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Validation of thermal equilibrium assumption in free convection flow over a cylinder embedded in a packed bed☆

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ABSTRACT

The validity of the local thermal equilibrium assumption in the free convective steady flow over a circular cylinder heated at constant temperature and embedded in a packed bed of spheres is investigated numerically. For this purpose, the *Forchheimer–Brinkman-extended* Darcy momentum model and the local thermal non-equilibrium energy model are solved numerically using a spectral element method. Numerical solutions obtained over broad ranges of representative dimensionless parameters, i.e. Rayleigh number ($10^3 \le Ra \le 5 \times 10^7$), solid-to-fluid thermal conductivity ratio ($0.1 \le kr \le 10^4$), cylinder-to-particle diameter ratio ($20 \le D/d \le 100$), porosity ($0.3 \le \varepsilon \le 0.7$), are used to present conditions at which the local thermal equilibrium assumption can or cannot be employed. This study yields that the local thermal equilibrium *LTE* assumption is true at lower Rayleigh number, higher solid-to-fluid thermal conductivity ratio, higher cylinder-to-particle diameter ratio and lower porosity. In addition, it is found that the solid conductivity has the significant influence on satisfying the *LTE*, where it is completely satisfied in the system for all values of flow and structural parameters, i.e. Ra, D/d and ε, at higher kr, and vice versa, it cannot be satisfied at lower kr, for the whole ranges of other parameters.

1. Introduction

It has been established that the local thermal equilibrium (*LTE*) energy model for convection in porous media, which assumes thermal equilibrium between the solid and fluid phases, is not necessarily a good approximation depending on problem parameters. The analysis of heat transfer in porous media based on the local thermal non-equilibrium (*LTNE*) energy model has been found to be more involved as the use of the two-phase model requires information on additional modes of heat transfer that emerge to account for the energy interaction between the two phases. Therefore, many researchers have utilized the *LTE* model for predicting flow and thermal fields in porous media without investigating the validity of the assumption of *LTE*, which is very necessary. The origin of the two-phase model is the classical model established by Schumann [26] who proposed a simple two-equation formulation to account for the non-equilibrium condition for forced convective incompressible flow in a porous medium. The Schumann model is a simplified model which neglects the diffusion terms in both phases, and predicts the mean fluid and solid thermal fields as a function of axial position and time. In recent years, more attention has been paid to the *LTNE* model and its use has considerably increased in numerical and theoretical research for convection heat transfer in porous media.

By using the *LTNE* model, there has been a considerable effort in assessing the validity of the *LTE* assumption in forced convection flows through porous media. Whitaker and his co-workers, Carbonell and Whitaker [6], Whitaker [28], Quintard and Whitaker [21] and Quintard and Whitaker [22], have performed a pioneering work in this regard. Based on the order of magnitude analysis, they proposed a criterion in the case where the effect of conduction is dominant in porous channel. Lee and Vafai [15] presented a practical criterion for the case of Darcian flow in channel subjected to a constant heat flux. Later, Kim and Jang [13] presented a general criterion for the *LTE* expressed in terms of important engineering parameters such as Darcy, Prandtl and Reynolds numbers. Their criterion which was checked to be applied for conduction and/or convection heat transfer in porous media, is more general than previous one suggested by Whitaker and his co-workers above.

Nield [19] clarified the circumstances under which the *LTNE* may be important in a saturated porous channel using an analytical approach for phase temperature fields and Nusselt number. The analytical work of Minkowycz et al. [16] established a new area of failure for the *LTE* assumption corresponding to the presence of rapidly changing surface heat flux. They investigated the conditions when there is a relatively

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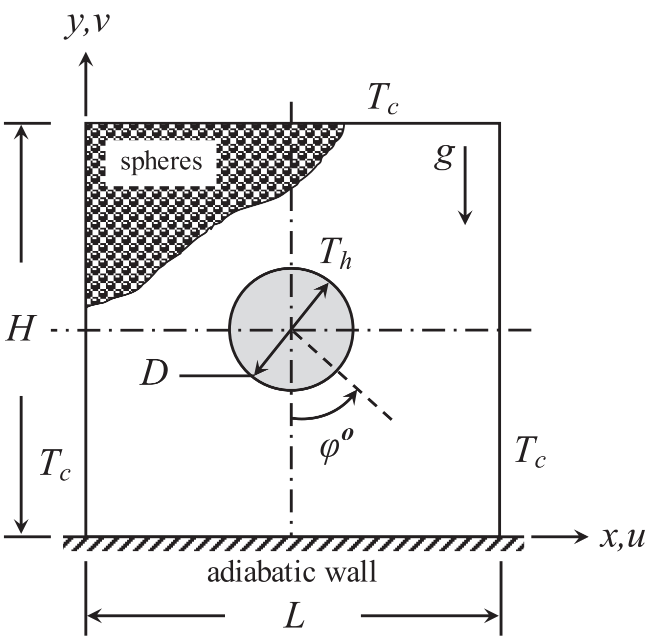


Fig. 1. Physical model and coordinate system.

small departure from the *LTE* condition due to a rapid transient heating for a saturated porous medium. The applicability of the *LTE* model for the micro-channel sink was also analytically assessed by Kim et al. [14] for the case where the bottom surface is uniformly heated by constant heat flux and the top surface is insulated.

Numerically, Vafai and Sözen [27] assessed the validity of the *LTE* assumption for a forced convective gas flow through a packed bed of uniform spherical particles by presenting an error contour maps based on qualitative ratings for three types of materials; lithium-nitrate-trihydrate, sandstone and steel. Following, Amiri and Vafai [1] examined this validity in a packed bed confined by walls at constant temperature, using the same qualitative error maps used by Vafai and Sözen [27]. Khashan and Al-Nimr [12] presented quantitative *LTE–LTNE* region maps for the problem of non-Newtonian forced convective flow through channel filled with porous media for a broad ranges of representative dimensionless parameters such as Péclet number, Biot number, power-law index, fluid/solid thermal conductivity ratio and microscopic and macroscopic frictional flow resistance coefficients, to examine whether the *LTE* assumption can or cannot be employed. Celli and Rees [7] analyzed analytically and numerically the effect of the *LTNE* on forced convective thermal boundary layer flow in a saturated porous medium over a horizontal flat plate. This effect was found to be at its strongest close the leading edge with $O(x^{-1})$ in magnitude, but the maximum discrepancy between the temperature fields decreases with the distance from the leading edge, and the *LTE* condition is attained at large distance.

