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AN EXPERIMENTAL STUDY OF NATURAL CONVECTION IN INCLINED POROUS MEDIA

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Abstract—An experimental investigation of natural convection in liquid saturated confined porous medium has shown that the mode and intensity of convective motions are affected by the angle of inclination of the medium and certain properties of the saturating fluid. In systems investigated natural convection started at a Rayleigh number less than that predicted by the linear theory (i.e. $Ra\cos\theta = 4\pi^2$) and the maximum level of convective motion was attained when the heated side of the cell was at an angle of 10 degrees from the horizontal. As the angle of inclination was increased further to 20 and 30 degrees, the convection patterns approached unicellular configuration.

NOMENCLATURE

Roman letters

- Cp, heat capacity [$m^2/s^2\,°K$];
- g, gravitational acceleration, = 9·807 [m/s^2];
- h, heat transfer coefficient [$kg^2/°C\,s^3$];
- K, permeability [m^2];
- L, characteristic length (normal distance between the two isothermal surfaces of the cell);
- Nu, Nusselt number [dimensionless];
- Ra, Rayleigh number [dimensionless];
- T, temperature [°C];
- ΔT_0, $T_h - T_0$ [°C].

Greek letters

- β, coefficient of thermal expansion [$°C^{-1}$];
- θ, angle of inclination with the horizontal [°];
- ρ, density [kg/m^3];
- λ, thermal conductivity [$kg/°C\,s^3$];
- μ, fluid viscosity [kg/m s].

Subscripts

- f, fluid;
- h, at the hot surface;
- m, solid–fluid mixture;
- 0, at the cold surface (reference surface);
- s, solid;
- x, in the direction of x.

Dimensionless numbers

- Nu, Nusselt number, $= \dfrac{hL}{\lambda}$;
- Ra, Rayleigh number, $= \dfrac{\rho_f K g \Delta T_0 L_x Cp_f \beta \rho_0}{\mu \lambda_m}$.

1. INTRODUCTION

NATURAL convection occurs frequently as a result of density inversion caused by either the thermal expansion of a fluid, or the concentration gradients within a fluid system. For a simple physical interpretation of convection, one may consider a horizontal layer of a viscous fluid in which a temperature gradient is set up by heating from below. Convective motions will commence in such a system as soon as the vertical temperature gradient is greater than a given critical value. The buoyancy forces now become strong enough to overcome the opposing viscous retardation forces within the fluid. A theoretical analysis of this problem was first attempted by Lord Rayleigh [14]. He derived the dimensionless group:

$$Ra = \frac{g\rho_0\beta Cp_f \Delta T_0 L_x K \rho_f}{\lambda_m \mu}$$

subsequently named the Rayleigh number, which determines the onset and the magnitude of convective motions in a fluid.

Natural convection can also take place in a porous medium saturated with a fluid, when the medium is heated from below. Lapwood [13] was one of the early investigators to recognize this. In more recent years Wooding [17], Elder [7], Karra [12], Aziz, Holst

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and Karra [1], Combarnous [4], Holst [8], Holst and Aziz [9, 10], Aziz, Kaneko and Mohtadi [2] and Bories [3] have extended the study of natural convection in porous media. It has generally been found that the conditions necessary for the onset of natural convection in porous media are somewhat complex, due to flow restrictions imposed by the solids. Large temperature gradients are normally required to start convective currents. Darcy's law must be used to describe flow in porous media and Navier–Stokes equations for flow in fluid layers.

Natural convection on very large scale occurs both in the atmosphere and within the earth. The phenomenon has long been of interest to geophysicists, astrophysicists, meteorologists and petroleum reservoir engineers. In petroleum reservoirs, natural convection can occur as a consequence of geothermal gradients, thermal stimulation of a reservoir by steam or segregated forward combustion [5]. In all such situations it is highly beneficial to be able to predict the onset of natural convection within the reservoir and the contribution of the convective currents to the transfer of heat from one region to another.

The present investigation was motivated mainly by the interest of the authors in the possibility of enhanced recovery of petroleum from reservoirs by induced natural convection. The paper describes an experimental study of natural convection in porous media where the heated sides are either horizontal or inclined. The Rayleigh number was varied within the range 19–162 by appropriate choice of fluid–solid properties.

2. PREVIOUS WORK

An extensive review of literature on natural convection in porous media presented recently by Holst [8] shows that virtually all past investigators have been concerned with convection in horizontal porous media for which the temperature gradient and the gravitational field are co-linear. Very few investigations have been carried out on natural convection in inclined systems. The only published work covering inclined systems appears to be by Dirksen [6] and Bories [3]. Dirksen found that when the system was inclined more than 10 degrees from the horizontal, convection currents became visible at Rayleigh numbers much smaller than the critical Rayleigh number for horizontal systems. Subsequently, Combarnous [5] obtained heat transfer data for inclined porous media systems. A mathematical solution of the appropriate mass, energy and momentum equations led Holst and Aziz [10] to conclude that the level of convection could depend strongly on the angle of inclination. These authors also concluded that maximum convection should occur at an angle of 40° from the vertical, at Rayleigh numbers of 50–60, provided that the aspect ratio is one.

3. EXPERIMENTAL DETAILS

(a) *The model and the materials*

The experimental model used in the present study was, basically, that used by Holst [8] and described briefly by Holst and Aziz [10]. It consisted of a rectangular box measuring 18 in. × 6 in. × 3 in., constructed from 1/2 in. thick linen base phenolic plastic material with 3/8 in. thick copper plates for the top and bottom surfaces to ensure isothermal boundary conditions. The model was placed on a plywood support base which could be elevated on one side in order to give the desired degree of inclination within the range 0–35 degrees from the horizontal. A schematic diagram of the model is shown in Fig. 1.

