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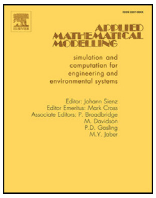

Characterizing flow resistance in 3-dimensional disordered fibrous structures based on Forchheimer coefficients for a wide range of Reynolds numbers

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ABSTRACT

The flow resistance in 3-dimensional fibrous structures are investigated in particle Reynolds number representing flow characteristics with strong inertia. The resistance coefficients are established based on steady state simulations of single-phase processes of water numerically. An automatized simulation process in COMSOL is developed with a MATLAB algorithm in which production runs could be carried for various 3-dimensional fibrous structures. Simulation of flow processes ranging from Reynolds numbers at creeping flow levels to high Reynolds number at approximately 1000 are calculated and a numerical data set is established in order to estimate Forchheimer coefficients which are used to correlate a dimensionless friction factor to a modified Reynolds expression for porous media.

The friction factor and dimensionless permeability are calculated for fibrous structures with (i) disordered unidirectional fibers (ii) an isotropic fiber orientation in-plane perpendicular to the flow, and (iii) an isotropic fiber structure in a the 3-dimensional space. Empirical correlations of the friction factor and Reynolds number are used to compare our simulation data in order to assess the validity of our models and flow resistance estimations. The dimensionless permeability is moreover compared to other numerical simulations of flow through fibrous structures in order to assess flow resistance at low Reynolds number.

It is concluded that flow resistance in the isotropic fiber arrangement in space is lower than the in-plane isotropic orientation and disordered unidirectional fiber arrangements at creeping flow conditions, however, all friction actors converges towards the same value at higher Reynolds numbers indicating that fiber orientation is independent at high inertia flow regimes. Overall, our numerical simulations agree well to classical empirical formulations for a wide range of Reynolds number. However, the comparison differs considerably depending on the porosity level.

1. Introduction

The concept of porous media flow is widely encountered in various fields such as filtration theory, petroleum engineering, soil mechanics etc. The solid matrix of the porous medium is constituted by a unified pattern of solid materials creating a dense structure such as a packed bed of solid grains, entanglement of fibrous material or a connected pin-fin arrangement

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Nomenclature

A	Area [m^2]
C	Dimensionless friction factor [-]
D	Fiber diameter [m]
F	Force [N]
K	Permeability [m^2]
L	Sample length [m]
M	Sample points [-]
N	Sample points [-]
n	Normal of the interface [-]
p	Pressure [Pa]
P	Fiber position [m]
r	Fiber radius [m]
S	Specific surface area [m^{-1}]
t	Unit tangent of surface [-]
u	Local velocity coefficient [m/s]
U	Velocity magnitude [m/s]
V	Volume [m^3]
Z	Pseudorandom integer [-]

Greek symbols and mathematical operators

α	Viscous resistance coefficient [Pa·s]
β	Inertial resistance coefficient [kg/m^4]
ε	Porosity [-]
ϑ	Brinkman screening length [m]
μ	Viscosity [Pa·s]
ρ	Density [kg/m^3]
Σ	Summation [-]
$\langle \cdot \rangle$	Volume-averaged property [-]

Subscript

0	Superficial
Ergun	Ergun
f	Friciton
fiber	Fiber
i, j, k	Tensor indices
x, y, z	Cartesian coordinates

Acronyms

DVI	Digital volumetric imaging
FRV	Flow representative volume
NSD	Normalized standard deviation
NS	Navier–Stokes
Re	Reynolds

from a heat exchanger. Understanding the flow mechanics in porous media is essential in order to assess flow resistance which could result in accurately predicting pressure drop in a time efficient manner through numerical simulations.

The flow resistance in fibrous structures has been numerically analyzed in recent years. With the increasing computer capacity available, researchers are nowadays able to numerically study friction and permeability in 3-dimensional fibrous structures. However flow resistance in porous media has its origin in experimental and empirical studies, most notably the study conducted by Ergun [1] in which the widely known empirical Ergun equation is used to calculate pressure drop in columns of packed spheres. This work is followed by a vast field of studies in which the Ergun equation is used as a validation tool and is the basis for many modifications of empirical equations for prediction of pressure drop and flow resistance characterization of porous media [2–8].

Flow resistance in porous media is often characterized with the hydraulic permeability. A notable study of permeability compiling experimental data and empirical formulations is presented by Jackson and James [9]. They review a vast field of data for various fiber arrangements which are used today for model validation of numerical permeability calculations for creeping flow conditions. Such numerical studies calculate the dimensionless permeability for various arrangements of 3-dimensional fibrous structures [10–14]. The dimensionless permeability is also related to the level of orientation through