The validity of the equilibrium model has also been addressed for natural convection, but with perhaps less attention. Baytas and Pop [5], Banu and Rees [3], Baytas [4], Saeid [24], Badruddin et al. [2] and Saeid [25] all have found that when the interfacial heat transfer coefficient and the porosity-scaled fluid-to-solid thermal conductivity ratio have large values then the thermal equilibrium state is approached in the two-phase porous system, i.e., both fluid and solid phases have the same thermal field and Nusselt number. In addition, the results of

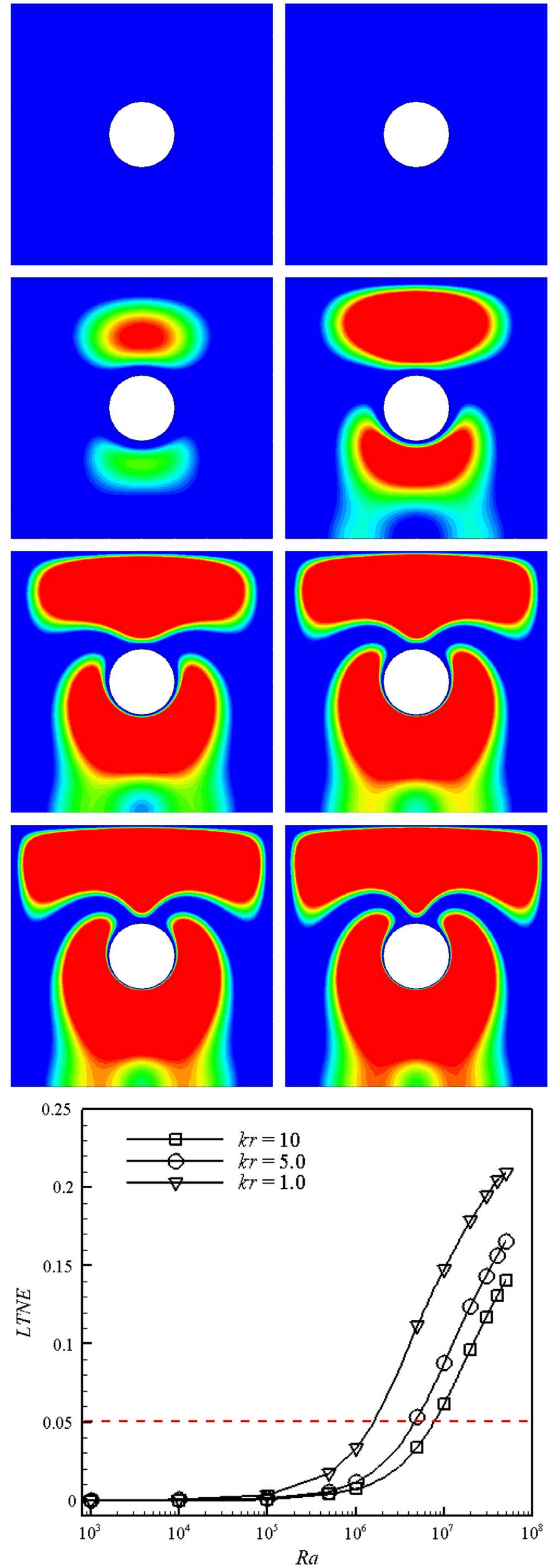


Fig. 2. Effect of *Ra* on: (Left) the local temperature difference between the fluid and solid phases around the heated cylinder, from top left to bottom right $Ra = 10^5$, 10^6, 5×10^6, 10^7, 2×10^7, 3×10^7, 4×10^7 and 5×10^7, at $kr = 10$, with red (blue) colors have magnitudes of ≥ 0.1 (≤ 0.05), and (Right) the *LTNE* parameter against *Ra* for different values of *kr*. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Mohamad [17] indicated that the *LTE* model is difficult to justify for the non-Darcy regime, and when the thermal conductivity of the solid phase is higher than that of the fluid phase. Rees and Pop [23] who used an asymptotic analysis to investigate free convective boundary-layer flow close to a vertical plate emphasized on that the thermal equilibrium between the two phases is justified at increasing distances from the leading edge. Mohamad [18] who used a different approach to examine numerically the same convective boundary-layer of Rees and Pop [23] pointed out that the non-equilibrium parameter, fluid/solid conductivity ratio and the porosity of the porous medium used have a significant influence on the thermal equilibrium condition. It was revealed that this condition becomes unjustified if the solid conductivity is equal to or greater than fluid conductivity, the non-equilibrium parameter less than or equal to unity and the porosity is high.

Moreover, based on their numerical and experimental results, Phanikumar and Mahajan [20] concluded that for the material of metal foams in general, the developed *LTNE* energy model must be employed instead of the traditional *LTE* model. They reported that the *LTNE* effects become significant at high Rayleigh and Darcy numbers. Haddad et al. [10] found that the *LTE* assumption is mainly controlled by four parameters which are Biot, Rayleigh, Darcy numbers and the ratio of effective to dynamic viscosity, in the problem of free convection over a vertical flat plate embedded in porous media. In their study, it was mentioned that this assumption is not valid for relatively low values of Darcy, Biot numbers and viscosity ratio, and high values of Rayleigh number. Khashan et al. [11] observed that in a porous rectangular cavity heated from below the effect of the *LTNE* depreciates as Darcy decreases, and as the effective fluid/solid conductivity ratio, Rayleigh and Biot numbers increase. They presented contours for the local *LTNE* parameter, which is the phase temperature difference, within the entire cavity, at various values of Rayleigh number.