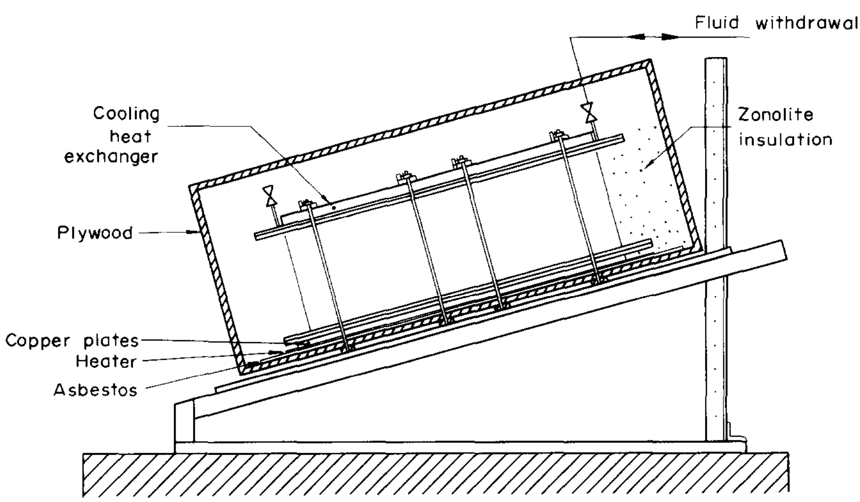

FIG. 1. Schematic diagram of the experimental model.

Uniform heating of the lower surface of the box was provided by means of electric film heaters. The top surface was fitted with a water jacket for cooling. The temperature of the hot (lower) and cold (upper) surfaces of the box was controlled to within ±0·05°C by suitable controllers. Up to 55 thermistor probes (Fenwal Electronics, type GA44LZ) were embedded at various points in the model and 8 probes were attached to the outside walls of the model. Each probe was inserted into transparent 5/64 in. i.d. PVC shrinkable tubing. In order to maintain flexibility and satisfactory insulation, heat was applied to shrink the tubing to a diameter of approximately 1/16 in. The thermistor probes were calibrated prior to their installation in the model. Figure 2 shows the location of probes and their channel numbers.

electric vibrator. This was done to ensure uniform packing. After completion of packing, the model was saturated with the test fluid, using simple suction technique. Heating of the bottom surface and cooling of the top surface of the model was now started simultaneously. The change in temperature of the saturating fluid caused a change of its volume. This was compensated for by provision of an appropriate tap on the top surface of the model. For each experiment simultaneous temperature measurements were made at all thermistor points, at frequent intervals of time. This enabled an accurate knowledge to be obtained of both the transient and steady state temperature distribution within the system for each series of experiments. Steady conditions were obtained normally, after 4–5 h. The reading, recording and processing of experimental data were done with the aid of a Hewlett–Packard data acquisition and reduction system. The central element of the system was an HP2115A digital computer with 8K core capacity. The peripheral supporting equipment consisted of the following:

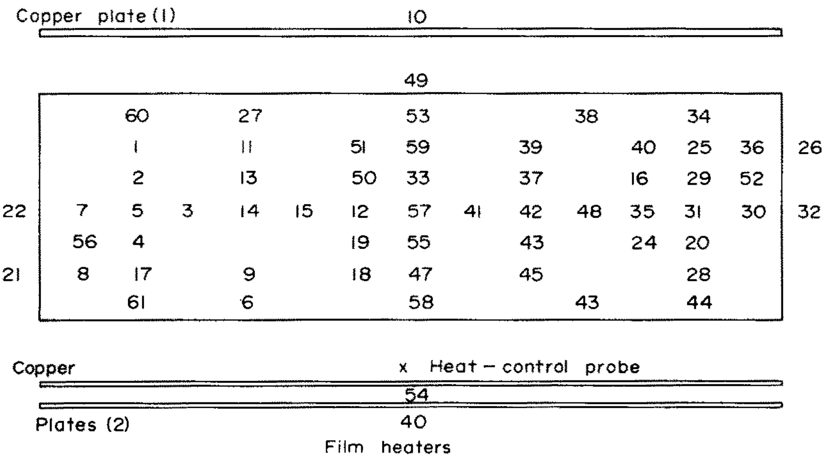

FIG. 2. Location of thermistor probes.

HP2911 Crossbar Scanner
HP2402A Digital Voltmeter (DVM)
ASR Model 33 Teletype Printer
High Speed Paper Tape Reader
HP3030 Magnetic Tape Unit.

A schematic sketch of the experimental apparatus and the data acquisition system used is shown in Fig. 3. A complete description can be found elsewhere [11]. Detailed analysis of results and plotting of figures were carried out on an I.B.M. 360/50 digital computer and a Calcomp plotter.

Heptane and ethanol (Fisher Scientific Inc.—99·5 per cent purity) were used as the saturating fluids. The choice of heptane and ethanol was based on the fact that these liquids were non-toxic, non-corrosive, readily available and had the suitable physical properties for the planned experiments.

Two different grades of silica sands with different permeabilities were employed as porous media (sand-A 14/16 mesh and sand-B 12/14 mesh, both supplied by Gopher State Silica Inc.). The sand particles were essentially spherical in shape and had a narrow size distribution.

