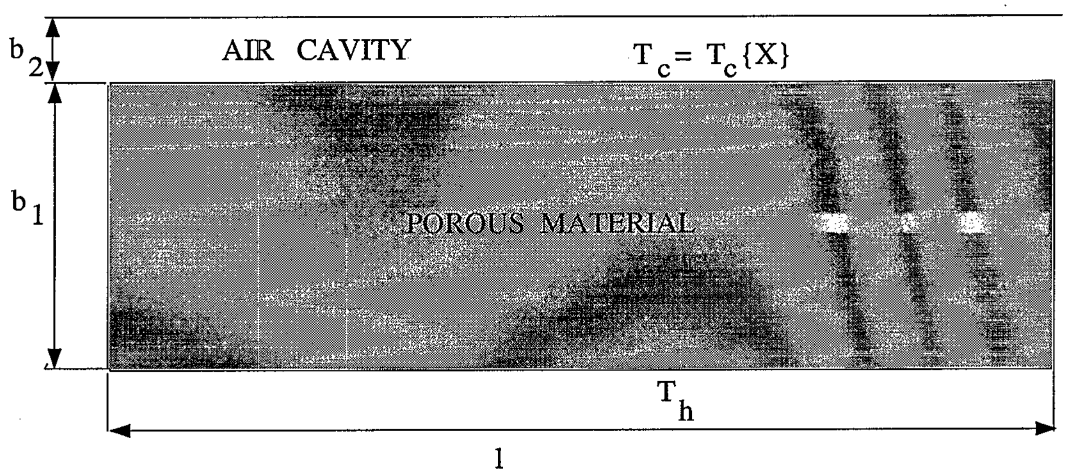


Figure 1: *Schematic diagram of the physical model.*

a. Continuity:

$$\frac{\partial}{\partial x}(U_D) + \frac{\partial}{\partial y}(V_D) = 0 \tag{5}$$

b. Momentum:

$$\frac{\partial}{\partial x}(P) + \frac{\partial}{\partial x}\left(\mu_{eff}\frac{\partial}{\partial x}U_D\right) + \frac{\partial}{\partial y}\left(\mu_{eff}\frac{\partial}{\partial x}U_D\right) - \frac{\mu_{eff}}{K}U_D = 0 \tag{6}$$

$$\frac{\partial}{\partial y}(P) + \frac{\partial}{\partial x}\left(\mu_{eff}\frac{\partial}{\partial x}V_D\right) + \frac{\partial}{\partial y}\left(\mu_{eff}\frac{\partial}{\partial y}V_D\right) - \frac{\mu_{eff}}{K}V_D + \rho g\beta(T - T_c) = 0 \tag{7}$$

c. Energy:

$$U_D\frac{\partial}{\partial x}(T) + V_D\frac{\partial}{\partial y}(T) = \alpha\frac{\partial}{\partial x}\left(\frac{\partial}{\partial x}T\right) + \alpha\frac{\partial}{\partial y}\left(\frac{\partial}{\partial y}T\right) + \frac{S}{\rho c_p} \tag{8}$$

The two sets of equations are coupled by the following synchronization conditions of the fluid (air cavity)/porous layer interface.

$$T|_{x=s^-} = T|_{x=s^+} \tag{9}$$

$$k_f\frac{\partial}{\partial}(T)|_{x=s^-} = k_{eff}\frac{\partial}{\partial}(T)|_{x=s^+} \tag{10}$$

