Numerical Simulation of Pressure Loss in Porous Media in Oscillating Flow

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Abstract: In this study, the pressure loss in two types of porous media for both unidirectional and oscillatory flows is analyzed using commercial software Comsol©. The numerical results are compared with those obtained in the previous experiments performed by the author of this article. The porous media used in these experiments consist of mono-sized stainless steel balls with diameters of 1 mm and 3 mm, the liquid phase being water. The permeability and inertial coefficient for each type of medium is obtained from the analysis of the experimental data. The unidirectional flow has a surface velocity range of 20-100 mm/s, while the oscillating flow has two different frequencies of 0.233 Hz and 0.35 Hz and two different flow oscillation amplitudes of 170 mm and 195 mm, making a total of eight separate oscillating flow conditions for two types of porous media, for both in the experiments and the numerical studies. The results have shown that Comsol© can produce reliable results on fluid flow problems in porous media, provided that the relevant flow and porous media parameters have been selected correctly.

Key-Words: Porous media, Oscillating flow, Pressure loss, Darcy, Forchheimer.

1 Introduction

A porous medium is a material that contains pores through which a fluid can flow. Due to its complex structure, the liquid flowing through a porous medium is mixed in a chaotic manner, which considerably improves the heat transfer between the liquid and the solid phase comprising the medium. This advantage makes porous media preferred in many heat transfer areas such as cryocoolers, Stirling engines, solid matrix heat exchangers, electronic device cooling, and regenerators. The source of this favorable property, however, leads to a disadvantage: the same geometry causes a large pressure drop along the line, which leads to an increase in pump energy costs. It is therefore important to consider the friction loss in designing the above systems regardless of the flow type; unidirectional or oscillating. As the name implies, a unidirectional flow is one that has a certain, unaltered direction. On the other hand, an oscillating flow is one which changes its direction every half period, as in the case of the working fluid in a reciprocating engine such as an internal combustion engine. Because of their unprecedented heat transfer properties, porous media have therefore been studied by many researchers and are still of great interest.

The fluid flow through porous media was first studied by Henry Darcy, a French hydrologist, some 150 years ago. He designed a water filter for the city's drinking water system and established the first theory of fluid flow through porous media. Ergun [1] experimentally calculated the permeability coefficients and the inertia coefficients of porous media. Özdemir [2] investigated the pressure loss through porous media consisting of wire screens for unidirectional flow conditions, using Ergun's equations to define the permeability and other parameters of the media used in his experiments. Zhao and Cheng [3] experimentally investigated oscillatory pressure drops through a woven screen packed column. They found that the cyclic mean pressure drop of the oscillatory flow was several times higher than that of unidirectional flow. Ju et al. [4] performed experiments to determine the oscillatory flow characteristics for a regenerator consisting of stacks of wire meshes in a cryogenic pulse tube refrigerator, the fluid phase being gas, causing both a phase lag and a pressure drop. Hsu et al. [5] investigated experimentally pressure-velocity correlations of stationary and oscillating flows in regenerators made of wire screens. They found that as the flow amplitude becomes large, the relationship between pressure drop and velocity becomes non-linear. Dukhan et. al [6] carried out experiments to determine the unidirectional pressure drop in a wind tunnel for the air flow through metal foam samples with a variety of porosities and to obtain correlations concerning pressure loss. Cha [7] studied experimentally and numerically hydrodynamic parameters of microporous media for oscillatory and stationary flow, finding that the pressure drop in oscillatory flow is generally higher than that of unidirectional flow as a function of packing material and the oscillation frequency. Shen and Ju [8] summarized typical experimental results and correlations of the friction factor of regenerators at different operating frequencies at room temperature and cryogenic temperatures. They presented a new correlation of the friction factor for the oscillating flow regenerator. Leong and Jin [9] and Jin and Leong [10] conducted experiments on unidirectional and oscillatory flows through open-cell aluminum foams. They concluded that the flow resistance increases with the shape coefficient and decreases with increasing permeability for a given porosity, the resistance being the main cause of pressure loss due to the increased flow rate. Ju and Shen [11] studied the oscillating flow characteristics of cryogenic cooler regenerators at low temperatures and proposed universal friction factors for various temperature conditions that should be used in regenerator designs. Riberio et al. [12] worked to create equations for representing wall effects in densely packed porous media exposed to unidirectional flow, and found that the average porosity in the medium increases as D/dp decreases. Cheadle et al. [13] investigated packed ball-and-roller friction factors under oscillating flow conditions using CFD analysis, and completed oscillatory flow effects are much more apparent at higher oscillating frequencies. In his dissertation, Pamuk [14] investigated unidirectional and oscillatory water flows through two different porous media made of stainless steel balls. Pamuk and Özdemir [15] investigated unidirectional and oscillatory flows through porous media and provided correlations for friction factors. Malico et al. [16] conducted direct numerical simulations of the flow through regular porous media consisting of equally sized, staggered square cylinders. They found that the pressure drop dominates and the entrance and exit effects are negligible. Pamuk and Özdemir [17] stressed in their book section that it is important to decide the type of the medium when it comes to comparing the cost of constructing the porous medium to energy cost due to pressure loss. Dai and Yang [18] conducted a numerical study using Lattice Boltzmann Method (LBM), which is an efficient new way compared to that of the traditional continuum Navier-Stokes method. They developed their simulation work firstly in a two-dimensional empty planar channel, and then through porous media. According to the authors, the simulation results have shown a great effectiveness of the implementation of the LBM. Bağcı et al. [19] obtained characteristics of oscillating water flow in open-cell metal foam experimentally. They presented and discussed the effect of flow displacement and frequency on important variables. They also compared their results to other studies from the literature employing oscillating air and water in various kinds of porous media. Xiao et al. [20] performed an experimental and simulation study to investigate characteristics of regenerator in an oscillating flow, using steady flow as reference. They found that the oscillating flow can share the same correlation equations of steady flow for friction factor within a prescribed kinetic Reynolds number range and dimensionless fluid displacement. Ni et al. [21] proposed a cycle rate through porous media, a particularly basic parameter, based on the dimensionless pressure drop as a correction factor for the similarity parameters of the oscillating flows. A modified dimensionless fluid displacement is introduced based on the cycle rate, and a correlation equation is proposed to calculate the cycle-averaged friction factor of porous media.