By reviewing the literature, it appears that the validity of the *LTE* assumption has been fairly assessed in the natural convection mode of heat transfer. However, this assessment has been only tested in porous channels or over flat plates where the flow fields are considerably simpler. Therefore, an aim is to investigate the validity of the *LTE* assumption for the application of free convection heat transfer from a circular cylinder embedded in a packed bed of spheres and to find the conditions under which this assumption would be justifiable. The departure from local thermal equilibrium is to be captured by solving the problem numerically using the *LTNE* model that incorporates the effect of thermal dispersion. A *Brinkman–Forchheimer-extended* Darcy model that incorporates non-Darcian effects, i.e., including the solid boundaries and inertia effects, is adopted to accurately predict the hydrodynamic behavior.

2. Analysis

The analysis is carried out for steady two-dimensional free convective laminar flows over a circular cylinder embedded in a homogenous and isotropic packed bed of spheres as shown in Fig. 1. The cylinder of diameter D is buried in an enclosed packed bed of spherical particles of overall height $H = 4D$ and length $L = 4D$. The bed is surrounded on four sides by impermeable boundaries. The lower horizontal wall is adiabatic, while other walls are held at a constant temperature T_c. The surface temperature of the cylinder is suddenly changed to T_h at time $t > 0$, and subsequently maintained at that temperature. This sudden change in the temperature introduces unsteadiness in the flow field. The mathematical formulation of the problem and the numerical method of

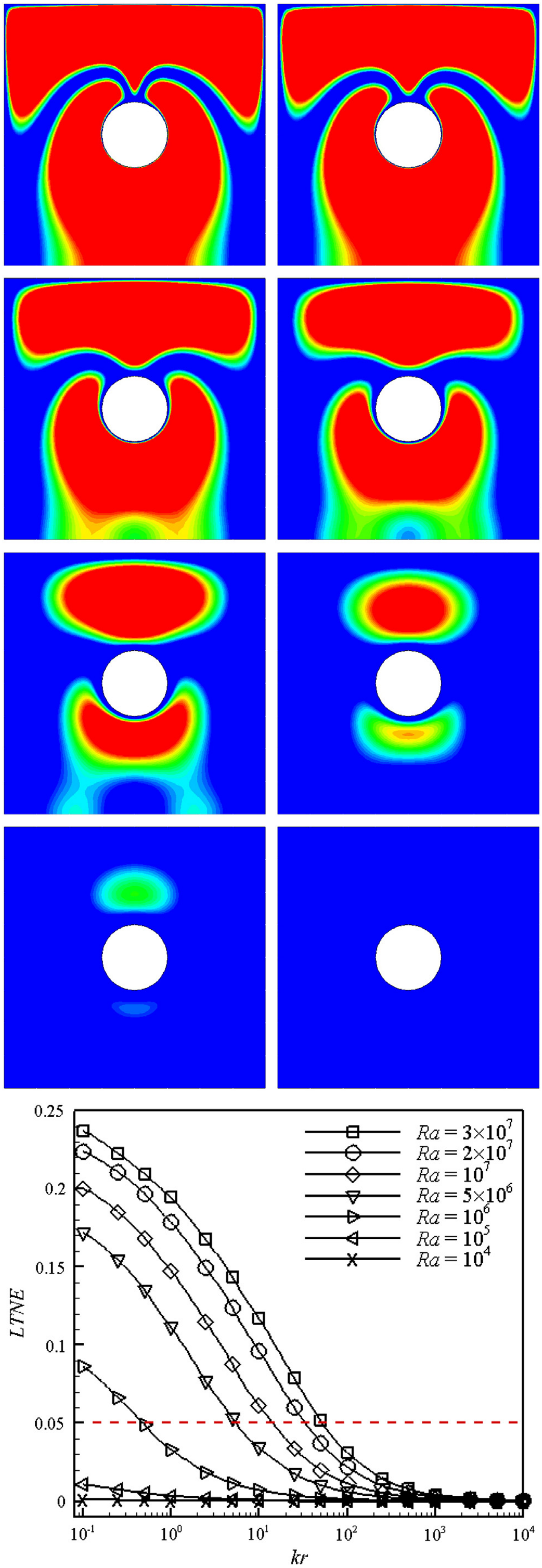


Fig. 3. Effect of kr on: (Left) the local temperature difference between the fluid and solid phases around the heated cylinder, from top left to bottom right $kr = 0.25$, 1, 5, 10, 25, 50, 100 and 500, at $Ra = 2 \times 10^7$, with red (blue) colors have magnitudes of ≥ 0.1 (≤ 0.05), and (Right) the *LTNE* parameter against kr for different values of Ra. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

