Pergamon

Int. J. Heat Mass Transfer. Vol. 40, No. 10, p. 2499, 1997

0017-9310/97 $17.00+0.00

PII: S0017-9310(96)00327-4

LETTERS TO THE EDITORS

Comments on "Turbulence model for flow through porous media"

Masuoka and Takatsu [1] have written a significant pioneering paper on turbulent flow through porous media. However, the foundation of their model is questionable. The model is based on the assumption (page 1) that "it seems reasonable to suppose that the Forchheimer flow resistance and dispersion are caused mainly by turbulent mixing (diffusion) in porous media". This statement in turn is based on the observation that "there is an interesting report [2] in which the turbulence vortices begin to appear at $Re_d \approx 10$ and gradually cover the flow domain (pore space) as Reynolds number increases and velocity measurements with a hot wire anemometer confirm the existence of turbulence in packed beds [3, 4]. In addition to these reports, there exist many experiments in which the deviation from Darcy's law is observed at $Re_d \approx 10$ and not only the effect of the Forchheimer flow resistance, but also the effect of the dispersion, gradually become predominant as the Reynolds number increases".

In fact, Bear's 1972 book [2, page 181] reads:

> "Chauveteau and Thirriot (1967) perform experiments ... For $Re < 2$, the flow obeys Darcy's law and the streamlines remain fixed. As Re increases, streamlines start to shift and fixed eddies begin to appear in the diverging areas of the model. They become larger as Re increases. At $Re = 75$ turbulence appears and starts to spread out as Re increases. Turbulence covers some 50% of the flow domain at $Re = 115$ and 100% of it at $Re = 180$. The deviation from Darcy's law is observed at $Re = 2$–3. Thus the deviation from Darcy's law as the velocity increases is associated with gradual shifting of streamlines due to the curvature of the microscopic solid walls of the pore space."

In the next paragraph, on page 182, Bear [2] concludes that "Most experiments indicate that actual turbulence occurs at Re values at least one order of magnitude higher than the Re at which deviation from Darcy's law is observed." Further, the smallest Reynolds numbers (based on particle diameter and superficial velocity) for which results were reported in refs. [3] and [4] were 4780 and 2500, respectively.

Thus none of the references quoted by Masuoka and Takatsu [1] lend support for their assumption that the Forchheimer flow resistance and dispersion are caused *mainly* by turbulent mixing in porous media. Rather, the evidence indicates that they are *not* caused mainly by turbulent mixing, but are merely *affected* by it and then only at Reynolds number values considerably higher than those at which the Forchheimer resistance first becomes important. (In associating flow resistance and dispersion in this way, I am considering, for simplicity, the case where the Prandtl number is of order unity.)

I conclude that Masuoka and Takatsu [1] are not justified in formulating their equation (12), in which the drag force caused by the molecular (nonturbulent) stress is equated to the Darcy term alone, in the way that they have done. It is not clear to me how this affects the rest of the paper.

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Pergamon

Int. J. Heat Mass Transfer. Vol. 40, No. 10, pp. 2499–2500, 1997

0017-9310/97 $17.00+0.00

PII: S0017-9310(96)00328-6

Authors' reply

We emphasize that a turbulence model [1] is proposed for the flow through porous media at high Reynolds number, and call the flow resistance in this high Reynolds number regime as the Forchheimer resistance.

According to the book [2] of "Transport Phenomena" by R.B. Bird *et al.*, the flow at low particle Reynolds number ($Re_d < \sim 10$) is characterized by the Blake–Kozeny flow resistance (called "the Darcy flow resistance"), and the flow at high particle Reynolds number ($Re_d > \sim 1000$) is characterized by the Burke–Plummer flow resistance (called "the Forchheimer flow resistance"). Furthermore, it is read in this book that the flow characteristics in the transition regime from Darcy to Forchheimer law ($\sim 10 < Re_d < \sim 1000$) can be well described by the Ergun equation, which is formulated as the combination of the Blake–Kozeny and Burke–Plummer equations. This description of flow characteristics qualitatively supports the observation of turbulence in Bear's book [3], and the quantitative difference in the values of Reynolds number will be due to the internal geometric configuration in porous media (reference length). Furthermore the velocity measurements with a hot-wire anemometer [4, 5] confirmed the existence of turbulence at high particle Reynolds number ($Re_d > \sim 1000$), where the Forchheimer flow resistance becomes predominant. The flow through porous media obviously becomes turbulent at high Reynolds number and we also identify this fact from the experiments for the Hele–Shaw flow across tube banks [6]. Attention is given to the dominant regime of the Forchheimer flow resistance ($Re_d > \sim 1000$) in order to clarify the nature of this flow resistance.

Thus we consider the Darcy flow resistance as a molecular drag force and the Forchheimer flow resistance as a turbulent drag force in our turbulence model [1], and also interpret the deviation regime from Darcy to Forchheimer law as the transition regime from laminar to turbulent flow. On the other hand, a similar discussion is possible about the dispersion.

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