(b) *Procedure*

Before an experimental run, the model was pressure tested for leaks. Sand was then slowly poured into the model while the model was being vibrated with an

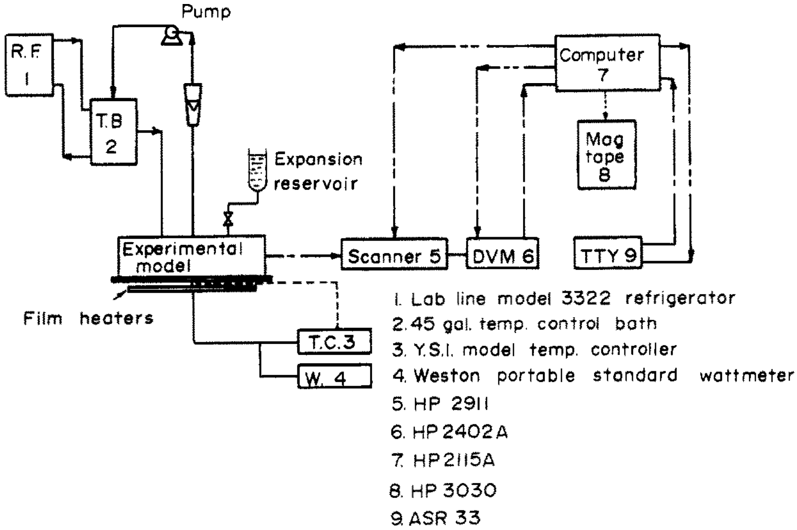

FIG. 3. Schematic sketch of the data acquisition system.

4. RESULTS

The results reported in this paper pertain to a total of 52 experimental runs. Ethanol was used as the saturating fluid in 29 runs and heptane in the remaining 23 runs. Sand-A, was chosen as the solid medium for 17 of the 52 experiments. The angle of inclination was varied from 0° to 30°, from the horizontal and the induced temperature difference between the heated and cooled surfaces of the model ranged from 17·2°C to 57·7°C.

A number of experiments were carried out to obtain conduction heat transfer data for the model using different combinations of porous media and saturating fluids. In some of these experiments the model was heated from the top and cooled from the bottom in order to eliminate convection effects altogether. Good agreement was obtained between the experimentally determined thermal conductivities for the system and the predicted values [15]. Figure 4 shows a typical steady state temperature distribution map obtained for ethanol/sand-A system when the heat transfer was entirely by conduction. In this figure the dimensionless temperature (TEMP) along two isothermal plates is plotted against the dimensionless horizontal distance (Z) in the model.

The density, viscosity, specific heat and the coefficient of thermal expansion of the saturating fluids changed appreciably within the temperature range encountered in the model. The reference temperature used in the calculation of Rayleigh number was the arithmetic mean of the hot and cold surfaces of the model in each experiment.

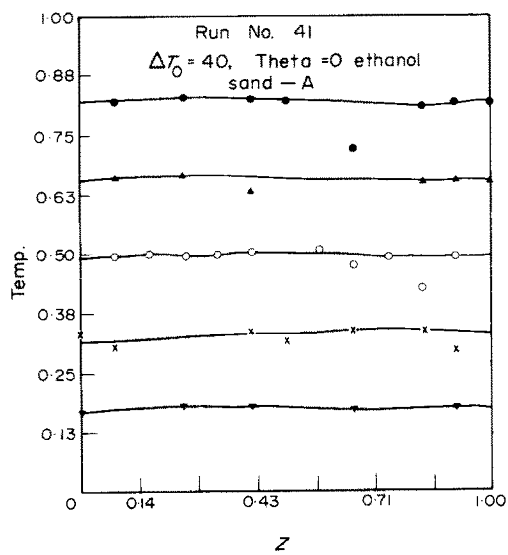

FIG. 4. Steady state temperature distribution for the system, ethanol/sand-A.

(a) *Natural convection in horizontal systems*

The results of these experiments were compiled in terms of the usual dimensionless groups, namely, the Nusselt number and the Rayleigh number. Figure 5 shows the relationship between the steady state Nusselt number and the Rayleigh number for the systems investigated. The results for heptane/sand-B system agree well with the empirical correlation of Elder [7] i.e.

$$Nu = \frac{Ra}{40} \pm 10 \text{ per cent} \qquad (1)$$

shown as the continuous line in Fig. 5. The Nusselt

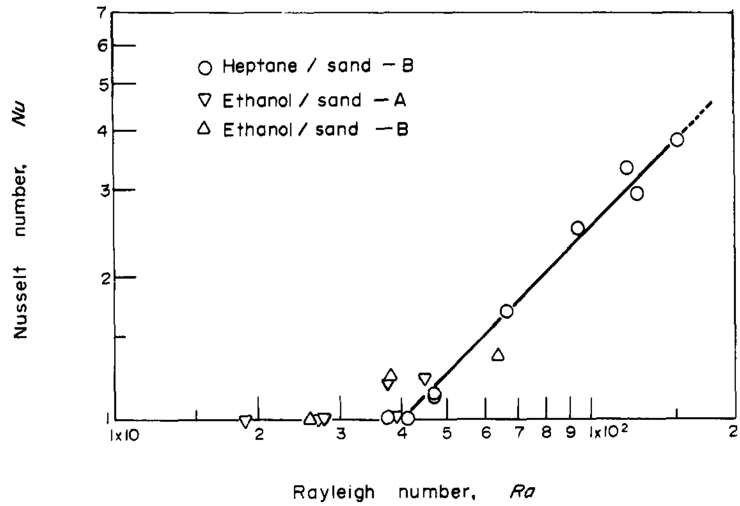

FIG. 5. Nusselt number vs Rayleigh number for horizontal systems.

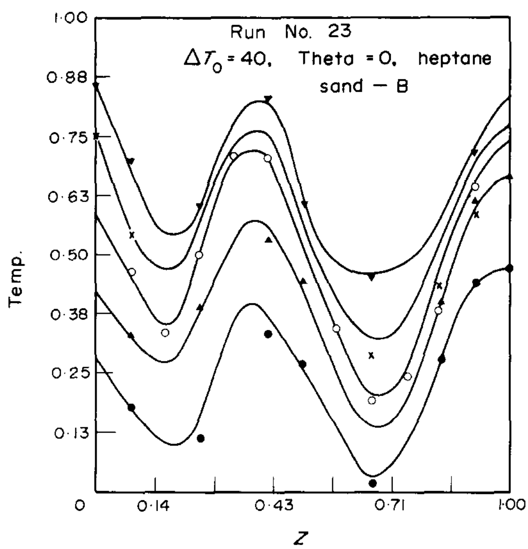

FIG. 6. Effect of ΔT_0 on temperature distribution for the system, heptane/sand-B ($\Delta T_0 = 40°C$).