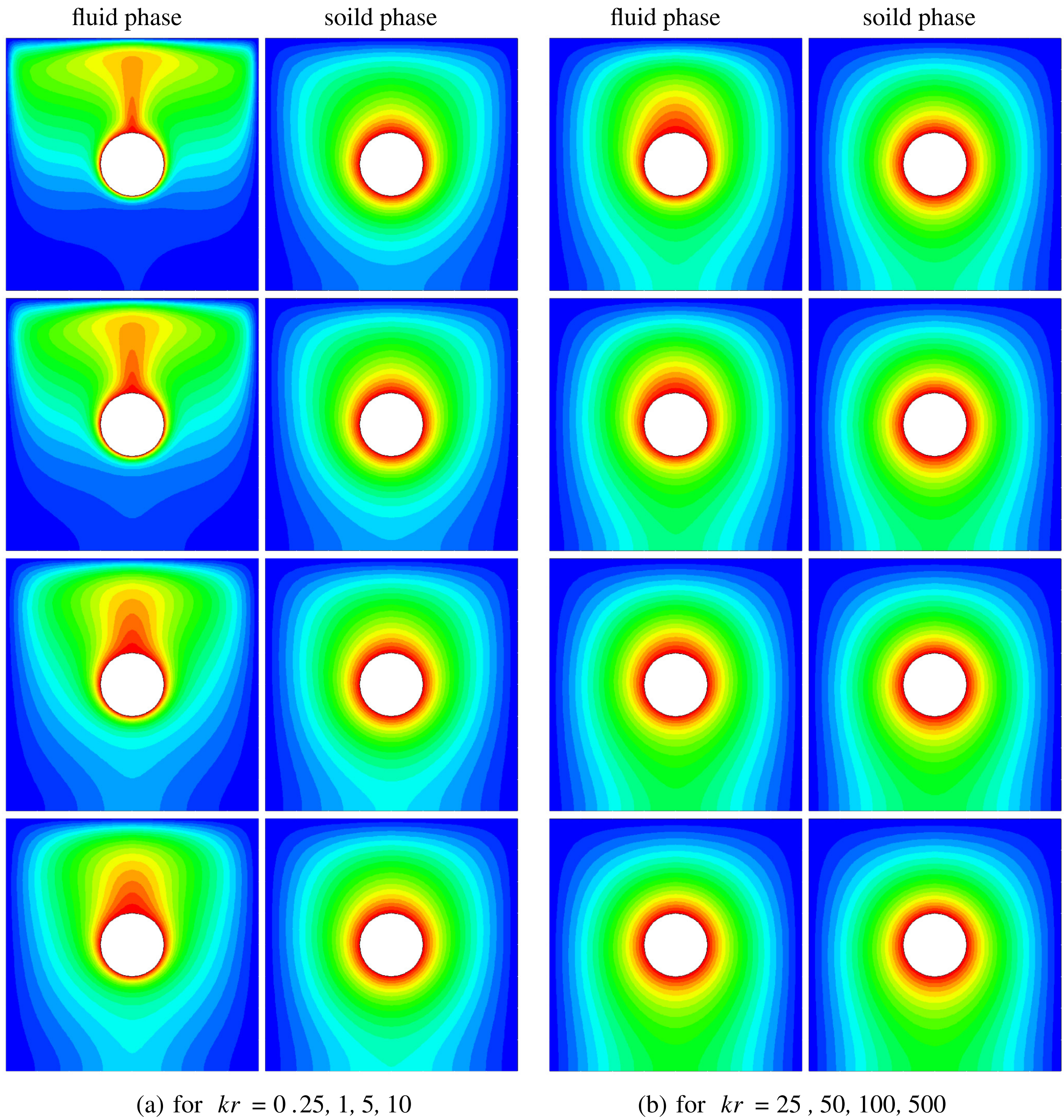


Fig. 4. Temperature distributions for both fluid and solid phases, for different values of *kr*, from top to bottom, (a) $kr = 0.25, 1, 5, 10$ and (b) $kr = 25, 50, 100, 500$, at $Ra = 2 \times 10^7$, with red (blue) colors have magnitudes of 1 (0). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

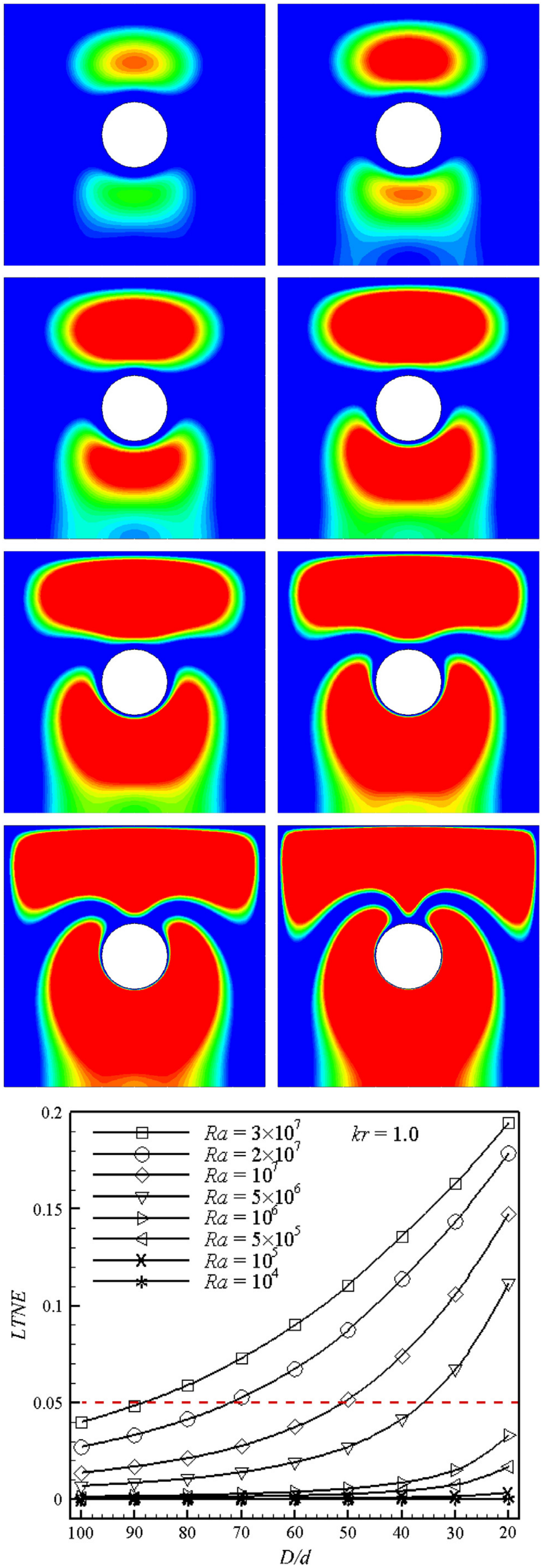
solution with the accuracy test of the computational code used are described in detail in our previous work of Gazy and Mark [8], except Biot number *Bi* that has been taken as a unity in this study.

3. Results and discussion

The assessment of the *LTE* assumption and the corresponding one-equation energy model was investigated under various flow conditions and porous medium thermal and structural properties. This was accomplished by introducing a number of dimensionless groups such as Rayleigh number $Ra \in [10^3, 5 \times 10^7]$, solid-to-fluid thermal conductivity ratio $kr \in [0.1, 10^4]$ which covers a wide range of metallic and non-metallic porous materials with air chosen as the working fluid with $k_f = 0.025(W/m \cdot K)$ and $Pr = 0.71$, cylinder-to-particle diameter ratio $D/d \in [20, 100]$, and porosity $\varepsilon \in [0.3, 0.7]$. The degree of non-equilibrium is calculated by using the *LTNE* parameter defined as:

$$LTNE = \frac{\Sigma_N |\theta_s - \theta_f|}{N}, \tag{1}$$

where θ_s and θ_f are the dimensionless solid and fluid temperature, respectively, and N is the total number of nodes in the domain. This equation which was used by Wong and Saeid [29] and Gazy et al. [9] is a simple measure of the mean difference between the fluid and solid



