THERMAL CONVECTION AT LOW RAYLEIGH NUMBER FROM
CONCENTRATED SOURCES IN POROUS MEDIA*

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ABSTRACT

A simple mathematical theory is proposed for the analysis of natural convective motion, at low Rayleigh number, from a concentrated source of heat in a fluid-saturated porous medium. The theory consists of retaining only the leading terms of series expansions of the dependent variables in terms of the Rayleigh number, is thus linear, and is valid only in the limit of small Rayleigh number. Based on fundamental results for a variety of isolated sources, superposition is used to provide solutions for situations of practical interest. Special emphasis is given to the analysis of sub-seabed disposal of nuclear waste.

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NOMENCLATURE

a	Radius of sphere
C_p	Specific heat
D	Burial depth for heat source
g	Acceleration of gravity
H	Length of line source
k	Permeability
L	Reference length
P	Pressure
Q	Strength of heat source
R	Radial distance, spherical coordinates
r	Normalized spherical radial coordinate
r	Radial distance, cylindrical coordinates
Ra	Rayleigh number
s	Integration variable for line source
T	Temperature
t	Time
$\underline{v}$	Velocity vector
v_R, v_Φ	Velocity components in spherical coordinates
V_R, V_Φ	Non-dimensional velocity components in spherical coordinates
v_r, v_θ	Velocity components in cylindrical coordinates
V_r, V_θ	Non-dimensional velocity components in cylindrical coordinates
y	Vertical coordinate

NOMENCLATURE (cont)

Greek

β	Coefficient of thermal expansion
η	Non-dimensional parameter ($r/2\tau^{1/2}$)
θ	Non-dimensional temperature difference
κ	Thermal conductivity
μ	Viscosity
ρ	Density
τ	Non-dimensional time
Φ	Spherical coordinate
ψ	Stream function
Ψ	Non-dimensional stream function

Subscripts

α	Denotes surface of sphere
∞	Reference condition
e	Effective value
$0,1,2,\dots$	Indicates terms in power series

Superscript

• Denotes quantity normalized by division by L

INTRODUCTION

It has been suggested by Bishop and Hollister¹ that the mid-plate, mid-gyre regions of the major oceanic basins be investigated as possible repositories for high level radioactive waste. It was proposed that solidified nuclear waste be encapsulated in suitably designed containers and implanted in the seabed below the surface of the sedimentary layer. This scheme would provide a series of barriers to the release of radionuclides into the environment.

One such potential barrier is the seabed material itself which, although composed primarily of very fine, compacted clay, is still sufficiently porous to permit interstitial pore water migration. An implanted container of waste material, which is generating heat, can cause an upward migration of pore water due to thermally induced convective motion. Interstitial water motion is a key parameter in studies of radionuclide transport which can ultimately determine the effectiveness of the seabed as a barrier to the release of radionuclides into the water column.

In this paper, a simple mathematical model is proposed for the analysis of thermal convection from a concentrated source of heat in a fluid-saturated porous medium of low permeability. It is assumed that the Rayleigh number (Ra) associated with the natural convection process is small enough so that the temperature distribution is unaffected by the fluid motion and is established by thermal conduction. This assumption is shown to be reasonable for parameters typical of the seabed. The temperature field is

then used to predict the associated velocity distribution through use of Darcy's law and the Boussinesq approximation. In essence, the theory consists of retaining only the leading terms of series expansions of the dependent variables in terms of the Rayleigh number. This general approach has been utilized previously by several authors. Yamamoto² used a Rayleigh number expansion to obtain a solution for the steady natural convection induced by a constant temperature sphere embedded in an infinite porous medium. Steady thermal convection induced by a variety of concentrated sources was studied by Hickox⁶ for the limiting case $Ra \rightarrow 0$. Bejan³ presented solutions, in terms of power series in Ra , for transient and steady natural convection induced by a concentrated heat source in an infinite porous medium. Most recently, Hodgkinson⁴ obtained solutions for thermal convection associated with an idealized spherical nuclear waste repository in a permeable rock mass, also for the limiting case $Ra \rightarrow 0$.