2 Experiment: Porous Medium and the Oscillating Flow Generator

A schematic diagram of the experimental setup whose test section is in the middle is shown in Fig. 1. This test chamber is connected to an oscillation generator by means of pipes of 32 mm in diameter and hydraulic (high pressure) hoses of ½ in. diameter. The main component of oscillation generator is a double-acting cylinder which is connected to an electrically driven moto-reducer by means of a flywheel and an adjustable crank-arm. The test chamber consists of the above stainless steel tube of 305 mm length with an inner diameter of 51.4 mm. The volume of this cylinder is filled with 1 mm and 3 mm stainless steel balls, each consisting of a different porous medium. The maximum stroke of the movement obtainable by the oscillation mechanism is 200 mm. Rotational speed in rpm of the 7.5 kW moto-reducer is controlled via a variable speed AC-drive. Additionally, an adjustment system mounted on the flywheel allows changes in stroke. Two pressure transducers are mounted at both ends of the test chamber to measure the pressure difference caused by the flow through the porous medium. Unidirectional flow, on the other hand, is obtained from regulated tap water at a known flow rate. The pressure loss along the pipeline is calculated using the signals collected by the data acquisition system and the data is then correlated to the corresponding flow rate. According to the Darcy law, the pressure loss in a porous medium is directly proportional to the flow velocity at very low flow velocities (creeping flow). After this proportionality with the flow rate, the pressure loss begins to increase rapidly and becomes a quadratic function of velocity, called the Forchheimer flow regime. Therefore, the pressure drop can be defined as $\Delta P = aU + bU^2$, where a and b are constants that depend on the porous medium, both the solid and liquid phases. In fact it is in the form of:

$$\frac{\Delta P}{L} = \frac{\mu}{K}U + \frac{\rho F}{\sqrt{K}}U^2 \tag{1}$$

where the left side of the equation is referred to as the pressure gradient or pressure loss per unit length in the flow direction. The first term on the right is the Darcy expression, which represents the pressure drop per unit length that is proportional to the flow velocity. Here, μ is the dynamic viscosity, the only source of fluid friction at lower flow rates, and K is the permeability, which represents the availability of flow paths. Permeability is a function of the porosity, ε, which represents the percentage of the void in the porous matrix, or in other words, the volume of liquid flowing through the medium. The second term on the right is called the Forchheimer term, which is proportional to the square of the flow rate. Other terms in the Forchheimer term are ρ and F, density and Forchheimer coefficient, which represent friction due to geometry. The porosity, ε, is calculated by measuring the void volume in the porous medium. The permeability K and the Forchheimer coefficient F are obtained using the least squares method based on the experimental data. The coefficients of the fitting curve (second order polynomial) are used to calculate K and F.

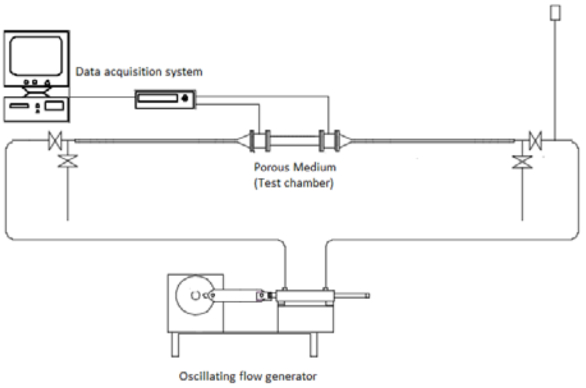

Fig. 1. Test chamber and oscillating flow generator [14].

