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A macroscopic turbulence model for flow in porous media suited for channel, pipe and rod bundle flows

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Abstract

In the literature, a macroscopic two-equation turbulence model is proposed for analyzing turbulent flows through porous media of particular morphologies (arrays of square or circular rods, packed spheres). This model has been adapted to longitudinal flows in channels, pipes and rod bundles, in order to be able to analyze turbulent flows within nuclear power reactor circuits and core using a macroscopic turbulence model. The additional source terms of the macroscopic k–ϵ equations, which appear as an output of the volume-averaging process, are modeled using the kinetic energy balance and physical considerations. The two unknown constants of the closure expression are determined from the spatial averaging of microscopic k–ϵ computations and from numerical and experimental results available in the literature. This present model has been first successfully evaluated in various simple geometries such as channel and pipe. Good agreement was also obtained between this present model and an experiment of decreasing turbulence inside a rod bundle.
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Keywords: Turbulence modeling; Porous media; Incompressible flow; Volume-average

1. Introduction

In the core of a nuclear power reactor, complex thermohydraulic phenomena occur and a detailed description of the flow may be required. Time-dependent, high resolution simulations based on Large Eddy Simulation (LES) or on Reynolds Averaged Navier–Stokes (RANS) models are able to give the desired detailed flow field prediction. However, the exorbitant run time associated with such simulations and the actual limit of the calculators restrict their use to a limited region of the system. Furthermore, these simulations depend on the state of the flow in the remaining part of the system. This requires either an artificial isolation of the interesting region, or, preferably a coupling between the high resolution description on that region and another description of the remaining part of the system based on a less detailed, cheaper resolution. Macroscopic descriptions such as those developed in the porous media framework, could fulfill this need for a coarse resolution. Indeed, with a porous media formulation, all the complex geometry of the core reactor would not be described, reducing the cost of the computation, but the overall effect of the solid would be taken into account in the model. Therefore, a porous media formulation seems well adapted to the development of a turbulence model dedicated to charged medium such as those encountered in the core of a nuclear reactor. However, in order to be able to later consider the coupling between the different levels of description, the macroscopic turbulent model has to be consistent with microscopic turbulent models, and thus to be properly derived.

In the study of flow through porous media, the first works were mainly based on semi-empirical laws [8]. It is only recently that general equations for flows through porous media were formally derived using the volume-averaging technique [33]. Lage [21] gives a very interesting and comprehensive review of this history of the modeling of

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Nomenclature

c_1, c_2, C_μ	turbulence model constants
C_f	friction coefficient
c_p, y^+_{lim}	macroscopic turbulence model constants
D_h	hydraulic diameter
k	turbulent kinetic energy
K	permeability
p	pressure
Re_H	Reynolds number
S_w	wall friction surface
u_i	velocity

Special symbols

$\langle\psi\rangle$	volume average
$\langle\psi\rangle_\mathrm{f}$	intrinsic average
$\overline{\psi}$	ensemble mean
ψ'	fluctuation
$\delta\psi$	deviation from intrinsic average

Greek symbols

ϕ	porosity
ϵ	dissipation rate of turbulent kinetic energy
ν	kinematic viscosity
ν_t	turbulent viscosity
ν_{t_ϕ}	macroscopic turbulent viscosity
ρ	fluid density
$\tilde{\sigma_k}, \tilde{\sigma_\epsilon}$	macroscopic Prandtl numbers

flow through porous media starting from the work of Darcy. The volume-averaging technique is a rigorous mathematical procedure used to derive the governing mass, momentum and energy equations in porous media [3,34]. Different authors use this formalism to derive macroscopic turbulence models. For instance, Masuoka and Takatsu [23] derive a 0-equation turbulence model using the local volume-averaging technique. They model the effective eddy diffusivity as the algebraic sum of the eddy diffusivities estimated from two types of vortices: the pseudo vortex and the interstitial vortex. Studying also turbulent flow and heat transfer through stacked spheres, Alvarez et al. [1] propose a 1-equation turbulence model.

Two-equation macroscopic turbulence models are also proposed in the literature. Antohe and Lage [2] derive a two-equation macroscopic turbulence model applying the time averaging operator to the extended Darcy–Forchheimer model. Getachew et al. [13] extend this work by taking into account higher order terms. Following another approach, Nakayama and Kuwahara [25] propose a two-equation macroscopic turbulence model obtained by spatially averaging the Reynolds-averaged Navier–Stokes equations. However, for turbulent flows, the order of application of the two operators (time-averaging for turbulence and volume averaging) is important. Pedras and de Lemos [27] show that the two approaches lead to similar equations for the mean flow, but that the turbulence kinetic energies resulting from the two different approaches are different. In particular, they show that, applying first the time-averaging operator, allows to take into account the turbulence inside the pores. Thus, the latter approach will be used in our study.

Applying the volume-averaging theory to the microscopic transport equations of turbulent kinetic energy and its dissipation rate, Nakayama and Kuwahara [25], and Pedras and de Lemos [28], establish a macroscopic two-equation turbulence model. They obtain a new set of equations for the transport of the volumetric averaged turbulence kinetic energy and its dissipation rate. These new equations involve additional terms which quantify the influence of the medium morphology on the turbulent kinetic energy and dissipation level. The main difficulty of the approach is to propose a closure for these additional terms and unfortunately there is no general well-developed closure expression valid for any kind of porous media morphology for these additional terms. Nakayama and Kuwahara [25], and Pedras and de Lemos [28] propose different models for these additional terms. The important point is that the correlations, or the constant of their models are obtained by integrating microscopic results obtained from numerical experiments over a unit porous structure. Different unit porous structures have been already considered: regular morphology made of square [25], circular [30] or elliptic [29] rods. This method of integrating microscopic results obtained from numerical experiments over a unit porous structure has also been used with success by Kuwahara et al. [19,20] and Nakayama et al. [26] to study thermal dispersion and interfacial heat transfer coefficient in porous media.

We are interested in modeling the core of nuclear power reactors using the porous media approach. The different nuclear cores that are under study are characterized by elongated geometries, and by a large number of identical elements. As can be seen in Fig. 1, which shows examples of gas cooled reactors, we can have to compute the turbulent flows around more than thousands of needles, and we are interested by different geometries: channels, tubes and needles. Furthermore, in the core of the reactor, the flow is longitudinal whereas in the studies by Nakayama and Kuwahara [18,25], and Pedras and de Lemos [28–30] only transverse flows were considered. Chung et al. [6] have already studied a porous media made of channels. However, their work is based on the model of Antohe and Lage [2]. As mentioned previously, this model does not allow to take into account the turbulent kinetic energy inside the interstices, while we are precisely interested in knowing

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