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EXPERIMENTAL DETERMINATION AND VALIDATION OF PRESSURE THROUGH A POROUS MEDIUM

INTERNSHIP REPORT

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Executive summary

The goal of this research is the design of a fast modular set up used for the measurement of pressure loss through a porous medium. Measurements done with this set-up will eventually reduce extensive simulation effort. In order to design the experimental set-up a literature review has been conducted from which design requirements and guidelines are defined. Also an analytical method is examined which in a later stadium of the research is used to validate the obtained experimental results.

Using the information acquired by means of a literature study a schematic functional design is made. The functional design leads to the final design and required components. Test with various porous media are conducted and compared to the analytical method of Sabri Ergun (chapter 3). Very good comparison is achieved between the experimental results and Erguns theory, proving that the design work resulted in a working experimental method. More validation of the experimental results is done with a CFD model, similar results of both the CFD model and experimental results where obtained (chapter 4). Therefore a validated experimental method is obtained.

The acquired constants to model the behavior of a porous medium from the experiment, are then tested in simulation software Ansys CFX. Thereby the CFD computations of a scaled down porous medium (chapter 4) in CFX is eliminated. This leads to a reduction of the computational time using the experimental method by a factor of eleven when compared to the CFD simulation.

The pressure loss measurement method can be used to eliminate the computational effort of a simulation of a porous part in a larger system. Thereby the 44 hours computational time needed for the CFD simulation are eliminated and can be replaced by the pressure loss experiment (4 hours). Therefore it can be concluded that a validated fast experimental method for pressure drop measurement through a porous medium is achieved.

Contents

Nomenclature

Symbols

A_c	cross sectional area cartridge
Da	Darcy number
D_p	particle diameter
ε	void fraction
f	friction factor
K	permeability
$\dot{m}$	mass flow rate
G	superficial mass flow rate per unit area
P	static pressure
q	dynamic pressure
ρ_{air}	density of air
ρ_{part}	solid density of particle
R	specific gas constant
Re	Reynolds number
Nre	modified Reynolds number
T	static temperature
V	velocity
V_s	superficial velocity
T	temperature
ΔP	pressure drop
L	equivalent length
μ_{air}	dynamic viscosity of air

Chapter 1

Introduction

1.1 Background

Porous media are used in a wide range of applications. The properties of porous media make them applicable for specific user cases. Also many common materials behave like a porous media. In depth knowledge of the behavior of a porous medium is needed, to understand and predict the working principles of these medium. With better understanding, applications of porous media can be improved. In this research two test cases for a porous medium are considered.

1.2 Aim and purpose

Nowadays many structural and flow problems are solved numerically. Using fundamental physical relations (e.g. Euler and Navier Stokes) in numerical computations to solve complex problems. These FEM [1] and FVM [2] are estimations of the real physical phenomena. The quality and trustworthiness of these models depends on the quality of the mesh and the numerical method. The computational effort for the meshing and numerical analyses, increases significantly with the complexity of the structural or flow problem. Therefore FVM like numerical computation of porous media is computational very demanding. Flow analyses programs such as CFX [3] tend to use estimation methods for porous media, depended on Darcy's law and Navier Stokes [1]. These are analytical equations which compute pressure loss, depended on velocity and the velocity squared of the flow through the porous medium. These equations are based on an simplified case using the generalized void fraction and permeability coefficient K. Therefore the quality/trustworthiness is questionable if the porous medium has additional properties that might effect the flow (e.g. surface roughness, shape, size distribution and packing).

The aim of the research is to develop a quick, easy, reliable and validated method for: determination of pressure drop per unit length through a porous medium. Thereby decreasing: extensive computational effort, time and accounting for porous medium specific properties that might effect the flow.

1.3 Method

For the design of the experimental set-up basic estimations are needed for the geometry, flow rate and pressure drop per unit length. Therefore the Ergun equation [2] in equation 1.1 is used in Matlab which is later explained in chapter 2. The script is used to estimate and determine the design aspects for the test user cases. Furthermore a literature study is done in order to determine the design guidelines of the experimental set-up.

$$\frac{\Delta P}{L} = 150\frac{\mu(1-\epsilon)^2}{D_p^2\epsilon^3}\nu_s + 1.75\frac{\rho(1-\epsilon)}{D_p\epsilon^3}\nu_s^2 \tag{1.1}$$

Parallel to the design process of the experimental set-up, the pressure drop is analyzed using CFX. CFX is used to mesh the porous geometry and numerically compute the pressure drop. By means of both Matlab and CFX, the values obtained with the experimental set-up are validated. The flowchart A.1 shows a schematic overview of the sequence and methods used.

[1] finite element method
[2] finite volume method
[3] ANSYS CFX an computational fluid dynamics software package of ANSYS

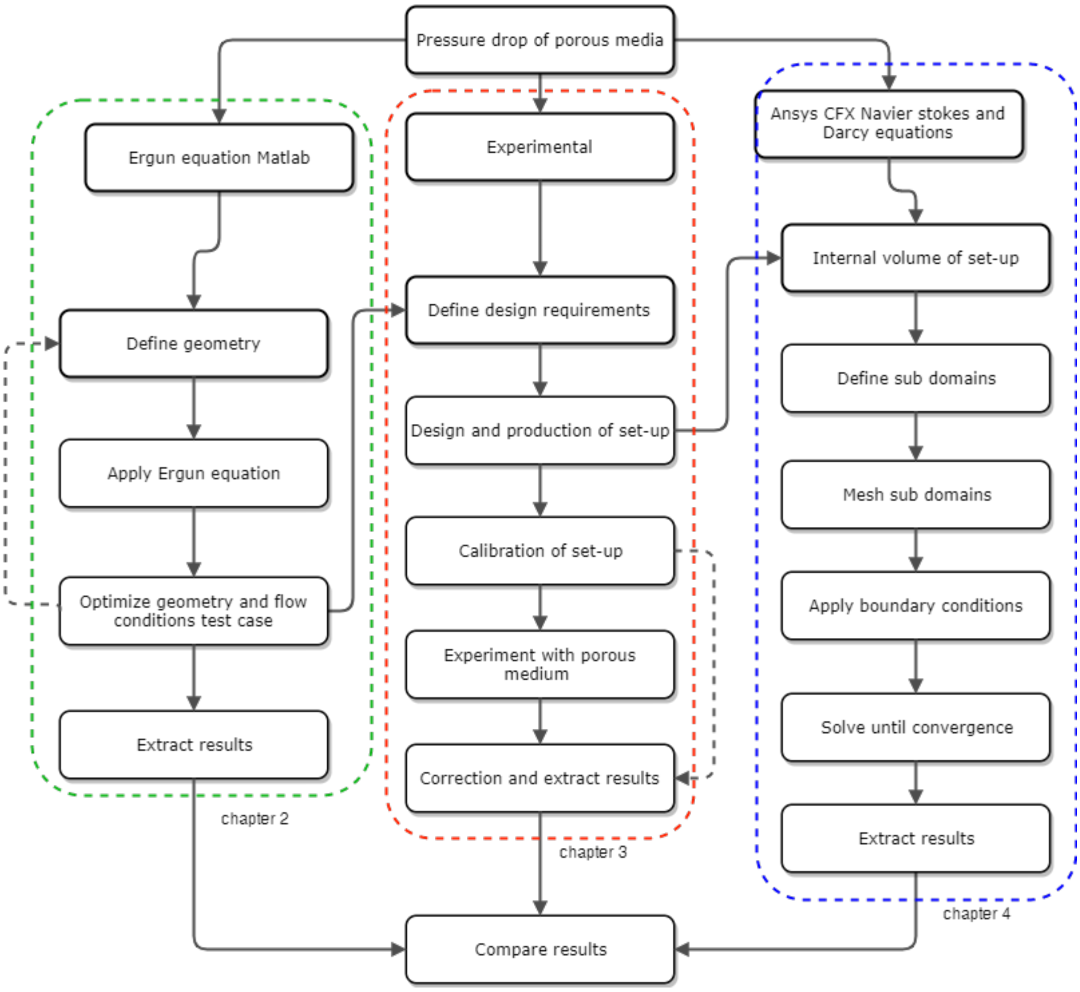


Figure 1.1: Flowchart method

The flowchart in figure (A.1 shows the alliterations and dependency of the design steps. The dotted arrow lines indicate multiple alliterations between several steps. For simplification reasons and ease of reading the process is divided in three parts: Ergun (green), Experimental (Red) and CFX (Blue).

1.4 Outline of report

In the second chapter the theory behind porous media is introduced. Available literature on the Ergun analytical approach are discussed and presented. This literature is used as the groundwork for the experimental set-up. Multiple phenomena are discussed and looked into. Additionally interviews and review sessions with field experts are conducted to enrich the field expertise.
The understanding of porous behavior is used in chapter three. This chapter presents the geometry and the flow regimes are defined for the test media. The beads of the test media are discussed and analyzed. A set-up is build and used to obtain data of the test media.
The fourth chapter presents a different solution route to determine the pressure drop. This is done by numerical simulation of the test media in CFX. First a random packing is simulated in Solidworks to obtain the void space of the media. The quality of the mesh is discussed and tested. Multiple simulations are done in order to obtain the pressure drop per unit length.
Finally the test results obtained are validated with the analytical and simulation results. A comparison with the experimental obtained data is used to discuss the performance of the set-up.

Chapter 2

Literature

2.1 Porous medium

The test case as mentioned in the introduction consist out of randomly stacked spherical particles. The choice for a defined porous medium is desirable. With the known properties of the particles the void fraction, weight and inter-facial area concentration can be determined accurately. As the theoretical equations are based on spherical particles, the geometrical conditions of the test cases are identical to the theory of Ergun [3]. Another reason for using known particles, simplification of the numerical computation (because a comparable volume is possible to render with CAD software), resulting in more comparable results.

