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Numerical simulation of a liquid imbibition in a system of parallel channels

Introduction

There are different types of liquids percolation processes in the porous media and one of them is the spontaneous imbibition. It is practically used in a numerous industrial technologies and can be also observed in the natural environment. This type of transport occurs if a wetting liquid rises in a porous media by means of the capillary force. The imbibition process in a capillary was the subject discussed in a great number of the scientific publications. Majority includes the results of the experiments and mathematical modeling of this process taking into consideration different influential factors [*Zhmud et al., 2000; Siebold et al., 2000; Hamraoui et al., 2002; Xue et al., 2006*]. More recently, a liquid imbibition into the media with porous structure has become an actual point at issue. The imbibition of polymer wicks with hexadecane, dodecane, and decane was studied and described in the work of *Masoodi et al.* [*2007*].

The non-modified polypropylene sorptive material imbibition with oil based compounds was investigated experimentally and after that, the obtained results were approximated by equations [*Sęk et al., 2015*]. During the experiments, it was possible to observe that the imbibition process occurs quicker in one part of the sorbents and relatively slower in another [*Alava et al., 2004; Błaszczyk et al., 2014; Sęk et al., 2015*]. Therefore, a liquid front raised non-uniformly during wicking process and achieved different heights in the sorptive material [*Sęk et al., 2015*]. The spontaneous imbibition occurs in the multi-channel structures depending on their types, thus, it cannot be described sufficiently precise applying only an analytical approach due to the complexity of the investigated process.

Thus, this work provided a simulation of the process of the spontaneous imbibition process with a single-phase liquid for a short time that is difficult to trace in case of the experimental research. An examples of such porous media were nonwoven materials, whose pores voids can be represented as a system of channels with different width in which liquid rising occur. The purpose of these simulations was to investigate the influence of the distance between such channels representing voids in nonwoven sorbent on the imbibition rate in such medium.

Simulation process

Application used. A single-phase liquid rising in the capillaries with various sizes was conditioned by the capillary forces. Such imbibition process was investigated by means of CFD simulations performed in *Comsol Multiphysics 5.0* using the *Laminar Two-Phase Flow, Level-Set* application mode. The reinitialized level set method for description of interface between air and a liquid and *Navier-Stockes'* equation are applied in this mode [*Comsol Multiphysics, 2012, Xu et al., 2014*].

Mass and momentum transport. The interphase transport was described by equation:

$$\frac{\partial \phi}{\partial t} + u \cdot \nabla \phi = \gamma \nabla \cdot \left(\varepsilon \nabla \phi - \phi (1-\phi) \frac{\nabla \phi}{|\nabla \phi|} \right), \qquad (1)$$

where: t is the time of the process, s; φ is the volume fraction of a liquid; ε is a parameter which determines the interface thickness, m; u is the a liquid velocity, m/s; γ is the amount of reinitialization.

The *Navier-Stockes'* equation was applied for characterization of mass and momentum transport of the liquid with constant density, considering the capillary effects due to appending a parameter of surface tension. Thus, it was represented in the form of:

$$\rho \frac{\partial u}{\partial t} + \rho (u \cdot \nabla) u = \nabla \left[-pI + \mu \left(\nabla u + (\nabla u)^T \right) \right] + F_{st} + \rho g, \qquad (2)$$

$$\nabla \cdot u = 0$$

where: ρ is the density of a liquid, kg/m^3; μ is the viscosity, Ns/m^2; p is the pressure, Pa; g is the acceleration of gravity, m/s^2; F_{st} is the surface tension in boundary air-liquid [*Comsol Multiphysics, 2012; Xu et al., 2014*].

Prototype material. The nonwoven polypropylene sheets applied for the different liquids sorption from the environment served as a prototype material for geometry construction for the current simulations. It was defined experimentally that the average diameter of a polypropylene fiber was equal to $0.23 \cdot 10^{-3}$ m and this value was denoted as d_f.

Obviously, the process of imbibition occurs in the voids formed between polypropylene fibers. For preliminarry research decribed in this publication, such voids were assumed to be represented in a form of vertical channels applying two-dimensional geometry model. The two-channel system visualized voids between three fibers and the distance between them was supposed to be equal to d_f, $2d_f$, $5d_f$, $10d_f$, and $20d_f$.