$$U|_{x=s^-} = U_D|_{x=s^+} \tag{11}$$

$$V|_{x=s^-} = V_D|_{x=s^+} \tag{12}$$

$$P|_{x=s^-} = P|_{x=s^+} \tag{13}$$

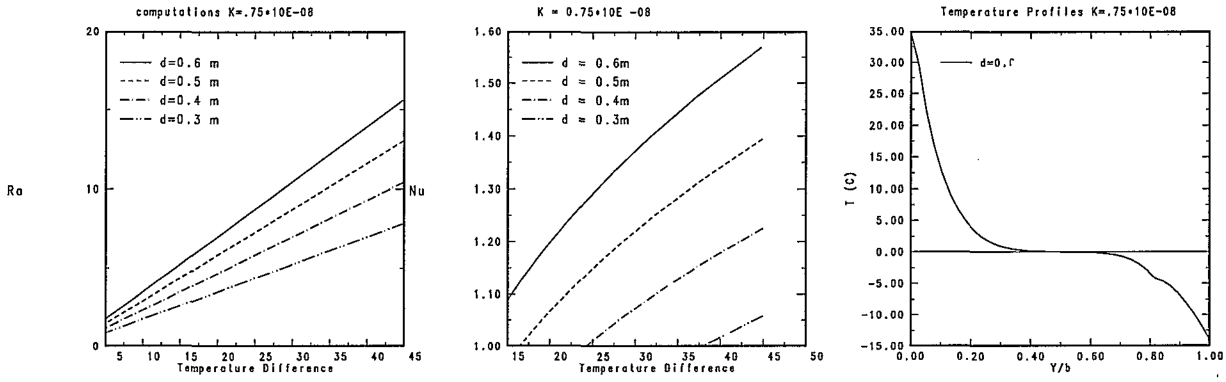


Figure 2: *The influence of temperature difference on Rayleigh's number (2.a) , Nusselt's number (2.b) and temperature profiles (2.c) in Loose - Fill insulation (permeability, $K = 0.75 * 10E - 08$) with air cavity.*

$$\mu_f \frac{\partial}{\partial}(V) + \mu_{eff} \frac{\partial}{\partial}(U) = \mu_{eff} \frac{\partial}{\partial}(V_D) + \mu_{eff} \frac{\partial}{\partial}(U_D) \tag{14}$$

$$\mu_f \frac{\partial}{\partial}(U)\,|_{x=s^-} = \mu_{eff} \frac{\partial}{\partial}(U_D)\,|_{x=s^+} \tag{15}$$

The continuity of the temperature, heat flux, normal and the tangential velocities, and the pressure across the fluid/porous interface are expressed in Eqs. 9, 10, 11, 12 and 13 respectively. The adherence of the derivatives of the normal and shear stress are given in Eqs. 14 and 15. It is assumed that $\mu_{eff} = \mu_f$. In order to combine the two sets of equations, the above equations are solved in dimensionless form.

## 3.1 Boundary Conditions

To solve the above set of equations, following are the thermal boundary conditions often used in heat transfer problems: a. Dirichlet condition (imposed temperature)

$$T = T_h \tag{16}$$

for 'warm' surface. b. Nuemann condition (imposed heat flux)

$$T = T(x) \tag{17}$$

for 'cold' surface.

## 3.2 Heat Transfer Results

The overall heat transfer rate across the enclosure is expressed in terms of Nusselt's number which is defined as

$$Nu = \frac{hl}{k_f} \tag{18}$$

In a steady state, for a global system, the Nusselt's number is a characteristic of the heat exchange. Nusselt's number is a function of Rayleigh's number and for horizontal porous layer and is evaluated at any horizontal plane and is calculated as follows [7].

$$Nu = \frac{\frac{1}{l}\int_0^l (k\frac{\partial T}{\partial Y} - \rho_f c_f V T)\partial X}{-\partial \Delta k / K} \tag{19}$$

