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FRICTION FACTOR OF THE FLUID FLOW THROUGH POROUS MEDIA

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Abstract: *This paper deals with the theoretical foundations aimed for modeling and simulation of fluid flow through porous structures and related friction. Different approaches to determination of the analytical solution of the friction factor are presented, as well as formulas that are used in specific flow regimes. Review of fluid types from aspect of viscosity are shown, namely Newtonian and non-Newtonian fluids and related aspects of the fluid behaviour. Review of the established dependencies of the friction factor on the influential factors is presented, such as on Reynolds number, pore geometry, permeability and inertia coefficients. Differences between smooth and rough surfaces in contact with the fluid are observed, from aspects of friction. Geometry of the porous structure essentially influences the flow and governs the friction, as well as the surface roughness. The pressure drop within a porous structure is directly influenced by the permeability and drags force coefficients and can well characterise cellular materials. Wall roughness typically enhances the turbulence and transition from laminar to turbulent flows appears earlier for rough than for smooth surfaces. One short example of CFD modeling of the fluid flow through porous media is shown, as well as generation of the Voronoi based open cell pattern.*

Keywords: *friction factor, fluid flow, CFD, porous structure, Voronoi meshing.*

1. INTRODUCTION

Porous materials have gained much attention for numerous industrial applications, whereas the main property enabled is related to the lighter materials in otherwise robust elements. Porous material is a material containing voids in certain percentage. The solid portion of the material is often called the "matrix" or "frame". The voids or pores can be empty (e.g. in the case of shock absorbers) or filled with a fluid (e.g. in the case of filtration systems). Porosity is eminent property, but other features are also important, such as permeability, tensile strength, electrical conductivity or any other related to the end application. However, porosity is not a simple term, because it is directly describing the material only in case of poroelastic medium. Porosity can be interconnected, thus making continuous network of solid matrix and open pores. In other case, porous material can have closed voids resulting in rather different methods of characterisation and design, from several aspects (fabrication, mechanical behaviour, etc.). For materials with open porosity, effective porosity (pore space accessible to flow) is also introduced as the process parameter.

Most of the natural materials exhibit some degree of porosity (rocks, soil, wood, biological tissues – bones), as well as many artificial ones (cement, concrete, ceramics) and numerous applications use its concept (e.g. filtration systems that directly use porosity in its function). Fluid flow through open channels (e.g. river basin or pipes) is rather different than the flow through porous medium, whereas some part of the fluid is retained within pores constantly during the flow. The basic law related to the fluid flow through porous medium is Darcy's law, as given in equation (1), established by, Henry Darcy in 1856. It is based on his experiments with water passing through sand. It is a simple direct relationship between the discharge rate through a porous medium, pressure drop over certain distance and fluid viscosity.

$$Q = \frac{CA\Delta(P - \rho g z)}{L} \tag{1}$$

where: Q is volumetric flow rate [m^3/s]; P is pressure [Pa]; ρ is density [kg/m^3]; g is gravitational acceleration [m/s^2]; z is vertical coordinate (measured downwards) [m]; L is length of sample [m]; C is constant of proportionality [m^2/Pa s]; A is cross-sectional area of sample [m^2].

Darcy's law is valid in the case of macroscopic flow, that is, when flow regions are much larger than the pore sizes. However, when micro and nano voids are observed, different set of parameters must be taken into account. There are several influential parameters describing fluid flow through porous materials introducing complexity in calculations and theory. Observation of nano/micro scales only increase these complexities, and many issues are under investigation in scope of these new applications. For example, permeability is not a property related to the pore size. It is related to certain region that contains some number of pores and representative elementary volume (or length scale) needs to be defined. Dynamic behaviour of the fluid, especially in case of porous medium, often introduce Darcy friction factor, which is essentially different that friction coefficient in case of solid contacts. It describes the friction losses during the flow in pipes and open channels, and it is studied also for porous nano/micro structures.

