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Turbulent flow over a layer of a highly permeable medium simulated with a diffusion-jump model for the interface

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Abstract

Flow over a finite porous medium is investigated using different interfacial conditions. In such configuration, a macroscopic interface is identified between the two media. In the first model, no diffusion-flux is considered when treating the statistical energy balance at the interface. The second approach assumes that diffusion fluxes of turbulent kinetic energy on both sides of the interface are unequal. Comparing these two models, this paper presents numerical solutions for such hybrid medium, considering here a channel partially filled with a porous layer through which fluid flows in turbulent regime. One unique set of transport equations is applied to both regions. Effects of Reynolds number, porosity, permeability and jump coefficient on mean and turbulence fields are investigated. Results indicate that depending on the value of the stress jump parameter, substantially dissimilar fields for the turbulence energy are obtained. Negative values for the stress jump parameter give results closer to experimental data for the turbulent kinetic energy at the interface.

Keywords: Turbulence modeling; Porous media; Volume-average; Time-average; Interface; Stress jump

1. Introduction

Investigation of flow over layers of permeable media has many applications in several environmental and engineering analyses. Turbulent atmospheric boundary layer over forests under fire [1], flow over vegetation and crop fields [2], currents at bottom of rivers [3], as well as grain storage and drying, can be characterized by some sort of porous layer over which a fluid permeates. Also, practical analysis of engineering flows can further benefit from more realistic mathematical and numerical modeling, as in the case of shell-and-tube heat exchangers [4] and nuclear reactor core [5], for example, where the rod bundles can be seen, in a macroscopic view, as a permeable medium.

When the domain of analysis presents a macroscopic interfacial area between a porous substrate and a clear flow region, the literature proposes the existence of a discontinuity in the momentum diffusion flux between the two media [6,7]. Analytical solutions involving such models have been published [8–10]. Also, in such works volume average properties for a homogenous treatment of flow in porous media are obtained by means of the volume-average theorem (VAT) [11,12].

Purely numerical solutions for two-dimensional hybrid medium (porous region-clear flow) in an isothermal channel have been considered in [13] based on the turbulence model proposed in [14–17]. That work has been developed under the double-decomposition concept [18–27]. Non-isothermal flows in channels past a porous obstacle [28] and through a porous insert have also been presented [29,30]. In all previous work of [13,28–30], the interface boundary condition considered a continuous function for the stress field across the interface.

Recently, the interface jump condition has been investigated for laminar flows, either considering non-linear effects in momentum equation as well as neglecting the Forchheimer term in the macroscopic model [31]. Therein, the authors simulated laminar flow over such interfaces

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Nomenclature

c_F	Forchheimer coefficient in Eq. (4)
c_1, c_2	constants in Eq. (9)
c_k	constant in Eq. (8)
c_μ	constant in Eq. (7)
Da	Darcy number, $Da = K/H^2$
$\mathbf{D}$	deformation rate tensor, $\mathbf{D} = [\nabla \mathbf{u} + (\nabla \mathbf{u})^T]/2$
d	particle or pore diameter
G^i	production rate of k due to the porous matrix, $G^i = c_k \rho \phi \langle k \rangle^i \lvert \bar{\mathbf{u}}_D \rvert / \sqrt{K}$
H	distance between channel walls
$\mathbf{I}$	unit tensor
k	turbulent kinetic energy per unit mass, $k = \overline{\mathbf{u}' \cdot \mathbf{u}'}/2$
$\langle k \rangle^v$	volume (fluid + solid) average of k
$\langle k \rangle^i$	intrinsic (fluid) average of k
K	permeability
L	axial length of periodic section of channel
p	thermodynamic pressure
$\langle p \rangle^i$	intrinsic (fluid) average of pressure p
P^i	production rate of k due to mean gradients of $\bar{\mathbf{u}}_D$, $P^i = -\rho \langle \overline{\mathbf{u}'\mathbf{u}'} \rangle^i : \nabla \bar{\mathbf{u}}_D$
$\overline{\mathbf{R}}$	time average of total drag per unit volume
Re_H	Reynolds number based on the channel height, $Re_H = \frac{\rho \lvert \bar{\mathbf{u}}_D \rvert H}{\mu}$
s	clearance for unobstructed flow
S_φ	source term
$\bar{\mathbf{u}}$	microscopic time-averaged velocity vector
$\langle \bar{\mathbf{u}} \rangle^i$	intrinsic (fluid) average of $\bar{\mathbf{u}}$
$\bar{\mathbf{u}}_D$	Darcy velocity vector, $\bar{\mathbf{u}}_D = \phi \langle \bar{\mathbf{u}} \rangle^i$
$\bar{\mathbf{u}}_{D_i}$	Darcy velocity vector at the interface
$\bar{\mathbf{u}}_{D_p}$	Darcy velocity vector parallel to the interface
u_{D_n}, u_{D_p}	components of Darcy velocity at interface along η (normal) and ξ (parallel) directions, respectively
u_{D_i}, v_{D_i}	components of Darcy velocity at interface along x and y, respectively
x, y	Cartesian coordinates