Simple, algebraic solutions are obtained for the steady-state thermal and flow fields induced by point and line sources as well as those resulting from a constant temperature sphere embedded in a semi-infinite, fluid-saturated, porous region below a horizontal, permeable boundary on which the temperature and pressure are constant. Based on the work of Bejan, the transient response to an embedded point source is also analyzed for the same geometry. Application of these results to the sub-seabed disposal of nuclear waste is considered. A solution which describes the steady natural convection due to a point source situated at the base of a semi-infinite region is also presented. All solutions are obtained subject to the low Rayleigh number limit, $Ra \rightarrow 0$.

BASIC THEORY

In this section, a mathematical model is developed for the description of axisymmetric free convection in a fluid-saturated porous medium. The medium is assumed to be rigid, homogeneous, and isotropic and the fluid incompressible, with density changes occurring only as a result of changes in the temperature according to

$$\rho = \rho_{\infty} [1 - \beta (T - T_{\infty})] \quad (1)$$

where ρ is the density, T is the temperature, β is the coefficient of thermal expansion, and the subscripts refer to reference conditions. In accordance with the usual Boussinesq approximation, density changes are accounted for only in the buoyancy term in the equations of motion. It is also assumed that the fluid and matrix are in thermal equilibrium and that the fluid motion can be adequately described by Darcy's law. Permeability, viscosity, effective thermal diffusivity, and the coefficient of thermal expansion are assumed constant and dispersion effects are neglected.

The equation of continuity, Darcy's law, and the energy equation are then

$$\text{div } \underline{v} = 0, \quad (2)$$

$$\frac{\mu}{k} \underline{v} = - \text{grad} (P + \rho g z), \quad (3)$$

$$(\rho c_p)_e \frac{\partial T}{\partial t} + \rho_{\infty} c_p \underline{v} \cdot \text{grad } T = \chi_e \text{div} (\text{grad } T), \quad (4)$$

where v , k , μ , κ_e , p , g , ρ , and C_p are, respectively, the velocity vector, permeability, dynamic viscosity, effective thermal conductivity, pressure, acceleration due to gravity, density, and specific heat. The subscript e refers to effective values. The elevation z is measured vertically upward.

Since only axisymmetric convection is to be considered, it is convenient for purposes of analysis to write Equations (2)-(4) in terms of spherical polar coordinates (R, Φ) with associated velocity components (v_R, v_Φ) . In subsequent developments, it will be helpful to also make use of the cylindrical polar coordinates (r, z) with associated velocity components (v_r, v_z) . The relationship between the two coordinate systems is illustrated in Figure 1. The continuity relation given by Equation (2) is identically satisfied through the introduction of an appropriately defined stream function ψ , and the pressure is eliminated by taking the curl of Equation (3) after substituting for the density from Equation (1).

After implementation of the procedure described above, it is also convenient to write the resulting equations in non-dimensional form through the introduction of the non-dimensional parameters

$$r = R/L, \quad z' = z/L, \quad \tau = t \kappa_e / (\rho c_p)_e L^2,$$

$$(v_R, v_\Phi) = \frac{\rho_e c_p L}{\kappa_e} (u_R, u_\Phi), \quad \Psi = \frac{\rho_e c_p}{\kappa_e L} \psi, \quad (5)$$

$$\Theta = \frac{\kappa_e L}{Q} (T - T_\infty),$$

where Q is the rate of energy release from the concentrated source and L is a length scale which can conveniently be set equal to $k^{1/2}$. Equations (1)-(4) can now be written in final, non-dimensional form, as

$$\frac{1}{r^2} \frac{\partial}{\partial \Phi} \left(\frac{1}{\sin \Phi} \frac{\partial \Psi}{\partial \Phi} \right) + \frac{1}{\sin \Phi} \frac{\partial^2 \Psi}{\partial r^2} = Ra \left(\cos \Phi \frac{\partial \Theta}{\partial \Phi} + r \sin \Phi \frac{\partial \Theta}{\partial r} \right), \quad (6)$$

