Flow Optimisation through Porous Ceramic Throttle

M. Ebner, Y. S. Mutlu, B. Nestler and E. Glatt

***Abstract*—Dynamics of fluids in porous media is of importance in many fields of practical interest. Currently scientists at the Medical Sensors and Devices Laboratory at the Luebeck University of Applied Sciences are developing a throttle system for a gas-driven infusion device whose centrepiece consists of a nanoporous ceramic unit for regulating the flow in the range of micro- to nanoliters per minute. Aim of the present paper is to obtain a better understanding regarding the underlying flow phenomena through already existing specimen to improve their actual design. Against this background several measurements were done, including Micro-CT scanning of the present samples and determination of the fluid flow in the course of experimental set-ups. Combined with flow simulations using actual dimensions of the investigated specimen a validation of the existing throttle concept is possible.**

I. Introduction

Flow regulation for adjusting the right type and constant dose of medication to the patients need is of high interest in pain alleviation. As implantable gas-driven infusion pumps are very reliable and capable to provide constant flow rates they are promising to help patients who are suffering chronic pain to regain quality of life [1]. As at present no *adjustable* throttles for gas-driven infusion pumps exist, current development at the Medical Sensors and Devices Laboratory at the Luebeck University of Applied Sciences is now focussing on this issue, where some prototypes made of porous ceramic for regulating the flow rate have already been designed. At a pressure difference of $2.5\,$bar, produced by the infusion device, a flow between $70\,$nl/min to $1400\,$nl/min can be regulated. The emphasis is now on testing, evaluating and optimizing this throttle concept. For this purpose this paper begins with the theoretical background of flow phenomena in porous media to understand the essential principles.

A. Theory

Theoretically the governing equations of classical mechanics for any continuum, namely the Navier-Stokes equations, could be used for describing the flow of fluids through porous media. Keeping in mind that for a well-stated problem one needs to know as well all boundary conditions this approach is out of scope for practical purposes due to the complex and generally unknown inner geometry of porous media. Thus with a further macroscopic approach these microscopic conservation principles are averaged over some representative elementary volumes to obtain governing equations on even a coarser level. For simplicity reasons, only a single-phase of Newtonian fluids in an isotropic porous media is regarded whereby the focus of investigations consists in using steady-state equations for creeping flow, where inertial effects can be neglected. Under these assumptions the volume averaged Navier-Stokes equation, or more precisely the volume averaged momentum equation, leads to the *Stokes-Brinkman equation*

$$\nabla p = -\frac{\eta}{\kappa}\mathbf{u} + \eta_{\text{eff}}\,\Delta\mathbf{u}, \tag{1}$$

[2, §3.5]. In (1) $\mathbf{u}$ denotes the three-dimensional velocity, p the pressure, κ the permeability, η the fluid viscosity and η_{eff} the effective viscosity, where all these parameters shall be understood as volume averaged ones. In general the effective viscosity η_{eff} is not supposed to be the same as the fluid viscosity η due to the dispersion of viscous diffusion flux and phenomena in porous media which are simplified by parameters like tortuosity and are strongly dependent on the type of porous media and the strength of flow. Although the choice of η_{eff} is still a highly debated topic in literature it is set equal to η in most weak flow applications [2].

It is notable that for spatial points within free flow regions the permeability κ tends to infinity and therefore (1) becomes the *Stokes equation*, whereas in permeable regions the dominating terms of (1) lead to the *Darcy equation* [2]

$$\nabla p = -\frac{\eta}{\kappa}\mathbf{u}, \tag{2}$$

which has shown to be a good approximation for the flow of fluids through porous media despite the simple linear relationship [3]. If the flow rate or total discharge $\mathbf{q} = A\,\mathbf{u}$ through a cross-section area A in the direction of its normal is considered, the equation

$$\mathbf{q} = -\frac{\kappa}{\eta}\,A\,\nabla p \tag{3}$$

may be obtained from (2) as the governing law for fluids through porous media in the variable of flow $\mathbf{q}$.