The imbibition process was simulated using two types of the system: the first consisted of channels with the same size, while for the second type, their widths were different. The second type of the channels systemis represented schematically in the Fig. 1.

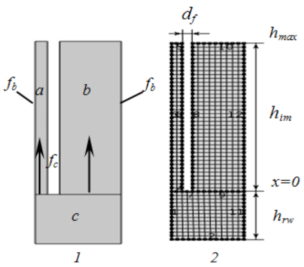

Fig. 1. The structure of the investigated two-channel system: 1 – geometry of d_f -5d_f channel system; 2 – a mesh for d_f -5d_f channel system

As shown in the Fig.1.1, the first and the second channels were denoted as *a* and *b*, respectively. A fiber separating two channels was represented in a form of a void and named as f_c, and two lateral were depicted as f_b (Fig. 1.1). Initially, both channels were assumed to be fully filled with air. At the level $x = 0$, the channels contacted with a single-phase liquid presented in a reservoir *c* with the height h_{rw} (Fig. 1). For this investigation, h_{max} was assumed to be equal to $5 \cdot 10^{-3}$ m, which was smaller than in the experiments. It was done with the purpose to reduce the time of calculation.

Boundaries. At the boundary of the inflow, the acting force was considered to be represented by the hydrostatic pressure. According to the assumed model, there was only a liquid inflow and consequently, its volume fraction was assumed to be maximal at this boundary. Whereas, at the outlet boundary, the pressure was supposed to be equal to zero. The boundary condition of inside fibers walls, i.e. f_b and f_c, is defined as the wetted wall.

Results

According to obtained results, in two-channel systems, the imbibition process depended on a size of the channel and its increasing caused prolongation of the time needed to achieve the assumed maximal height. This tendency was defined for all investigated cases. As an example, the results of such simulations for channel systems d_f–5d_f and d_f–10d_f for the same t_{im}=0.016 are plotted in Fig. 2 and 3.

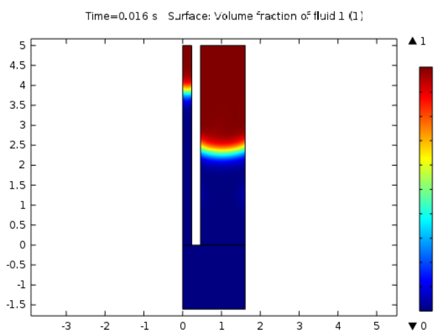

Fig. 2. Height of a liquid front for a channel system d_f -5d_f for t_{im} = 0.016 s (channel *a* with a width of d_f and *b* with a width of 5d_f)

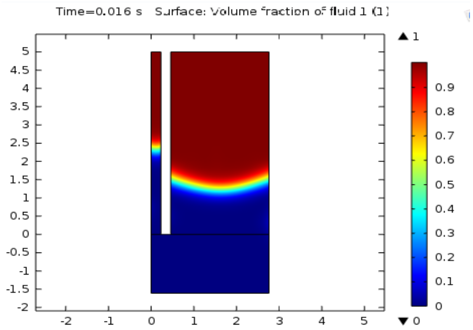

Fig. 3. Height of a liquid front for a channel system d_f –10d_f for t_{im} = 0.016 s (channel *a* with a width of d_f and *b* with a width of 10d_f)

As shown in Fig. 2, at the process time of 0.016 s, the liquid in the channel d_f raised at the height of $3.9\cdot10^{-3}$ m. However, for the same size channel, the height of a liquid front was lower and equaled to $2.5\cdot10^{-3}$ m in case of the enlarged width of the second channel, i.e. 10d_f (Fig. 3). The obtained results can be explained by difference of pressure on the boundary of the reservoir *c* and two channels. Thus, for channel with size of d_f in a system d_f–5d_f, the pressure value was 1.18 higher than for the same channel in the system d_f–10d_f.

Fig. 4-6 show the results concerning the changes of a liquid front height vs time for the different two-channel system. The height on the graph represents in a form of the normalized values h_n and calculated according to such expression as: $h_n = h_{im}/h_{max}$.

For two-channel system in which one had a width of d_f, the imbibition process depended on the change of a width of the second one (Fig. 4). The fastest liquid rising was observed in case of width of 2d_f (0.018 s) and 5d_f (0.02 s), while the lowest was for 20d_f (0.026 s). As shown in Fig. 5, the imbibition rate in channel with 10d_f was also quicker for the lower value of the second channel, i.e. d_f, 2d_f, and 5d_f. The same tendencies were observed for other investigated systems.