$$\begin{aligned} \frac{\partial \Theta}{\partial r} + \frac{1}{r^2 \sin \Phi} \left(\frac{\partial \Psi}{\partial \Phi} \frac{\partial \Theta}{\partial r} - \frac{\partial \Psi}{\partial r} \frac{\partial \Theta}{\partial \Phi} \right) &= \frac{1}{r^2} \frac{\partial}{\partial r} \left(r^2 \frac{\partial \Theta}{\partial r} \right) \\ &+ \frac{1}{r^2 \sin \Phi} \frac{\partial}{\partial \Phi} \left(\sin \Phi \frac{\partial \Theta}{\partial \Phi} \right), \end{aligned} \quad (7)$$

where Ra is the Rayleigh number

$$Ra = \frac{k \rho_\infty^2 c_p g \beta Q}{\kappa_0^2 \mu}, \quad (8)$$

and the velocities are related to the stream function by

$$V_R = \frac{1}{r^2 \sin \Phi} \frac{\partial \Psi}{\partial \Phi}, \quad V_\Phi = - \frac{1}{r \sin \Phi} \frac{\partial \Psi}{\partial r}. \quad (9)$$

In the limit of small Rayleigh number ($Ra \rightarrow 0$), solutions to Equations (6) and (7) can be sought through expansion of the dependent variables in power series in Ra , viz

$$\begin{aligned} \Psi &= \Psi_0 + Ra \Psi_1 + Ra^2 \Psi_2 + \dots, \\ \Theta &= \Theta_0 + Ra \Theta_1 + Ra^2 \Theta_2 + \dots. \end{aligned} \quad (10)$$

The zeroth-order functions correspond to a state of pure conduction, hence there is no fluid motion and $\Psi_0 = 0$. The zeroth-order temperature distribution is obtained from the solution of

$$\frac{\partial \Theta_0}{\partial \tau} = \frac{1}{r^2} \frac{\partial}{\partial r} \left(r^2 \frac{\partial \Theta_0}{\partial r} \right) + \frac{1}{r^2 \sin \Phi} \frac{\partial}{\partial \Phi} \left(\sin \Phi \frac{\partial \Theta_0}{\partial \Phi} \right). \quad (11)$$

The first non-zero contribution to the stream function is then found from the solution of

$$\frac{1}{r^2} \frac{\partial}{\partial \Phi} \left(\frac{1}{\sin \Phi} \frac{\partial \Psi_1}{\partial \Phi} \right) + \frac{1}{\sin \Phi} \frac{\partial^2 \Psi_1}{\partial r^2} = \cos \Phi \frac{\partial \Theta_0}{\partial \Phi} + r \sin \Phi \frac{\partial \Theta_0}{\partial r}. \quad (12)$$

In the examples which follow, only solutions to the linear system comprised of Equations (11) and (12) will be considered. The linearity of this system can be used to advantage in that superposition of certain basic solutions is thus allowed. However, all solutions are then, of necessity, limited to cases for which the Rayleigh number is small ($Ra \rightarrow 0$).

Also, in the cases to be considered subsequently, thermal energy is released continuously at a finite rate from a concentrated source. Hence, in the absence of any bounding surfaces which can inhibit motion, any deviation from an isothermal state will result in fluid motion. Therefore, no lower limit for the occurrence of natural convective motion is expected.

FUNDAMENTAL SOLUTIONS

In this section, certain fundamental solutions to Equations (11) and (12) are identified for concentrated sources in an unbounded region. These results then form the basis for super-

position models involving more complex boundary geometries. Since it is a straightforward exercise to verify that the quoted results satisfy the appropriate differential equations, details of the solution procedure are omitted.