Table 1. Historical approximations to the Colebrook–White relation: friction factor, f

Equation	Author	Year	Range	Ref.
$f = 0.0055(1 + (2 * 10^4 * \frac{\varepsilon}{D} + \frac{10^6}{Re})^{\frac{1}{3}})$	Moody	1947	$Re = 4000 - 5.10^8$ $\frac{\varepsilon}{D} = 0 - 0.01$	[1]
$\frac{1}{\sqrt{f}} = -2\log(\frac{\frac{\varepsilon}{D}}{3.71} + (\frac{7}{Re})^{0.9})$	Churchill	1973	Not specified	[2]
$f = 8\left[(\frac{8}{Re})^{12} + \frac{1}{(\Theta_1 + \Theta_2)^{1.5}}\right]^{\frac{1}{12}}$ where $\Theta_1 = \left[-2.457\ln((\frac{7}{Re})^{0.9} + 0.27\frac{\varepsilon}{D})\right]^{16}$ $\Theta_2 = (\frac{37530}{Re})^{16}$	Churchill	1977	Not specified	[2]
$A = 0.11(\frac{68}{Re} + \varepsilon)^{0.25}$ if $A \geq 0.018$ than $f = A$ and if $A < 0.018$ than $f = 0.0028 + 0.85A$	Tsal	1989	Not specified	[3]
$f = \left[-21\log(\frac{2.18\beta}{Re} + \frac{\varepsilon}{3.71})\right]^{-2}$ $\beta = ln\frac{Re}{1.816\ln(\frac{1.1Re}{\ln(1 + 1.1Re)})}$	Brkić	2011	Not specified	[4]

Table 2. Examples of different fluids from aspect of viscosity

Viscoelastic	Amorphous polymers, semicrystalline polymers, biopolymers, blood clots, metals at very high temperatures, toothpaste, gelatine	combination of elastic and viscous effects under deformation
Time-dependent viscosity	Synovial fluid, printer ink, gypsum paste	viscosity increases with duration of stress
	Yogurt, aqueous iron oxide gels, gelatin gels, pectin gels, some clays, many paints, many colloidal suspensions	viscosity decreases with duration of stress
Non Newtonian Viscosity	Silica nano-particles are dispersed in a solution of polyethylene glycol; quicksand; corn starch in water	Shear thickening
	Blood, some silicone coatings, some silicone oils, sand in water, ice	Shear thinning (pseudoplastic)
	Water, Blood plasma	Generalized Newtonian fluids. Idealized fluid where viscosity is constant.

There is a number of existing phenomenological equations that enable calculation of Darcy friction factor, depending on the flow regime (laminar, transitional, turbulent in smooth or rough conditions, free surface), as well as many approximations, as given in Table 1. Friction factor has been studied by many research groups, but mainly for the pipe flow. The simplest formula is for the laminar flow in the pipe, for Reynolds number less than 2320, as given in equation (2).

$$f = \frac{64}{Re} \tag{2}$$

Beside the Reynolds number, roughness ε is introduced and pipe diameter D. Development of the friction factor equations through years is given in Table 1. It only reflects complexity of the exact determination of the friction factor and additional issue of porous materials represents state-of-the-art subject of research nowadays. There are different parameters that can be observed as influential and a good review is given in [14, 19].

2. FRICTION FACTOR IN NON-NEWTONIAN FLUIDS IN POROUS MEDIA

Unlike the water, synovial fluids and blood belong to a group of non-Newtonian fluids. These fluids do not follow the Newton's Law of viscosity and exhibit viscosity that is dependent on the shear rate. Comparison of non-Newtonian, Newtonian, and viscoelastic properties and examples of fluids are given in Table 2 [6].

Flow of non-Newtonian fluids through porous materials is important for many applications, such as oil recovery, liquid polymer molding, blood flow through bone scaffolds, etc.

