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New Criterion for Local Thermal Equilibrium in Porous Media

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In this paper, a general criterion for local thermal equilibrium in forced convection flows through porous media under a constant heat flux boundary condition is presented in terms of parameters, including the boundary heat flux, the area of cross section, the effective thermal solid-to-fluid conductivity ratio, characteristic length for pore size, porosity, Nusselt number, fluid conductivity, and the heat source of solid phase. To check the validity of the proposed criterion for local thermal equilibrium, the forced convection phenomena in the porous medium between two parallel plates subjected to constant heat flux are studied by numerical method based on the Brinkman–Forchheimer extended Darcy model. The temperature difference between solid and fluid phases in a representative elementary volume are studied by comparing the effects of relevant parameters in this new criterion. In addition, the proposed criterion is consistent with the existing experimental and numerical results for convection heat transfer in a porous medium.

Nomenclature

a_{sf}	=	specific surface area
C_f	=	fluid specific heat
D	=	distance of parallel
Da	=	Darcy number
d_p	=	diameter of particle
F	=	geometric function
h_{sf}	=	interfacial heat transfer coefficient
K	=	permeability
L	=	characteristic length for system
Nu	=	Nusselt number
Pr	=	Prandtl number
p	=	pressure
q	=	heat source of solid phase, W/m^3
q_w	=	boundary heat flux, W/m^2
Re_{dp}	=	particle Reynolds number
S	=	flow section area
T	=	temperature
t	=	time
u, v	=	effective velocity components
V	=	volume of porous medium
η	=	viscosity of fluid
κ	=	effective solid-to-fluid thermal conductivity ratio
λ	=	conductivity of fluid or solid
ρ	=	density
φ	=	porosity

Subscripts

eff	=	effective
f	=	fluid
in	=	inlet
s	=	solid
w	=	wall

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I. Introduction

FLUID flow and heat transfer in a porous medium has been extensively investigated due to its relevance in a wide variety of engineering applications. From an energy equation point of view, there are two different models for investigating the energy transport in porous media: a local thermal equilibrium (LTE) model and a local thermal nonequilibrium (LTNE) model. The LTE model assumes the solid phase temperature is equal to that of the fluid phase in a representative elementary volume (REV), which is simple and straightforward, but valid only when the temperature difference between the solid and fluid phases is very small. The LTNE model requires additional information to account for the modes of energy communication between the two considered phases. A number of investigations have been reported on the validity of the LTE assumption in the forced convection channel flow.

Carbonell and Whitaker [1], Whitaker [2], and Quintard and Whitaker [3,4] presented a criterion for the validity of the assumption of LTE. Their criterion is proposed in the case where the effect of conduction is dominant. Amiri and Vafai [5] presented an error contour map in terms of the particle Reynolds number, the Darcy number, and the ratio of thermal diffusivity based on the qualitative ratings. Nield [6] concluded that the effect of LTE is to increase the Nusselt number at the interface between the fluid and solid phases. Lee and Vafai [7] proposed a criterion for the validity of the LTE model in the case of flow through a porous channel subjected to a constant heat flux on the top and bottom walls by using analytical solutions based on the Darcian flow model. Kim et al. [8] showed that the assumption of LTE in a microchannel heat sink, which is modeled as a porous medium, is valid as the Darcy number approaches zero and the effective fluid-to-solid thermal conductivity ratio goes to infinity. Even though studies on local thermal equilibrium have been conducted for many years, a general criterion for the validity of the local thermal equilibrium assumption has not been available, to the authors' knowledge.

The aim of this study is to present a more general criterion for the LTE assumption under the condition of constant wall heat flux. To do this, a theoretical analysis is performed for the case when the effect of convection heat transfer is dominant in a channel filled with particles. To check the validity of the new criterion for the LTE assumption, the steady-state incompressible flow through a porous bed between two parallel plates subjected to constant wall heat flux is studied by using the numerical method based on the Brinkman–Forchheimer extended Darcy model. The effects of the boundary heat flux, the area of cross section, the effective thermal solid-to-fluid conductivity

ratio, characteristic length for pore size, porosity, Nusselt number, fluid conductivity, and the heat source of the solid phase on the temperature difference between solid and fluid phases in a REV are studied systematically.