Unlike a unidirectional flow, which is stationary or independent of time, the oscillating flow is transient (or time dependent). Since the flow velocity changes with time, there is an acceleration, which also causes inertial forces:

$$\rho\left(\frac{\partial\langle v\rangle}{\partial t} + \frac{\langle v\rangle\cdot\nabla\langle v\rangle}{\varepsilon}\right) = -\nabla\langle P\rangle + \mu\nabla^2\langle v\rangle - \frac{\mu\varepsilon}{K}\langle v\rangle - \frac{\rho F\varepsilon}{\sqrt{K}}\left|\langle v\rangle\right|\langle v\rangle \tag{2}$$

To determine K and F, a similar procedure is also used for oscillating flow, except that the maximum values of pressure gradient and flow rate are considered in the calculations as follows:

$$\left(\frac{dP}{dz}\right)_{max} = \frac{\mu_a}{K}u_{max} + \frac{\rho_a F}{\sqrt{K}}\left|u_{max}\right|u_{max} \tag{3}$$

The flow reversal is obtained by the oscillation generator, which consists of a double-acting cylinder connected to an electrically driven motor-coaster by means of a flywheel and a crank arm. The amplitude of the flow displacement and the frequency of the oscillation are changed by adjusting the flywheel radius and the motor speed reducer, respectively. The frequency of the oscillation, f, is defined as the number of flow reversals per second, so the angular frequency $\omega=2\pi f$. The above flow displacement and the velocity are then related to each other as follows:

$$x_m(t) = \frac{x_{max}}{2}(1 - Cos\,\omega t) \tag{4}$$

Where $x_{max}=x_{pmax}A_p/A=2RA_p/A$ is the flow displacement. Here are R, A_p and A flywheel radius, cross-sectional areas of the double-acting cylinder and the test chamber, respectively. The mean flow velocity in the channel is defined as

$$u_m(t) = u_{max}Sin\,\omega t \tag{5}$$

By definition, the time derivative of the displacement is the velocity, $u_{max}=\omega x_{max}/2$.

Using the experimental data for unidirectional flow and oscillatory flow, the performer of the experiments obtained the following values shown in Table 1 [14].

Uncertainty in the experimental data is considered by identifying the main sources of errors in the primary measurements such as pressure, dimensions of the test chamber and balls, volume, time and frequency. Then, an uncertainty analysis based on the method described by Figliola and Beasley [22] is performed. The uncertainties of angular frequency, maximum fluid displacement x_{max}, dimensions, the amplitude of area averaged fluid velocity and pressure gradient ($\Delta P/L$) are estimated to be 0.43%, 0.51%, 1.95%, 0.23% and 1.76% respectively.

Table1: Porosity, Permeability and Forchheimer coefficients for the porous media [14].

Medium	*Porosity, ε*	$K \times 10^9$ (m^2)	*F*
1 mm balls (Unidirectional)	0.369	0.844	0.596
1 mm balls (Oscillating)		1.713	0.758
3 mm balls (Unidirectional)	0.3912	8.87	0.580
3 mm balls (Oscillating)		9.915	0.593

3 Numerical Procedure

Due to the geometry of the flow domain, the axisymmetric case is selected for both stationary and transient cases. An extra fine physics-controlled mesh of 191,633 mesh points is preferred, as from this resolution on, the solution becomes grid independent. The meshing is even finer near the wall (right boundary) as shown in Figure 2, to take into consideration the boundary layer effects. The width shown is half the pipe radius (25.7 mm), with the left boundary being the centerline of the pipe.

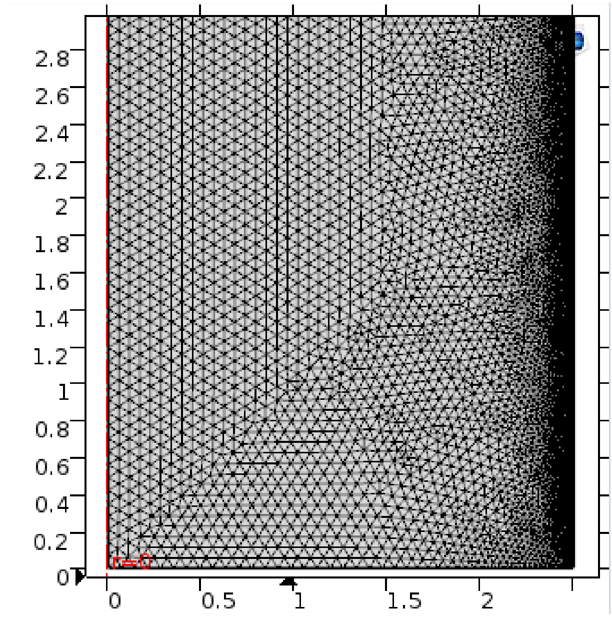

Fig. 2. Extra fine physics-controlled mesh.