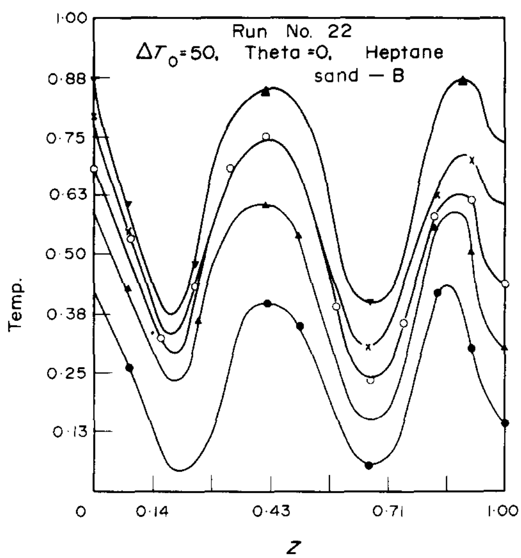

FIG. 7. Effect of ΔT_0 on temperature distribution for the system, heptane/sand-B ($\Delta T_0 = 50°C$).

number in equation (1) is the ratio of effective conductivity over thermal conductivity of the system. The latter can be determined by experiments in which the top plate is heated so as to eliminate convection in the system. Figure 5 also indicates a critical Rayleigh number of approximately 40($\sim 4\pi^2$) which is the value predicted from the linear theory [8] and confirmed experimentally by Combarnous [4] and others. For ethanol/sand systems the critical *Ra* was substantially less than that predicted from the linear theory and was around 28.

The effect of induced temperature difference (ΔT_0) on the steady state temperature distribution for heptane/sand-B system is shown in Figs. 6 and 7. Figure 6 shows that a 4-cell convection pattern is established at $\Delta T_0 = 40°C$. This 4-cell pattern is very stable. At $\Delta T_0 = 50°C$ (Fig. 7), a 5-cell pattern becomes evident but the 5-cell configuration is not very stable. Holst [8] obtained similar results, with the same model but with a different grade of sand.

Typical steady state temperature distribution for ethanol/sand systems are shown in Figs. 8 and 9. These

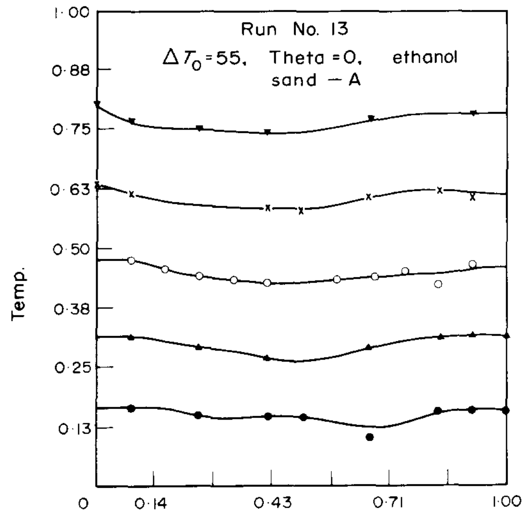

FIG. 8. Effect of ΔT_0 on temperature distribution for the system, ethanol/sand-A ($\Delta T_0 = 55°C$).

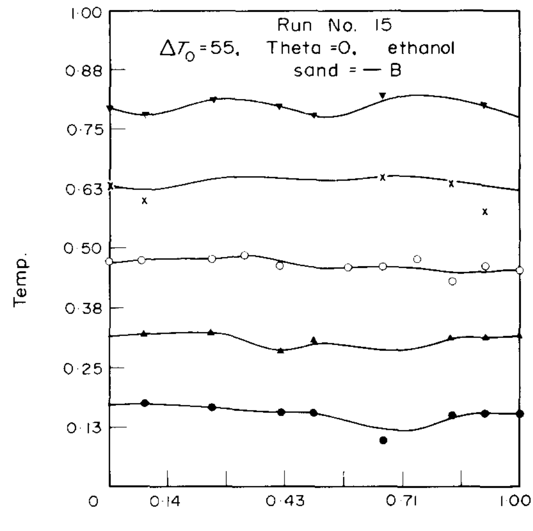

FIG. 9. Effect of ΔT_0 on temperature distribution for the system, ethanol/sand-B ($\Delta T_0 = 55°C$).

figures correspond to Rayleigh numbers of 45 and 64 respectively. It can be seen that at these Rayleigh numbers there is evidently some convection but the change in the Nusselt number, as the Rayleigh number is increased from 45 to 64, is very small (significantly smaller than the corresponding change predicted by equation (1)). This suggests an anomaly. Attempts have been made to explain this anomaly in terms of the temperature dependency of the fluid medium [4, 8, 16] but the explanations are far from adequate.