Due to manufacturability, a cylindrical (column) geometry is used for the cartridge holding the particles. Channeling effects causes high velocity flow at the wall of the column, therefore decreasing the pressure drop. Hence, effecting the trustworthiness of the pressure drop scalability per unit length. Therefore the ratio between the diameter of the particle and the column has to be sufficiently small. Although not found in literature, industries use 1:15 particle to column diameter ratio as a rule of thumb (according to [4], [5] and interview with field expert Dr. Ir. N. Kruyt [12-09-2017]). Therefore the same procedure is used for both test cases.

The packing of the medium is determined by gravity, at the moment that the particles are deposited in to the cartridge. This introduces a uncertainty in the properties of the medium, the void fraction may differ depending on the deposit. With measurements of the weight of different deposits in the same cartridge, deviation and average void fraction can be determined. Therefore multiple measurements [1] are conducted with a estimated cartridge size, of 50mm diameter and 100mm length (which is examined in the next chapter). The average weight of one bead [2] and the full cartridge weight [3] is determined. This used to calculate the void fraction, in table 2.1 the properties of the medium are presented.

Diameter $[D_p]$	Supplier	Solid density $[\rho_p]$	Weight bead	Weight cartridge	Void fraction $[\varepsilon]$
$2,5 \pm 0,2 [mm]$	Muehlmeier	$2500 \pm 40 [kg/m^3]$	$0.0202[g]$	$306.58[g]$	0.37544
$3,0 \pm 0,3 [mm]$	Aldrich	$2520 \pm 40 [kg/m^3]$	$0.0377[g]$	$298.38[g]$	0.39214

Table 2.1: Properties porous medium [6], [7]

2.2 Ergun equation

The nature of the porous medium can be considered as a packed column. Demand of oil and gas industry have pushed the research, on flows through packed columns (which are used for distillation processes). Through the years much research is done, on the friction related to the pressure drop through packed columns. When a fluid flows through a packed bed, pressure losses are induced due to friction factors and expansion coefficients. As mentioned in the introduction, the Ergun equation is a analytical estimation for the pressure drop per unit length. Sabri Ergun investigated fluid flow through packed columns in 1952 [2]. The Ergun equation 2.1, describes the pressure drop per unit length through a porous medium.

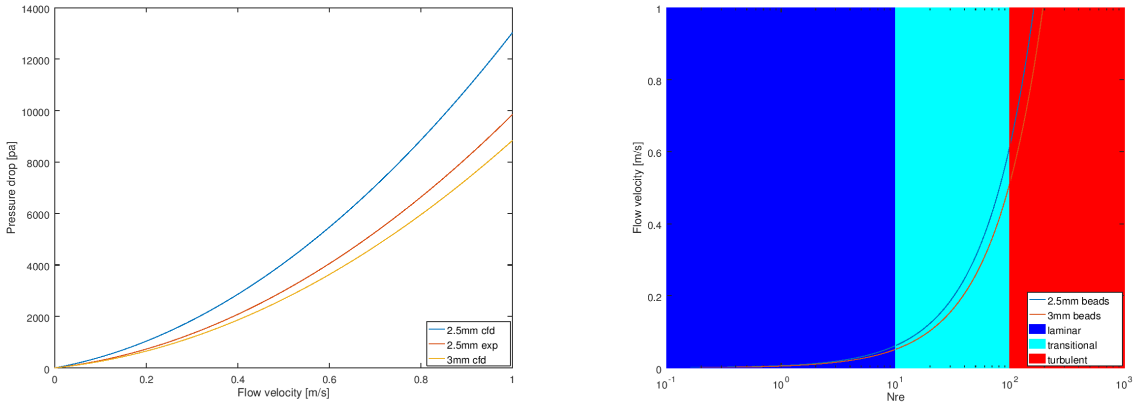
$$\frac{\Delta P}{L} = 150\frac{\mu(1-\epsilon)^2}{D_p^2\epsilon^3}\nu_s + 1.75\frac{\rho(1-\epsilon)}{D_p\epsilon^3}\nu_s \tag{2.1}$$

The equation is plotted in Matlab for the porous mediums of the three validation cases **??**. The 3mm CFD case is future examined in chapter 4. Hence, the pressure drop is highly sensitive to the void fraction, therefore these are precisely determined for each specific case. The applied validation cases are Ergun 2.5mm, Ergun 3mm and CFX 3mm beads. The results of these cases are used to validated the experimental method. Figure **??** show the estimated pressure drop per unit length.

$$Nre = \frac{D_p G}{\mu} \tag{2.2}$$

According to Perry [8] the flow regimes are depended on the modified Reynolds number equation 2.2. Where G is the superficial mass flow over the cartridge cross sectional area. From Perry's [8] the flow regimes can be identified. The modified Reynolds number is plotted in figure 2.1b including the flow regimes. This is done for the same superficial velocity range, yielding between zero and one meter per seconds.

[1] All measurements are conducted with a calibrated Mettler Toledo ME204T scale
[2] Concluded from ten measurements with twenty beads
[3] Concluded from average of ten pours



(a) Per unit length

(b) Modified Reynolds number

Figure 2.1: Pressure drop according to Ergun and flow regimes

2.3 Flow

The flow conditions are based on a previous and a pending commercial project of Demcon Bunova[4]. The considered flow regime is between $0[m/s]$ up to $1[m/s]$. With the choice of a cartridge diameter of 50mm, the Reynolds number of the cartridge is sufficiently low to only expect laminar flow (in case of the empty cartridge). It can be concluded that at low velocity (laminar flow) the first part of the Ergun equation (linear to the velocity) is dominant and as the velocity increases the second (velocity squared) part becomes dominant. In case of our experiment the transition region is roughly between $0.05 - 0.6$ [m/s]. The conditions are based on ambient air, the used properties can found in table 2.2.

	V_s	T_{air}	ρ_{air}	μ_{air}
Ambient air	$0 - 1[m/s]$	$293[K]$	$1.185[kg/m^3]$	$1.831 \cdot 10^{-5}[kg/m \cdot s]$

Table 2.2: Flow properties

2.4 Conclusions and design parameters

Extracted on the literature study and appointments with experts on the research topic, design guidelines can be concluded. These are separated in guidelines for the functionality of the experimental method and guidelines to secure the working principle.

Guidelines functionality:

- Use and maintenance should be possible for an engineer with only the manual, without any additional training.
- Quick set-up is of importance, fully operational within 30 minutes.
- Suitable for different porous media. Range of particles size $0.05 - 3[mm]$.
- Modular system for easy adjustment, transition to different particles ranges in the near future.

Guidelines working principle:

- Porous medium holder netting should be sufficiently fine. Thereby wake and non-uniform flow distribution is minimized (from interview with prof. H. Hoeijmakers [07-09-2017]).
- Wall effects can be of great influence, therefore these should be minimized. As a rule of thumb the diameter of the cross sectional area should be at least 15th times larger than the particle size (according to [4], [5] and the interview with dr. ir. N. Kruyt [12-09-2017]).
- Ingoing flow at the porous medium, should have an even distribution over the flow area. Therefore the contraction expansion chambers should have a smooth transition [9]. In addition to that a flow straighter can be used to secure even flow [10].

[4]Due to the confidential nature of these case no future references can made in this report

- Static Pressure after and before the medium, should be measured directly after and before the medium, to eliminate pressure drop due to the tube.
- Flow rate should be sufficient to match desired flow velocity up to: $1[m/s]$.

Chapter 3

Experimental set-up

The experimental set-up is discussed in this chapter. The main goal is a realization of a reliable, practical and fast experimental method to measure the pressure drop through a porous media. Measurements are performed for two test cases, with 2.5 and 3 [mm] beads as porous media. First the basic principles and components are reviewed. Then the final design, production and assembly is briefly discussed. A step by step manual is presented in order to work with the set-up. Finally the conducted measurements are analyzed and compared to Erguns theory [2].

3.1 Working principle

In order to fulfill each of the specifications set in the previous chapter the following flowsheet has been designed figure (3.1). Eight basic components are required. These components are: the compressor, a flow controller, a temperature sensor, a flow straightener, a pressure sensor, a filter and the porous medium. An overview of the components and their functionality is schematically shown in 3.1. This model is used as the conceptual design of the set-up.

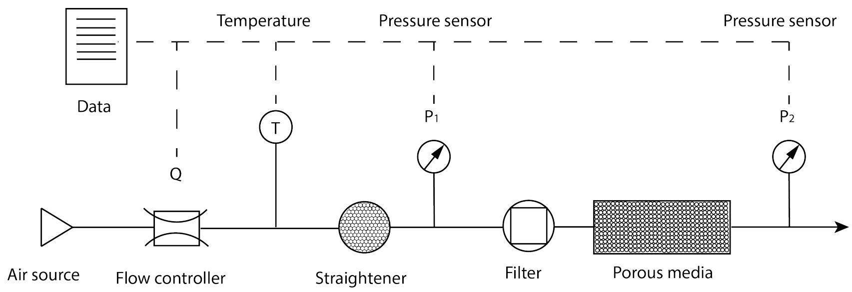


Figure 3.1: System model set-up

The flow is compressed by the compressor in this case air is used. The discharge pressure of the compressor is $8[bar]$. The flow controller is a combination of a valve and a flow meter. The flow meter [1] measures both the volume flow and the temperature of the flow. The honeycomb straightener is used for an even flow distribution. The filter supports the particles of the porous medium right at the inflow side of the medium. Between the straightener and the filter the first pressure measurement point is allocated, directly after the porous medium the second pressure measurement point is located. The differential static pressure is measured between these two points. This is done by means of a differential pressure transducer [2].