The same ε, K and F parameters obtained in the experiments are also used in Comsol©, where Brinkman equations are chosen as physics. Boundary conditions for both unidirectional and oscillating flow are: inlet velocity and pressure, left-boundary symmetry, and right-border no-slip. A constant inlet velocity constraint is defined as $u = U$ for the first case (stationary), whereas for the second case (transient) it is defined as $u_m(t)=u_{max}Sin\omega t$.

The total computing time on an Intel(R) Core(TM) i3-2350M CPU@2.30GHz, 2 cores computer running Windows 10 is 10-20 minutes, depending on the configuration of the problem (stationary or transient) and the parameters.

4 Results and Discussion

4.1. Unidirectional Flow

Figures 3-6 show the longitudinal pressure distribution along the pipe and the radial velocity distribution at the pipe outlet in unidirectional flow for 1 mm and 3 mm porous media, respectively. The channel effect near the wall can be observed in radial velocity distributions. It is caused by the increased porosity near the wall, which causes the flow to have a higher local velocity, which becomes zero on the wall due to the non-slip boundary condition.

Figures 7 and 8 show the comparison of the experimental results for 1 mm and 3 mm media with those of Comsol© for the unidirectional flow.

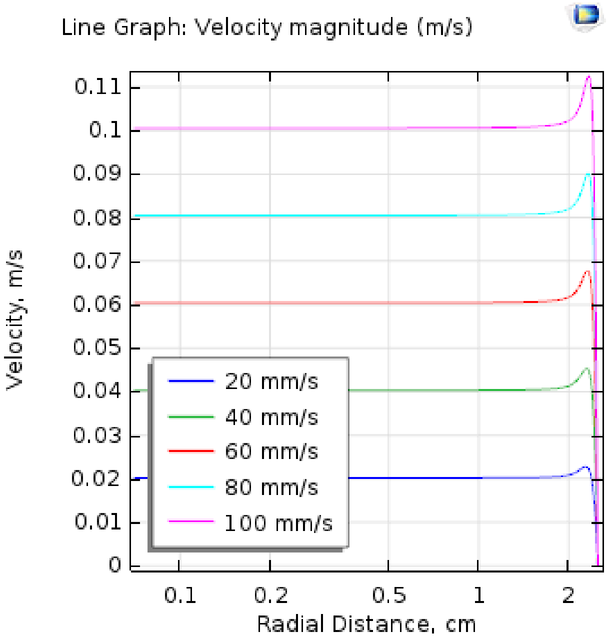

Fig. 3. Radial velocity distribution at the pipe exit, 1 mm medium.

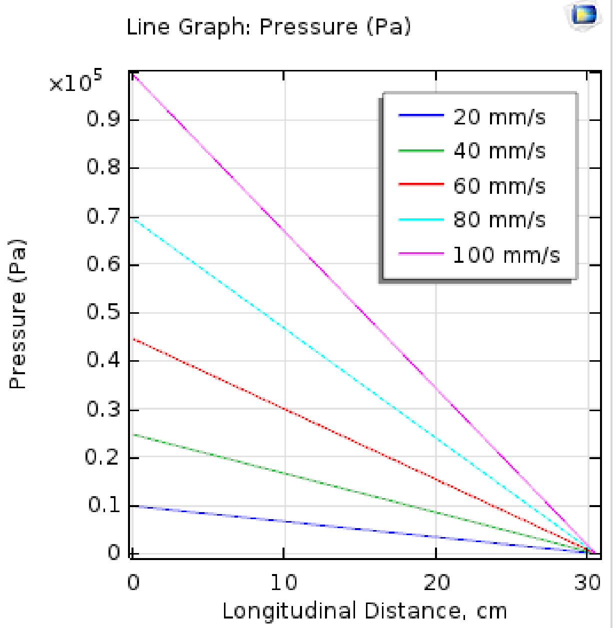

Fig. 4. Longitudinal pressure distribution along the pipe, 1 mm medium.