II. Materials and Methods

A. Porous Ceramic Throttle

The present throttle prototype is made of the porous ceramic zirconia dioxide (ZrO_2) whose material properties are already well investigated in [1]. Its porosity is about $30\,\%$, characterized by homogeneously distributed grains with a mean diameter of $0.17\,\mu$m and the permeability κ was measured to be $7.5 \times 10^{-17}\text{m}^2(1 \pm 14\,\%)$. The porous ceramic, as the

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centrepiece of the throttle, is in cylindrical shape with a diameter of 1.1 mm and a length of 12 mm which is melted into a transparent glass capillary. For adjusting the flow rate five boreholes are added where the exact positions got laser-marked to dispose of comparable samples. The boreholes themselves are done by ultrasonic-assisted drilling to avoid undesired damages to the sensitive ceramic surface like a melt layer or smashed pores at the borehole bottom which would influence the flow phenomena [4]. The ZrO_2-cylinders were produced by the company Metoxit in Thayngen (CH), the glass capillary by SI Analytics in Mainz (D) and the boreholes were externally drilled by the company RS Ultraschalltechnik in Blankenhain (D). A throttle sample is shown in Fig. 1.

Fig. 1. Sample of manufactured ZrO_2-throttle

The final aim of this paper is to validate the existing throttle design concerning flow rates and applicability. Thus the real geometric dimensions were of major interest. For this purpose Micro-CT-Technology was applied to examine three available specimen. The mean values of their measured dimensions, whereby the accuracy is stated ± 5 % of the measured value, are shown in Table I and linked with the model of the throttle system in Fig. 2.

TABLE I
MEASURED DIMENSIONS OF MICRO-CT IMAGES

i	a_i [µm]	d_i [µm]
1	400	570
2	950	560
3	970	540
4	950	540
5	950	540

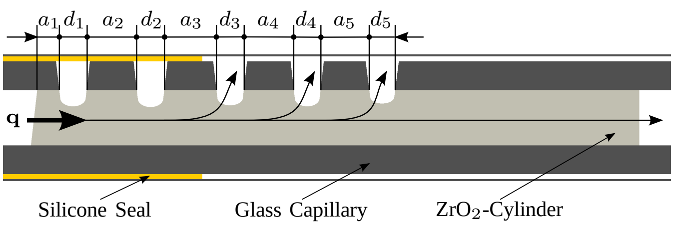

Fig. 2. Simulation model

Furthermore the borehole-depths within the porous ceramic of every single hole were examined, whose order of magnitude is (300 ± 14) µm. Additionally the front side profile was investigated to map the throttle geometry as complete as possible. In Fig. 3 a front side profile of one specimen is shown.

By means of Fig. 2 the functionality of the throttle system can be illustrated as follows: The fluid passes through the porous ceramic, whereby the flow rate $\mathbf{q}$ is dependent on the number of open boreholes which can only be sealed by sliding the silicone seal forward and backward. The more holes are open the higher becomes the flow rate because unsealed holes offer the possibility for the fluid to bypass the highly resistive zirconia, moving to the less decelerating gap instead. If all holes are sealed the fluid has to proceed the entire ZrO_2-cylinder, which yields the lowest possible flow rate. Consequently the flow is step-wisely adjustable.

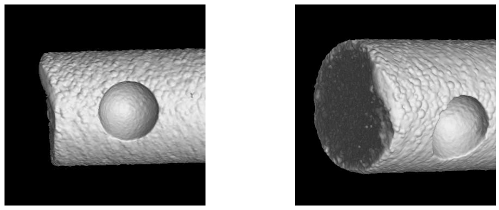

Fig. 3. Micro-CT of ZrO_2-cylinder front side in different views

As a testing fluid aqua ad injectabilia (water for injection) was used, having a viscosity $\eta = 9.34 \times 10^{-4}$ kg/(m s). The producer is B. Braun Austria GmbH, Maria Enzersdorf, Austria. It was chosen because the viscous behaviour, as well as the actual viscosity, are comparable to the original drug mixture in the infusion device.