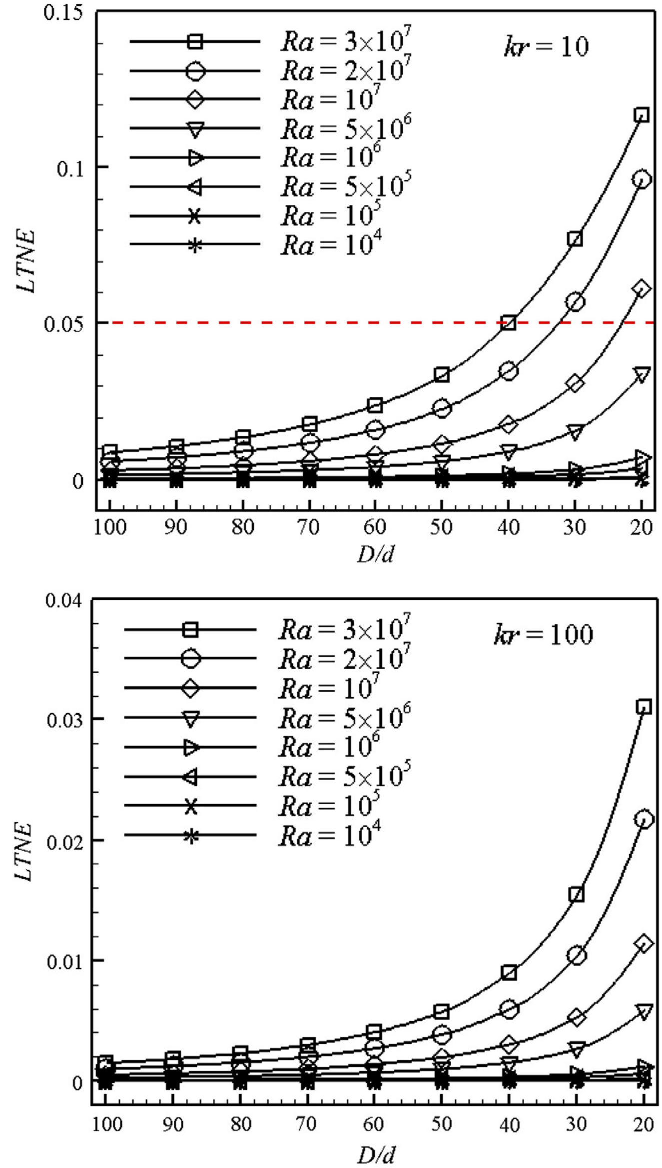


Fig. 6. The trends of *LTNE* against *D/d* at different *kr*: (Left) $kr = 10$, and (Right) $kr = 100$, and for different values of *Ra*.

over the domain. In essence, to validate the *LTE* assumption, the local temperature difference between the fluid and solid phases should be negligibly small. Thus, the *LTE* condition can be declared to be satisfied when the *LTNE* parameter becomes less than 0.05.

Fig. 2 shows the results of the effect of Rayleigh number *Ra* on the *LTNE* parameter at different values of thermal conductivity ratio *kr*, and on isotherms of the local temperature difference between the fluid and solid phases inside the packed bed and around the heated cylinder. These results are obtained at $D/d = 20$ and $\varepsilon = 0.5$. It is obvious from this figure that the decrease in *Ra* causes the *LTNE* to decrease, and approaching towards thermal equilibrium between the two phases. The elevation of *Ra* values corresponds to high convection heat transfer rates released from the cylinder and subsequently higher speed flows in the bed. Also, the influence of increasing *Ra* value seems more

Fig. 5. Effect of *d* on: (Left) the local temperature difference between the fluid and solid phases around the heated cylinder, from top left to bottom right $D/d = 90 - 20$ in step of 10, at $Ra = 2 \times 10^7$ and $kr = 1.0$, with red (blue) colors have magnitudes of ≥ 0.1 (≤ 0.05), and (Right) the *LTNE* parameter against *D/d* for different values of *Ra*. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

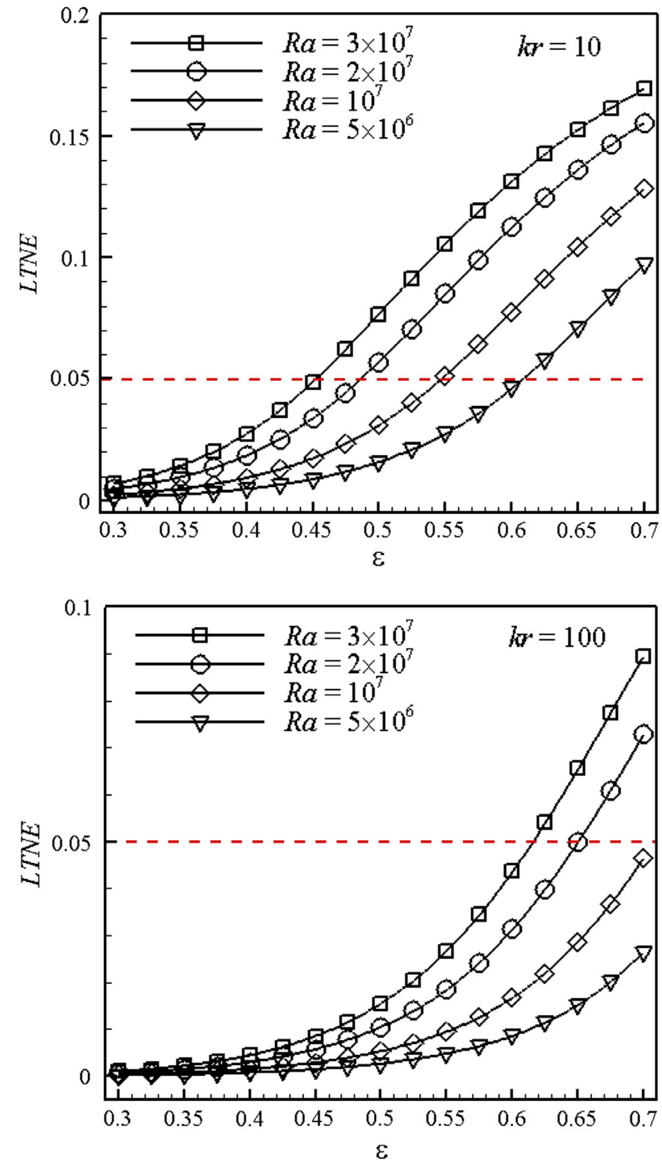


Fig. 8. The trends of *LTNE* against ε at different *kr*: (Left) $kr = 10$, and (Right) $kr = 100$, and for different values of *Ra*.