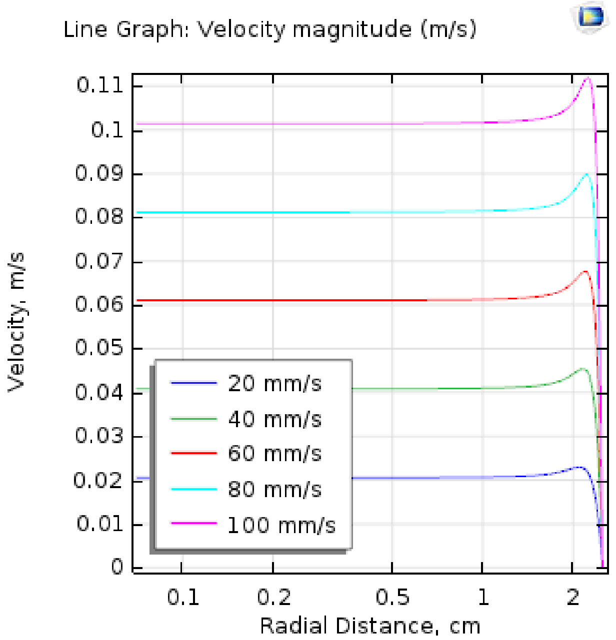

Fig. 5. Radial velocity distribution at the pipe exit, 3 mm medium.

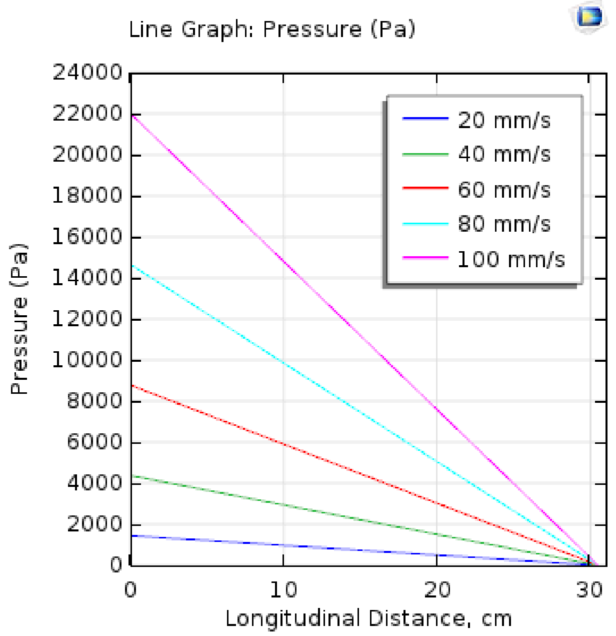

Fig. 6. Longitudinal pressure distribution along the pipe, 3 mm medium.

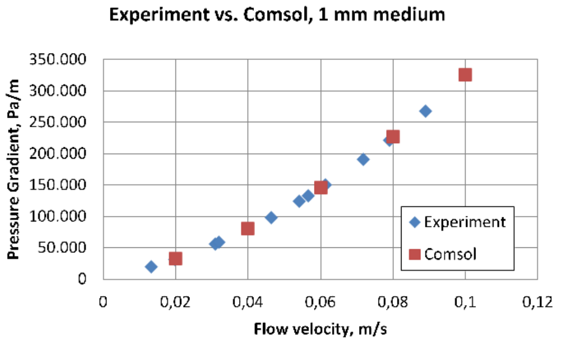

Fig. 7. Experiments vs. Comsol©, Unidirectional Flow, 1 mm medium.

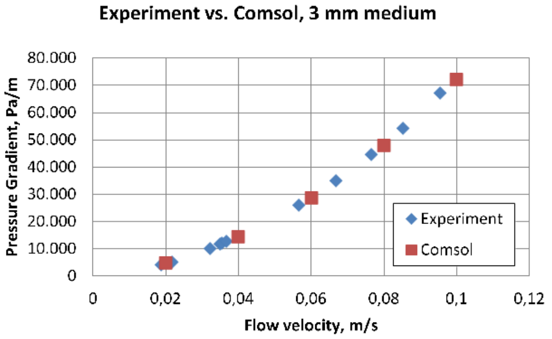

Fig. 8. E xperiments vs. Comsol©, Unidirectional Flow, 3 mm medium.

It can be clearly seen that both experimental and simulation results of unidirectional flow are very close to each other, proving the reliability of Comsol© solutions in unidirectional flow through porous media. The validity of model and the grid has thus been shown.

4.2. Oscillating Flow

As stated above, the same model is used except that a transient case is chosen for the oscillating flow with the time-dependent inlet velocity constraint. Eight different cases of oscillating flow through porous media are considered: two different frequencies of 0.233 Hz and 0.35 Hz and two different flow oscillation amplitudes of 170 mm and 195 mm for each type of porous media. As in the case of unidirectional flow, the experimental results are compared to numerical results obtained from Comsol©.