Greek symbols

β	interface stress jump coefficient
μ	fluid dynamic viscosity
μ_{eff}	effective viscosity for a porous medium
μ_{t_ϕ}	macroscopic turbulent viscosity
ε	dissipation rate of k, $\varepsilon = \mu \overline{\nabla \mathbf{u}' : (\nabla \mathbf{u}')^T}/\rho$
$\langle \varepsilon \rangle^i$	intrinsic (fluid) average of ε
ρ	density
ϕ	porosity
$\boldsymbol{\varphi}$	general dependent variable
η, ξ	generalized coordinates

and validated their results against analytical solutions by [8–10]. Such work was based on the numerical methodology proposed for hybrid media and applied by [13,28–30]. The same numerical technique has been applied for computing turbulent flow [32] in a channel partially filled with a flat layer of porous material. Flows over wavy interfaces were also computed for both laminar [33] and turbulent flows [34]. There, the authors made use of the shear stress jump condition at the interface. Those works were also based on a numerical methodology specifically proposed for hybrid media [13,28–30].

A distinct line of investigation on turbulent flow over permeable media is based on the assumption that within the porous layer the flow remains laminar [35–38], which, in turn, precludes application of such methodology to flows through highly permeable media as atmospheric boundary layer over forests or crop fields.

Further, fine flow computations and experiments of flow over and inside a bed of rods in a two-dimensional channel have been presented [39]. Three-dimensional computational studies simulating flow over a layer formed by cubic blocks [40,41] also emphasize that depending on the permeable structure shape, turbulence may exists inside the porous bed and, as such, a turbulence model must be employed.

As seen, all models above considered either a flat or a rough (wavy) macroscopic interface limiting the porous substrate. The stress jump condition for the momentum equations was applied, but in most publications so far, no such flux discontinuity for the $\langle k \rangle^v$-equation has been considered. Motivated by that, Refs. [42,43] proposed a model that assumes diffusion fluxes of turbulent kinetic energy on both sides of the interface to be unequal, which differs from all studies presented up to now. The purpose of this contribution is to explore and further document such proposal, investigating now its behavior as medium properties, such as permeability and porosity, are varied.

2. Macroscopic mathematical model

2.1. Geometry and governing equations

The flow under consideration is schematically shown in Fig. 1 where a channel is partially filled with a layer of a porous material. A constant property fluid flows longitudinally from left to right permeating through both the clear region and the porous structure. The case in Fig. 1 uses symmetry boundary condition at the channel center ($y = 0$). Also, $H = 10$ cm is the distance in between the channel walls and s the clearance for the non-obstructed flow passage. It should be emphasized that the class of flow under consideration involves porous substrates having a high porosity and permeability.