Steady-State Point Source

When a point source of strength Q is located at the origin of the coordinate system, the appropriate steady-state solutions for the temperature and stream function are

$$\Theta_0 = \frac{1}{4\pi r}, \quad \Psi_1 = \frac{1}{8\pi} r \sin^2 \Phi. \quad (13a,b)$$

From this result, it is apparent that there is a singularity at the origin, and $(T - T_\infty)$ as well as the velocity components approach zero for large r . Additional terms in the series expansion are available in the paper by Bejan. Also, a numerical solution for this situation based on the use of similarity transformations, and valid for any Rayleigh number, was presented by Hickox and Watts.⁵

Transient Point Source

If a point source of strength Q is placed at the origin at time $\tau = 0$, Bejan has shown that the transient response is expressed by

$$\Theta_0 = \frac{1}{4\pi r} \operatorname{erfc} \eta, \quad (14a)$$

$$\Psi_1 = \frac{1}{8\pi} \tau^{1/2} \sin^2 \Phi \left[2\eta \operatorname{erfc} \eta + \frac{1}{\eta} \operatorname{erf} \eta - \frac{2}{\pi^{1/2}} \exp(-\eta^2) \right], \quad (14b)$$

where $\eta = r/2\tau^{1/2}$, erf is the error function, and erfc is the complementary error function. This solution is also singular at the origin and the far-field behavior is the same as that described for the steady-state case.

Steady-State Line Source

The steady-state solution for a vertical line source of length H , coincident with the vertical axis, symmetrically located about the origin, and with strength per unit length Q/H can be obtained from superposition of the fundamental results for a point source as given in Equation (13). Converting to cylindrical polar coordinates and assuming all lengths have been normalized with respect to the length scale L , allows the temperature and stream function to be expressed by the integrals

$$\Theta_0 = \frac{1}{4\pi H'} \int_{-H'/2}^{H'/2} \left[\kappa'^2 + (y' - s')^2 \right]^{-1/2} ds', \quad (15a)$$

$$\Psi_1 = \frac{1}{8\pi H'} \int_{-H'/2}^{H'/2} \kappa'^2 \left[\kappa'^2 + (y' - s')^2 \right]^{-1/2} ds', \quad (15b)$$

where primes denote that the indicated quantities have been normalized by division by the length scale L (i.e., $H' = H/L$, $\kappa' = \kappa/L$, $y' = y/L$, $s' = s/L$), and s' is an integration variable.

Integration then provides the results

$$\Theta_0 = \frac{1}{4\pi H'} \ln \left\{ \frac{y' + H'/2 + \left[(y' + H'/2)^2 + \kappa'^2 \right]^{1/2}}{y' - H'/2 + \left[(y' - H'/2)^2 + \kappa'^2 \right]^{1/2}} \right\}, \quad (16a)$$

$$\Psi_1 = \frac{1}{8\pi H'} \kappa'^2 \ln \left\{ \frac{\beta' + H'/2 + [(\beta' + H'/2)^2 + \kappa'^2]^{\frac{1}{2}}}{\beta' - H'/2 - [(\beta' - H'/2)^2 + \kappa'^2]^{\frac{1}{2}}} \right\}. \quad (16b)$$

These results exhibit a singularity along the portion of the β -axis occupied by the line source and have the same far-field behavior previously discussed in conjunction with the point source solution. For solutions expressed in terms of cylindrical polar coordinates, the velocity components are obtained from the non-dimensional relations

$$V_\kappa = \frac{1}{\kappa'} \frac{\partial \Psi}{\partial \beta'}, \quad V_\beta = -\frac{1}{\kappa'} \frac{\partial \Psi}{\partial \kappa'}. \quad (17a, b)$$

Steady-State, Constant-Temperature Sphere

Yamamoto has analyzed the natural convection process associated with an isothermal sphere of radius a and surface temperature T_a embedded in an infinite porous medium. Retaining only the leading terms of his solution provides

$$\theta_0 = \frac{1}{4\pi r}, \quad (18a)$$

$$\Psi_1 = \frac{1}{8\pi} \left[\frac{Lr}{a} - \left(\frac{Lr}{a} \right)^{-1} \right] \sin^2 \Phi, \quad (18b)$$

where the center of the sphere is coincident with the origin, and the energy release rate from the sphere is $4\pi a K_e (T_a - T_\infty)$. Hence, it is readily deduced that Equations (18) yield a temperature of T_a on the surface of the sphere. The stream function takes on the value zero on the surface of the sphere and velocities approach zero for large r .