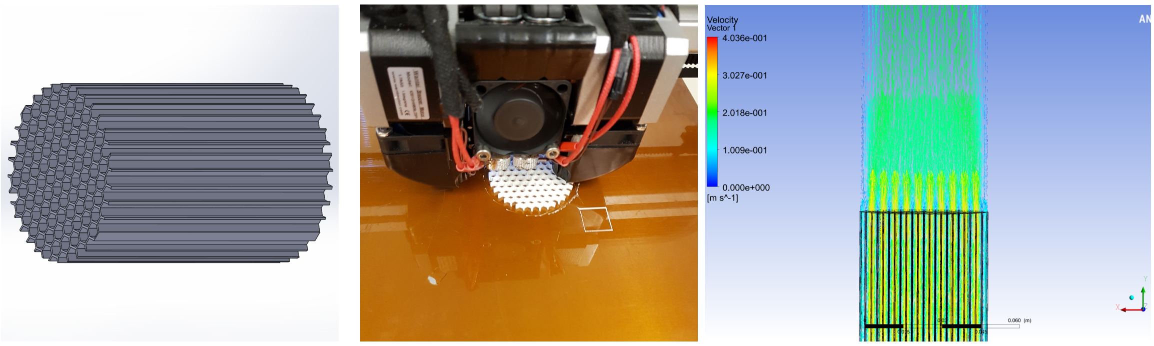
3.2 Design

This section focuses on the final design of the set-up. Mainly the parts within the flow path are discussed i.e. the tubing, the straightener and the porous medium. Finally a short overview of the set-up is presented.

One of the most important requirements is that the set-up is a modular system. In order to achieve this extensive research for off the shelf modular components has been performed. Thereby ensuring good manufacturability and short lead times. In combination with the cylindrical cartridge geometry the choice is made for KF-ISO vacuum tubing. The KF-ISO flanges are an international standard. These KF-ISO flanges are available in various sizes and couplings. Also high quality filter rings with known properties are produced for this system. These can be used directly as the filter for the set-up.

The flow straightener is designed as a honeycomb structure. The goal of the straightener is to decrease the Poiseuille flow behavior and to produce even flow distribution. In order to achieve this, smaller channels are preferred. This should be achieved with the smallest cross sectional area interruption. Therefore a honeycomb like structure is chosen. A honeycomb construction can have a large amount of channels to the interruption of the cross section [10] in comparison with round or square geometries. The 3D CAD design is made in Solidworks figure 3.3 and the working principle is verified with a CFD simulation figure 3.2c. The honeycomb part is 3d printed[3] (figure 3.2b) because of the complex geometry and in order to reduce the cost of manufacturing.

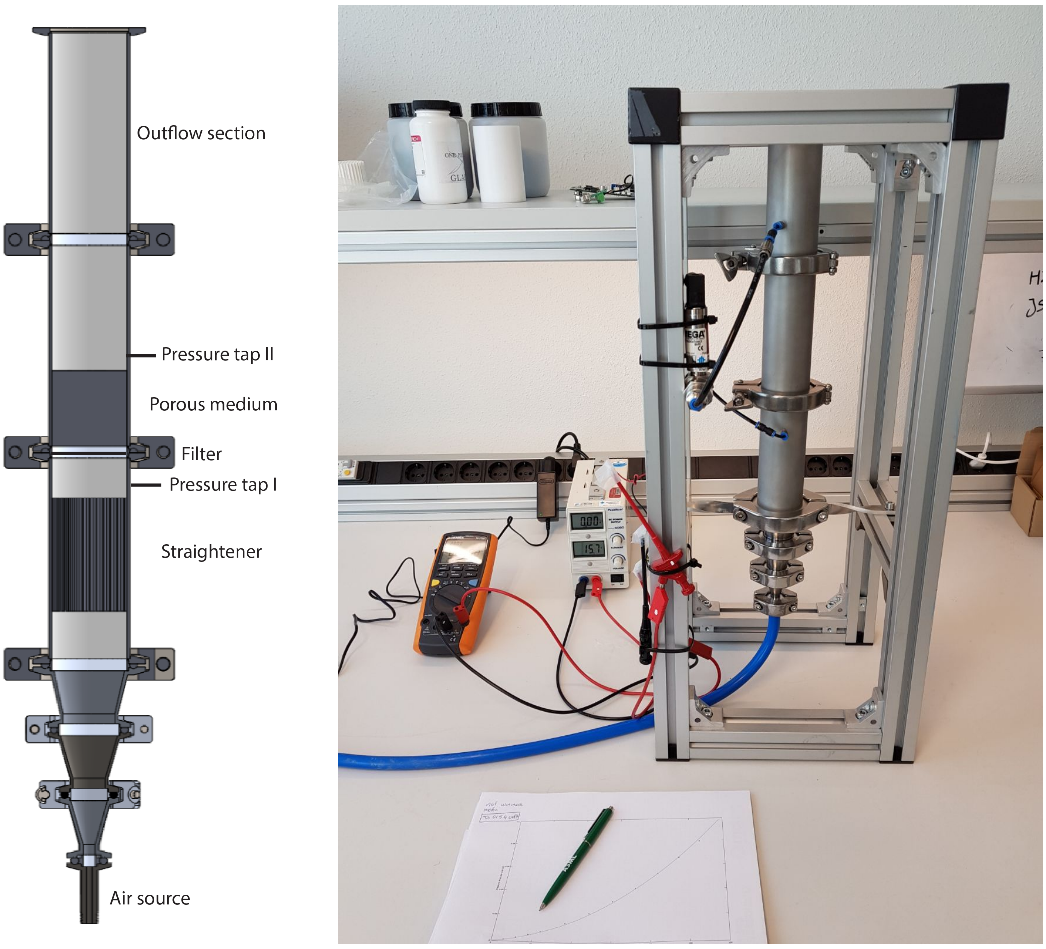
[1] TSI 4043 mass flow meter $200[l/min]$ calibrated at 09-11-2017
[2] Omega differential pressure transducer $1[bar]$ calibrated at 26-04-2017 read out with calibrated Fluke multimeter
[3] Used printer is a Felix 3.0, material used is white PLA plastic



(a) CAD design (b) 3D printing (c) CFX simulation honeycomb

Figure 3.2: Honeycomb

Picture 3.3a shows the complete CAD drawings of the set-up. The reducer valve located at the air source is connected at the bottom with the flow meter in between the valve and the set-up.The cross sectional area smoothly increases before it reaches the honeycomb. The sections are clamped together using KF-ISO clamps. Centering rings are used in combination with an O-ring, in order to ensure secure and airtight connection. The centering ring connecting the section containing the honeycomb and the section containing the porous medium, includes the filter where the particles are laying on. The pressure taps are located in walls of the bottom and top section. The main function of the pressure taps is to measure the static pressure differential over the media.



(a) Section view CAD render (b) Picture of complete set-up

Figure 3.3: Final design

3.3 Measurements

In order to conduct the measurements multiple steps are required. This section describes the process step by step. Additionally the post-processing of the measurements is briefly discussed.

1. Generate related Ergun plot with a Matlab file [4]. The graph should be pasted in form_experiment word document (appendix A). This document is used to log measurements and quickly check if they are in the correct regime.

2. Prepare all required components consisting of:

   - DC power supply 24v
   - Differential pressure transducer (calibrated)
   - Multimeter (calibrated)
   - Setup
   - Compressor with valve
   - TSI flow meter and porous media

3. Connect inflow of the flow meter with the reducer valve which is allocated at the compressed air outlet connect the outside of the flow meter with the set-up. When using the flow meter check if correct fluid is selected (air).

4. The omega pressure transducer should be connected to both of the pressure taps[5]. The power source is connected to the red and black wire pair of the pressure transducer. The other pair (yellow and black) is connected to the multimeter, yellow at the positive and black on the comm port. Multimeter should be set at DC [mV] [6].

5. The pressure transducer doesn't start on zero. Therefore before each experiment the read of the multimeter should be noted (without any flow). This zero value is can later be subtracted from the results.

6. The measurements can be conducted by opening the reducer valve. Multiple measurements should be done with varying volume flow. Volume flow can be adjusted by changing the setting of the valve.

3.4 Data analysis

A Matlab file [7] can be used for the post-processing step of the measurements. By means of the Matlab file each measurement can be analyzed and compared with Erguns theory. The results of all measurements [8] are plotted in figure 3.4. The results of the two conducted experiments match very well with Erguns theory. Especially at lower velocity the results are very comparable. Figure 3.4 also shows that the higher velocities lead to more absolute variation compared to Erguns theory. The 2.5 [mm] experiment has an average deviation of -1.12 % and 3 [mm] experiment -0.33 % compared to Erguns theory.

[4] Property of Demcon Bunova located on the companies network storage analyze_octave_exp_cfd_ergun.m
[5] If the multimeter has a negative value the pressure taps should be switched with one another
[6] 10 [V] DC complies with 1 [bar] static pressure difference
[7] analyze_octave_exp_cfd_ergun.m
[8] All results are extrapolated to 1[m] to simplify comparison