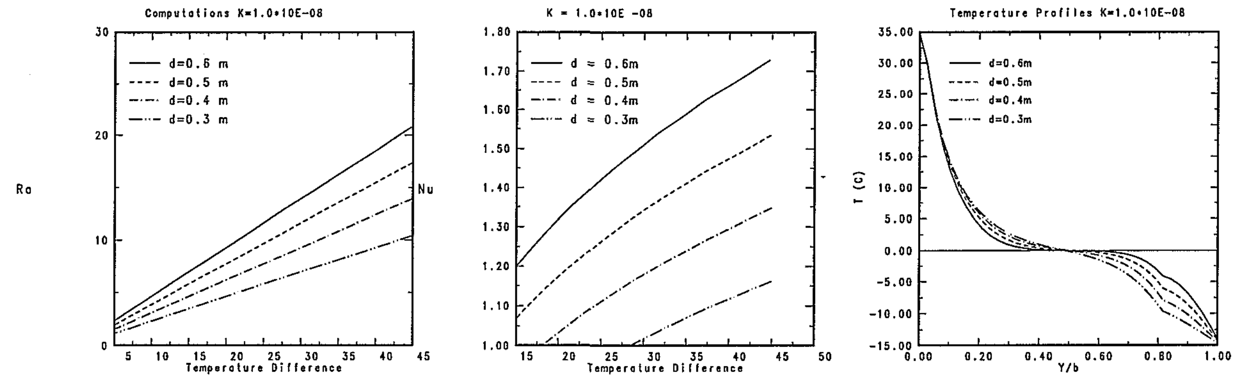


Figure 3: *The influence of temperature difference on Rayleigh's number (3.a) , Nusselt's number (3.b) and temperature profiles (3.c) in Loose - Fill insulation (permeability,* $K = 1.0 * 10E - 08$*) with air cavity.*

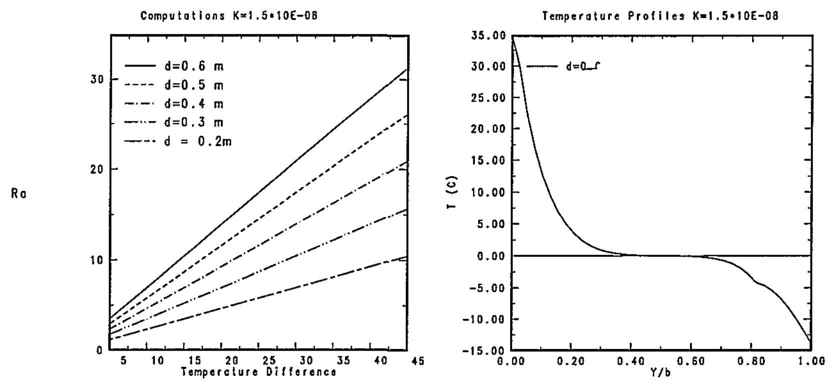


Figure 4: *The influence of temperature difference on Rayleigh's number (4.a) and temperature profiles (4.c) in Loose - Fill insulation (permeability,* $K = 1.5 * 10E - 08$*) with air cavity.*

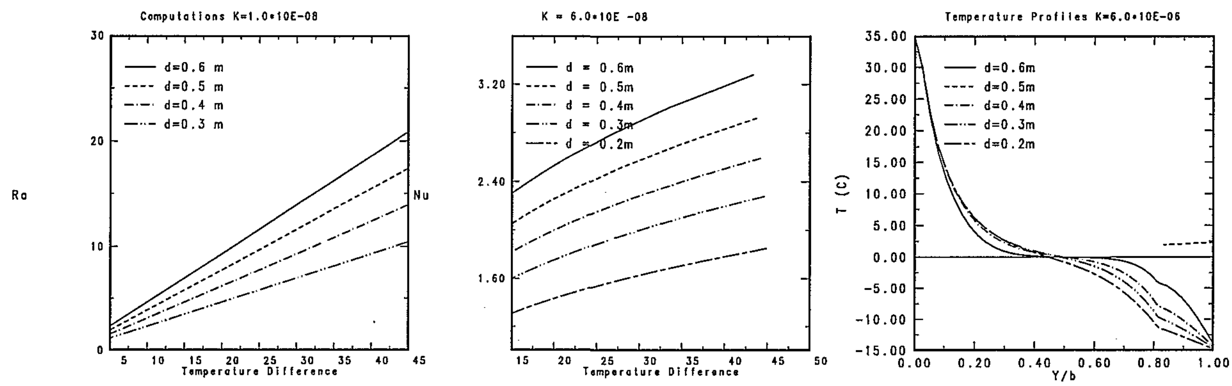


Figure 5: *The influence of temperature difference on Rayleigh's number (5.a) , Nusselt's number (5.b) and temperature profiles (5.c) in Loose - Fill insulation (permeability,* $K = 6.0 * 10E - 08$*) with air cavity.*