B. Simulation Model

For solving the Stokes-Brinkman equation (1) in the fluid flow domain the CFD software GeoDict (www.geodict.com), developed by Math2Market GmbH, a spin-off from the Fraunhofer ITWM Kaiserslautern (D), was used. It is especially designed for dealing with porous media and composite materials. The intermediate cross-section of the throttle in the GeoDict-simulation model is already visualized in Fig. 2 whereby all information gained from the Micro-CT was processed.

Due to the symmetric shape of the ceramic throttle only one half got modelled and provided with proper symmetric boundary conditions. Therefore a finer discretization of the fluid domain without increase of computational cost was possible. For the computation a mesh with voxel length of 30 µm was generated and as the underlying numerical method the Explicit Finite Volume solver for isotropic flow conditions was chosen. Further input parameters were the pressure of 2.5 bar, the permeability $\kappa = 7.5 \times 10^{-17}$ m^2 and the viscosity η as defined above. As dependent variable the absolute flow rate in horizontal direction, referring to Fig. 2, was regarded.

C. Experiments

To prove the simulation results an experimental set-up shown in Fig. 4 was used.

The pressure source was connected to a pressure container, filled with the testing fluid aqua ad injectabilia. Next the container was linked with the pressure sensor GE PDCR-200 followed by a ceramic bacterial filter with pore sizes of 0.22 µm. After the particle filter, the flow sensor Sensirion LG16-0150-D was installed before finally the test specimen completed the measurement set-up. The ceramic throttle was pre-filled under vacuum in order to prevent trapped air inside the throttle system and afterwards integrated in a metal housing. The seal caps were glued to a PEEK hose which were

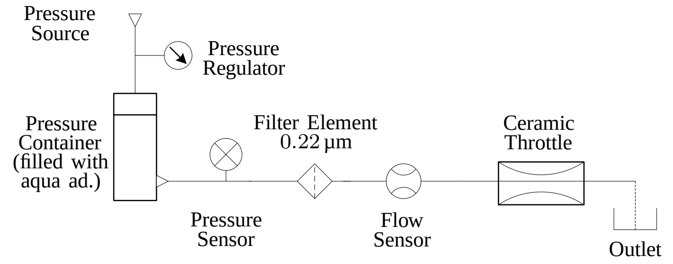

Fig. 4. Blockdiagram of measurement set-up

used in fittings varying between 1/32, 1/16 and 1/8 inch outer diameters for connecting the whole system. Before starting the measurements, the system was completely filled with the test fluid and the remaining air bubbles got removed. For adjusting the flow, the relevant boreholes were sealed by a PVC hose using a force of 15 N to close them properly.

With reference to the specifications the accuracy for the flow sensor is $\leq 5.5\,\%$ of the measured value, including deviations due to fluctuations in ambient temperature and signal noise error by using a 16 bit sampling rate. For the pressure sensor an accuracy of $\leq 0.3\,\%$ of the full scale pressure range is stated. As the measurements were carried out at 2.5 bar the corresponding pressure range of 0 bar to 3 bar yields an absolute error of ± 9 mbar.

Since the flow resistance of ZrO_2-throttle dominates the whole hydraulic system, the position of the pressure sensor in the measurement set-up is not of practical purpose. This becomes clear by considering all the connectors as long cylindrical pipes where the flow resistances of each part can easily be computed by means of the *Hagen-Poiseuille law*. The resulting values are negligibly small compared to the ZrO_2-throttle resistance, given by *Ohm's law* in hydraulic analogy, i.e. the resistance equals pressure divided by flow rate.

III. Results and Discussion

A. Results

Based on the explanations above the resulting flow rate as a function of open boreholes got obtained and summarized in Table II, where the values are in the unit of nl/min.