significant at the low *kr* value of equal or less than unity. At this stage, the conductive thermal energy transfered from the heat source to the solid phase is quite low due to the high thermal resistance. Then, this suppresses the sensitivity of the solid phase to *Ra* variation, which is different from the fluid phase. As the magnitude of *kr* value is increased; however, the significance of *Ra* variation becomes noticeable in the solid phase. This is likely attributed to the increase in the solid effective thermal conductivity over its fluid counterpart for $kr > 1$. As shown, the response of the solid phase to *Ra* variations as *kr* increases decreases the temperature discrepancy between the two phases. This is clear at high values of $Ra > 10^6$. The isotherms which are obtained at $kr = 10$ illustrate that the domain of the local *LTNE* condition appears to extend around the cylinder and in the vicinity of the top wall of the bed with the increase in *Ra* value. Apparently, higher speed flows as *Ra* increases do not allow sufficient energy communication between the phases to

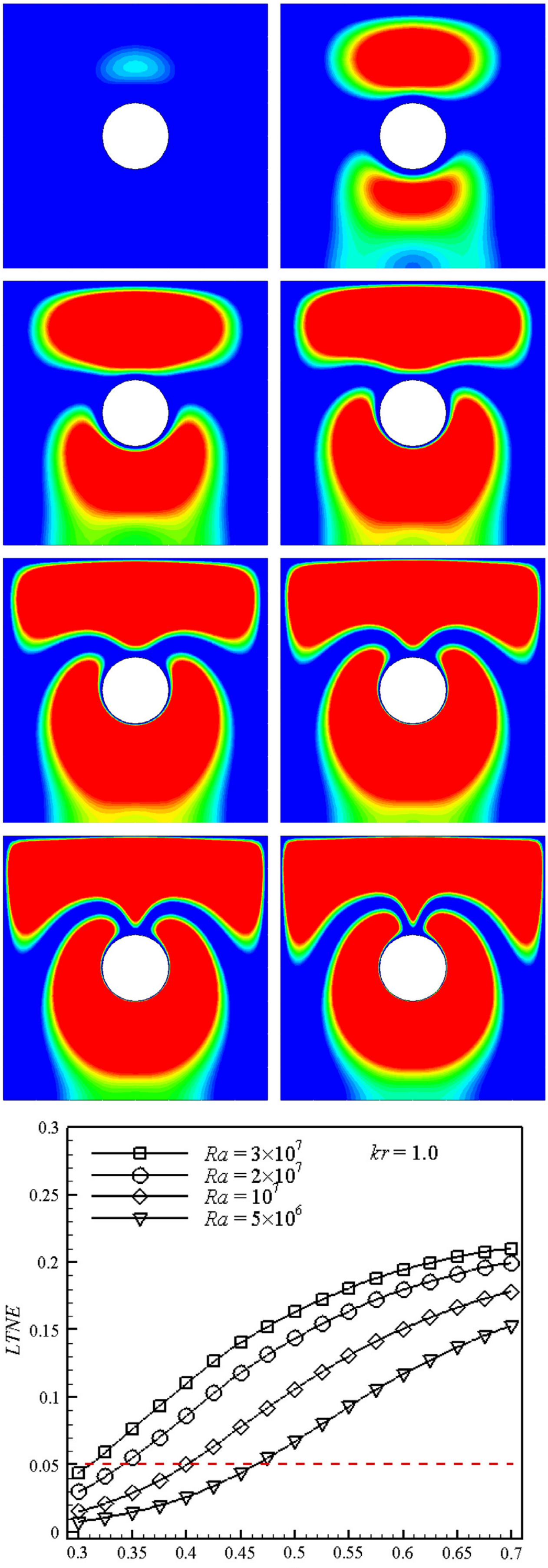


Fig. 7. Effect of ε on: (Left) the local temperature difference between the fluid and solid phases around the heated cylinder, from top left to bottom right $\varepsilon = 0.35 - 0.7$ in step of 0.05, at $Ra = 10^7$ and $kr = 1.0$, with red (blue) colors have magnitudes of ≥ 0.1 (≤ 0.05), and (Right) the *LTNE* parameter against ε for different values of *Ra*. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