(b) *Natural convection in inclined systems*

The effect of angle of inclination on the mode of heat transfer in the systems investigated can be inferred with reference to Figs. 10 and 11. Figure 10 shows a plot of experimentally determined Nusselt number against Rayleigh number, for heptane/sand-B system, with the angle of inclination as parameter. Figure 11 is a similar plot for ethanol/sand-B system. These figures reflect the influence of the angle of inclination (θ), particularly the change of angle from 0° to 10°,

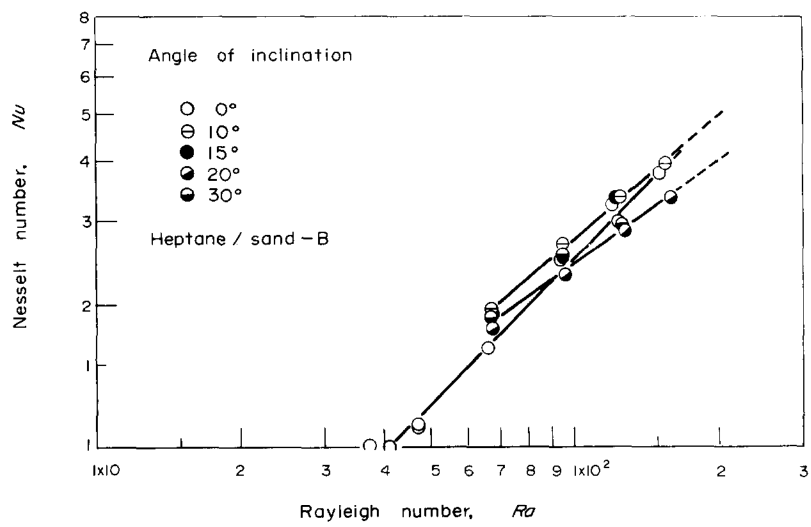

FIG. 10. Effect of angle of inclination on the mode of heat transfer for the system, heptane/sand-B.

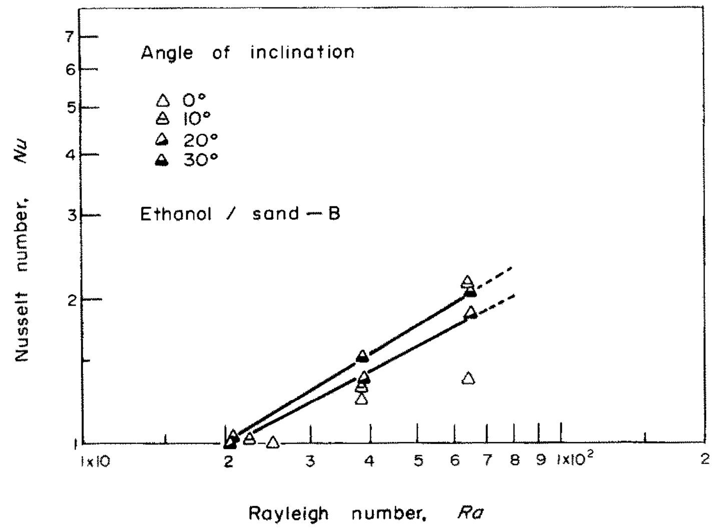

FIG. 11. Effect of angle of inclination on the mode of heat transfer for the system, ethanol/sand-B.

resulting in a significant change in the Nusselt number. Figure 12 shows the steady state temperature distribution for heptane/sand-B system corresponding to a temperature difference (ΔT_0) of 50°C and the angle of inclination (θ) of 10° from the horizontal. It shows clearly that a 3-cell pattern is established under these conditions.

A comparison of Fig. 12 and Fig. 7 suggests that the thermal stability conditions for the horizontal system ($\theta = 0°$) and the inclined system ($\theta = 10°$) are very different. This difference is even more marked for ethanol/sand systems. Figure 13 clearly indicates the presence of cellular convective motion when the $\Delta T_0 =$ 55°C and the angle of inclination is 10° to the horizontal. There is a much lower level of convection in the same system with the same ΔT_0, when the angle of inclination is zero (Fig. 9). This suggests the possibility of the existence of a lower critical Rayleigh number at an angle of 10°.

When the model is in a more sharply inclined

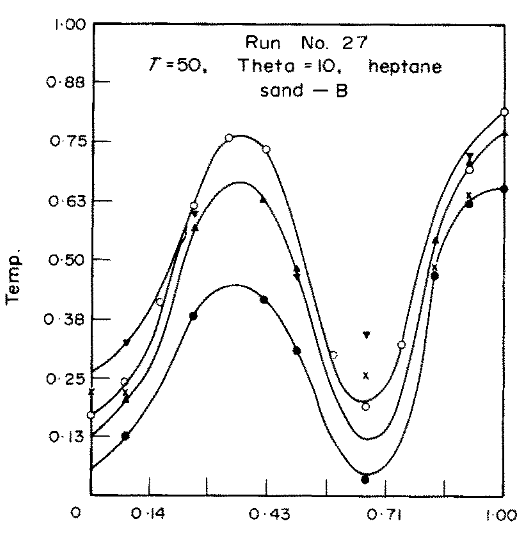

FIG. 12. Temperature distribution for the system, heptane/sand-B ($\theta = 10°$, $\Delta T_0 = 50°C$).

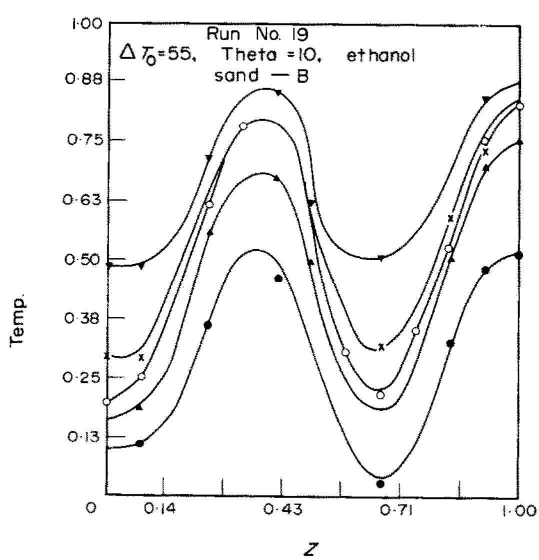

FIG. 13. Temperature distribution for the system, ethanol/sand-B ($\theta = 10°$, $\Delta T_0 = 55°C$).