Steady-State Point Source at the Base of a Semi-Infinite Region

For a point source situated on the lower, insulated, boundary below a semi-infinite region, the temperature and stream function are given by

$$\theta_0 = \frac{1}{2\pi r}, \quad (19a)$$

$$\Psi_1 = \frac{r}{4\pi} \cos \Phi \left[(\tan \Phi + 1)^{-1/2} - 1 \right], \quad (19b)$$

where the source is, as usual, located at the origin and the behavior for large r is as previously described for a point source. A numerical solution for this case is also presented in the paper by Hickox and Watts.

Although this case is not used in the superposition models described subsequently, it is included for completeness. In order to illustrate the solution for this configuration, isotherms and streamlines obtained from Equations (19) are plotted in Figure 2.

CONCENTRATED SOURCES BELOW A PERMEABLE BOUNDARY

Thermal and Flow Fields

If a thermally active container of nuclear waste material is emplaced in the sediment below the seabed, the situation resembles that depicted in Figure 3 where a concentrated source is located in the sediment a distance D below the sediment-water interface. The interface is represented as a horizontal, permeable boundary on which the pressure and temperature are both constant.

For small Rayleigh number, the thermal and flow fields associated with the concentrated source can be determined approximately through superposition of the solutions to the linear system described by Equations (11) and (12), in the previous section. The boundary conditions at the interface are satisfied by locating an appropriate image of the concentrated source at the mirror image point above the boundary. The image is thus a source of negative strength (sink) located a distance D above the interface. The direction of gravity is also reversed in the image plane.

In Figures (4)-(7), non-dimensional representations are presented for solutions obtained by the superposition principle described above. In all cases, a permeable boundary on which pressure and temperature are constant has been assumed. Figure 4 depicts isotherms and streamlines for steady flow induced by a point source located a distance D below the interface. As an example of the transient behavior associated with a point source, isotherms and streamlines are plotted in Figure 5 for a non-dimensional time τ of 0.1. For large time, the isotherm and streamline patterns approach those of Figure 5. In Figure 6, results for a line source of length H are presented. In this figure, the top of the line source is located a distance D below the interface. Finally, in Figure 7, results for a constant temperature sphere buried a distance D below the interface are presented.

Note on Velocities

Explicit relations for the velocity components associated with a concentrated source can be obtained by differentiation of the formulas for the stream functions given in the previous section.

The relations between velocity components and stream function in spherical and cylindrical polar coordinates are given by Equations (9) and (17), respectively. Once formulas for the velocities are derived for individual sources, superposition can be used to predict velocities for the geometries treated in this section. These results can then be used to predict the fluid particle paths produced by a particular concentrated source, thus providing an estimate of the maximum distance traversed by a fluid particle in a given time interval. This latter result is of some importance in evaluating the potential for convective transport of radionuclides; a topic considered briefly in the following section.

APPLICATION TO SUB-SEABED DISPOSAL OF NUCLEAR WASTE

As an example of the application of the ideas developed in the previous section, brief consideration will be given to the prediction of the flow field associated with the sub-seabed disposal of nuclear waste. Currently, it is conjectured that such a disposal scheme would consist of emplacing a cylindrical canister of nuclear waste material at a depth of approximately 30 m below the sediment-water interface. Suggested canister dimensions are 3 m in length and 0.3 m in diameter. Thermal considerations for the canister design require the initial thermal output to be no greater than 1.5 kW. A generic disposal site, located in the Central North Pacific is currently under study. The water depth and bottom temperature in this region are approximately 5000 m and 1.5°C, respectively.