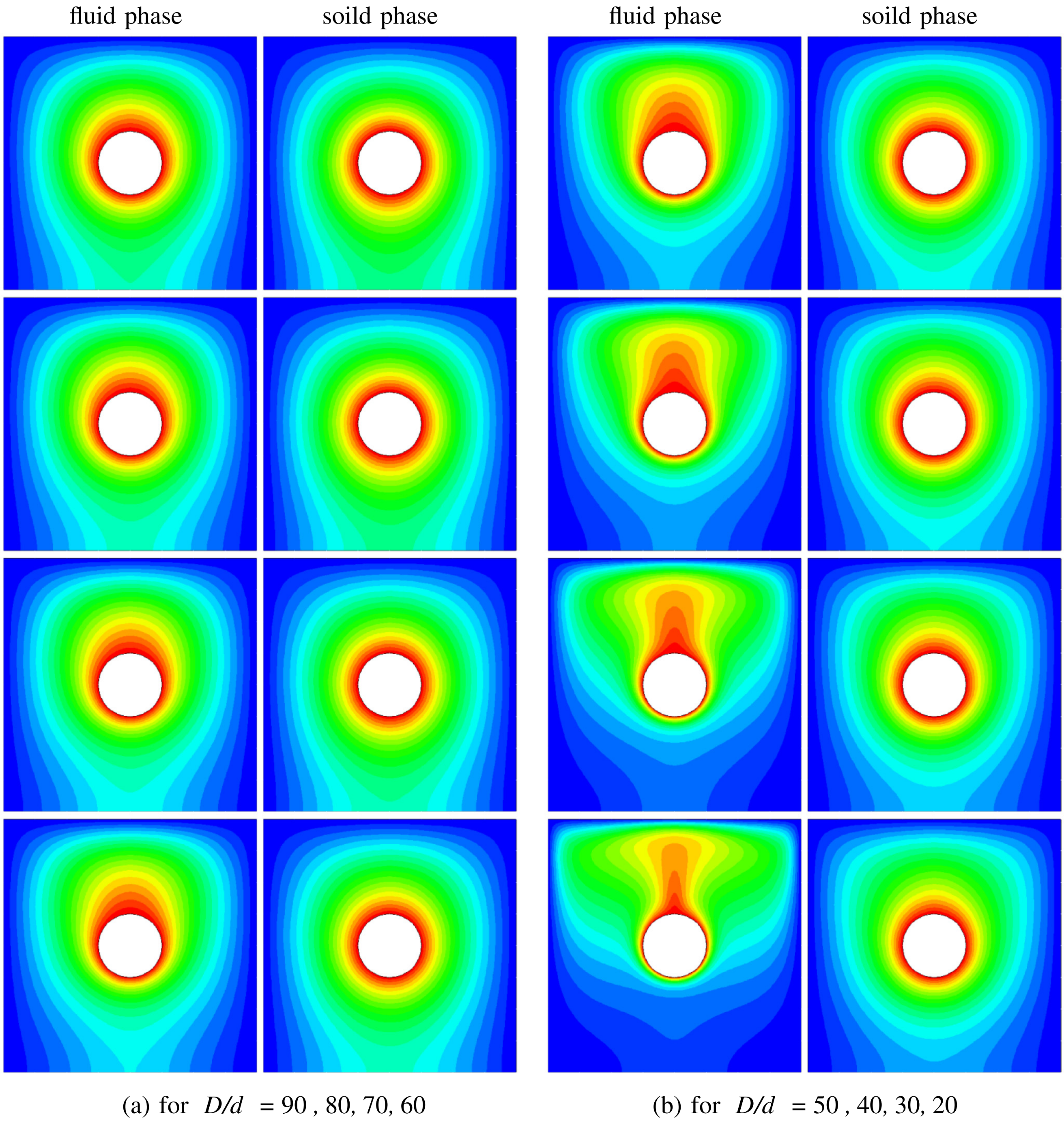


Fig. 9. Temperature distributions for both fluid and solid phases, for different values of D/d, from top to bottom, (a) $D/d = 90, 80, 70, 60$ and (b) $D/d = 50, 40, 30, 20$, at $Ra = 2 \times 10^7$ and $kr = 1.0$, with red (blue) colors have magnitudes of 1 (0). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

retain *LTE* status in the regions of the buoyant flow path below and above the cylinder close to the floor and the ceiling, respectively, of the bed.

The results of the *LTNE* against the thermal properties, i.e. solid/fluid thermal conductivity ratio *kr*, of the porous medium are presented in Fig. 3 at $D/d = 20$, $\varepsilon = 0.5$, and for different values of *Ra*. It is seen that in addition to the increase of *Ra* value, the *LTNE* condition can also be triggered by lower values of *kr*, and the temperature difference between both phases is relatively large. It is obvious that a lower *kr* as opposed to a higher *kr*, puts much constraint on the validity of the *LTE*. This is because that the degrading impact it implies a low energy transport capability by the fluid as compared to its solid counterpart. As a result, the fluid exhibits poor ability to bring the solid phase to its operating temperature. It can also be seen in the figure that the unfavorable effect of low values of *kr* on the *LTE* condition becomes more significant at higher *Ra*. However, the effect of *Ra* on the trend of *kr* against *LTNE* vanishes at high values of $kr \geq 10^3$. This may be attributed to that the fluid convection dominates the heat transfer process in the porous medium and the solid temperature is much more influenced by the degree of the internal heat exchange between the fluid and solid phases rather than influenced by its own conductivity. However, the increase in *kr* reduces the value of the *LTNE* leading towards thermal equilibrium between the solid and fluid phases at high *kr*. Higher *kr* implies that we have more solid having high thermal conductivity compared with less