Figures 9-16 show the comparison of the experimental results for media of 1 mm and 3 mm with those of Comsol© for oscillating flow. It can be clearly seen that both results are very close to each other, as in the case of unidirectional flow, which proves the reliability of Comsol© solutions also with oscillating flow through porous media. It is interesting to observe the inflection near the horizontal axis for both the experiments and the numerical solutions caused by the deceleration-acceleration of the flow represented by the inertial term in the momentum equation. As can be seen in these figures, the slope of the pressure gradient is subjected to an abrupt change near the oscillation axis. The rate of pressure gradient is low within this region where flow velocity is very low, but it is considerably higher for the other region. This abrupt change may mean that the flow regime inside the porous medium changes. Four distinct flow regimes for steady flow through porous medium are determined with pore Reynolds number defined as $Re_p = \rho(u_m / \varepsilon)d / \mu$. These regimes are Darcy flow regime ($Re_p<1$), inertial flow regime ($1<Re_p<150$), unsteady laminar flow regime ($150<Re_p<300$) and unsteady-and chaotic flow regime ($Re_p>300$). The instant average velocity of oscillating flow changes 0 to 0.12 m/s, so that Reynolds number increases up to approximately 300.

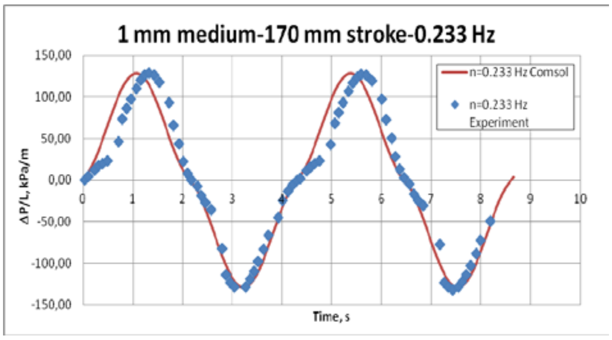

Fig. 9. Experiments vs. Comsol©, Oscillating Flow, 170 mm, 0.233 Hz, 1 mm.

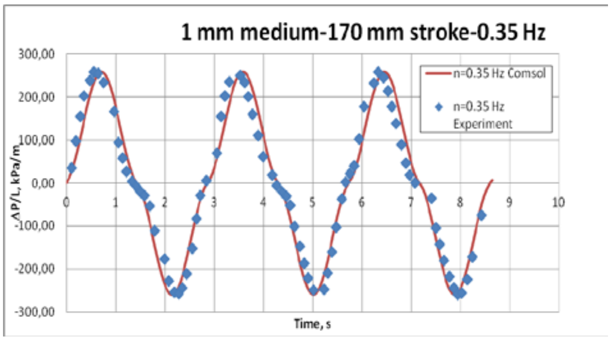

Fig. 10. Experiments vs. Comsol©, Oscillating Flow, 170 mm, 0.35 Hz, 1 mm.

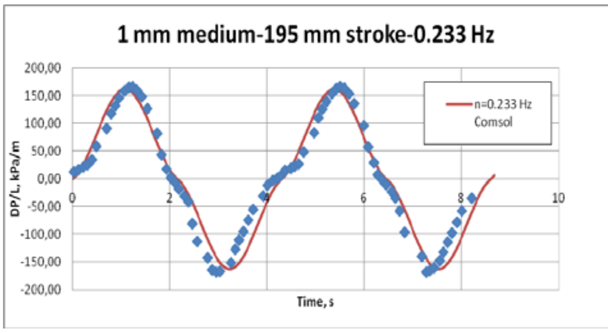

Fig. 11. Experiments vs. Comsol©, Oscillating Flow, 195 mm, 0.233 Hz, 1 mm.

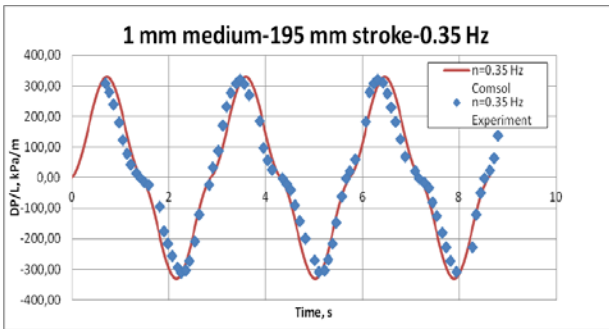

Fig. 12. Experiments vs. Comsol©, Oscillating Flow, 195 mm, 0.35 Hz, 1 mm.

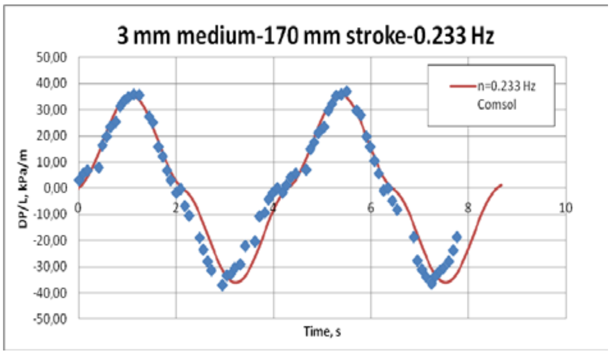

Fig. 13. Experiments vs. Comsol©, Oscillating Flow, 170 mm, 0.233 Hz, 3 mm.

