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Thermal boundary conditions of local thermal non-equilibrium model for convection heat transfer in porous media

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ABSTRACT

A thermal boundary condition model at the boundary adjacent to an impermeable wall was developed for the local thermal non-equilibrium (LTNE) model for convection heat transfer in porous media. The model was validated by comparison with pore-scale numerical simulations and macro-scale LTNE model numerical simulations. The concept of the tangential interfacial thermal resistance was developed to explain the mechanism for the splitting of the heat flux between the solid and fluid phases at the wall.

1. Introduction

When using the local thermal non-equilibrium (LTNE) model for porous media, the treatment of the boundary conditions for the energy equation significantly affects the simulation results. Alazmi and Vafai [1] compared eight different forms of the constant wall heat flux boundary conditions for the LTNE model in porous media. They found that different boundary conditions led to substantially different results. On the contact interface between an impermeable wall and a porous medium there are two main approaches for treating the energy equation boundary conditions for constant wall heat flux [2]. The first is based on the assumption that the heat flux is divided between the two phases relative to the physical values of their effective thermal conductivities and temperature gradients. This normally assumes that the fluid temperature is locally equal to the solid phase temperature. The second method assumes that the fluid heat flux is locally equal to the solid phase heat flux.

However, there is no simple method to choose which approach to use in practice for the thermal boundary conditions. A number of papers have analyzed this problem, e.g. Amiri et al. [2], Hwang et al. [3], Martin et al. [4], Lee and Vafai [5], Kim and Kim [6], Nield and Kuznetsov [7], Jiang et al. [8–11], Yang and Vafai [12,13], and Imani et al. [14].

Hwang et al. [3] used the first approach with good agreement between their numerical and experimental results with a sintered porous channel. Kim and Kim [6] argued that the first approach is physically reasonable for an impermeable wall with a finite thickness with comparisons to their experimental results for micro-channels and sintered porous media channel. The second approach is better for very thin impermeable walls.

Jiang and Ren [8] and Jiang et al. [9] investigated four different treatments of constant heat flux boundary conditions by comparing numerical results with experimental data for forced convection heat transfer of water and air in plate channels filled with non-sintered particles or sintered porous media using the LTNE model. Jiang and Lu [10,11] then investigated the details using pore-scale numerical simulations. Their investigation pointed out that the problem also largely depends on the contact conditions. For the constant wall heat flux boundary condition for convection heat transfer in porous media with a finite wall thickness, the proper model is $T_{ws} \approx T_{wf}$ when no thermal contact resistance exists (as in sintered porous media), while $q_w \approx q_{ws} \approx q_{wf}$ is better with a thermal contact resistance (as in non-sintered porous media). Imani et al. [14] conducted pore-scale numerical simulations for a circular fin array porous medium to estimated the heat flux ratios between the two phases at the heated boundary with different Reynolds numbers, solid to fluid conductivity ratios, and porosities.

Another similar problem is about the thermal boundary conditions at the interface between a clear fluid and a porous medium. This has been analyzed in the past, e.g. Ochoa-Tapia and Whitaker [15], Alazmi and Vafai [16], Yang and Vafai [17,18], Wang and Shi [19], and Nield and Kuznetsov [20]. Ochoa-Tapia and Whitaker [15]

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Nomenclature

A	area [m^2]
a_{sf}	phase interface area per unit volume [m^{-1}]
c_p	heat capacity [J/kg K]
d	diameter [m]
G	thermal tortuosity parameter
h_{fs}	interfacial heat transfer coefficient [W/m^2 K]
k	thermal conductivity [W/m K]
k_{stg}	effective stagnant thermal conductivity for the LTE condition [W/m K]
L	characteristic length [m]
l	length [m]
l_{wf}	length of a unit cell at the wall-to-porous-medium interface [m]
$\mathbf{n}_{fs}$	unit normal vector
Q_{fs}	interfacial heat transfer per unit volume [W/m^3]
q	heat flux [W/m^2]
$\dot{q}_v$	internal heat generation [W/m^3]
R	superficial thermal resistance per unit area [K m^2/W]
ΣR	total superficial thermal resistance per unit area defined by Eq. (56) [K m^2/W]
r	radius [m]
T	temperature [K]
V	volume [m^3]