# 4 Influence of Thickness of Insulation and Temperature Difference

The influence of thickness of insulation and temperature difference on Rayleigh's number in horizontal insulation made of mineral wool with air cavity is shown in Fig. 2a. The magnitude of Rayleigh's number increases with the increase in the temperature difference between hot and cold surface of the insulation and the thickness of the insulation. From Fig.2a we can conclude that there is a considerable influence of air flow in the air cavity on the natural convection or the thermal properties of the insulation. We can also infer that greater the thickness of the insulation stronger is the influence of air movement in the air cavity on the natural convective effects on the thermal properties of insulation. Fig. 2b shows the influence of temperature difference on the natural convection (Nusselt's number) in horizontal insulation, made of mineral wool, with air cavity. Also the effect of natural convection (Nusselt's number is a measure of natural convection) decreases by 10 to 12 percent as shown in Fig. 2b, when the thickness of the insulation is decreased by 10 cm, at a temperature difference of $45^oC$. We can see from the same that the influence of convection increases with the increase in temperature difference over the insulation and the thickness of insulation. The temperature profiles in Figs. 2c, 3c, 4b and 5d for mineral wool, loose - fill insulation, insulation made of small polystyrene balls and insulation made of large polystyrene balls respectively are shown. There is a clear peneteration of air from the air cavity into the insulation since the deviance in the value of temperature near the boundary between the insulation - air cavity boundary is considerable.

# 5 Results and Discussion

The work presented in this report deals with the influence of convective flow on the global heat transfer rate in insulation with an air cavity. Numerical investigations are carried out to predict the combined influence of convective flow on the thermal properties of mineral wool, loose - fill insulation, insulation made of small polystyrene balls and insulation made of large polystyrene balls with air cavity. Air permeability and the thickness of the insulation are the most significant parameters for the influence of natural convection on the global heat transfer rate in porous medium (insulation). The main conclusions of the results obtained are summarized below.

1. Conducting numerical investigations in the case of horizontal insulating medium with air cavity is of great practical interest since this can be directly coupled to attic configurations, where the influence of air movement in the air cavity has an influence, to a great extent, on the thermal properties of the loose - fill insulation.

2. The flow in air cavity tends to increase influence of convection or the global heat transfer rate on the thermal properties of the insulation. Due to the convective flow in the air cavity the magnitude of Reyleigh's number increases by appoximately 7 percent.

3. Since, the value of Reyleigh's and Nusselt's number is a measure of the influence of natural convection on the thermal prorerties of the insulation, Figs. 2a, 2b, 3a, 3b, 4a, 5a, and 5b indicate that with an increase in permeability of the insulation, leads to an increase of air movement in the insulation and therefore an increase in the influence of natural convection on the thermal properties of the insulation.

4. The flow inside the air cavity has a tendency to increase the net effect of convection (Nusselt's number) on the thermal properties of the insulation.

5. There is a clear purging of air from the air cavity in to the insulation as shown in Figs. 2c, 3c, 4b and 5c.

6. The insulation thickness, thickness of the air cavity and temperature difference play an important role on the magnitude of Rayleigh's number, and inturn on the global heat transfer rate

# References


[1] S.V. PATANKAR, Numerical heat transfer and fluid flow, McGraw-Hill, Washington, 1980.

[2] C.M. RHIE and W.L.CHOW, Numerical study of the turbulent flow past an airfoil with trailing edge separation, *AIAA J.*, **21**, pp. 1527-1532, 1984.