position, the warm fluid adjacent to the lower (heated) surface of the model tends to flow upwards while the cold fluid adjacent to the upper (cooled) surface tends to flow downwards. This results in the appearance of a single cell motion as shown in Figs. 14 and 15. A plot of steady state Nusselt number as a function of the Rayleigh number of heptane/sand and ethanol/sand systems at different angles of inclination ($\theta = 10°$, 20° and 30°) is shown in Fig. 16. The experimental results can be represented, with reasonable accuracy, by the following expression

$$Nu = 0{\cdot}082\,(Ra\cos\theta)^{0{\cdot}76}. \quad (2)$$

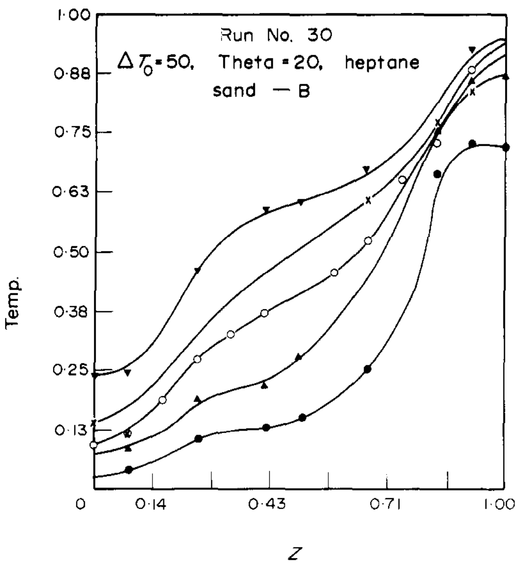

FIG. 14. Single cell convective pattern ($\Delta T_0 = 50°$C, $\theta = 20°$) for the heptane/sand-B system.

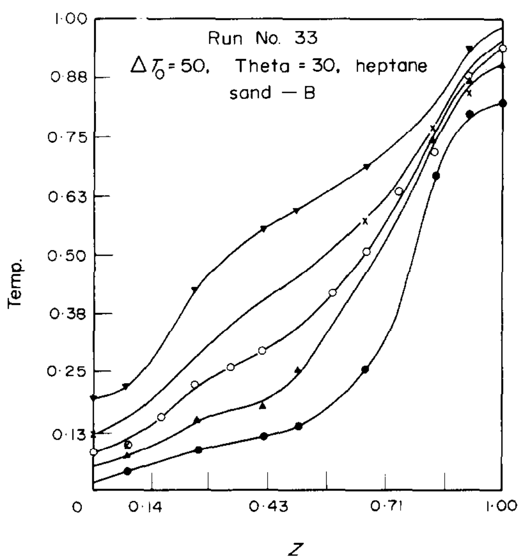

FIG. 15. Single cell convection pattern ($\Delta T_0 = 50°$C, $\theta = 30°$) for the heptane/sand-B system.

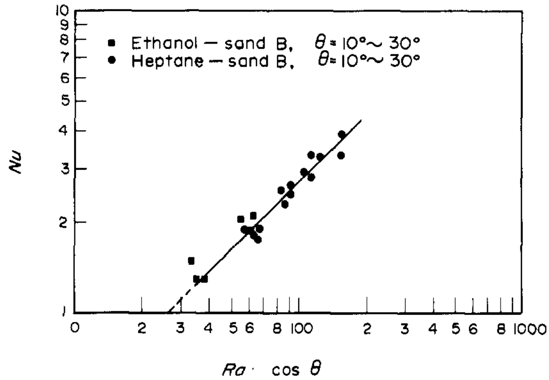

FIG. 16. Nusselt number vs modified Rayleigh number for inclined systems.

5. DISCUSSION

The bulk of published work on natural convection in porous media relates only to horizontal systems and much of this work is theoretical. An attempt is made here to compare the present results with those published previously.

Holst [8] studied, both theoretically and experimentally, the temperature distribution in a horizontal porous medium consisting of 14/16 mesh sand saturated with heptane. The temperature profile theoretically predicted by Holst is shown in Fig. 17 and his experimentally determined profile in Fig. 18. These two figures can be compared with the results of the present investigation, shown in Fig. 19. The Rayleigh number in all three cases was approximately 65. The physical model used in the present work was the same as that used by Holst. However, Fig. 19 represents results obtained for a different grade of sand and for a different temperature gradient. The differences between Figs. 18 and 19 are significant.

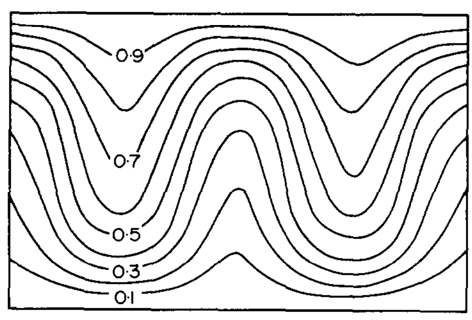

FIG. 17. Theoretical temperature profile of Holst.

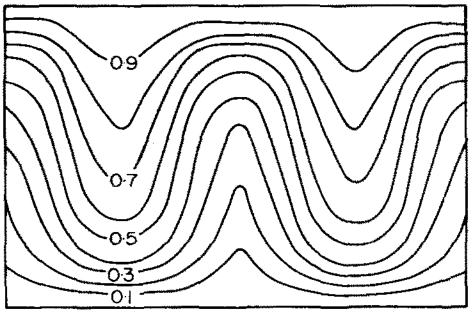

FIG. 18. Experimental temperature profile of Holst.

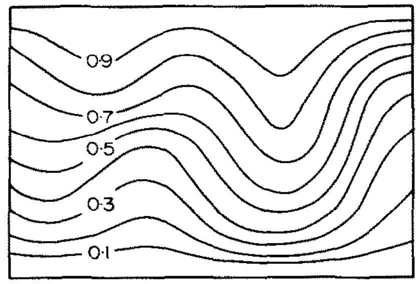

FIG. 19. Experimental temperature profile—present work.