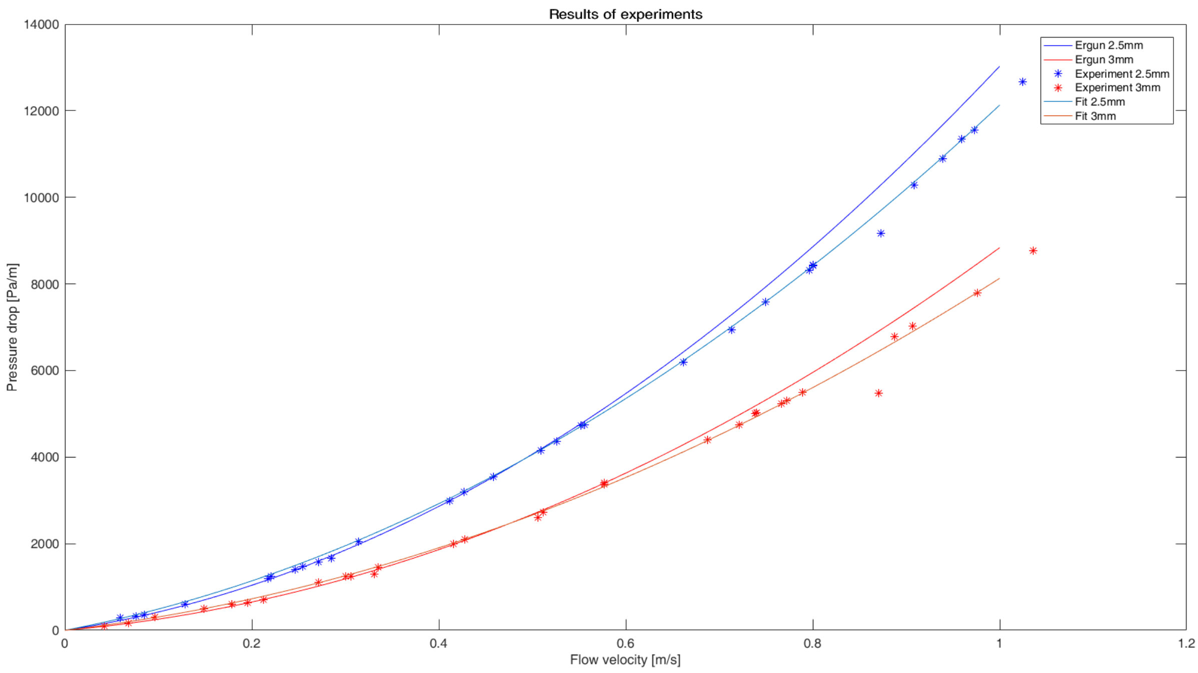


Figure 3.4: Results of experiments

Fits are made with use of Matlab figure 3.4, these are second degree exponential fits. The fits are used to extract two constants C_1 the permeability coefficient and C_2 expansion coefficient. The extracted constants in equation 3.4 can be used in chapter 4 to eliminate the computational effort of a CFD calculation for the exact geometry of a porous medium. The constants are presented in table 3.1.

$$\frac{\Delta P}{L} = C_1 \cdot V_s + C_2 \cdot V_s^2 \tag{3.1}$$

Bead size	C_1	C_2
2.5[mm]	4099.8	8031.2
3[mm]	2513.4	5616.6

Table 3.1: Constants obtained from experiments

3.5 Conclusions

It can be concluded that an easy and fast experimental method is realized, in order to measure the pressure drop through a porous medium[9]. The measurements are considered to be reliable[10] at low velocities ($V_s < 0.5$[m/s]) as can be seen in figure 3.4. As velocity increases absolute variation in the results and deviation to Erguns theory increases. More tests and measurements would be desirable, to further validated and guarantee reliability.

[9] For porous mediums with particles that are sufficiently small $D_P < 3,33$[mm]

[10] Based on the two presented test cases of 2.5[mm] and 3[mm] glass beads

Chapter 4

CFD validation

This chapter discusses the CFD simulations used to analyze the pressure drop for the 3[mm] beads test case as discussed in chapter 2. The geometry is drawn using Solidworks. A mesh is constructed by means of Ansys mesh, the computation and post-processing of the simulation is performed with the Ansys CFX 18.2 software.

4.1 Geometry and parameters

The geometry of the void volume of the porous medium is required to correctly model the flow through the medium. The exact geometry of the experimental porous medium is hard to model in any CAD program, due to the random and complex geometry. With the use of Solid Works an estimation of the geometry is modeled. With use of a gravity model [11] and the solid density of the particles, a large amount of particle bodies are virtually deposited. The particles virtually travel though a funnel in to the cartridge shaped volume. When the particles are subtracted from the cartridge internal volume, a void space geometry remains. Due to the large computational effort of such a complex geometry, the choice is made to extract a smaller geometry [1] than the total porous medium. Because we are only interested in the pressure drop per unit length, the results can be extrapolated to the real experiment.

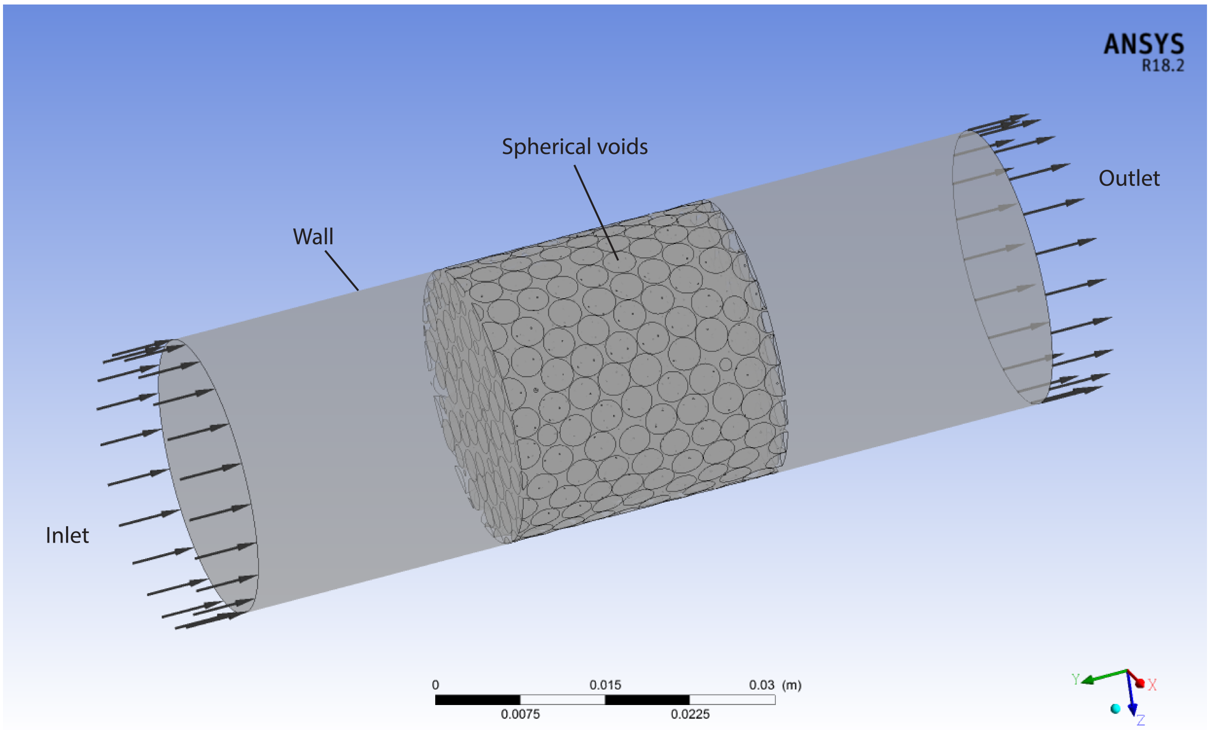


Figure 4.1: Overview of CFX model

The geometry drawn in solid is exported to Spaceclaim[2] where a cylindrical inflow and outflow geometry are added (figure 4.1). This is done in order to simulate the conditions similar to the experimental set-up. The parameters used for the simulation are comparable to the parameters of the experiment. The boundary conditions used for the simulation are presented in table 4.1.

Location	condition	value
Inlet	steady in flow	$0.15, 0.3, 0.45, 0.6, 0.9m/s$
Outlet	static pressure	$1atm$
Cylindrical wall	free slip wall	
Spherical voids	no slip wall	

Table 4.1: Boundary conditions

[1] Cylindrical part 25mm in diameter and 25mm height
[2] CAD program part of ANSYS software

4.2 Mesh

The mesh has to be sufficiently fine to capture all the flow phenomena present in the domain, in order to eventually obtain a converging solution. Inflation layers are required at the tight channels between the beads. Without a sufficient amount of inflation layers no boundary layer effects will be calculated, in these tight channels. Six inflation layers are found to be sufficient, for a converging solution and still be computable with available computing time. Figure 4.2 shows section overview and figure 4.3 a close up of the mesh, the properties of the mesh are presented in table 4.2. In the close up (figure 4.3) the round holes are the contact points between the beads.