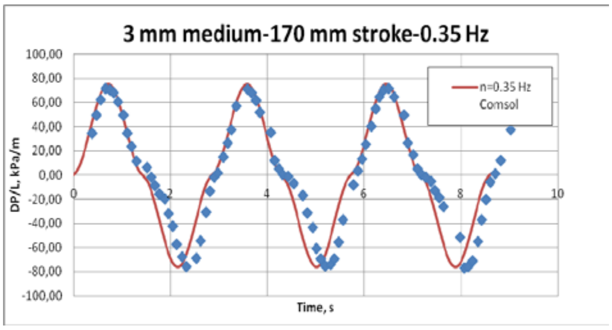

Fig. 14. Experiments vs. Comsol©, Oscillating Flow, 170 mm, 0.35 Hz, 3 mm.

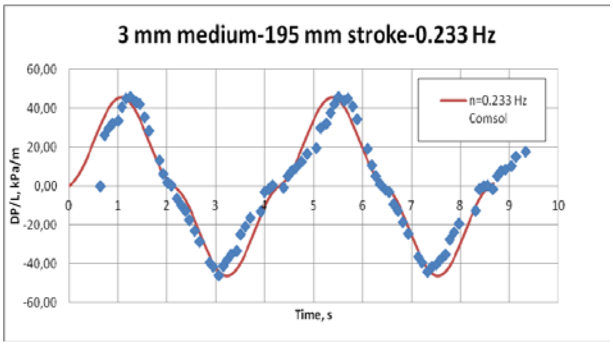

Fig. 15. Experiments vs. Comsol©, Oscillating Flow, 195 mm, 0.233 Hz, 3 mm.

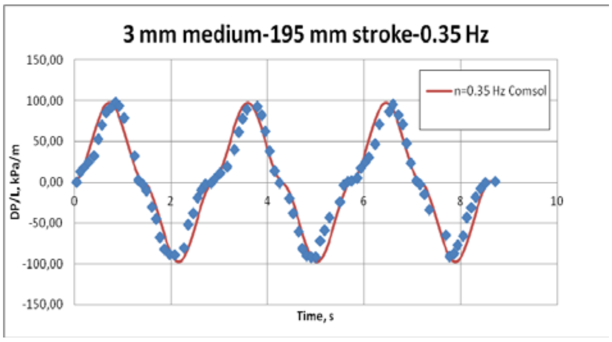

Fig. 16. Experiments vs. Comsol©, Oscillating Flow, 195 mm, 0.35 Hz, 3 mm.

As in the case of unidirectional flow, Figures 10-16 show that the model and the grid are valid also for the cases of oscillation flow.

5 Conclusion

The pressure drop through two types of porous media, for both unidirectional and oscillatory flow, where the fluid phase is water, is numerically studied in this study using Comsol© commercial software. The results are then compared to the results of a series of experiments, also conducted by the author of this study, which validate the numerical model with great success. Thus, it has been demonstrated that Comsol© is a powerful computational tool for the treatment of fluid flow problems in porous media for both uni-directional and oscillatory flow. It can be concluded that with careful modeling, including a faultless geometry with a sufficiently fine grid size that optimizes between the accuracy of the results and the computation time, along with a series of carefully and properly chosen parameters and boundary/initial conditions, the software works very well and produces reliable solutions, as shown in this paper, so it is unnecessary to create expensive experimental setups and spend a lot of time doing experiments, especially in improving the design of devices implementing oscillating flow through porous media. A follow up to this study would be the simulation of oscillating flow through metal mesh (as in the case of cryocoolers) and metal foams as porous media and to compare the experimental results found in the literature to simulations, in order to show that the model is still valid independent of the type of the medium.

Acknowledgments

I would like to thank the Istanbul Technical University for giving access to their lab facilities to carry out the experiments whose results were used in this paper

Nomenclature

A	cross-sectional area of the test chamber
A_p	cross-sectional area cylinder
d	ball diameter
D	inner diameter of test chamber
f	frequency
F	inertial coefficient
K	permeability
L	length of the porous medium
ΔP	pressure difference
$\Delta P/L$	pressure gradient
R	radius of flywheel
t	time
u_m	cross-sectional mean fluid velocity
u_{max}	amplitude of mean fluid velocity [m/s]
x_m	temporal fluid displacement at the inlet
x_{max}	maximum fluid displacement at the inlet
v	velocity vector
ε	porosity
ρ	fluid density
ω	angular frequency
μ	dynamic viscosity

References:

[1] Ergun, S., 1952, F luid flow through packed columns, Chemical Engineering Progress, Vol. 48, No.2, pp. 89-94.