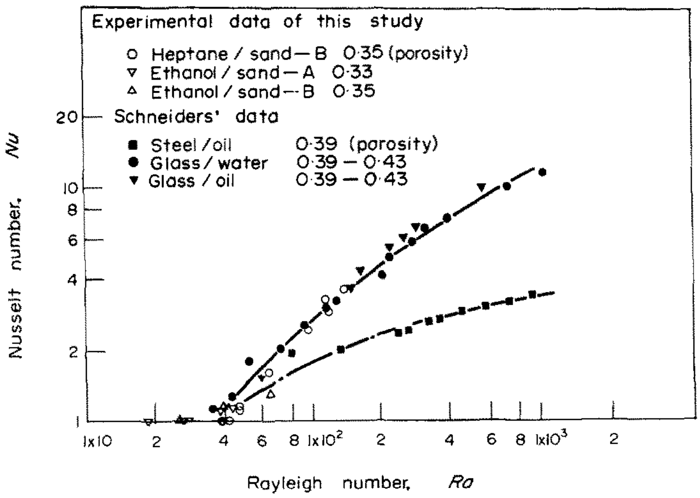

FIG. 20. Comparison of present results with those of Schneider (horizontal systems).

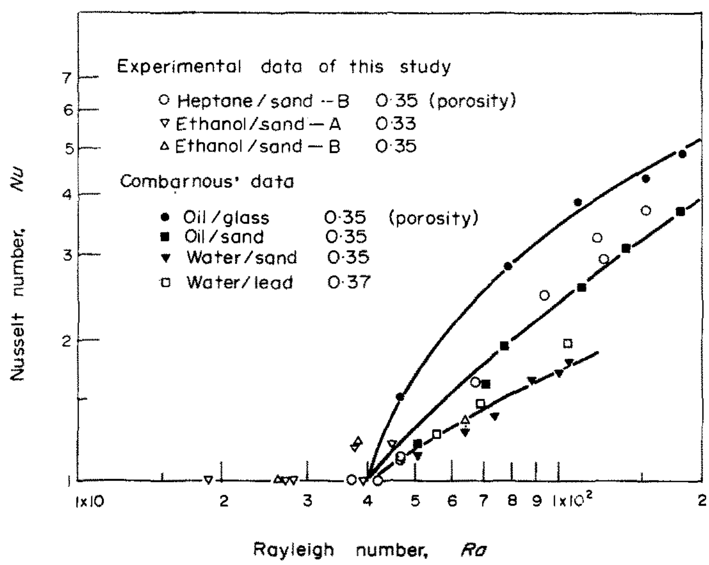

FIG. 21. Comparison of present results with those of Combarnous (horizontal systems).

Schneider [16] and Combarnous [4] investigated natural convection in horizontal systems, using sand, steel spheres, lead spheres, and glass beads as the porous media, and oil and water as the fluid phases. A comparison of the present results with those of Schneider and Combarnous is made in Figs. 20 and 21, in which Nusselt number is plotted against Rayleigh number for each system. The interesting features of these two figures are

1. The close agreement between the results for heptane–sand systems obtained in this study and the oil–sand, and oil–glass systems obtained previously by Combarnous and Schneider.
2. The similarity between the behavior of ethanol–sand system and water–sand, water–lead and oil–steel systems. In all such systems the porous media have high thermal conductivity (e.g. steel and lead) and/or the fluid viscosity is highly temperature dependent (water and ethanol). Consequently a higher temperature gradient is necessary to induce natural convection and the Nusselt number is appreciably lower.

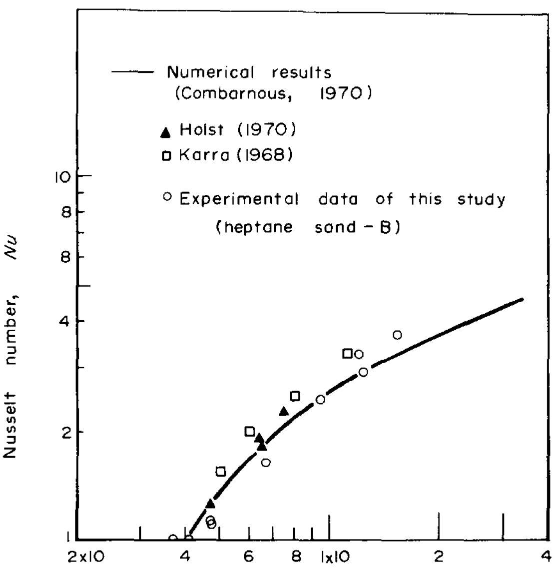

FIG. 22. Comparison of present results with numerical predictions (horizontal systems).

A comparison of the present experimental data with numerical predictions of Karra [12], Combarnous [4] and Holst [8] is given in Fig. 22. As shown clearly in this figure, there is an excellent agreement between the numerical predictions and the experimental results.

For inclined systems, the only data with which we can compare the present results are those reported by Combarnous [4] and Bories [3]. The comparison with Combarnous' results is shown in Figs. 23 and 24.

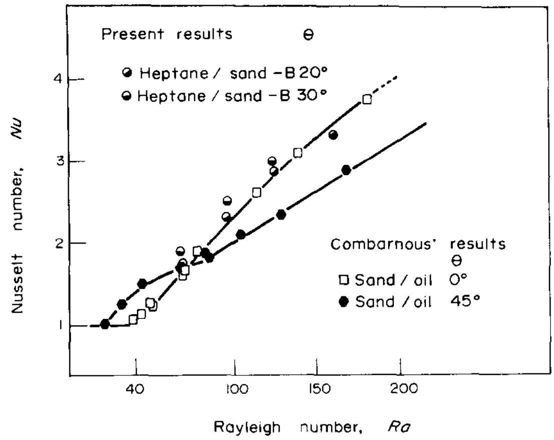

FIG. 23. Comparison of present results for the system heptane/sand-B ($\theta = 20°$ and $30°$) with the system oil/sand ($\theta = 0°$) of Combarnous.