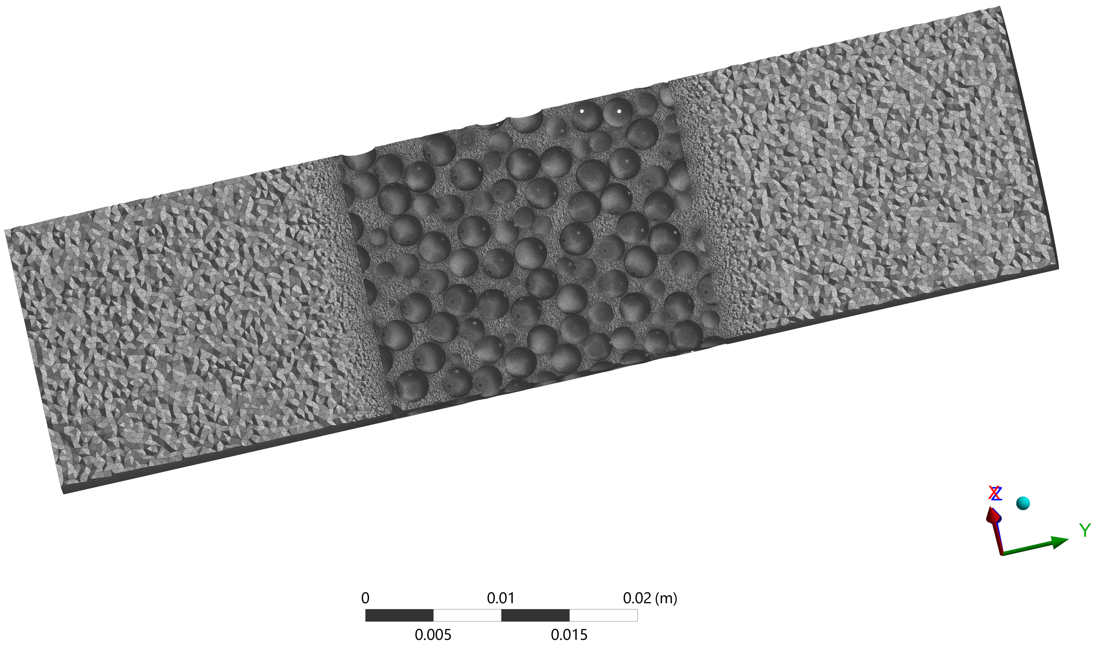


Figure 4.2: Mesh side view

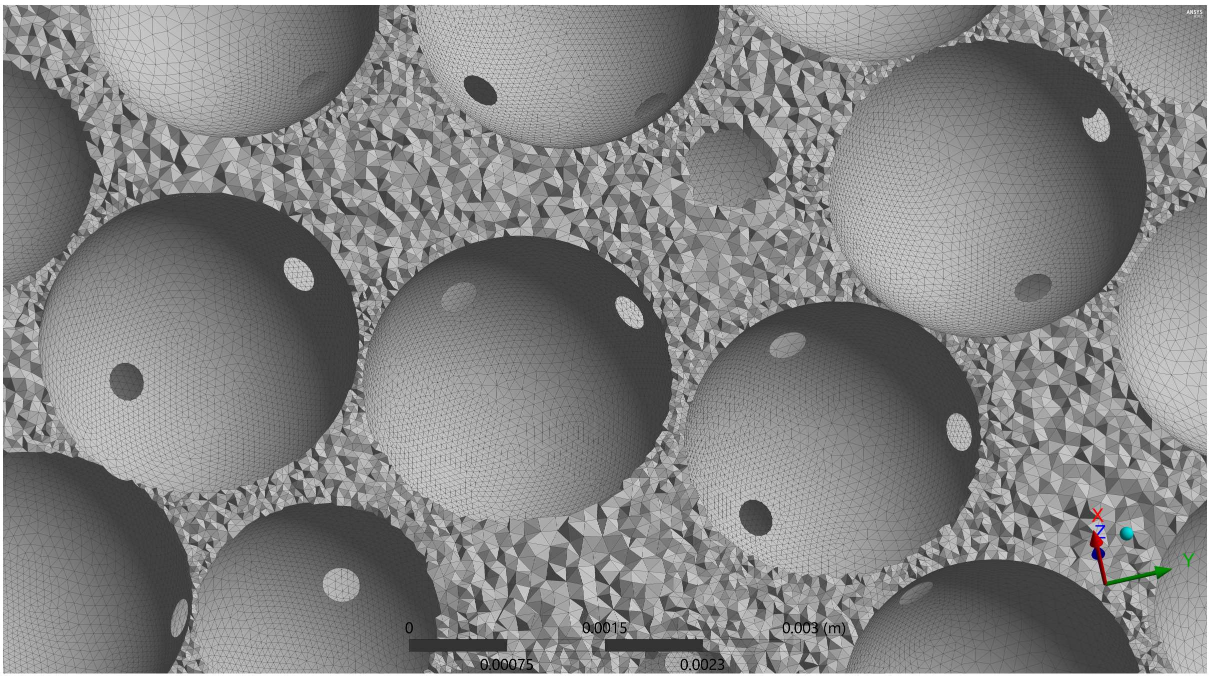


Figure 4.3: Close up

Bulk volume	void volume	void fraction	faces	element order	elements	nodes	inflation layers
12272 $[mm^3]$	4676.2 $[mm^3]$	0.38105	917	Linear	$41e^6$	$13.6e^6$	6

Table 4.2: Mesh properties 3mm beads 25mm cylinder

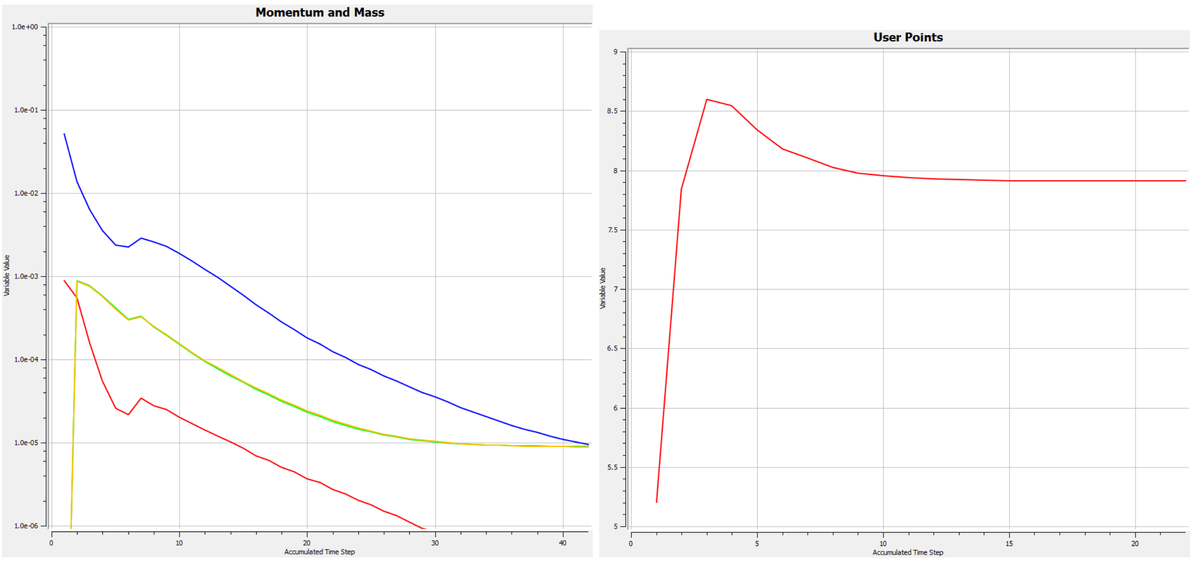
As expected the mesh is very large and complex. A large amount of elements and nodes are needed to properly capture the geometry. This is caused by the small channels between the spheres. As well the small contact points of the spheres create infinite sharp edges which are very hard to capture in a mesh.

Fluid	Temperature	Density	Dynamic viscosity	Flow type
Air	$293[K]$	$1.185[kg/m^3]$	$1.831 * 10^{-5}[kg/m * s]$	Laminar

Table 4.3: Used fluid properties in Ansys CFX 18.2

4.3 Simulation

The amount of iterations should be sufficient in order to achieve a correct solution. The convergence is measured as the difference between the current solution and the solution of the previous iterations. If this difference is sufficiently small [3] one can conclude that the solution will not chance significantly as iterations increase. Therefore the solution yields trustworthy results. The computations are stopped after 100 alliterations as then the solution has converged.



(a) Momentum and mass 0.1[m/s]

(b) Monitor point pressure drop 0.1[m/s]

Figure 4.4: Convergent of solution

The solutions converges to $< 10^{-5}$ with in 100 iterations (figure 4.4a). During the simulation a monitor point is used to monitor the development of the flow. The monitor point is the pressure difference between the pressure taps (located above en below the porous medium). In case of 0.1 [m/s] the monitor points remains stable after only 20 iterations (figure 4.4b). Eleven different velocities are computed, these results are shown in table 4.4 and plotted (figure 4.8).

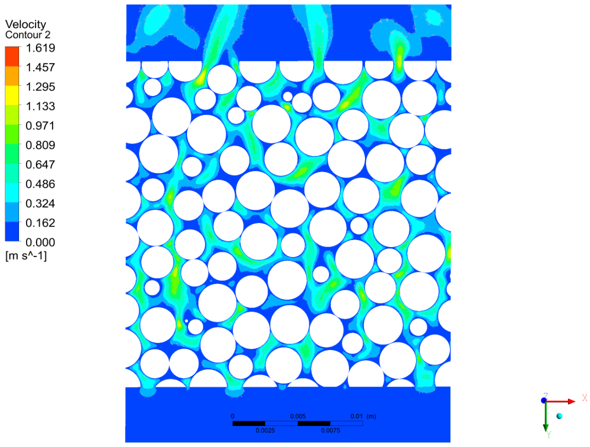
Cylindrical porous medium 25mm by 25mm

V_s [m/s]	0.05	0.1	0.15	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
Δ_P [Pa]	3.5	7.9	13.3	19.8	35.4	54.6	77	102.8	131.8	163.9	199.1

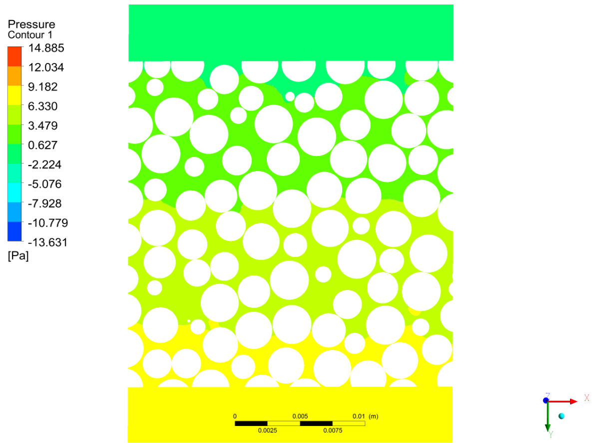
Table 4.4: CFX results 3mm beads 25mm cylinder

The velocity through the medium at three different speeds is shown (figures 4.5a, 4.6a and 4.7a). Locally high velocities arise when the gaps sizes decreases. Also the figures show a relative small wake after the porous medium. The velocity profile quickly evens after the beads over the cross sectional area.

