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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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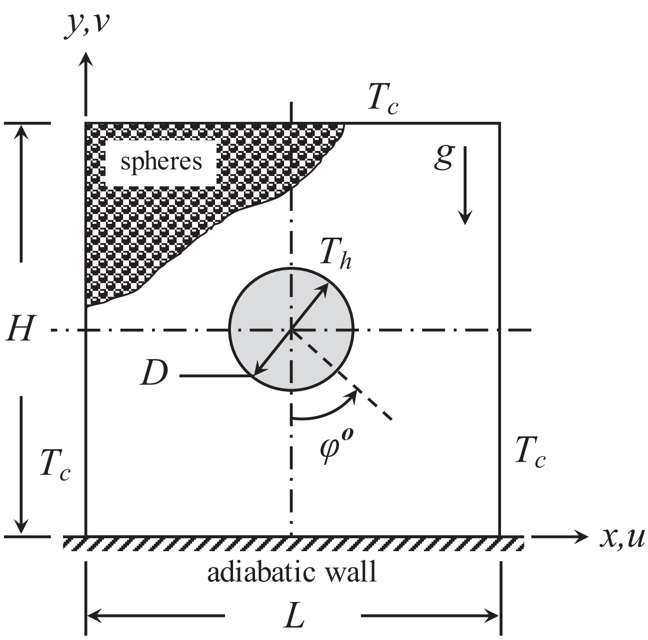


**Fig. 1.** Physical model and coordinate system.

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

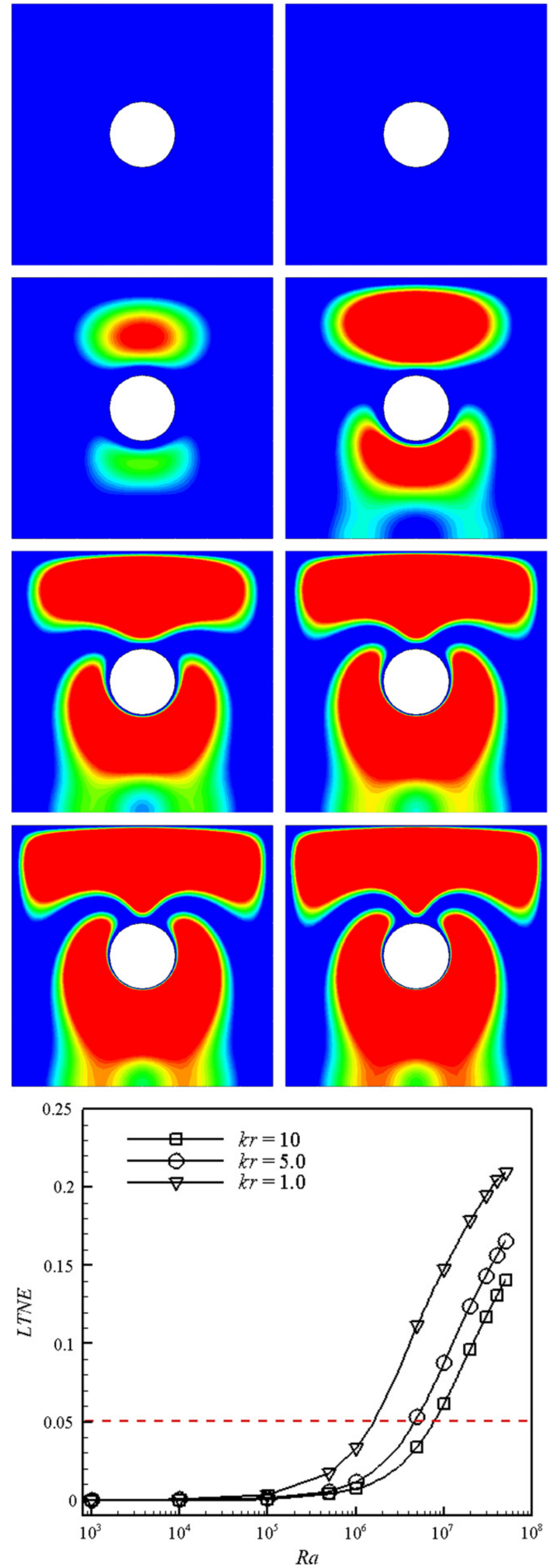


**Fig. 2.** Effect of *Ra* on: (Left) the local temperature difference between the fluid and solid phases around the heated cylinder, from top left to bottom right $Ra = 10^5$, $10^6$, $5 \times 10^6$, $10^7$, $2 \times 10^7$, $3 \times 10^7$, $4 \times 10^7$ and $5 \times 10^7$, at $kr = 10$, with red (blue) colors have magnitudes of $\geq 0.1$ ($\leq 0.05$), and (Right) the *LTNE* parameter against *Ra* for different values of *kr*.