In general, non-Newtonian fluids can be classified as:

- Time-independent or generalized Newtonian fluids
- Time-dependent fluids
- Viscoelastic fluids

Friction coefficient can be calculated by using several equations, as previously mentioned, but in the case of porous structures it is still under development and is applied with more or less accuracy in modeling. Good reviews of possible approaches in modeling of flow through the porous structures are given in [18, 19, 20].

For single void, normalized friction coefficient calculated as the function of Reynolds number is shown in Fig. 1, whereas comparison of different pore sizes, flow lengths and empirical coefficients reflecting flow regimes are shown. The difference from idealized Newtonian fluid can be clearly seen. Another important parameter is the roughness of the surface over which the fluid is flowing, which essentially influence the friction in boundary layers. Flow behaviour over smooth (Fig. 2a) and rough surfaces (Fig. 2b) usually relates to a different regimes and friction factor dependence on Reynolds number is shown in Fig. 2 [7] with obvious differences. The transition between laminar and weak turbulent flow can be clearly seen. Navier–Stokes equations are applied at the microscopic level, whereas these are reduced to Stokes equations when non-linear part is neglected. If only one width of the pore is presented for both cases of rough and smooth surfaces, very obvious difference in values of the friction factor can be seen in Fig. 3 [7]. It can also be seen that friction factor decreases with increase of Reynolds number, what can be typically expected. However, Figs. 2 and 3 shows that some opposite behaviour can be expected in certain ranges of Reynolds number. This can be especially well observed in Fig. 3, for both smooth and rough surfaces, but more pronounced in case of smooth surface. Wall roughness typically enhances the turbulence and transition from laminar to turbulent flows appears earlier for rough than for smooth surfaces (denoted by the sudden fluctuation of values in the presented curves). Tzelepis et al. [7] suggested the certain threshold on the factor dependence on the fracture width (or pore size if porous structure is considered) and roughness, meaning that after some value of Re, no dependence can be observed, but this needs further investigations.

However, there is a limited literature on fully porous structures related to the friction factor and all analytical solutions are mainly related to some approximations of those for pipe or open channel flows with introduction of wall roughness. Geometry of porous structure essentially influences the flow and some recent papers have started to deal with this topic, such as very good article on this subject is written by Kumar and Topin [8].

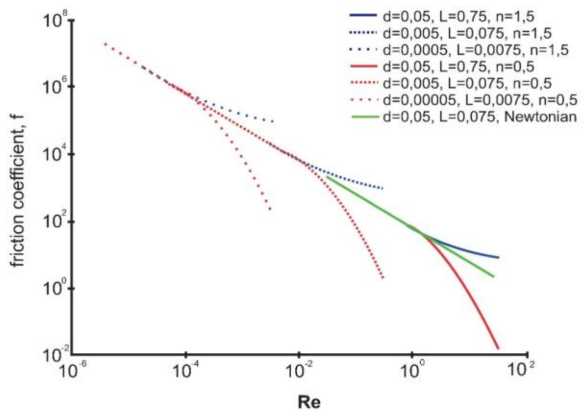

Figure 1. Friction coefficient dependence on Reynolds number for non-Newtonian fluids in comparison to Newtonian fluids [6]