[3] $Alliteration_n - alliteration_{n-1} < 10^4$ is assumed to be sufficiently small

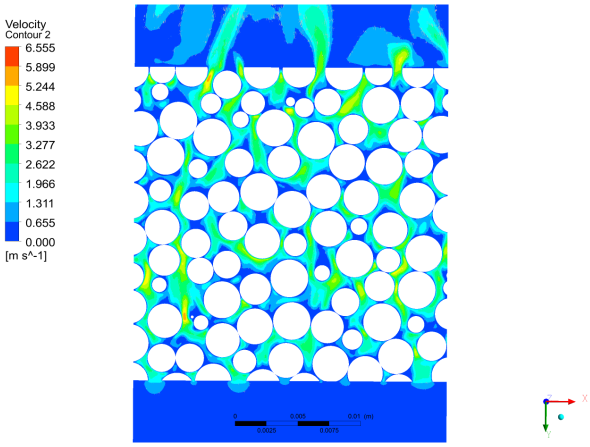


(a) Velocity profile 0.1[m/s]

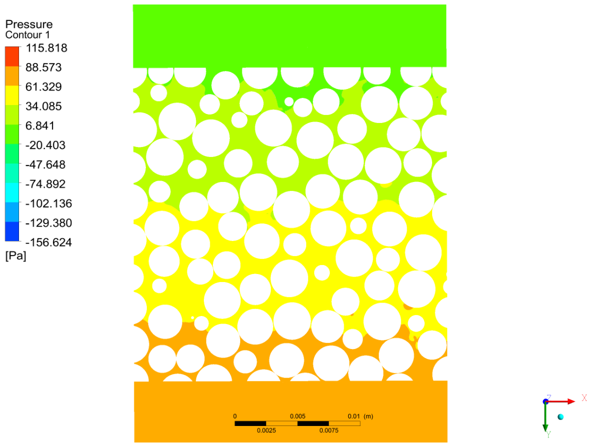


(b) Pressure profile 0.1[m/s]

Figure 4.5: Velocity and pressure profiles 0.1 [m/s]

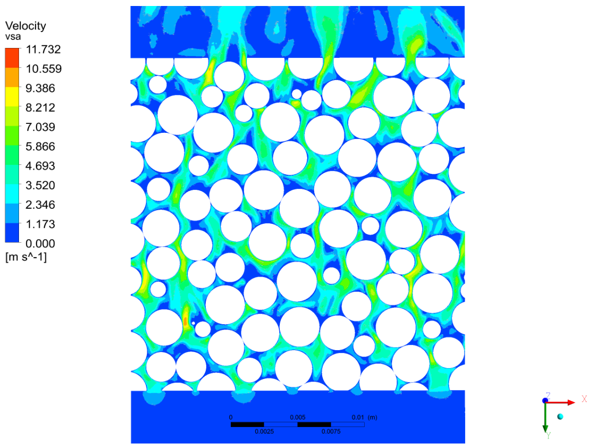


(a) Velocity profile 0.5[m/s]

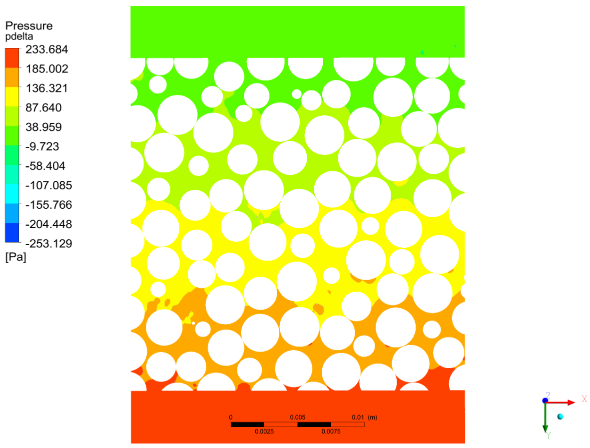


(b) Pressure profile 0.5[m/s]

Figure 4.6: Velocity and pressure profiles 0.5 [m/s]



(a) Velocity profile 0.5[m/s]



(b) Velocity profile 0.9[m/s]

Figure 4.7: Velocity and pressure profiles 0.9 [m/s]

The pressure drop through the porous medium is presented (figures 4.5b, 4.6b and 4.7b). Here the increasing pressure drop for higher velocities is clearly visible. Also the even pressure distribution before and after the medium is proven. Therefore the location of the pressure taps is validated. Because the flow directly after the medium doesn't have a variation in pressure over it's cross section. The results are plotted in figure 4.8 together with the complying Ergun equation. In general the results are very comparable as expected. The results show an overshoot at low velocities ($V_s < 0.5$[m/s]), as the velocity increases the CFX results have an overshoot compared to Erguns theory.

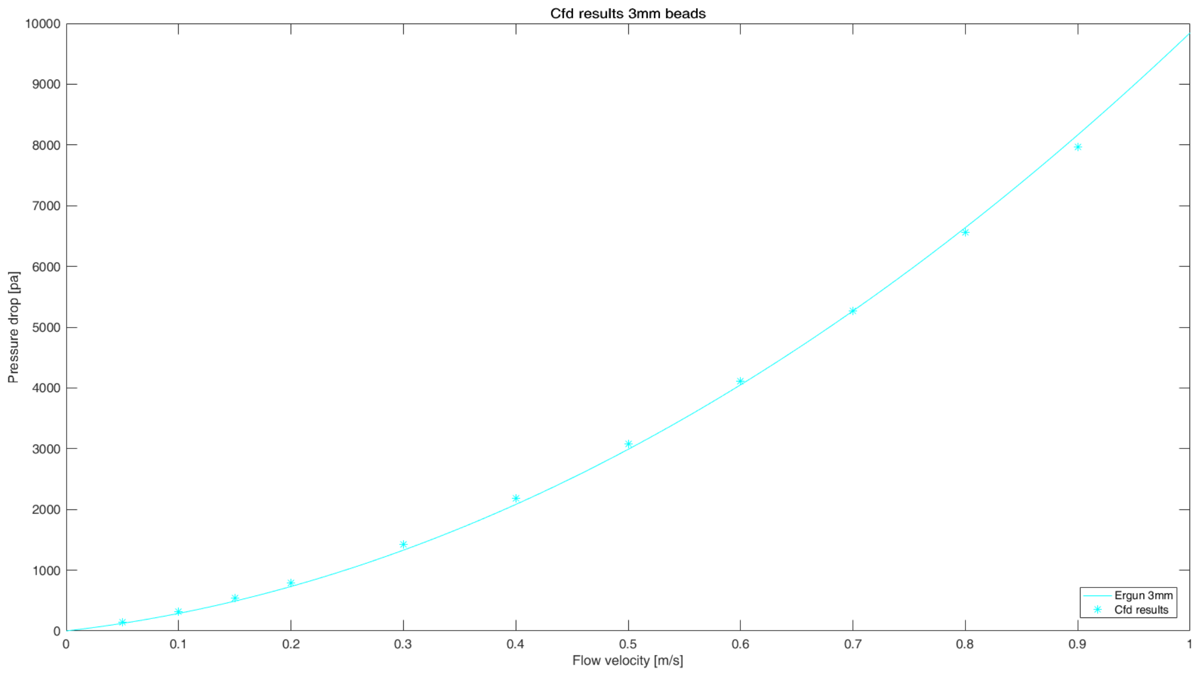


Figure 4.8: Results of CFD and Erguns theory

4.4 Conclusions

The CFD simulations are very time demanding. This is partly due to the complex mesh that is very hard to achieve. Furthermore the computational time is very extensive. For each velocity a new simulation is required. Therefore in this case a velocity versus pressure drop parameter study requires eleven simulations. The combination of the complex mesh, extensive simulation time and the demand of multiple velocities makes these simulations very time consuming. The experimental method instead of the CFD simulations is thereby very interesting for the industry. As expected it can be concluded that the results of the simulations comply with Erguns theory (figure 4.8). The results are considered to be reliable[4]. Also from this chapter it's concluded that down scaling of the geometry of the experiment to 25 by 25 [mm] cylinder for the simulation, did not effect the results. But the smaller geometry made construction of the mesh and the simulation more efficient. Therefore the scalability of the porous medium is tested. For the future it is interesting to research the threshold, when the ingoing and outgoing flow effects dominate the solution. Hence, the maximum downscaling possibility for the geometry simulated in CFD.

[4]Based on the presented test cases of 3[mm] spherical particles with cylindrical volume of 25 by 25[mm]

Chapter 5

Performance method

5.1 Combined results

The results of the experiments and CFD are plotted with complying Ergun theory (figure 5.1). It can be concluded that the experimental results comply with Erguns theory, at low velocities. Also as expected Erguns theory fully complies with the simulations in CFX. In comparison the CFD simulations took 44 hours with only a small fraction of the volume (25 by 25 [mm]), compared to the experimental volume (50 by 100 [mm]) which took approximately 4 hours