[2] Özdemir, M., 1996, “Forced convection heat transfer in porous medium of wire screen meshes”, Ph.D. Thesis, Istanbul Technical University, May 1996

[3] Zhao, T.S. and Cheng, P., 1996, “ Oscillatory pressure drops through a woven screen packed column subjected to cyclic flow”, Cryogenics 36 (1996) 333-341

[4] Ju, Y., Jiang, Y., Zhou, Y., 1998, “Experimental study of the oscillating flow characteristics for a regenerator in a pulse tube cryogenic cooler”, Cryogenics 1998 Volume 38, Number 6

[5] Hsu, C., Fu, H., Cheng, P., 1999, “On pressure-velocity correlation of steady and oscillating flows in regenerators made of wire screens”, Transactions of the ASME, Vol. 121, MARCH 1999

[6] Dukhan N., Feliciano, R., Hernandez, A., 2006, “Air flow through compressed and uncompressed aluminum foam: Measurements and correlations”, Transactions of the ASME, 1004 / Vol. 128, SEPTEMBER 2006

[7] Cha, J.J., 2007, “Hydrodynamic parameters of micro porous media for steady and oscillatory flow: Application to cryogenic cooler regenerators”, A dissertation presented to the Academic Faculty, Georgia Institute of Technology, August 2007

[8] Shen, Q.Q. and Ju, Y.L., 2008, “ A new correlation of friction factor for oscillating flow regenerator operating at high frequencies”, CP 985, Advances in Cryogenic Engineering, Transactions of the Cryogenic Engineering Conference-CEC, Vol. 53

[9] Leong, K.C. and Jin, L.W., 2006, "Effect of oscillatory frequency on heat transfer in metal foam heat sinks of various pore densities", International Journal of Heat and Mass Transfer 49 (2006) 671–681

[10] Jin L.W. and Leong K.C., (2008) “ Pressure drop and friction factor of steady and oscillating flows in open-cell porous media”, Transport in Porous Media (2008) 72:37–52 DOI 10.1007/s11242-007-9134-3 Published online: 15 May 2007 © Springer

[11] Ju, Y. and Shen, Q., 2009, “Comparative study of oscillating flow characteristics of cryogenic cooler regenerator at low temperatures”, Front. Energy Power Eng. China 2009, 3(1): 80–84

[12] Riberio, A.B., Neto, P., Pinho, C., 2010, “Mean porosity and pressure drop measurements in packed beds of mono sized spheres: Side wall effects”, International Review of Chemical Engineering, Vol.2, N.1, January 2011

[13] Cheadle, M.J., Nellis, G.F., Klein, S.A., 2011, “Regenerator friction factor and Nusselt number information derived from CFD analysis”, Cryogenic coolers 16, Edited by S.D. Miller and R.G. Ross Jr., International Cryogenic cooler Conference, Inc, Boulder, CO, 2011

[14] Pamuk, M.T., 2012, “Heat transfer in oscillating flow through porous media consisting of steel balls”, Ph.D. Thesis, Istanbul Technical University, July 2012

[15] Pamuk, M.T. and Özdemir, M., 2012, “Friction factor, permeability and inertial coefficient of oscillating flow through porous media of packed balls”, Experimental Thermal and Fluid Science 38 (2012) 134–139

[16] Malico, I., Ferrão, C., Ferreira de Sousa, P.J.S.A., 2015, "Direct Numerical Simulation of the Pressure Drop through Structured Porous Media", Defect and Diffusion Forum, Vol. 364, pp. 192-200

[17] Pamuk, M.T. and Özdemir, M., 2014, “Hydrodynamic Aspects of Oscillating Flow through Porous Media Consisting of Steel Spheres”, Progress in Exergy, Energy and the Environment (Springer©) (2014) pp 663-640.

[18] Qunte Dai, Q. and Yang, L. , “LBM numerical study on oscillating flow and heat transfer in porous media”, Applied Thermal Engineering 54 (2013) 16-25

[19] Bağcı, Ö., Dukhan, N., Özdemir, M., “Characteristics of oscillating liquid flow in foam-like highly-porous media: An experimental study”; Experimental Thermal and Fluid Science 60 (2015) 96–105

[20] Xiao, G., Peng, H., Fan, H., Sultan, U., Ni, M., “Characteristics of steady and oscillating flows through regenerator”, International Journal of Heat and Mass Transfer 108 (2017) 309–321

[21] Ni, M., Peng, H., Sultan, U., Luo, K., Xiao, G., “A quantitative method to describe the flow characteristics of an oscillating flow including porous media”, International Journal of Heat and Mass Transfer 119 (2018) 860–866

[22] Figliola, R.S. and Beasley, D.E., Theory and Design for Mechanical Measurements, JohnWiley, 2006.