II. Criterion for Local Thermal Equilibrium

The criterion derived for the case where conduction is dominant, by Carbonell and Whitaker [1], is expressed as

$$\frac{\varphi(\rho C_p)_f d_p^2}{t}\left(\frac{1}{\lambda_f}+\frac{1}{\lambda_s}\right) \ll 1 \tag{1}$$

where φ, ρ, Cp, d_p, t, λ_f, and λ_s denote porosity, fluid density, fluid specific heat, characteristic length scale of pore size, time scale, fluid conductivity, and solid conductivity, respectively.

Another criterion mentioned by Kaviany [9] is expressed as

$$\Delta T_L \gg \Delta T_l \tag{2}$$

where ΔT_L and ΔT_l are the temperature difference occurring over the dimension of the system and the temperature difference between the solid phase and fluid phase in the REV, respectively.

The literature [10] deduces another criterion from Eq. (2) as follows:

$$Pr_{\text{eff},f} Re_{d_p} Da^{1/2} \frac{\varphi}{Nu} \ll 1 \tag{3}$$

where the effective fluid Prandtl number, the Reynolds number, the Darcy number, the Nusselt number, and the effective thermal diffusivity are defined, respectively, as

$$Pr_{\text{eff},f} = \frac{\upsilon}{\alpha_{\text{eff},f}}, \qquad Re_{d_p} = \frac{u_p d_p}{\upsilon}$$

$$Da \sim \frac{d_p^2}{L^2}, \qquad Nu = \frac{h_{\text{sf}} d_p}{k_f}$$

From the criterion, the effect of LTE on a porous medium is shown to become stronger as either any one of the Reynolds number, the Prandtl number, or the Darcy number decreases, or the Nusselt number increases.

Here, we present a new criterion.

There is a straightforward criterion: the temperature difference between the solid phase and the fluid phase in the REV is small:

$$T_s - T_f \to 0 \tag{4}$$

The volume-averaged energy equations of the solid phase is

$$\frac{\partial}{\partial x}\left(\lambda_{s,\text{eff}}\frac{\partial T_s}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda_{s,\text{eff}}\frac{\partial T_s}{\partial y}\right)-h_{\text{sf}}\alpha_{\text{sf}}(T_s-T_f)+q=0 \tag{5}$$

When the effective conductivity of the solid is constant, Eq. (5) can be rearranged as

$$T_s - T_f = \frac{\lambda_{s,\text{eff}}[(\partial^2 T_s/\partial x^2)+(\partial^2 T_s/\partial y^2)]+q}{h_{\text{sf}}\alpha_{\text{sf}}} \tag{6}$$

The heat flux at the boundary is conducted to the solid phase and then transferred to the fluid phase by the interstitial heat transfer between the fluid phase and the solid phase. And so, the volume integral of the interstitial heat transfer rate is equal to the boundary heat flux to the solid phase:

$$q_s = \int_v \lambda_{s,\text{eff}}\left(\frac{\partial^2 T_s}{\partial x^2}+\frac{\partial^2 T_s}{\partial y^2}\right) = \int_l \lambda_{s,\text{eff}}\left(\frac{\partial T_s}{\partial y}\right)_w \tag{7}$$

The boundary heat flux to the fluid phase

$$q_f = \lambda_{f,\text{eff}}\left(\frac{\partial T_f}{\partial y}\right)_w \tag{8}$$

Here, we assume [11]

$$\left(\frac{\partial T_s}{\partial y}\right)_w = \left(\frac{\partial T_f}{\partial y}\right)_w \tag{9}$$

so that

$$q_s = q_w\frac{\lambda_{s,\text{eff}}}{\lambda_{s,\text{eff}}+\lambda_{f,\text{eff}}} = q_w\frac{\kappa}{\kappa+1} \tag{10}$$

where the effective thermal conductivity ratio

$$\kappa = \frac{\lambda_{s,\text{eff}}}{\lambda_{f,\text{eff}}} \tag{11}$$

The volume-averaged temperature difference is

$$T_s - T_f = \frac{q_w(\kappa/\kappa+1)L+qV}{h_{\text{sf}}\alpha_{\text{sf}}V} = \frac{(q_w/S)(\kappa/\kappa+1)}{h_{\text{sf}}\alpha_{\text{sf}}}+\frac{q}{h_{\text{sf}}\alpha_{\text{sf}}} \tag{12}$$