In all cases, the liquid continued to rise till achieving h_{max}. However, for channels with a width of 20d_f, the liquid front did not achieve the maximal supposed height (i.e. $5\cdot10^{-3}$ m), and was found in a range of $3\div3.2\cdot10^{-3}$ m, i.e. 60÷64% (Fig. 6).

The changes of time of the equilibrium height achievement vs variation of the channels size in the systems are shown in Tab. 1.

Tab. 1. Time of the assumed height achievement

Width of the second channel	Width of the first channel				
	d_f	2d_f	5d_f	10d_f	20d_f (the equilibrium height)
d_f	1.00	1.16	1.1	1.03	1.02
2d_f	1.48	1.00	1.16	1.06	1.08
5d_f	1.61	1.19	1.00	1.09	1.10
10d_f	1.91	1.19	1.16	1.00	1.12
20d_f	2.17	1.22	1.18	1.18	1.00

The time is represented in a form of the normalized values which were calculated in accordance to the following expression: $t_n = t_{dc}/t_{sc}$. The value t_{sc} represented the time needed to achieve the assumed h_{max} in case when two channels had the same width, i.e. d_f–d_f, 2d_f–2d_f, 5d_f–5d_f etc., and t_{dc} was the time of process duration for channels with different size. Thus, the significant difference between the time values were observed for d_f and they were in a range of 0.48÷1.17, while for 20d_f, it was the lowest and equaled approximately to 0.02÷0.12. For other investigated systems the difference laid in a boundary of 0.03÷0.22 (Tab. 1).

Conclusions

The simulations were conducted to investigate the imbibition process during short time intervals in a system of two channels with different width that represented the voids between fibers in sorption material and evaluate the influence of this parameter on the imbibition process.

The preliminary obtained data gave the possibility to conclude that the distance of 20d_f is large enough to reach the maximal assumed height by a liquid front.

The imbibition process depended on the variety of voids size which were formed between fibers. The rise of an imbibed liquid front vs shortest time was obtained if the distance between fibers was equaled to their width. The presence of voids with relatively large distances between supposed fibers, i.e. ≥ 10d_f, caused the prolongation of the process duration, even for the neighbor channel with relatively small size ≤ 10d_f. This phenomenon can be explained by the changes of pressure on the boundary channel-reservoir during the process.

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The study was funded in framework of the Foundation Program for Young Scientists in Lodz University of Technology – Grant 501/10-34-2-1015

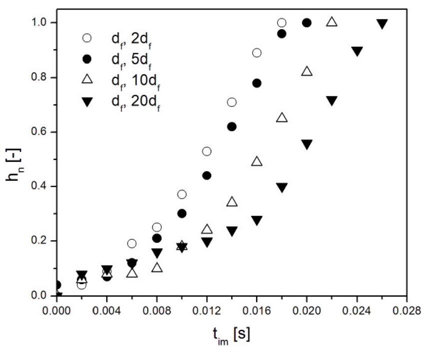

Fig. 4. Height of a liquid front vs imbibition time for channel d_f

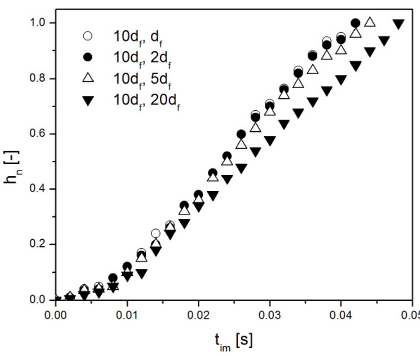

Fig. 5. Height of a liquid front vs imbibition time for channel 10d_f

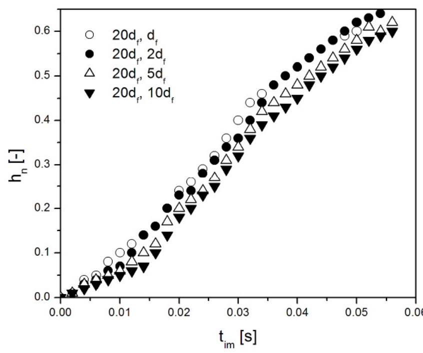

Fig. 6. Height of a liquid front vs imbibition time for channel 20d_f