TABLE II
FLOW RESULTS AS A FUNCTION OF OPEN BOREHOLES

	0	1	2	3	4	5
Spec. I	93.23	104.44	164.68	277.42	469.81	1261.98
Spec. II	120.75	220.00	281.00	390.40	658.80	1947.75
Spec. III	101.33	164.00	210.67	289.67	464.33	1270.00
Simulation	139.30	260.92	324.94	395.74	527.26	1325.74
Darcy	95.39	166.09	212.80	298.87	513.77	1731.73

The rows from one to three show the mean value of the measured flow rates of each specimen at given pressures of 2.45 bar (spec. I) and 2.49 bar (spec. II and III), respectively. The fourth row indicates the simulation results of GeoDict. Due to the simple geometry of the investigated throttles it is possible to use a convenient one-dimensional approximation of (3), namely

$$q = \frac{\kappa}{\eta}\, A\, \frac{\Delta p}{\Delta \ell}, \tag{4}$$

which is the Darcy law *for horizontal flow* [3]. In (4) Δp represents the (positive) pressure difference within the ceramic throttle and $\Delta\ell$ the length of the cylinder where the fluid has to pass through. Keeping in mind that the pressure loss between the source is negligibly small because of the dominating throttle flow resistance it is plausible to set $\Delta p = 2.5$ bar. For the length $\Delta\ell$ the distances from the front side of the ceramic to the centre of the corresponding boreholes were taken, which leads to the results of the fifth row in Table II. In summary the outcome is illustrated in Fig. 5, whereby as well the standard deviations of the measured flow rate mean values of each borehole adjustment are marked with error-bars, and in Fig. 6 where the relative deviations to the simulation results are shown.

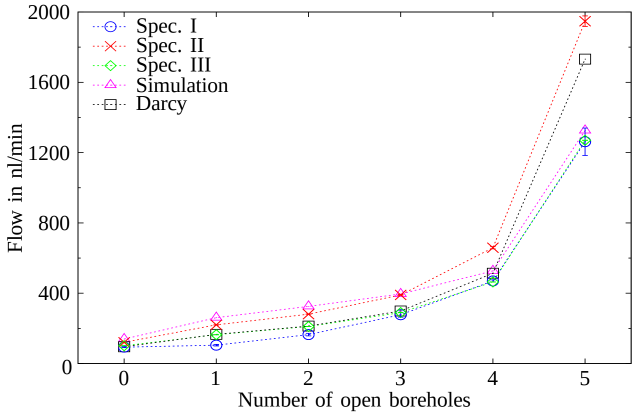

Fig. 5. Flow results of experiments, simulation and Darcy equation

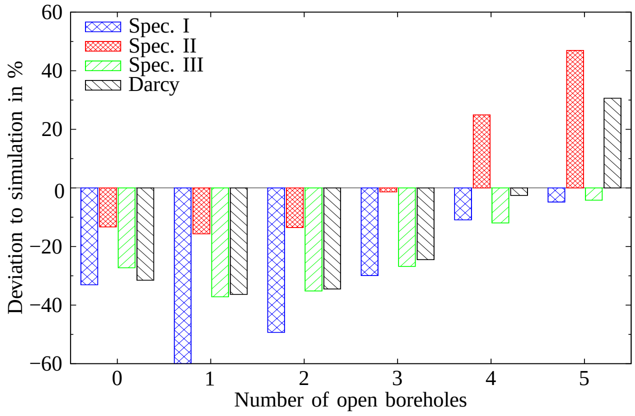

Fig. 6. Relative deviation of flow results to simulation

Hereafter the term "mode i" is used to describe the throttle adjustment of i open boreholes.

B. Discussion

First of all one has to understand that the permeability κ was determined in the former work [1] with an uncertainty of $\pm 14\,\%$ by measuring the flow through the entire ZrO_2-cylinder in dependency of different pressure values and then using Darcy's law (4). Hence the results in mode 0 of the specimen and the computation via Darcy law are supposed to agree quite well. Since specimen II has significantly higher flow rates throughout every single mode, Ohm's law implies a considerable lower flow resistance compared to the other samples. Possible explanations for these deviations could be the unnoticed existence of air bubbles in the experimental set-up or in the throttle itself or the presence of leakages in the measurement set-up. Despite carefully dealing these occurrences can never be excluded. Certainly the heterogeneity of these samples could simply be the reason too. Concerning the nominal pressure value of $2.5\,$bar, there was a deviation of less than $2\,\%$ for all the specimen. Taking account of the sensors' systematic error, each specimen's flow rate may differ up to $\pm 8\,\%$ of the stated value in Table II.