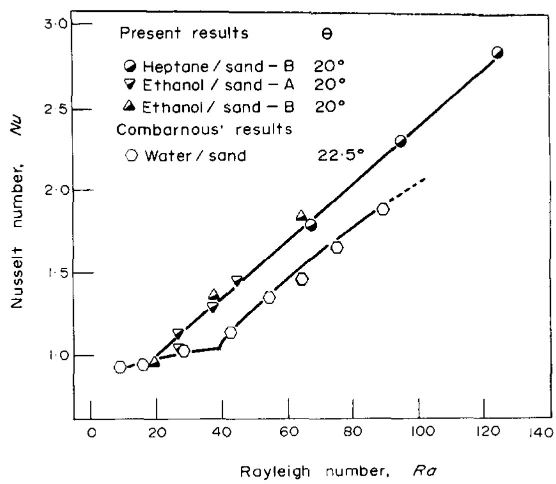

FIG. 24. Comparison of present results for the systems ethanol/sand and heptane/sand ($\theta = 20°$) with the system water/sand ($\theta = 22{\cdot}5°$) of Combarnous.

It is interesting to note that the line for $\theta = 45°$ in Fig. 23, intersects the line for $\theta = 0°$ at a Rayleigh number of approximately 75. In addition, the Nusselt numbers for $\theta = 45°$ in oil–sand system are significantly lower than the corresponding values for $\theta = 0°$ when Ra number is greater than 75. A similar trend was noted in the present work (see Fig. 10). It is apparent from Fig. 24, that the slopes of Nu vs Ra curves for the heptane/sand, ethanol/sand and water/sand systems are approximately equal but the critical Rayleigh numbers are appreciably different.

Bories [3] has recently shown that for inclined systems the product $Ra\cos\theta$ must exceed $4\pi^2$ before multi-cellular convection can take place. A comparison of the present results with those obtained by Bories is shown in Fig. 16. The solid line in this figure represents the best fit for Bories' results. It can be seen that the present experimental values are closely grouped around Bories' results. Unfortunately Bories gives no information on the nature of the porous media and the fluids used in his work.

CONCLUSIONS

1. For heptane/sand systems maintained in the horizontal position the critical Rayleigh number for the onset of natural convection can be predicted from the linear theory. Above this critical value, the Nusselt number and Rayleigh number can be correlated by equation (1). For ethanol/sand systems, the critical Rayleigh number is appreciably smaller than the predicted value. Sufficient data are not available for development of a correlation between Ra and Nu for this system.

2. The maximum number of convective cells appears to occur at an angle of 10° from the horizontal. With further increase in the angle of inclination, the multicellular motion is transformed to a unicellular pattern. For the systems studied, Nu and $Ra\cos\theta$ are correlated by equation (2).

3. Physical properties of the system, in particular the thermal conductivity of the disperse solid phase and the viscosity and the coefficient of thermal expansion of the fluid phase seem to influence the mode and intensity of convective currents.

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ETUDE EXPERIMENTALE DE LA CONVECTION NATURELLE DANS DES MILIEUX POREUX INCLINES

Résumé – Une recherche expérimentale sur la convection naturelle dans un milieux poreux saturé de liquide montre que le mode et l'intensité des mouvements de convection sont sensibles à l'inclinaison du milieu et à certaines propriétés du fluide. Dans les systèmes étudiés, la convection naturelle commence à un nombre de Rayleigh inférieur à celui qui est prévu par la théorie linéaire (soit $Ra\cos\theta = 4\pi^2$) et le niveau maximal du mouvement convectif est atteint quand le côté chauffé de la cellule fait un angle de 10 degrés avec l'horizontale. Lorsque l'angle d'inclinaison augmente jusqu'à 20, 30 degrés, la configuration de la convection s'approche du type unicellulaire.

EINE EXPERIMENTELLE UNTERSUCHUNG DER FREIEN KONVEKTION IN GENEIGTEN PORÖSEN STOFFEN

Zusammenfassung – Eine experimentelle Untersuchung freier Konvektion in einem flüssigkeitsgesättigten, begrenzten porösen Stoff hat gezeigt, daß die Art und die Intensität der Konvektionsbewegungen vom Neigungungswinkel des Stoffes und von gewissen Eigenschaften der Sättigungsflüssigkeiten abhängt. In den untersuchten Systemen setzt die freie Konvektion bei einer Rayleigh-Zahl ein, die kleiner war als von der linearen Theorie vorausgesagt (d.h. $Ra \cos \theta = 4\pi^2$). Die höchsten Werte der Konvektionsbewegung wurden ereicht, wenn die beheizte Seite der Zelle einen Winkel von 10° zur Horizontalen bildete. Wenn die Neigungswinkel auf 20° und 30° erhöht wurden, näherten sich die Konvektionsformen einer einzelligen Anordnung.

ЭКСПЕРИМЕНТАЛЬНОЕ ИССЛЕДОВАНИЕ ЕСТЕСТВЕННОЙ КОНВЕКЦИИ В НАКЛОННЫХ ПОРИСТЫХ СРЕДАХ

Аннотация — Экспериментальное исследование естественной конвекции в насыщенной жидкостью ограниченной пористой среде показало, что угол наклона среды и некоторые свойства насыщающей жидкости влияют на тип и интенсивность конвективных движений. В исследуемых системах естественная конвекция возникала при числе Релея, значение которого меньше рассчитанного по линейной теории (т. е. $Ra \cos \theta = 4\pi^2$), а максимальный уровень конвективного движения достигался в том случае, когда нагретая сторона ячейки находилась под углом 10° к горизонтали. При дальнейшем увеличении угла наклона до 20 и 30° структура конвективного движения принимала вид одноячейковой конфигурации.