Referring to Figure 3, it is assumed that the situation described above can be represented by the transient solution for a point source located a given distance below the sediment-water interface. Using current estimates for the thermophysical properties of the sediment, an initial Rayleigh number of approximately 10^{-3} is predicted. The condition of small Rayleigh number, required by the theory, is thus easily satisfied. For a burial time of one year, the corresponding non-dimensional time t is approximately 4.8×10^{15} . Assuming that the power output remains constant over the time period of interest, the associated streamline pattern at the end of one year is illustrated in Figure 3. Thermal properties are such that, at a distance of 3 m from the source, the temperature rise is only approximately 5°C . Hence the thermal field is relatively uninteresting and is not reproduced here.

Analyses using models such as the one just described can provide useful information for studies of the transport of radionuclides inadvertently released from emplaced canisters. In general, the transport of radionuclides in a fluid-saturated porous medium involves the four fundamental processes: convection, diffusion-dispersion, sorption, and radioactive decay. Assuming only weak concentrations of radionuclides in the pore water, the analysis of this section can provide estimates of the fluid velocity necessary to evaluate the convective transport. If the sorption process is temperature dependent, then predictions of the thermal field based on simple models will also prove useful.

The analyses discussed apply only to regions sufficiently far removed from the thermal source so that the physical processes are relatively unaffected by the geometry of the canister. Indications are that this distance need be no greater than a few canister lengths.

DISCUSSION

Subject to the small Rayleigh number limit, $Ra \rightarrow 0$, solutions have been presented which describe the thermal and flow fields produced by an isolated, concentrated, thermal source in a fluid-saturated porous medium. A variety of concentrated sources were considered. All solutions presented were obtained by retaining only the leading terms in expansions of the dependent variables in power series in the Rayleigh number, resulting in a system of linear partial differential equations for the description of the processes involved.

The linearity of the basic system allowed the use of superposition to obtain solutions for concentrated sources embedded in a semi-infinite region below a permeable boundary on which the pressure and temperature were held constant. This particular geometry was used as a model for the sub-seabed disposal of nuclear waste. Although attention was focused on a particular geometry in this paper, the principle of superposition can be used in conjunction with the various fundamental solutions to provide descriptions for a variety of geometries.

Additional comments are perhaps in order regarding the applicability of the results for small but finite values of the Rayleigh number. For a point source embedded in an infinite porous medium, Hickox and Watts have shown that the thermal field is relatively unaffected by convection for Rayleigh numbers less than unity. Hence, the results of this paper are expected to provide accurate descriptions for natural convective flows so long as the Rayleigh number remains less than unity. For the seabed disposal of radioactive waste, a Rayleigh number of only 10^{-3} is anticipated.

Hodgkinson has indicated that Rayleigh numbers on the order of 10^{-2} are expected for disposal of radioactive wastes in a hard rock depository. Hence, it is expected that the current results may find application in the analysis of proposed nuclear waste disposal schemes other than the one treated in this paper. Also, the possibility of applications in the analysis of geothermal systems should not be overlooked.

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FIGURE CAPTIONS

- Figure 1. Axisymmetric Coordinate Systems
- Figure 2. Steady-State Isotherms and Streamlines for a Point Source at the Base of a Semi-Infinite Region
- Figure 3. Concentrated Source Below a Permeable Boundary
- Figure 4. Steady-State Isotherms and Streamlines for a Point Source Located Below a Permeable Boundary
- Figure 5. Transient Isotherms and Streamlines for a Point Source Located Below a Permeable Boundary ($\alpha = 0.1$)
- Figure 6. Steady-State Isotherms and Streamlines for a Line Source Located Below a Permeable Boundary ($D/L = 2$)
- Figure 7. Steady-State Isotherms and Streamlines for a Constant Temperature Sphere Located Below a Permeable Boundary ($D/a = 6$)
- Figure 8. Transient Streamlines at One Year for Sub-Seabed Disposal of Nuclear Waste

Note: Figures not in final form.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8