The interstitial heat transfer coefficient, the interfacial surface area per unit volume, can be expressed as

$$h_{\text{sf}} = \frac{Nu\lambda_{f,\text{eff}}}{d_p}, \qquad \alpha_{\text{sf}} = \frac{A\varphi}{d_p} \tag{13}$$

By substituting Eq. (13) into Eq. (12), the criterion for local thermal equilibrium is presented by the following equation:

$$T_s - T_f = \frac{(q_w/S)(\kappa/\kappa+1)d_p^2}{A\varphi Nu\lambda_{f,\text{eff}}}+\frac{qd_p^2}{A\varphi Nu\lambda_{f,\text{eff}}} \tag{14}$$

So, the new criterion for local thermal equilibrium is

$$\frac{(q_w/S)(\kappa/\kappa+1)d_p^2}{A\varphi Nu\lambda_{f,\text{eff}}}+\frac{qd_p^2}{A\varphi Nu\lambda_{f,\text{eff}}} \to 0 \tag{15}$$

or

$$\frac{(q_w/S)(\kappa/\kappa+1)d_p^2}{A\varphi Nu\lambda_{f,\text{eff}}}+\frac{qd_p^2}{A\varphi Nu\lambda_{f,\text{eff}}} < (T_w - T_\infty)\cdot \text{allow error}(\%) \tag{16}$$

where q_w, S, κ, d_p, φ, Nu, $\lambda_{f,\text{eff}}$, T_w, T_∞, and allow error (%) are the boundary heat flux, the area of cross section, the effective thermal solid-to-fluid conductivity ratio, characteristic length for pore size, porosity, Nusselt number, fluid conductivity, boundary temperature, the inlet fluid temperature, and the allow error for analysis.

III. Mathematical Validation of the Criterion

A. Mathematical Formulation

The mathematical validation of the criterion is carried out for the two-dimensional steady-state flow through a parallel plate channel with height D, length L, and aspect ratio $L/D = 10$. The channel is considered to be filled with homogenous and isotropic porous medium as illustrated in Fig. 1. In addition, the porous medium is considered to have no spatial variation in porosity throughout the whole region, and fluid is injected through the left inlet at a constant temperature with a uniform inlet velocity u_{in}. Moreover, the walls are considered thin and are subjected to a constant heat flux q_w. Furthermore, viscous dissipation, gravitational effects, natural convection, and thermal radiation heat transfer are all assumed to have negligible effects on the velocity and temperature fields.

The steady-state volume-averaged governing equations presented for the LTNE model are given as follows:

Continuity

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}=0 \tag{17}$$

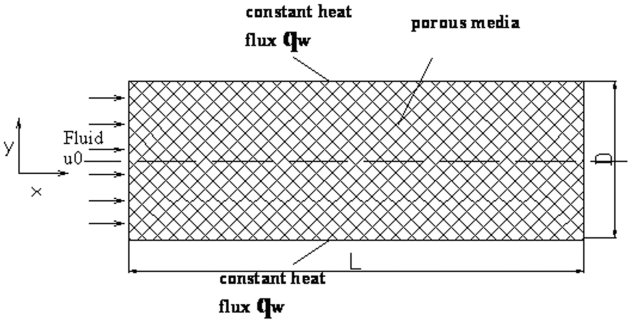

Fig. 1 Schematic diagram of a porous bed.

Momentum of X direction

$$\frac{\rho_f}{\varphi^2}\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}\right)=-\frac{\partial P}{\partial x}+\frac{\eta}{\varphi}\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)-\frac{\eta}{k}u-\rho_f\frac{F}{\sqrt{k}}\sqrt{u^2+v^2}u \tag{18}$$

Momentum of Y direction

$$\frac{\rho_f}{\varphi^2}\left(u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}\right)=-\frac{\partial P}{\partial y}+\frac{\eta}{\varphi}\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)-\frac{\eta}{k}v-\rho_f\frac{F}{\sqrt{k}}\sqrt{u^2+v^2}v \tag{19}$$

Fluid phase energy

$$\frac{\partial(C_f\rho u T_f)}{\partial x}+\frac{\partial(C_f\rho v T_f)}{\partial y}=\frac{\partial}{\partial x}\left(\lambda_{f,\mathrm{eff}}\frac{\partial T_f}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda_{f,\mathrm{eff}}\frac{\partial T_f}{\partial y}\right)+h_{\mathrm{sf}}\alpha_{\mathrm{sf}}(T_s-T_f) \tag{20}$$