Greek symbols

γ	thermal resistance ratio defined by Eq. (56)
δ	thickness [m]
ε	volume fraction
ε_w	void fraction at the wall-to-porous-medium interface
$\mathbf{\Lambda}_{fs}$	interfacial thermal tortuosity [K/m]
ρ	density [kg/m^3]
σ	k_s/k_f, thermal conductivity ratio
τ	time [s]

Subscripts

b	bulk
c	contact
eff	effective
f	fluid phase in porous media or the f^δ phase in the impermeable wall
ne	non-equilibrium region
p	particle
s	solid phase in porous media or the s^δ phase in impermeable wall
t	tangential direction to the wall-to-porous-medium interface
w	interface between an impermeable wall and a porous medium
x	x coordinate
y	y coordinate
z	z coordinate

Superscripts

δ	impermeable wall zone

Other symbols

$-$	intrinsic average variable
$\bar{\nabla}$	macro-scale gradient

presented heat flux jump boundary conditions based on the volume averaging method and the assumption of "local gradient equilibrium". The heat flux jump boundary conditions introduce an excess heat transfer coefficient to control the heat flux splitting between the solid and fluid phases at the interface and has been utilized in various studies [15–18].

The heat flux bifurcation phenomenon can occur near boundaries or interfaces as analyzed by Yang and Vafai [12,13,17,18] and discussed further by Nield [21] and Vafai and Yang [22].

As seen from the literature, the thermal boundary conditions at the interface between an impermeable wall and a porous medium with the LTNE model are influenced by many factors, including the impermeable wall thickness, the contact conditions, the flow field, and the thermal conductivity ratios between the impermeable wall and the two phases. The objective of the present study is to analyze the mechanism for splitting the heat flux between the two phases, considering all these factors. The volume averaging method given by Whitaker [23] is used to describe the heat transfer with the LTNE model used in the impermeable wall zone. This assumes that the LTNE model in the impermeable wall zone and its simplified form can be regarded as the appropriate thermal boundary conditions for the porous media zone.

2. Analysis using the LTNE model in an impermeable wall bounded by a porous medium

2.1. Non-equilibrium region in an impermeable wall bounded by a porous medium

The following analysis does not use the two assumptions proposed by Amiri et al. [2] quoted in the introduction but begins by considering the conjugate heat transfer process as a pore-scale mesoscopic problem near the interface between an impermeable wall and a porous medium.

At this interface, the wall temperatures between the two phases differ along with the wall heat fluxes during the heat transfer. This phenomenon was observed in the pore-scale numerical simulations of Jiang and Lu [11]. If the conduction at the interface is not in equilibrium, there must be a non-equilibrium region near the interface in the impermeable wall due to the temperature continuity and heat flux continuity requirements. In addition, if the impermeable wall is thick enough, the non-equilibrium region will reach equilibrium in the impermeable wall some distance from the interface.

A qualitative example is given in Fig. 1 and shown in Jiang and Lu [11] for heat conduction with $k_s \gg k_f$. Without a thermal contact

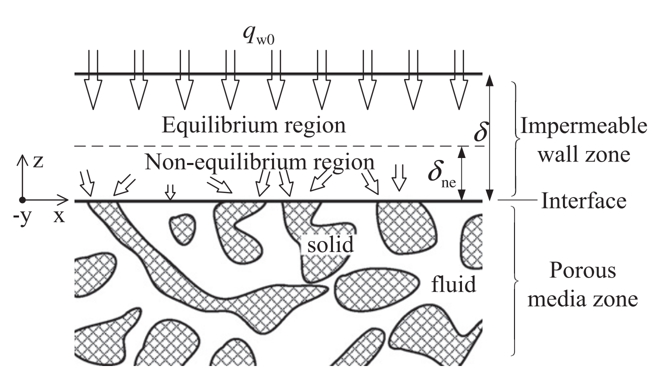

Fig. 1. Non-equilibrium region in an impermeable wall with $k_s \gg k_f$.