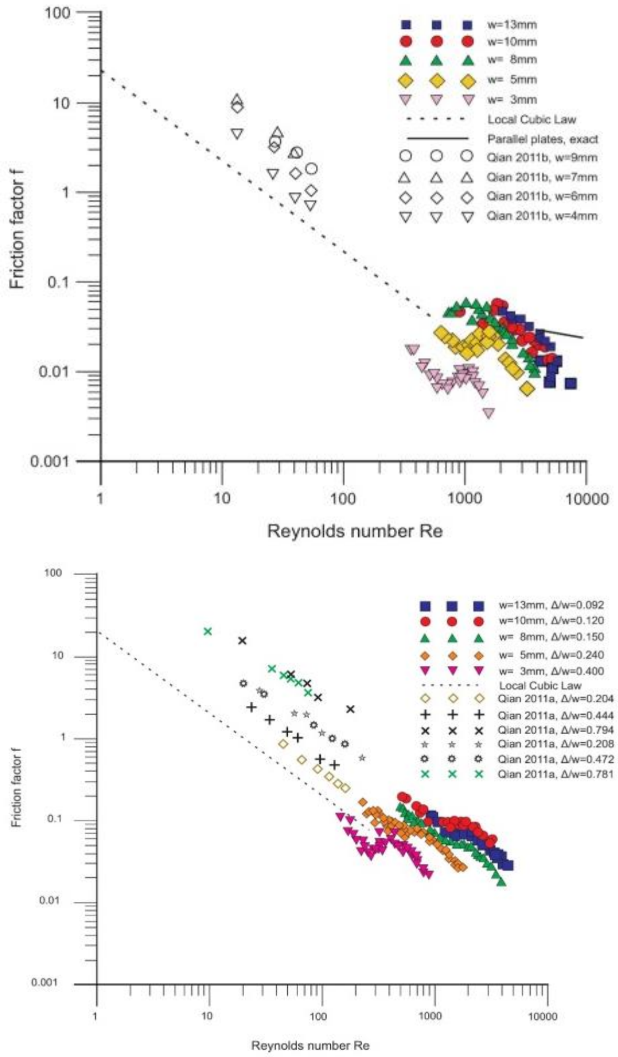

Figure 2. Constructed Moody diagram for all widths for a) smooth fractures and b) rough fractures [7]

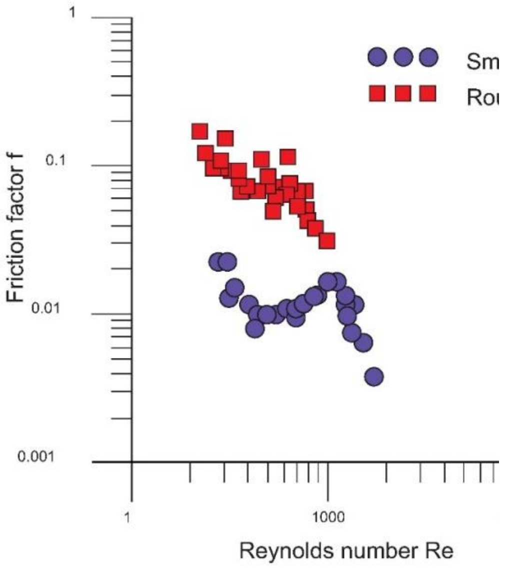

Figure 3. Constructed Moody diagram for 3 mm width – comparison of smooth fractures and rough fractures [7]

They enlisted several approaches in definition of properties of flow through open cell foams and analysed dependence of the particle diameter D_p on Reynolds number, used for pressure drop and friction factor calculations. This approximation considers the porous structure as the collection of grains closely packed, with the same specific surface area as the porous structure thus formed, what in reality can display rather large difference as can be seen in Fig. 4.

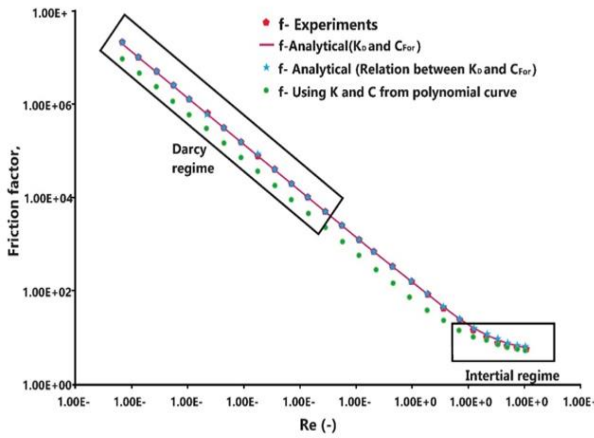

Figure 4. Comparison of analytical and experimental solutions for friction factor dependences on Reynolds number with influence of K and C coefficients [8]

Geometry of pores within the porous structure can be easily exactly determined, experimentally by using micro CT device [9]. Different formulas are used in different regimes and several parameters are important, whereas flow characteristics, K – permeability and C – inertia coefficients, are commonly obtained by experiment and used for fitting of analytical curves.