Solid phase energy [which is the same as Eq. (5)]

$$\frac{\partial}{\partial x}\left(\lambda_{s,\mathrm{eff}}\frac{\partial T_s}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda_{s,\mathrm{eff}}\frac{\partial T_s}{\partial y}\right)-h_{\mathrm{sf}}\alpha_{\mathrm{sf}}(T_s+T_f)+q=0$$

The permeability [12] of the packed bed is

$$K=\frac{\varphi^3 d_p^2}{150(1-\varphi)^2} \tag{21}$$

whereas the geometric function F [13] is

$$F=\frac{1.75}{150\varphi^{3/2}} \tag{22}$$

The effective viscosity of fluid is written as

$$\mu_{\mathrm{eff}}=\mu_f$$

The effective thermal conductivity of both phases are defined as

$$\lambda_{f,\mathrm{eff}}=\varphi\lambda_f,\qquad \lambda_{s,\mathrm{eff}}=(1-\varphi)\lambda_s$$

The specific surface area α_{sf} of the bed can be expressed as

$$\alpha_{\mathrm{sf}}=6(1-\varphi)/d_p \tag{23}$$

The fluid-to-solid heat transfer coefficient [14] is

$$Nu=h_{\mathrm{sf}}d_p/\lambda_f=2.0+1.1Pr^{1/3}Re_{d_p}^{0.6} \tag{24}$$

A no-slip boundary condition at the wall is employed for the momentum equation, whereas the boundary conditions for the energy equations are as follows [11]:

$$T_f=T_s,\qquad q_s=-\lambda_{s,\mathrm{eff}}\left(\frac{\partial T_s}{\partial y}\right)_w$$

$$q_f=-\lambda_{f,\mathrm{eff}}\left(\frac{\partial T_f}{\partial y}\right)_w,\qquad q_f+q_s=q_w$$

B. Results and Discussion

The numerical solution of the momentum and energy equations, described in the preceding paragraphs, is obtained by using the finite volume method. The SIMPLE algorithm for the pressure–velocity coupling is used. Convergence is measured in terms of the maximum change in each variable during iteration at each time increment. The maximum change allowed for the convergence check is set to 10^{-6} for the energy equation and 10^{-4} both for continuity and momentum equations. All computations have been carried out for a half-parallel channel $L\times(D/2)$ by using nonuniform grid arrangements with 1000×100 to ensure the results are independent of the grid system.

The influences of pertinent parameters mentioned in Eq. (15) on the temperature difference between the solid phase and the fluid phase are shown in Fig. 2. During calculation of the effect of q_w, $1/S$, $\kappa/(\kappa+1)$, d_p^2, $1/\lambda_{f,\mathrm{eff}}$, the other parameters keep constant, as follows, $q_w=100\ \mathrm{W/m^2}$, $1/S=0.1\ \mathrm{m^2}$, $\kappa=20$, $d_p=0.005$ m, $\lambda_{f,\mathrm{eff}}=0.0242\ \mathrm{W/(m\cdot K)}$, and the Nu is calculated by Eq. (24). But when calculating the effect of Nu, Eq. (24) is not included, but is used as an independent variable. When calculating the effect of the solid phase heat source, $q_w=0$, that is to say, the wall is adiabatic.

As showen in Fig. 2, the temperature difference between the solid phase and the fluid phase increases linearly with the increase of q_w, $1/S$, $\kappa/(\kappa+1)$, d_p^2, $1/\lambda_{f,\mathrm{eff}}$, $1/Nu$, and q, which implies the assumption in Eq. (9) is reasonable. From the numerical calculation shown in Fig. 2, the effect of local thermal equilibrium on a porous media is more obvious with the decrease of the q_w, $1/S$, d_p^2, and q, as well as with the increase of the Nusselt number and effective fluid thermal conductivity. In addition, when the effective solid-to-fluid thermal conductivity ratio is small, its effect is significant.

IV. Discussion About the Criterion

A. Discussion About the Nusselt Number

During the validation of the new criterion, the Nusselt number, based on the interstitial heat transfer coefficient presented by Wakao et al. [14], has been applied. However, for other porous media, the Nusselt number is calculated by the equation presented by other references.