Darcy's law in the form (4) describes a one-dimensional flow of an incompressible, homogeneous fluid when the cylinder consists of a homogeneous, isotropic porous media with a straight cross-section perpendicular to the flow-direction. Therefore it should only be understood as a convenient and simple approximation for describing the (very complex) underlying flow phenomena in the ceramic throttle. In reality, the fluid will bypass the ceramic via the borehole-gaps and then exits at the first reachable outlet, which clearly is not described by (4). The influence of this phenomenon increases with the number of opened holes. In case of mode 5, i.e. all boreholes are unsealed, the fluid exits mostly through the first hole. At this point the use of Darcy's law (4) is not justified and thus does not lead to reliable results, especially by considering the small dimensions and the complicated front side profile, cf. Table I and Fig. 3. Nevertheless, as observable in Fig. 5, the computation via Darcy's law as a simple description delivers correct qualitative results and therefore characterizes the flow rate almost inversely proportional to the distance, i.e. $q \sim 1/\Delta\ell$.

The simulation model solves the Stokes-Brinkman equation (1) on the entire flow domain and consequently one may expect more accurate solutions compared to the sole use of Darcy's law (4). Referring to Figs. 5 and 6 one realizes that the simulated flow rate results are higher than the others' in lower modes. In higher modes the results approach until finally the relative deviation is closer to zero or even changed the sign. The qualitative behaviour fits those of the other ones and the flow rates are always close to at least one of the specimen's results. However, the relative error is still high and requires further investigations for parameter optimisations of the simulation model. Especially the considerable uncertainty of the permeability κ offers a promising improvement possibility.

C. Possible Improvements of the Throttle Design

One idea for improving the design concerns the comparability of the throttle geometry of each specimen and proposes, additionally to the laser-marking for boreholes, a straight cross-section perpendicular to the flow direction at the front side of the ZrO_2-cylinder which would have advantages in view of flow rate predictions, especially in the highest mode.

Another suggestion aims at the (practical) applicability of the throttle: The percentage increasing steps of flow rates are very small in lower modes and rise tremendously towards the higher ones. A patient would probably wish a more moderate increase of drug dosage. Additionally the small distances between the boreholes are challenging for providing a proper (mechanical) sealing. Hence more (available) space of the infusion pump shall be occupied: By enlarging the ZrO_2-cylinder length to $\Delta\ell_0 = 30.41\,$mm and the diameter to $1.5\,$mm, Darcy's law (4) predicts a flow rate of $q_0 = 70\,$nl/min in mode 0 and furthermore determines the distances

$$\Delta\ell_i = \Delta\ell_0/(1+k)^i \quad \text{with} \quad k = \sqrt[5]{q_5/q_0} - 1$$

from the front side to the i-th borehole marking, where a uniform gain of flow rate from one mode to another was assumed. For a maximum flow of $q_5 = 1000\,$nl/min the computational results via Darcy and the simulation tool GeoDict are summarized with corresponding deviation in Table III.

TABLE III
RESULTS OF CHANGED GEOMETRY

i	$\Delta\ell_i$ [mm]	Darcy [nl/min]	Sim. [nl/min]	Deviation [%]
0	30.41	70.00	85.91	-18.52
1	17.86	119.15	145.45	-18.09
2	10.50	202.80	235.49	-13.88
3	6.17	345.17	355.33	-2.86
4	3.62	587.52	548.06	7.20
5	2.13	1000.00	800.40	24.94

IV. Conclusions

The Micro-CT-Imaging of the existing throttles enabled a deeper analysis of their geometry and the consequent impact of flow results. Especially the flow rate sensitivity to the front side profile was pointed out. A theoretical description of flow phenomena in porous media was summarized and a subsequent simplification to Darcy's law was argued which helped to characterize the flow in the porous ceramic throttle almost inversely proportional to the distance between ceramic front side and position of the first opened borehole. The actual mean geometry of the analysed specimen was processed in a GeoDict-simulation model and its results were compared to those obtained by experiments and Darcy's law for horizontal flow. The simulation model was shown to be a helpful tool but more specimen need to be examined to optimise the model parameters for expecting reliable flow results. Eventually two possible improvements of the existing throttle design were proposed.

Acknowledgements

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