Transp Porous Med
DOI 10.1007/s11242-012-0080-3

A Note on Local Thermal Non-equilibrium in Porous Media and Heat Flux Bifurcation Phenomenon in Porous Media

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Received: 20 September 2012 / Accepted: 21 September 2012

Abstract This work address a number of fundamental issues and concepts related to local thermal non-equilibrium and the heat flux bifurcation phenomenon in porous media. Different types of heat flux bifurcation phenomenon are discussed in relation to previous works by the authors.

Keywords Local thermal non-equilibrium · Heat flux bifurcation phenomenon · Porous media

We appreciate the interest expressed by Nield (2012) for recognizing the importance of the heat flux bifurcation phenomena, which was first, discovered and analyzed by Yang and Vafai (2010, 2011a, b). While we appreciate the effort put forth by Nield (2012) to highlight our work in the bifurcation area, his work (Nield 2012) carries a number of inaccurate statements.

The work of Yang and Vafai (2010) was one of the first attempts to study the heat flux bifurcation phenomenon in porous media under local thermal non-equilibrium (LTNE) condition. The exact solutions for both the fluid and solid temperature distributions for convective heat transfer within a channel fully filled with a porous medium subject to a constant wall heat flux boundary condition, with internal heat generation in both the fluid and solid phases, were obtained. In the work of Yang and Vafai (2010), the "heat flux bifurcation phenomenon" indicates that the direction of the temperature gradient for the fluid and solid phases are different at the wall. They also derived the necessary conditions for heat flux bifurcation. Yang and Vafai (2011a) demonstrated the existence of two primary types of heat flux bifurcations at the wall under temporal conditions. The first type is the same as the one discussed by

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Published online: 11 October 2012

Yang and Vafai (2010). The second type of heat flux bifurcation indicates that the direction of total heat flux at the wall changes along the channel. Both of these different types of heat flux bifurcation occur at the channel wall under temporal conditions. Furthermore, Yang and Vafai (2011b) demonstrated the existence of the third type of heat flux bifurcation, which occurs inside a porous medium for a composite system. This type of heat flux bifurcation demonstrates that the direction of internal heat exchange between solid and fluid phases changes at different transverse regions.

To investigate the heat flux bifurcation phenomenon in porous media at the wall, two primary approaches (Models A and B) for the constant wall heat flux boundary conditions presented for the first time by Amiri et al. (1995), were utilized in the works of Yang and Vafai (2010). The dimensionless internal heat generation in the solid phase, represented by the parameter β, is found to have a significant impact on the heat transfer characteristics. When β stands within a certain range, the heat flux bifurcation phenomenon in porous media at the wall will occur for Model A for the constant wall heat flux boundary conditions. However, the heat flux bifurcation phenomenon will not occur for Model B for the constant wall heat flux boundary conditions.

To investigate the heat flux bifurcation phenomenon inside a porous medium for a composite system, three models were utilized to describe the thermal interface conditions at the fluid–porous interface in the work of Yang and Vafai (2011b). The equivalence correlations between the three models were established. The ratio of heat flux for the fluid phase to the total heat flux at the interface, β, is found to have a significant influence on the temperature distributions in fluid and solid phases. And there is a minimum value for this ratio, which can be represented by the critical parameter β_{cr}. When the ratio of heat flux for the fluid phase to the total heat flux at the interface is larger than β_{cr}, which also means that the heat exchange between the fluid and solid phases does not approach infinity, and the temperatures for the two phases are not equal at the porous–fluid interface according to the equivalence correlations, the third type of heat flux bifurcation will occur.

When a constant temperature boundary condition, instead of a constant heat flux condition, is adopted, the temperature of the fluid and solid phases at the wall is set to the known boundary temperature, and no additional boundary thermal condition is required. However, the first type of heat flux bifurcation is also found to occur for constant temperature boundary condition over a given axial length in the works of Yang and Vafai (2010) under steady-state condition, and the first and second types of heat flux bifurcation is found to occur at the wall along the channel for constant temperature boundary condition in the works of Yang and Vafai (2011a) under temporal conditions.