In the microchannel heat sink subject to an impinging jet, the Nusselt number can be represented by the following correlation [10]:

$$Nu=1.2434Re_{d_p}^{0.1368}Pr_{\mathrm{eff},f}^{0.161}+2.0 \tag{25}$$

For the sintered metal, Kar and Dybbs [15], as well as Maiorov et al. [16], suggested the Nusselt number based on the interstitial heat transfer coefficient be written as

$$Nu=\frac{h_{\mathrm{sf}}d_p}{\lambda_f}\sim CRe_{d_p}^n\qquad (0<Re_{d_p}<10^2) \tag{26}$$

$n\approx 1.35$ in Kar and Dybbs [15],

$$Nu=\frac{h_{\mathrm{sf}}d_p}{\lambda_f}\sim CRe_{d_p}^n\qquad (0<Re_{d_p}<10^3) \tag{27}$$

$0.65<n<1.84$ in Maiorov et al. [16].

For the cellular ceramic, the Nusselt number presented by Fu et al. [17] is

$$Nu=\frac{h_{\mathrm{sf}}d_p}{\lambda_f}\sim CRe_{d_p}^n\qquad (0<Re_{d_p}<10^3) \tag{28}$$

$0.9<n<1.18$ in Fu et al. [17].

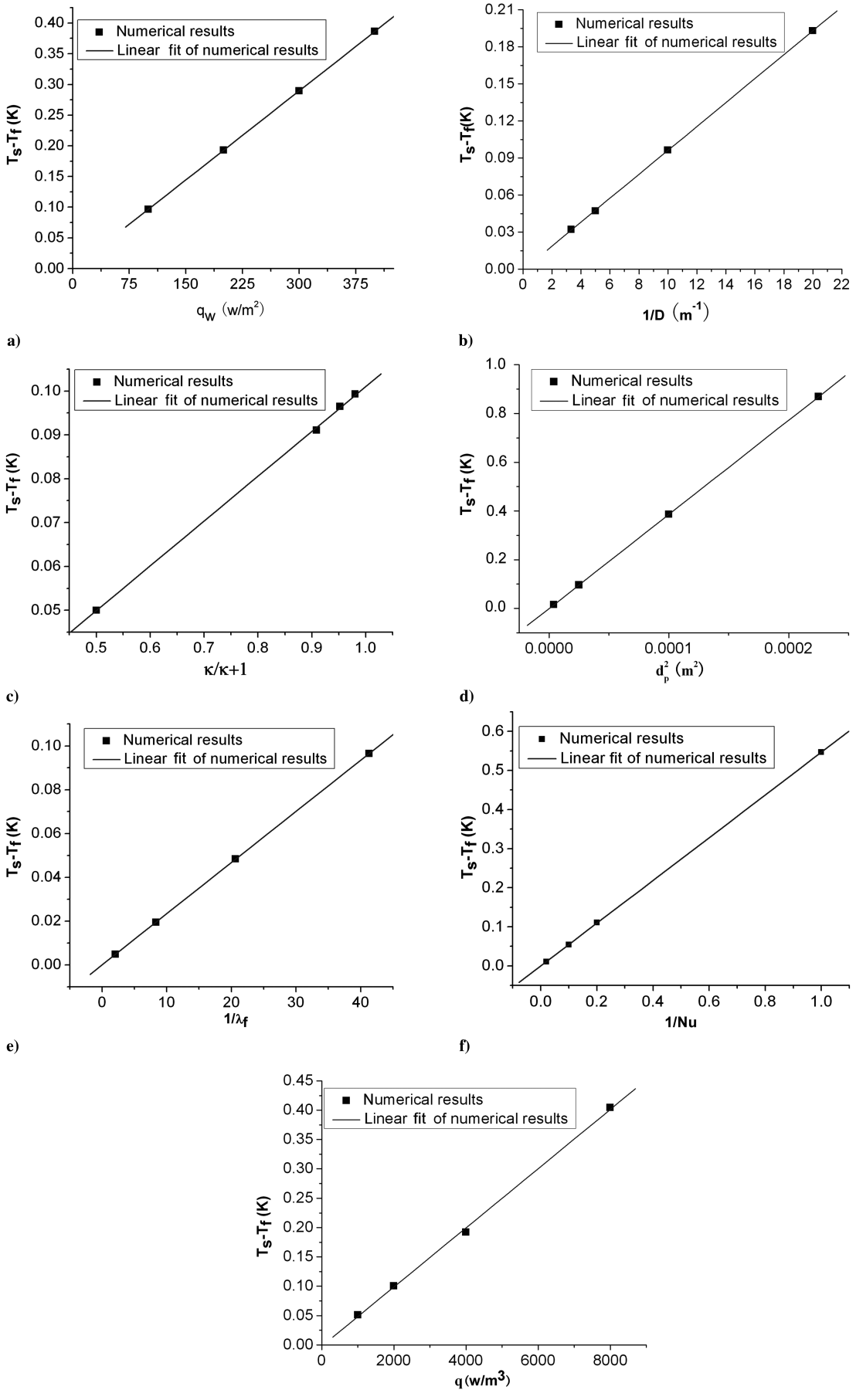

Fig. 2 Effect of pertinent parameters at the average temperature difference between two phases: a) boundary heat flux, b) characteristic length, c) effective thermal conductivity ratio, d) characteristic length for pore size, e) effective conductivity of fluid, f) Nusselt number, and g) heat source of solid phase.

In this case, the Nusselt number based on the interstitial heat transfer coefficient can be expressed in the form of

$$Nu = B + CPr^d Re_{d_p}^f, \qquad 0 < d < 1, \quad f > 0 \tag{29}$$

So, the criterion also can be written as

$$\frac{(q_w/S)(\kappa/\kappa+1)d_p^2 + qd_p^2}{A(B + CPr^d Re_{d_p}^f)\lambda_{f,\text{eff}}\varphi} \to 0 \tag{30}$$

B. Compared with Equation (1)

For the case in which conduction is the dominant heat transfer mode, the Nu approaches B, if there is no heat source in the solid phase, the criterion is expressed as

$$T_s - T_f = \frac{(q_w/S)(\kappa/\kappa+1)d_p^2}{AB\lambda_{f,\text{eff}}\varphi} \to 0 \tag{31}$$

Here,

$$q_w \cdot L = (\rho C_p)_f S \cdot u \cdot \Delta T_L \tag{32}$$

Equation (31) can be rewritten as