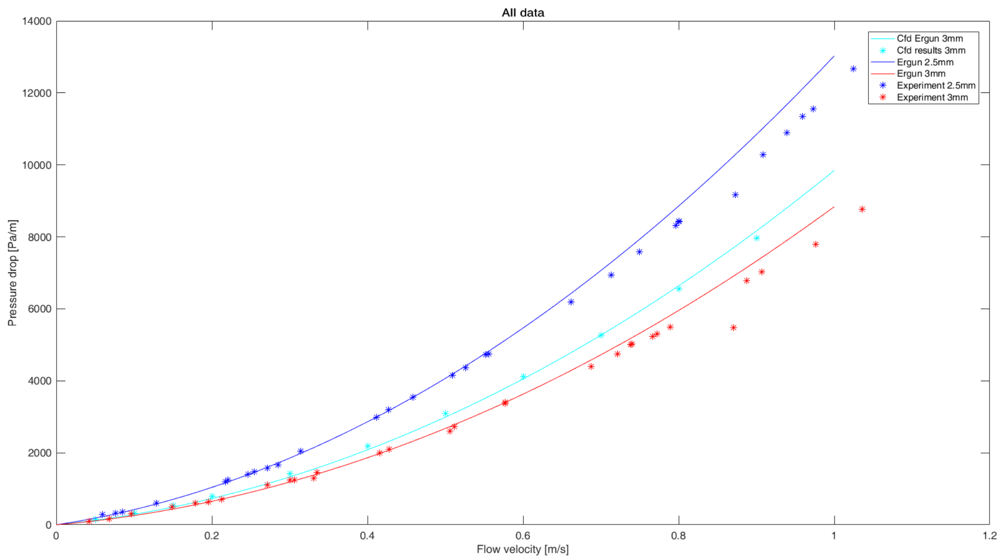


Figure 5.1: Combined results

5.2 Application of coefficients in CFX

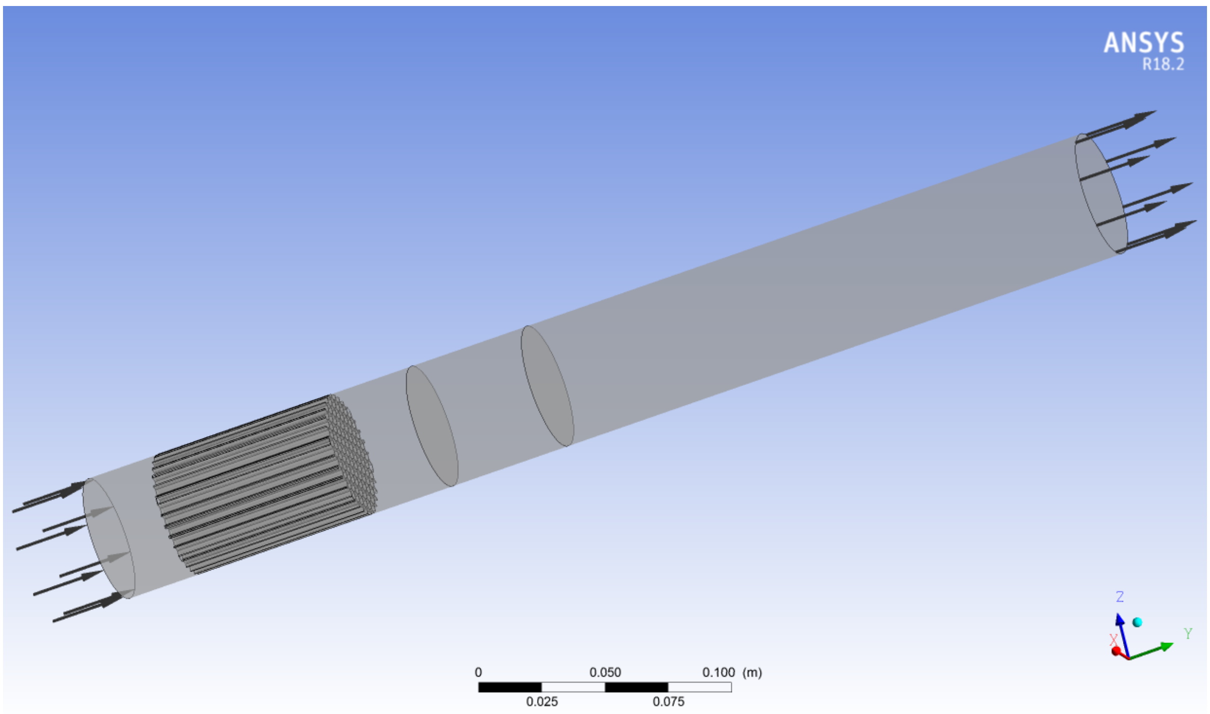
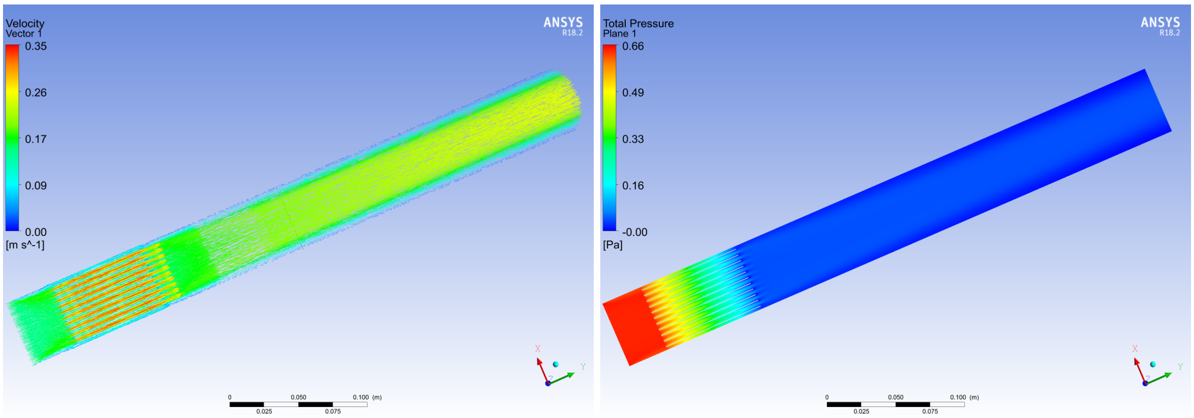


Figure 5.2: Overview using linear and quadratic coefficients

With use of Darcy's linear permeability term and the expansion losses quadratic losses term of the experiments (chapter 3) the computational effort of a system including a porous media can be decreased. When assuming the porous media as a black box in the system, the coefficients can be used to simulate the porous medium exactly (figure 5.2).



(a) Velocity profile

(b) Pressure profile

Figure 5.3: Performance profile

Using the experimentally determined coefficients a much smaller and simpler mesh will be sufficient, because only a exponential function has to be solved. The much smaller and simpler mesh means that all the complex flow phenomena doesn't have to be researched and are eliminated by the experiment. To prove the method, the coefficients (from 3) are used in a simulation with the geometry of the set-up (figure 5.3). The results comply with the exponential fit (figure 5.4 and table 5.1), proving that the method works.

Results 2.5mm				
V_s [m/s]	0.1	0.3	0.6	0.9
Δ_P [Pa]	24.86	98.98	270.65	515.04
Results 3mm				
V_s [m/s]	0.1	0.3	0.6	0.9
Δ_P [Pa]	15.9	64.73	180.31	346.4

Table 5.1: CFX simple geometry and experimental coefficients (chapter 3).

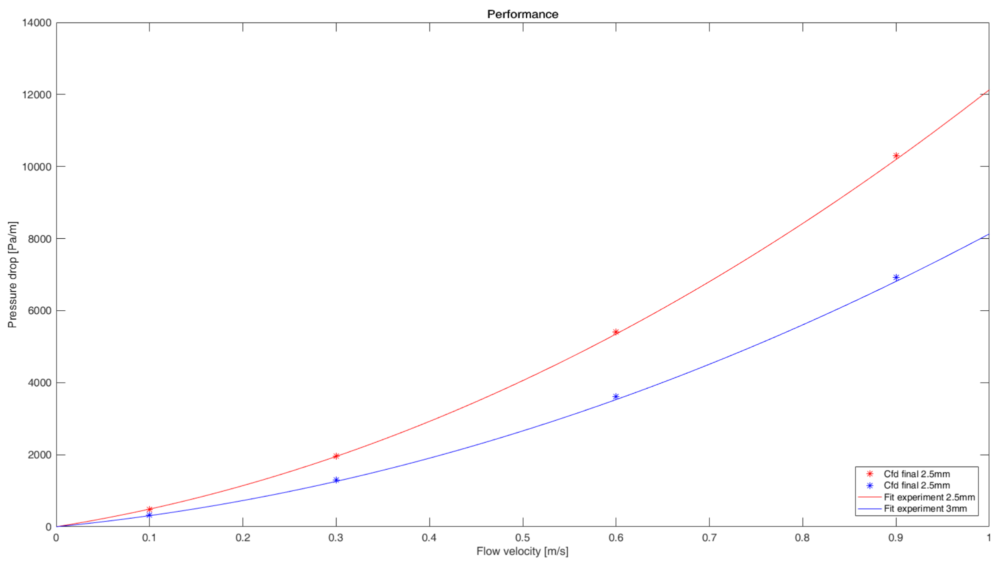


Figure 5.4: Performance results

5.3 Conclusions

The total amount of time for the experiment and the extraction of the coefficient took approximately 4 hours. Reducing computational time of 44 hours with a factor eleven. Setting up the mesh and simulation has taken more than a week. The simulation had to run for approximately 4 hours per velocity [1]. Thereby reducing the extensive effort of meshing and simulating the porous medium (as shown in chapter 4).

[1] The case of chapter 4 took a total computation time of 44 hours

Chapter 6

Conclusion

The goal was to develop a fast modular set up to measure the pressure loss through a porous medium. Eliminating extensive simulation effort. It can be concluded that an easy and fast experimental method, in order to measure the pressure drop through a porous medium[1] is realized.

The conducted measurements of pressure drop through a porous medium are considered to be reliable[2] at low velocities ($V_s < 0.5$[m/s]) (chapter 3). As velocity increases absolute variation in results and deviation to Erguns theory increases (maximum deviation of -6.89 %). Therefore reliability of the measurements at higher velocities can not be guaranteed yet. More test and measurements at higher velocities should be conducted and validated to guarantee reliability at these higher velocities.

The CFD computations are very demanding. This is partly due to the complex mesh that is very hard to generate. Furthermore the computational time is very extensive. For each velocity a new simulation is required. Therefore in this case a velocity versus pressure drop relation eleven simulations are required. The combination of the complex mesh, extensive simulation time and the demand of multiple velocities makes these simulations very time consuming.

The experimental method instead of CFD simulations is thereby very interesting for the industry because of the time reduction factor of eleven. As expected it can be concluded that the results of the simulations comply with Erguns theory (figure 4.8). The results are considered to be reliable[3].

Also from chapter 4 it's concluded that down scaling of the geometry of the experiment to 25 by 25 [mm] cylinder 6.24 % of the initial volume for the simulation, didn't effect the results. But the smaller geometry made construction of the mesh and the simulation more efficient. Therefore the scalability of the porous medium is tested. Hence, the maximum downscaling possible for the geometry simulated in CFD.

The total time of the experiment and extracting the linear and quadratic permeability losses took approximately 4 hours. Reducing computation and meshing times by a factor of eleven. Setting up the mesh and the simulation has taken more than a week. The simulation had to run for approximately 4 hours per velocity [4]. Thereby when a experiment is used reducing the extensive effort of meshing and simulating the porous medium (as shown in chapter 4).