Therefore, it is obvious that the three types of heat flux bifurcations are totally different concepts compared to the boundary/interface thermal conditions. Independent of the thermal conditions, the phenomenon of heat flux bifurcation studied by Yang and Vafai (2010, 2011a, b) can occur for a wide variety of systems. Moreover, contrary to what has been stated by Nield (2012), there is a single parameter (which can change for different cases), which can control the occurrence of the heat flux bifurcation phenomenon.

Furthermore, the comments by Nield on another paper of Yang and Vafai (2011c) are also wrong. Specific explanations are outlined below.

(1) In the paper of Yang and Vafai (2011c), a composite system which consists partly of a porous region and partly of an open region is studied. Therefore, the thermal condition at the interface should be considered. In the papers of Yang and Vafai (2010, 2011a), the porous medium occupies the entire configuration and the thermal condition at the

wall should be considered. Nield (2012) tries to explain the interface thermal condition based on the study on the boundary thermal condition. However, it should be noted that determining the thermal conditions at the interface and those at the wall are totally different aspects.

(2) Nield (2012) states, "They treated the five cases in a more-or-less even handed manner, and provided little discussion of the merits on physical grounds of their five models". However, in the work of Yang and Vafai (2011c), five models were developed to describe the thermal interface conditions between the open and porous regions. It was also established in detail that the results obtained from these models can be transformed between the models, and the equivalence correlations between different interface thermal models were developed, which can clearly show the physical consistency between different models. Furthermore, based on the physical attributes of the system, the restrictions were established to validate the thermal interface conditions. The Yang and Vafai's (2011c) analytical results clearly point out the range of validity for each model, which vary for different models. Therefore, the peculiarities of the five models were discussed in detail in the work of Yang and Vafai (2011c).

(3) Unlike what was stated in Nield (2012), in the work of Yang and Vafai (2011c), based on Models A, B1, B2, B3, and C, the total interface heat flux (q_{i}) distribution between the solid and fluid phases can be explicitly calculated.

(4) In the work of Yang and Vafai (2011c), Model B is presented for the thermal interface condition in view of the total heat flux distribution between the solid and fluid phases at the interface. Models B1, B2, and B3 are three possible ways to use Model B. However, Model B can also be used directly. The work of Yang and Vafai (2011c) demonstrate that, only when $\beta \geq \beta_{\mathrm{cr}}$ (β_{cr} denotes critical ratio of heat flux for the fluid phase to the total heat flux at the interface), Model B is valid. This analytical result clearly points out the range of validity for each model, which shows that Model B3 is not always valid.

In addition, it is clear that the boundary and interface conditions have important influence on heat transfer in porous media under LTNE condition. We agree that one of the key problems is "to determine how the total heat flux is split between the fluid and solid phases Nield (2012)". To solve the temperatures of solid and fluid phases under LTNE condition, Amiri et al. (1995) presented for the very first time two primary approaches for the constant wall heat flux boundary conditions under LTNE condition in porous media in 1995. Using one of the two primary approaches given in Amiri et al. (1995), Lee and Vafai (1999) investigated the forced convective heat transfer in a channel filled with a porous medium subject to a constant heat flux. Marafie and Vafai (2001) derived analytical solutions for the forced convective flow through a channel filled with a porous medium subject to a constant heat flux boundary condition, in which the Brinkman–Forchheimer-extended Darcy model was utilized. Alazmi and Vafai (2002) investigated the effect of using different boundary models for the case of constant wall heat flux condition under LTNE condition. It should also be noted that these models (Amiri et al. 1995; Lee and Vafai 1999; Marafie and Vafai 2001; Alazmi and Vafai 2002) can also be used to determine the total heat flux distribution at the wall for the case when a porous medium is attached to the channel wall.

In conclusion, we believe that heat flux bifurcations are highly pertinent physical phenomena occurring in porous media, which would offer a new and valuable direction to investigate heat transfer in porous media.

Acknowledgments We would like to thank Professor Nield for recognizing the importance of our work and for bringing additional attention to our work in this area.

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