[3] V. SHANKAR, L. DAVIDSON and E. OLSSON, Ventilation by displacement: Calculations of the flow in vertical plumes, Vol.1, pp.59-74, ROOMVENT'92, Aalborg, Denmark, 1992.

[4] L. DAVIDSON and B. FARHANIEH, CALC-BFC: A finite-volume code employing colocated variable arrangement and Cartesian velocity components for computation of fluid flow and heat transfer in complex three-dimensional geometries, Rept., Dept. of Applied Thermodynamics and Fluid Mechanics, Chalmers University of Technology, Gothenburg, Sweden, 1991.

[5] V. SHANKAR: Numerical investigation of turbulent plumes in both ambient and stratified surroundings, Tek. lic., Rept.,Dept. of Thermo and Fluid Dynamics, Chalmers University of Technology, Gothenburg, Sweden, 1993.

[6] N.Z. INCE and B.E. LAUNDER, Computation of turbulent natural convection in closed rectangular cavities, Proc. 2nd U.K. Natn. Conf. on Heat Transfer, University of Strathclyde, Glasgow, Vol. 2, pp. 1389-1400, 1988.

[7] A.A. DELMAS and E.K. WILKES, Numerical analysis of heat transfer by conduction and natural convection in loose-fill fiber-glass insulation -Effects of convection on thermal performance, Rept., Oak Ridge National Laboratory, 1991.

[8] C.G. BANKVALL, Mechanisms of heat transfer in permeable insulation and their investigation in special guarded plate, ASTM STD, 554, American Society for Testing and Material, Philedelphia, 1975.

[9] C.G. BANKVALL, Natural convective heat transfer in insulated structures, Ph.D thesis, Division of Building Technology, Lund, Sweden, 1972.

[10] C.G. BANKVALL, Heat transfer in fibrous materials, Journal of testing and evaluation, Vol. 1, No. 3, 1973

[11] M. SERKITJIS, Egen och patvingad konvection i lösull, Rept., Division of Building Technology, Chalmers University of Technology, Gothenburg, Sweden, 1992.

[12] M. SERKITJIS, Personal communications, Division of Building Technology, Chalmers University of Technology, Gothenburg, Sweden, 1992.

[13] C. BECKERMANN, S. RAMADHYANI, and R. VISKANTA, Natural convection flow and heat transfer between a fluid and a porous layer inside a rectangular enclosure, ASME J. Heat Transfer, 109, 363-370, 1987.

[14] J.G. GEORGIADIS and I. COTTON, Prandtl number effect on Bernard convection in porous media, ASME J. of Heat Transfer, 108, 284-289, 1986

[15] M.R.M - DEHGHAN, A.J.W. SMITH and R.N. WALKER, A study of laminar air flow through cracks by numerical simulation of differential equations, International Journal of Numerical Methods in Fluids, 14, pp. 1485-1496, 1992.

[16] T.W. TONG and E. SUBRAMANIAM, Natural convection in rectangular enclosures partially filled with a porous medium, ASME - JSME, Thermal engineering joint conference, ASME, New York, Vol. 1, pp. 331-338, 1983

[17] C.L. TIEN and J.T. HONG 1985, Natural convection in porous media under non-uniform permeability conditions in: Natural Convection, S. KAKAC et.al., eds, Hemisphere, Washington DC, 1984

[18] V. PRASAD and F.A. KULACKI, Natural convection in a rectangular porous cavity with constant heat flux on one vertical wall, ASME Journal of heat transfer, vol.106, 1984, pp.152-157.

[19] V. PRASAD and F.A. KULACKI, Convective heat transfer in a rectangular porous cavity-Effect of aspect ratio on flow structure and heat transfer, vol.106, 1984, pp.158-165.

[20] M. HAAJIZADEH, A. OZGUC and C.L. TIEN, Natural convection in a vertical porous enclosure with internal heat generation, International Journal of heat and mass transfer, vol.27, 1984, pp 152-157.