Kumar and Topin [8] suggested analytical solution for friction factor by using pressure drop within a porous structure as given in equation (3) and proven by good fitting with experimental data as shown in Fig. 5. The pressure drop within a porous structure is directly influenced by the permeability and drag force coefficients and can well characterise cellular materials [8, 9].

$$f = \nabla\langle P\rangle . \frac{d_h}{\rho V^2} \tag{3}$$

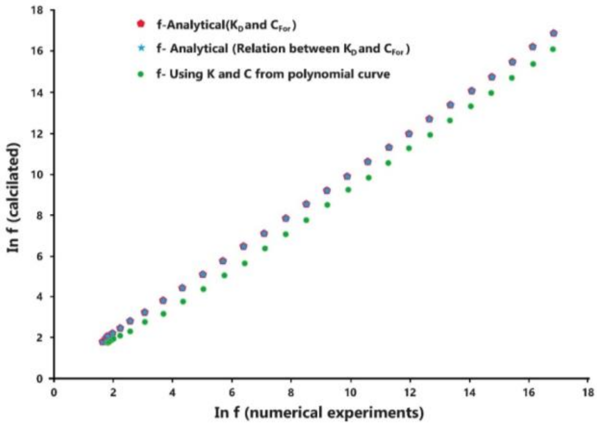

Figure 5. Comparison of analytical and experimental solutions for friction factor [8]

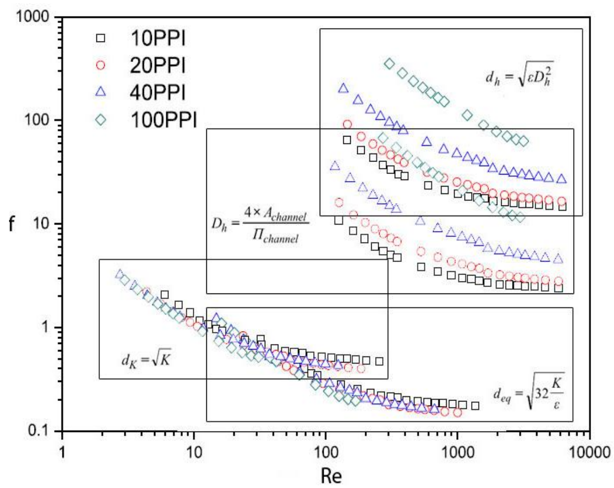

Figure 6. Friction factor dependence on: 1) the cross section area (D_h – central diagram); 2) equivalent diameter (d_{eq} – lower right diagram); 3) square root of permeability (d_k – lower left diagram) and 4) porosity (d_h – upper right diagram) [10]

Kim et al. [10] classified the relations between friction factor and Reynolds number for metal foams in several regimes: $Re < 20$, $Re > 2000$ and suggested that the dependence for foams is similar to classical Moody chart, as given in Fig. 6 [10].

The largest discrepancies with linear fit are exhibited for higher friction factors and inverse Reynolds number (1/Re), as well as for lower pore sizes and smaller cross section areas. Another correlation of the friction factor with Re for foams and different regimes is given in [16]. Approximations by using woven metal mesh screens have also been studied [17].

Besides the fundamental understanding of the friction within a fluid flow through the porous media and governmental basic parameters of the system, additional influences need to be considered as well, such as the temperature or magnetic field, especially in nano and micro domains and some recent research have been dealing with this. For example, magnetohydrodynamic nanofluids flow and transfer of heat are quite interesting for some new applications in micro systems [11, 12]. Those results indicated that volume fraction of nanoparticles can be related to some coefficients important for fluid dynamics, such as Nusselt number, but the type of the nanoparticle still remains the most important governing factor. However, magnetic field influence still needs clarifications.