$$T_s - T_f = \frac{(\rho C_p)_f \Delta T_L d_p^2}{ABt\varphi}\frac{\kappa}{\kappa+1}\frac{1}{\lambda_{f,\text{eff}}} \tag{33}$$

And so,

$$\frac{\Delta T_l}{\Delta T_L} = \frac{T_s - T_f}{\Delta T_L} = \frac{(\rho C_p)_f d_p^2}{ABt\varphi}\frac{\kappa}{\kappa+1}\frac{1}{\lambda_{f,\text{eff}}} \ll 1 \tag{34}$$

Then, Eq. (1) can be rewritten as

$$\frac{\varphi(\rho C_p)_f d_p^2}{t}\frac{\kappa+1}{\kappa}\frac{1}{\lambda_f} \ll 1 \tag{35}$$

It can be seen from Eqs. (34) and (35) that these two criteria are coincident, excluding the effect of κ. When the conductivity of fluid is fixed, the assumption of local thermal equilibrium is valid as the effective solid-to-fluid thermal conductivity is decreased. The same conclusion was drawn from the conclusion of Kim et al. [8], but it is worth mentioning that the conclusion gained by Eq. (35) is the opposite.

The criterion proposed in this study is more general than the previous criterion suggested by Kim and Jang [10], because the former includes the effect of effective thermal solid-to-fluid conductivity ratio.

V. Conclusions

A more general criterion for local thermal equilibrium under the condition of constant wall heat flux is presented in terms of parameters of engineering importance, which include the boundary heat flux, the area of cross section, the effective thermal solid-to-fluid conductivity ratio, characteristic length for pore size, Nusselt number, effective fluid conductivity, and heat source of the solid phase. The results presented in this study show that the effect of local thermal equilibrium on a porous medium will become larger with the decrease of the boundary heat flux, characteristic length for pore size, and heat source of the solid phase, as well as with the increase of the effective fluid Prandtl number, the particle Reynolds number, and effective fluid thermal conductivity. In addition, when the effective solid-to-fluid thermal conductivity ratio is small, its effect is significant.

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