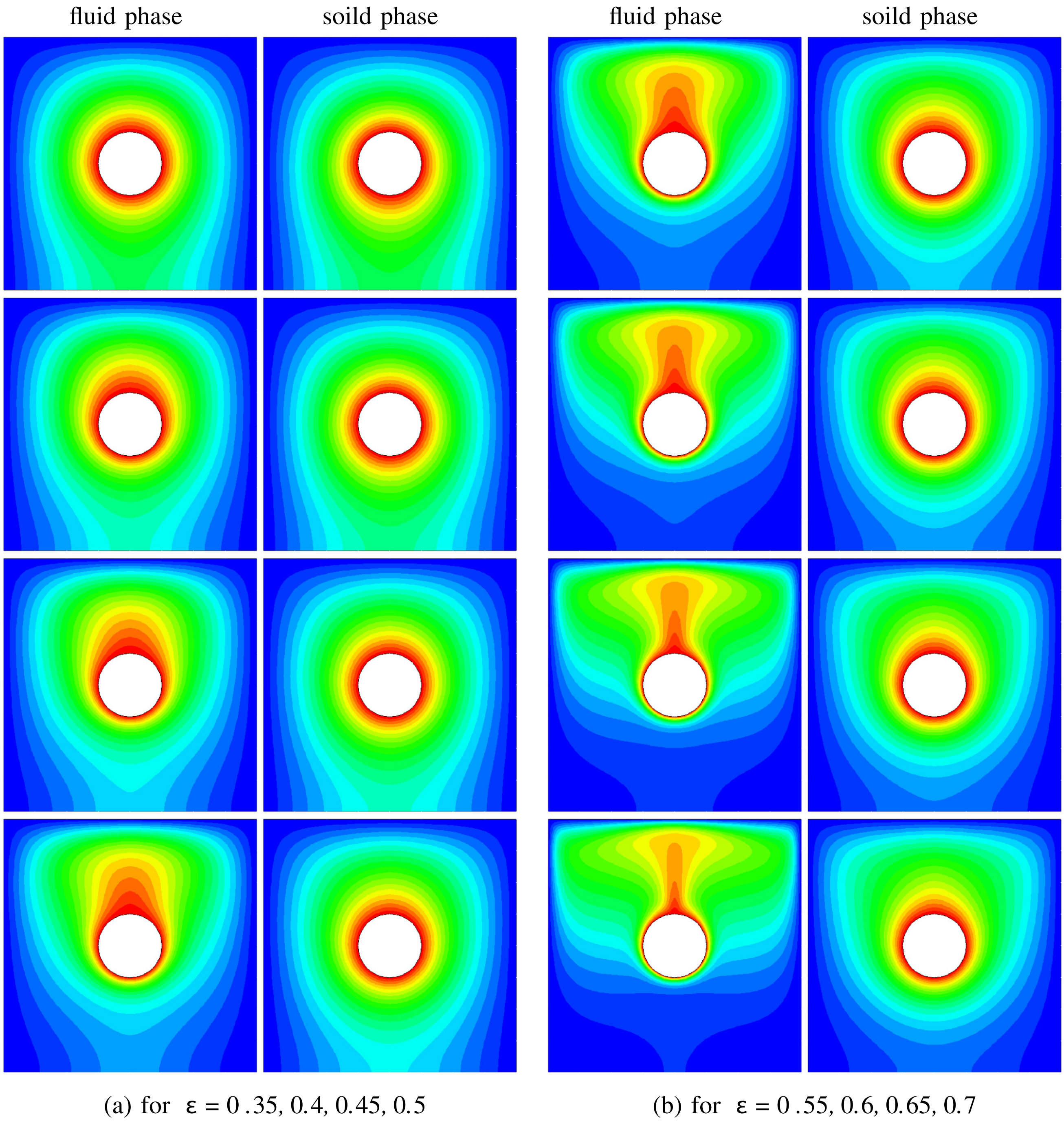


Fig. 10. Temperature distributions for both fluid and solid phases, for different values of ε, from top to bottom, (a) $\varepsilon = 0.35, 0.4, 0.45, 0.5$ and (b) $\varepsilon = 0.55, 0.6, 0.65, 0.7$, at $Ra = 10^7$ and $kr = 1.0$, with red (blue) colors have magnitudes of 1 (0). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

fluid having low thermal conductivity. This enables the solid to bring the fluid phase to its temperature easier.

Fig. 4 illustrates the effect of kr on the temperature distributions of both fluid and solid phases, at $Ra = 2 \times 10^7$. It is clear that the increase in kr reduces the discrepancy between the thermal fields of the two phases bringing them to be identical and satisfying the thermal equilibrium in the system.

Figs. 5–8 show the effect of the structural properties, i.e. particle diameter represented by cylinder/particle diameter ratio D/d and porosity ε, respectively, of the porous packed bed on the local temperature difference between the porous phases and the validity of the *LTE* assumption, at different Ra and kr. Opposite to the act of the thermal conductivity of the porous medium, the decrease in particle diameter or porosity tends to decrease the discordancy between the phase thermal fields, and consequently, leads to a reduction in the value of *LTNE*. This behavior seems to be opposite to the act of d and ε on *LTNE* in the application of forced convection around a circular cylinder embedded in a horizontal porous channel reported in our work of Gazy et al. [9].

The decrease in the particle size causes a decrease in the interfacial surface area and an increase in the particle contact area. This results in an increase in the conductive heat transfer within the solid particles, and however reduces the interfacial heat transfer between the fluid and solid phases. Consequently, this enables the fluid temperatures closer to the hardly changing solid temperatures. Although there is a considerable reduction in the value of *LTNE* by decreasing the particle diameter d, i.e. increasing the ratio D/d from 20 to 100, at $kr = 1.0$, this reduction becomes insignificant when kr increases.

In addition, the positive influence of increasing the porosity ε on *LTNE* illustrated in Figs. 7 and 8 is due to the removal of solid material from the porous packed bed and in particular in the area close to the cylinder. Less solid material results in the amount of heat transferred from the hot cylinder to the fluid phase becomes much higher than that moved throughout the solid particles. This increases the temperature differences between the moving fluid and the solid particles, and to attain the local thermal non-equilibrium between them specially at higher ε. As also seen in Figs. 5 and 6, the reduction in the value of *LTNE* when ε decreases becomes inconsiderable at higher kr.

Importantly, It is worth to notice from Figs. 5–8 that the influence of d and ε on the phase temperature differential and the validity of *LTE* assumption at low values of kr, i.e. $kr = 1.0$ and 10, is more pronounced than that of higher $kr \geq 100$. It is obvious that the porous packed bed becomes completely in thermal equilibrium at these high ranges of kr regardless of the effects of d and ε.

Figs. 9 and 10 show the influence of the parameters d and ε on the temperature distributions of fluid and solid phases separately. These figures are plotted at $kr = 1.0$. As can be seen that both of these parameters have a positive impact on the temperature difference between both phases and satisfying the non-equilibrium condition in the domain.

4. Conclusion

The current numerical investigation tackled the problem of steady free convection from an isothermal heated circular cylinder immersed in an air-saturated porous packed bed of spheres. The generalized form of the momentum equation is employed, which accounts for the effect of the solid boundary and the quadratic inertial effects. The two-equation model is considered for the representation of the local fluid and solid temperatures. The main objective of the current investigation is to examine the validity of the local thermal equilibrium *LTE* assumption in this problem upon varying a number of dimensionless parameters such as Rayleigh number, solid thermal conductivity, particle diameter and porosity of the packed bed. The favorable circumstances for the *LTE* assumption to hold in this particular application are identified. The results indicate that higher Rayleigh number, particle size and porosity have the effect of limiting the validity ranges of the *LTE* assumption. However, the circumstances of using porous packed bed with higher thermal conductivity are found to have a positive impact to satisfy the *LTE* condition. Interestingly, it is also concluded that the solid thermal conductivity is the main governor on satisfying the *LTE* condition in the bed. Thus, this condition is found to be justified at high solid thermal conductivity, and it is impossible to be secured at low solid thermal conductivity, for the entire ranges of other pertinent parameters.

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