Important areas of application are medical implants and human tissue represents the typical non-uniform porous structures [13]. The blood is known to be the non-Newtonian fluid, thus making modeling and simulation of the flow dynamics very complex and still under investigation from many aspects. In that sense, poroelasticity becomes important, as the property indicating interactions between the fluid flow and deformation of solids, during the flow through the porous structure [13].

3. Modeling of the fluid flow through porous media

Modeling of the fluid flow has been developed in the last decades in order to describe the system behaviour and predict its performance, as well as to determine the zones where the strengthening is needed. Determination of distributions of stress and strain within a porous structure is cutting edge research that will enable better material design. There are several approaches to the modeling of porous structures, but the majority still encounter principles used for solid structures and presence of voids still need to be comprehensively studied. One of the techniques used for modeling of the fluid flow through porous structure is by using Voronoi tessellation 3D effects. In the next example, dynamic behavior of pores under fluid effects is observed, by application of the simple steady sate viscous model based on commercial pre and post processing FEMAP TMG FLOW (CFD) software. A constant volumetric flow of water, $Q = 2$ l/s is applied and the structure is shown in Fig. 7. Mesh generation is schematically shown in Fig. 8 and Fig 9.

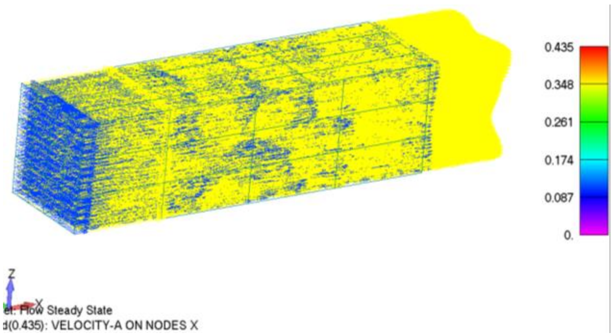

Figure 7. CFD modeling of the water flow through the porous structure

Initial conditions based on Navier–Stokes equations consider ambient temperature; mixing length laminar/turbulent flow model; and average Reynolds number of 14460. Distributions of the pressure and velocity are shown in Figs. 10 and 11, for the flow through the empty space represented by the given 3D structures in these images.