[1] For porous mediums with particles that are sufficiently small $D_P < 3,33$[mm]
[2] Based on the two presented test cases of 2.5[mm] and 3[mm] glass beads
[3] Based on the presented test cases of 3[mm] spherical particles with cylindrical volume of 25 by 25[mm]
[4] The case of chapter 4 took a total computation time of 44 hours

Chapter 7

Recommendations

Although the experimental method is considered to be very successful compared to CFD simulations in elimination of meshing and simulation time, further research would be interesting to increase knowledge and performance of the experimental method. Below some issues are presented that would be interesting in order to continue examination.

7.1 Experiment

- Method of determining the void fraction of the test media should be further studied and improved. This is currently acquired by weighing of the beads and calculating the void with use of the average diameter and solid density of the beads. As the void fraction is of great influence on the result, variation in the measurements should be eliminated. By measuring the exact solid volume of the beads bulk volume by submerging a more accurate results might be acquired.
- When increasing the volume flow the reliability is not yet tested. More test with increased volume flow are needed to prove reliability for higher flow velocities[1] ($v_s > 0.5$ [m/s]).
- For larger particles an cartridge with a larger diameter is needed and has to be validated. It would be interesting to test with 100 [mm] cartridge in order to measure particles up to 6.66 [mm] diameter. Thereby making the set-up more flexible for further projects.

7.2 CFD simulations

- When conducting the CFD simulations, the inflation layer was very hard the create. Researching the necessity of the inflation layer and amount of inflation layers to capture the flow phenomena through the small channels, would be interesting. With knowledge about the effect of the inflation layer on the results, it might be possible to reduce the amount of inflation layers. Meaning a reduction in the effort needed for the mesh and less extensive simulation time.
- As mentioned before (chapter 4) knowledge of the scalability of the simulated geometry is interesting. Then the smallest possible geometry can be used for the simulation. Although this would increase efficiency of the simulation it's very hard because it's different for each type of medium. Therefore the time reduction would be interesting if a large amount of simulations are required for one specific porous medium.

[1] In order to preform these experiments a different flow meter is needed with higher volume flow reach

Recommended Reading

[1] Compassis. Tdyn cfd + ht reference. http://www.compassis.com/downloads/Manuals/TdynReference.pdf. Accessed: 07-09-2017.

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Appendix A

From experiment

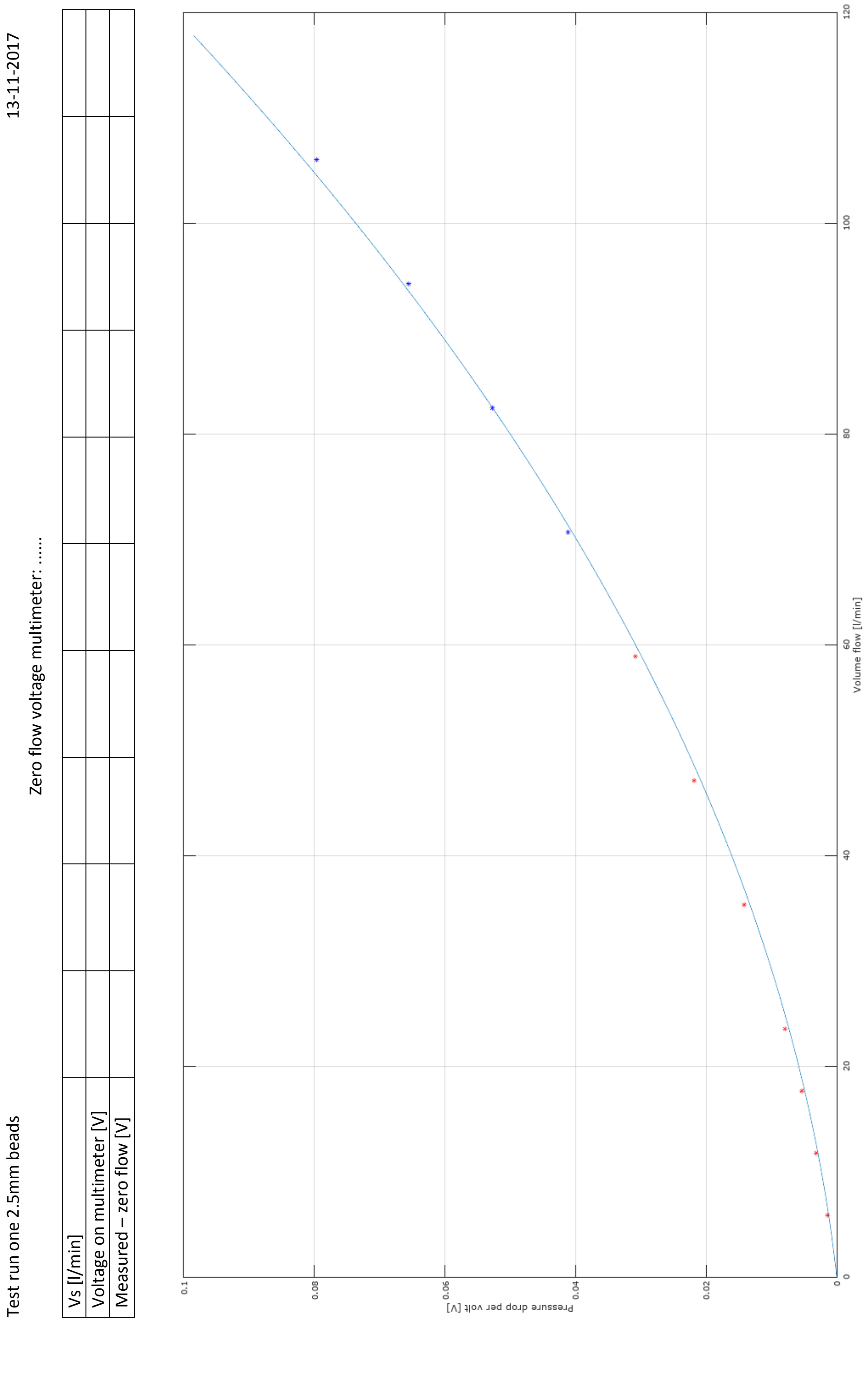

Figure A.1: From experiment

Appendix B

Measurements of experiment

First measurements										
V_s [l/min]	15.2	25.6	33.6	50.3	62	78	93.8	110.6	120.7	102.8
Voltage [V]	0.006	0.0119	0.0166	0.0319	0.0437	0.0619	0.0831	0.1089	0.1266	0.09169
Second measurements										
V_s [l/min]	9	10	29	30	32	48.5	60	84	94.3	113
Voltage [V]	0.0032	0.0035	0.014	0.0147	0.0157	0.0298	0.0415	0.0694	0.0844	0.1134
Third measurements										
V_s [l/min]	7	26	37	54	65	88.33	94.3	107	114.6	65.5
Voltage [V]	0.0029	0.0125	0.0204	0.0354	0.0473	0.0759	0.0842	0.1028	0.1155	0.04745

Table B.1: Measurements 2.5mm zero voltage correction: -0.0176 [V]

First measurements										
V_s [l/min]	50.4	68	87	93	115	32	21	5	11.4	17.5
Voltage [V]	0.021	0.034	0.05	0.055	0.078	0.011	0.006	0.001	0.003	0.005
Second measurements										
V_s [l/min]	25	36.1	39	59.6	60.3	81	85	91	90.3	102.6
Voltage [V]	0.007	0.0125	0.013	0.026	0.0272	0.044	0.0474	0.0531	0.0523	0.0548
Third measurements										
V_s [l/min]	23	8	35.4	39.5	49	68	87.2	106.8	122	104.6
Voltage [V]	0.0064	0.0017	0.0125	0.0146	0.02	0.0337	0.0503	0.0703	0.0876	0.0679

Table B.2: Measurements 3mm zero voltage correction: -0.0177 [V]

Appendix C

Employer and reflection

Company profile [1]

DEMCON BuNova is an engineering agency with a high-end expertise in the area of heat transfer, uid dynamics and structural analysis. DEMCON BuNova aims to be a partner to customers in achieving their goals in research, development and engineering programs. The goal is to develop and improve the insight and knowledge about mechanisms that determine the implementation of a customers product or process. DEMCON BuNova oers high-end virtual simulation facilities based on an academic approach. The added value of DEMCON BuNova as part of the DEMCON group is large, compared to a conventional CFD and/or FEM/FEA engineering company. The integration of DEMCON BuNova with the other DEMCON parts means that the expertise of BuNova rests on a foundation of a large amount of knowledge about measurements, design and production in a large variety of applications that make up the DEMCON group. This means that it is possible to shift very quickly from the performing of simulations to virtual prototyping, to (re-) design of products or parts and/or the doing of measurements. This makes that DEMCON BuNova is capable of acting as a full development partner of your product.

Reflection of internship

The design and building of the experimental set-up was very changeling and interesting. At the start the literature study was quite hard. As the project came along I anquired more knowledge and became more familiar with the topic. The building of the set-up was nice to do. Although delivering times or availability of need parts where sometimes long, with good communication it didn't effect the results of my internship. During the last month it was challenging to be working on the three different solutions routes at the same time. During that time the progress of the report lacked. In the last week the project where the internship was initially based on started. It was really nice to see and help with using the develop method for this commercial project. Although the report was close to finished the last week, I couldn't manage to finish the report with in the internship period. This might partly be due to the start of the commercial project and partly because I still wanted to do a final simulation (with the determined coefficients) to fully prove the method. Although this wasn't necessary, it did comply with the initially stated goal.

During the internship I have had great collaboration with my supervisor. He could steer me in the right direction and narrow down the goals. Helped me focus on the most important tasks to achieve the right results. As well he was supported the whole time and even the week after the internship when finishing my report. The team where I worked in was enthusiastic, interested and supportive to my assignment.

[1] Information provided by DEMCON source www.demcon.nl