ARTICLE IN PRESS

Computers and Mathematics with Applications ▮ (▮▮▮▮) ▮▮▮–▮▮▮

Contents lists available at ScienceDirect

Computers and Mathematics with Applications

journal homepage: www.elsevier.com/locate/camwa

On a multiscale approach for filter efficiency simulations

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ARTICLE INFO

Article history:
Available online xxxx

Keywords:
Filter efficiency
Multiscale simulations
Stokes–Brinkman equations
Microscale particle capturing

ABSTRACT

Filtration in general, and the dead end depth filtration of solid particles out of fluid in particular, is intrinsic multiscale problem. The deposition (capturing of particles) essentially depends on local velocity, on microgeometry (pore scale geometry) of the filtering medium and on the diameter distribution of the particles. The deposited (captured) particles change the microstructure of the porous media what leads to change of permeability. The changed permeability directly influences the velocity field and pressure distribution inside the filter element. To close the loop, we mention that the velocity influences the transport and deposition of particles. In certain cases one can evaluate the filtration efficiency considering only microscale or only macroscale models, but in general an accurate prediction of the filtration efficiency requires multiscale models and algorithms. This paper discusses the single scale and the multiscale models, and presents a fractional time step discretization algorithm for the multiscale problem. The velocity within the filter element is computed at macroscale, and is used as input for the solution of microscale problems at selected locations of the porous medium. The microscale problem is solved with respect to transport and capturing of individual particles, and its solution is postprocessed to provide permeability values for macroscale computations. Results from computational experiments with an oil filter are presented and discussed.

1. Introduction

1.1. Motivation

This paper concerns mathematical modeling and simulation of solid–liquid separation, i.e. filtration of solid particles out of a fluid. Filtration is important in many applications, e.g. automotive and aircraft industries, air conditioning, drinking water quality and water reuse, to name just a few. To design high quality filter elements, industries usually rely on the results obtained from laboratory experiments which is an expensive and time consuming procedure. In particular, filtration efficiency tests, which are defined by international standards, are conducted to evaluate the performance of filter media and filter elements. The filtration efficiency is measured as the ratio between the upstream particle count in the feed and the downstream particle count in the filtrate (in fact, the efficiency is measured individually for different sizes of particles). The filtration efficiency depends on both, microscale and macroscale quantities. This can shortly be explained as follows: the deposition (capturing of particles) essentially depends on the local velocity, on the microgeometry (pore scale geometry) of the filtering medium, and on the diameter distribution of the particles. The deposited (captured) particles change the

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http://dx.doi.org/10.1016/j.camwa.2014.02.022
0898-1221/

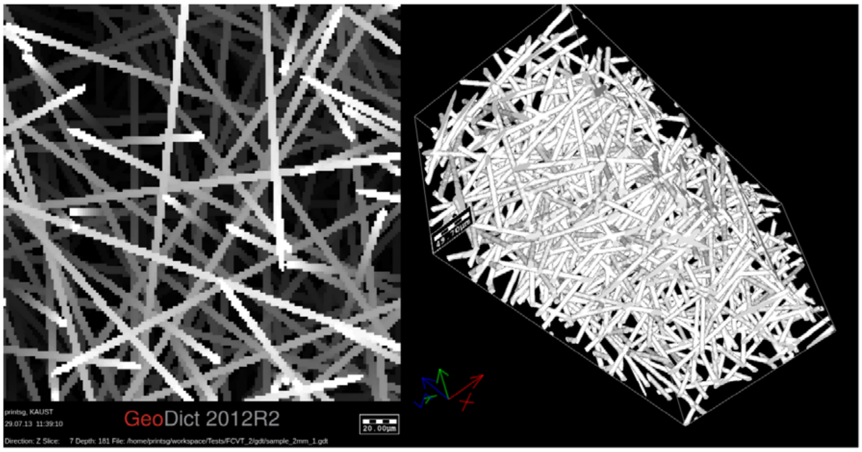

Fig. 1. Microstructure example.

microstructure of the porous media. The changes in the microgeometry influence the macroscale parameters, namely the intrinsic permeability of the filtering medium. The change in the permeability directly influences the velocity field and pressure distribution inside the filter element. As stated above, the local velocity influences the transport and deposition of particles. To account for the aforementioned interplay of microscale and macroscale effects in the accurate prediction of the filter efficiency, it is crucial to incorporate in the simulation algorithms the processes occurring at different scales.

Note that in particular cases, either the microscopic or the macroscopic effects may dominate, and in these cases the filtration efficiency can be predicted independently from either the microscale or the macroscale simulations. However, the cases with strongly coupled microscale and macroscale effects require truly multiscale simulations of the filtration processes.

Nowadays, Computer Aided Engineering, CAE, is widely used in aerospace, automotive, and other high-tech industries. Gradually, CAE becomes an every day approach also in industries which earlier have not used this approach. Despite the growing importance of the modeling and simulation of filtration processes, there is only limited literature to be found in this field. In the following subsections, we will shortly discuss selected papers devoted to this topic as a very basic overview.

1.2. Modeling and simulation of filtration processes at microscale

The existing computer power allows filtration processes to be simulated only in a small piece of the filtering medium when the pore scale geometry is fully resolved. The microgeometry of the filtering medium can be obtained either by taking 3D CT (computer tomography) images of small pieces of existing media, or by generating such microstructures by proper software tools. Samples of filtering media resolved at microscale are shown on Fig. 1. Mathematical model describing filtration of solid particles in rigid filtering medium was proposed in [1]. This model was the fundament on which the module FilterDict of the software tool GeoDict [2] was built. The following procedure is carried out. Laminar incompressible Stokes or Navier–Stokes equations are solved to compute the fluid flow in a given microstructure. Stochastic ordinary deferential equations describing motion of non-interacting particles, is solved using the above computed fluid velocity as input (see Section 3 for details). Various mechanisms for particles capturing are modeled and implemented: direct interception, inertial impact, diffusional deposition, size sieving, and clogging. The transported particles have mass and impulse, but no volume. However, the volume of the deposited particles is accounted for. The flow field is recomputed any time when a relatively large amount of particles are deposited, so that there are changes in the local flow. An impression about microscale simulation of filtration processes can be gained, e.g., from [1,3–6].

1.3. Modeling and simulation of filtration processes at macroscale

Despite the diversity in the various shapes and applications, all filter elements have a common design principle: the inlet(s) and the outlet(s) are separated with at least one filtering medium. A sketch of an automotive oil filter is shown in Fig. 2. In this paper we restrict our discussion to liquid filtration. The air (or gas) filtration is usually related to fast flows, and this is a subject of a forthcoming paper. The state of the art for the macroscale modeling of liquid filtration can be found in [7–11] and the references therein. In the referred studies, the Navier–Stokes–Brinkman system of equations is used as macroscopic model for describing the flow inside the filter element. The transport and capturing of particles are described by a convection–diffusion–reaction equation for the concentration of particles. This model is the basis for the development of two software tools, Suction Filter Simulation (SuFiS) [12], and Filter Element Simulation Toolbox, FiltEST [13]. SuFiS is a specialized software tool for oil filtration for automotive applications, while FiltEST is a general purpose software for

Please cite this article in press as: O. Iliev, et al., On a multiscale approach for filter efficiency simulations, Computers and Mathematics with Applications (2014), http://dx.doi.org/10.1016/j.camwa.2014.02.022