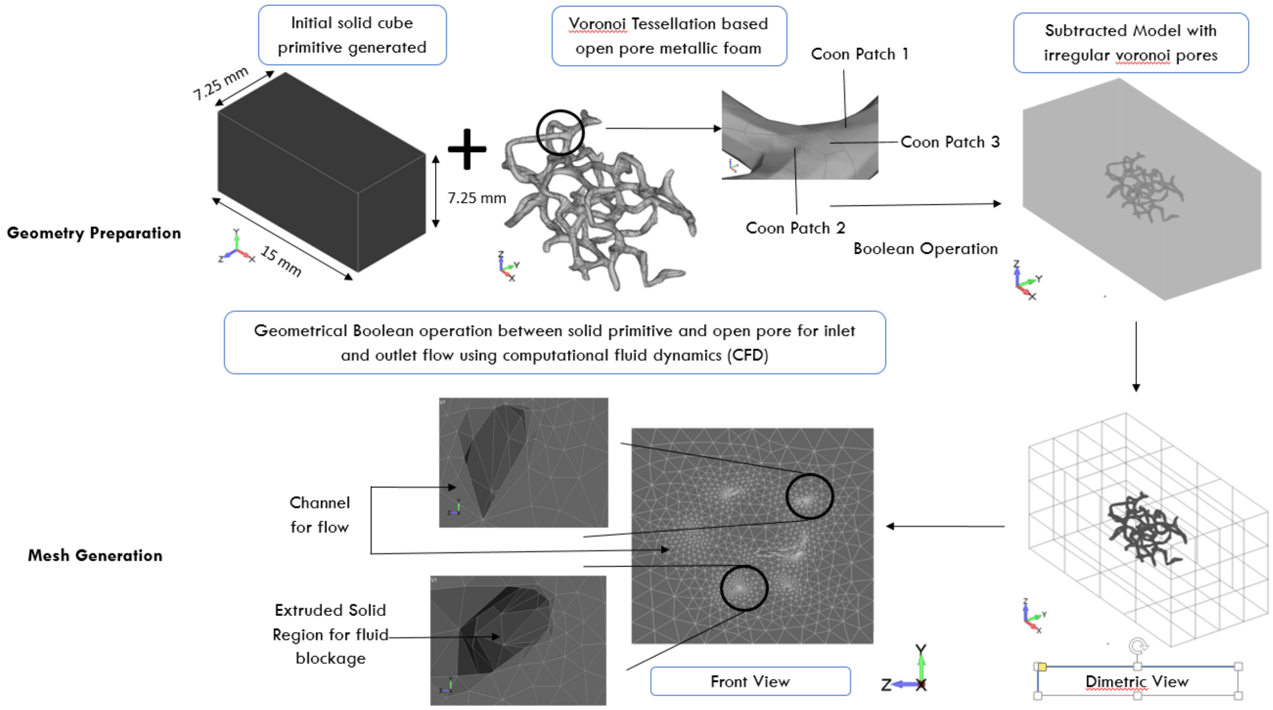

Figure 8. Design schematic and mesh generation procedure for the Voronoi based open pores pattern

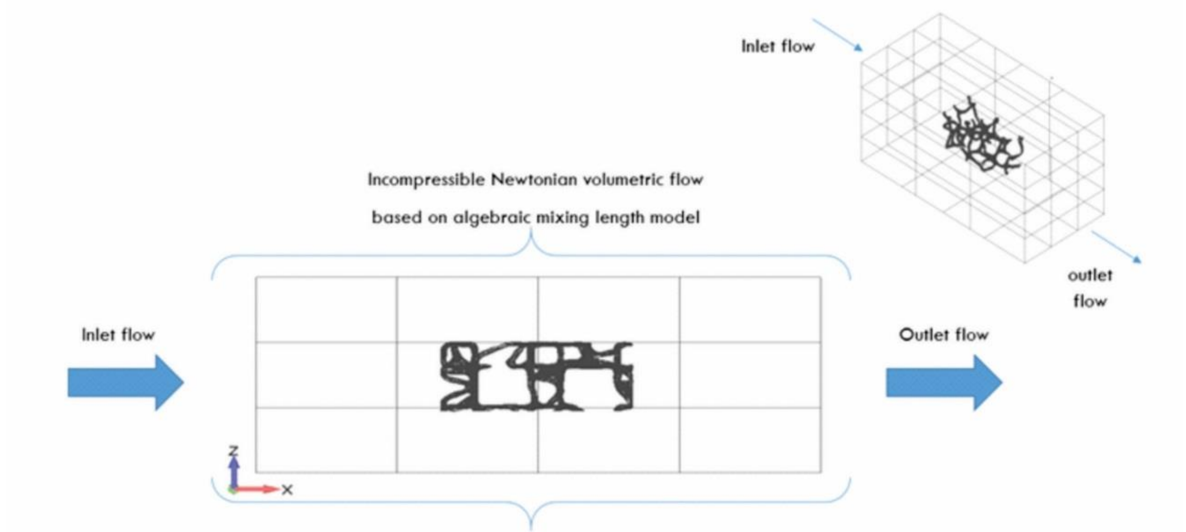

Figure 9. Computational domain definition for the incompressible Newtonian volumetric flow model based on algebraic mixing length model

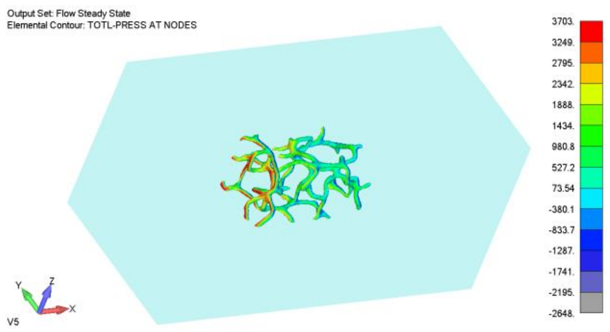

Figure 10. Pressure distribution at the boundary layers, in the x-direction

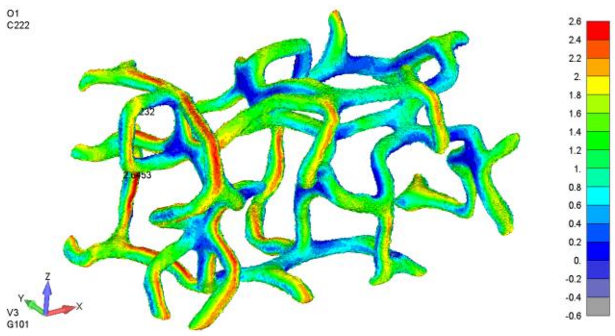

Figure 11. Velocity distribution at the boundary layers, in the x-direction

Skin friction drag pertains to the friction between the fluid and thin boundary layer on the surface of the object over which the fluid flows, usually consisting of the air. It is directly in connection with the properties of the material surface. The force that is exerted for dragging the layer of air attached to the surface of the object (e.g. inner pipe surface, or struts in porous structure) is called skin friction drag. Skin friction is due to the viscous drag within the boundary layer attached to the object surface, usually very thin, but it can become thicker within the rear zones, especially in the case of porous structures. Usually this zone exhibit laminar flow and transits to the turbulent in the rear zones. Shape of the surface greatly affects the zones with laminar and turbulent flow, and especially influences the transition point between the two of them. Good article on trasnsitional conditions is given in [15].

Various design methods are studied to provide laminar flow when it is possible. As in the previous case of the friction factor, skin friction coefficient can be calculated by using several equations, depending on the flow regime, and the basic one is given in equation (4).

$$C_f = \tau_w / q \qquad (4)$$

where τ_w is the local wall shear stress; q is the free-stream dynamic pressure. And for the turbulent flow, empirical formula is similar to the equation (2), as shown in the equation (4).

$$C_f = 0.074 / Re^{0.2} \qquad (5)$$

where Re is the Reynolds number.

The majority of theoretical equations are established for aerodynamic coefficients (e.g. for rockets) [5] and very limited literature exists related to the porous structures that represents the cutting edge current research related to several final applications, such as tissue scaffolds and associated processes.

CONCLUSIONS

Porous materials have gained much attention in the recent time due to many benefits that they can offer in both traditional applications as the substitution for heavy bulk materials, while retaining the strength and mechanical properties, and new applications, such as medical implants of new generations. However, the comprehensive properties of the porous structures are still under development, especially in the case of fluid flow through its voids. Dynamic fluid behaviour and its effects on mechanical integrity of the porous material elements (thin struts and matrix in general) is of the utmost importance for many new applications, including filtration systems, biomedical scaffolds and tissue engineering, or oil refining. Modeling and simulations represent valuable tool for determination of the weak points and further improvements, but also for prediction of its functional behaviour over time. Theoretical foundation for analytical solutions that are necessary for modeling is under development and many unanswered questions still exists. However, even with the existing ambiguities related to the transition between laminar and turbulent flow within the porous structure, distributions of pressures and velocities in boundary layers, and pressure drop over lengths, as well as the issue of all necessary influential factors, some new approaches have been studied and enabled rather well fitted analytical solutions related to the friction factor. Also, efficient new technologies, such as micro CT enabled exact determination of the real porous structure and opened up new avenues in this research topic.

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