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## Master Thesis


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# Numerical Flow Simulation in an Exhaust Air Bag Filter


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TITLE: **Numerical flow simulation in an exhaust air bag filter**

Im Prozess eines Fließbett-Wirbelschichtgranulators bei der inprotec AG in Genthin wird ein Schlauchfilter zur Reinigung der Abluft und Rückführung des Staubes als Keime in den Prozess eingesetzt.
In diesem Schlauchfilter sind Diffusoren eingebaut, um Staub und Luft zu verteilen und nicht direkt gegen die Schläuche zu schießen. Außerdem ist der Filterkörper mit einer Explosionsunterdrückungsanlage ausgestattet, deren Sensoren an mehreren Stellen im Filter platziert sind.
Mittels Strömungssimulation sind Geschwindigkeits- und Temperaturprofile im Filter zu ermitteln, um daraus Geometrieoptimierungen abzuleiten und die ideale Platzierung der Sensoren im Filter festzulegen. Im Verlauf der Arbeit sollen dafür verschiedene Geometrien der Diffusoren miteinander verglichen werden.

Der Arbeitsablauf gliedert sich wie folgt:

- die Geometrie eines Fließbett-Wirbelschichtgranulators in einer Form, die CFD-Simulationsgeeignet ist, abzubilden,
- eine Simulation der Strömung und Temperaturverteilung im Filter durchzuführen,
- verschiedene Geometrien der Diffusoren nachzusimulieren,
- Auswertung von den numerischen Ergebnissen,
- Schriftliche Dokumentation.

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Start: **7. December, 2021**
Due: **26. April, 2022**

# Declaration

I hereby declare that I prepared the work submitted without inadmissible assistance and the use of any aids other than those indicated. Facts or ideas taken from different sources, either directly or indirectly have been marked as such.

Further, I have not made any payments to third parties either directly or indirectly for any work connected with the contents of the submitted thesis.

The work has not so far been submitted either in Germany or abroad in the same or similar form as the Bachelor-/Master thesis and has also not yet been published as a whole.

Magdeburg, 26.04.2022

Ware, Shubham Shivajirao

## Abstract

Downtime due to unscheduled maintenance is one of the prominent causes of inefficiency of operations in industries. Identifying and optimizing certain critical processes can often solve the problem to manageable levels. At the Inprotec plant, the air exhaust filter has been facing problems of clogging and moisture saturation due to an ill-designed flow diverter at the inlet, eventually causing a certain portion of filter bags to take an extra filtering load than the others. This project aimed to optimize the flow and try to eliminate the problem of clogging and identify a better location for fire hazard sensors—which are currently placed at positions that might not be optimum to ensure the desired functioning. Initially, the flow is analyzed without current design changes, and then with the current inlet diffuser manifold, by analyzing the two certain changes were done to the design to achieve close to homogeneous flow through most filter bags.

In the present study, the results of multiple modifications are analyzed based on flow behavior; qualitatively and quantitatively. Some modifications show promising perspectives and will bring tangible value when implemented. CFD simulation showed that although information such as velocity distribution, flow behavior, and pressure distribution in the filter is tough to obtain by physical measurement, this data is relatively easily tractable using CFD investigation and is very beneficial for designing filters and optimizing retro-modifications.

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# List of Symbols

| **Symbol** | **Unit** | |
|---|---|---|
| $u$ | m/s | Velocity |
| $g$ | $m/s^2$ | Gravitational acceleration |
| $P$ | Pascal(Pa) | Pressure |
| S | - | Standard deviation |
| $D$ | - | Darcy's Coefficient |
| $F$ | - | Forchheimer's Coefficient |
| $\kappa$ | - | Permeability |
| $\vartheta$ | $m^2/s$ | Kinematic viscosity |
| $\rho$ | $Kg/m^3$ | Density |

# List of Abbreviations

| | |
|---|---|
| CFD | Computational fluid dynamics |
| EU | European union |
| CAD | Computer aided design |
| 3D | 3-Dimentional |
| GUI | Graphical user interface |

# 1. Introduction

## 1.1 Background

Inprotec AG specializes in powders and granulates. Where operation is done batch process, processing various products and materials such as detergents, synthetic additives, construction materials, feedstuff, additives, and also sensitive substances such as hormones, proteins, vitamins etc. The processes like fluidized bed drying, coating, spray drying, and spray granulation are undertaken. Fluidized beds are used to precisely and gently dry the moist powders and granulate them within a short amount of time. On the other hand, spray drying is the classic thermal method for continuously drying liquids in large quantities. At the spray drying plants at the Genthin site, materials such as watery solutions, suspensions, or emulsions are transformed into solid powders in multistage or single-stage procedures.

In spray drying, raw materials are sprayed into the stream of hot air and subsequently atomized and dried. Pre-heated air is administered in the drying chamber in large quantities, hence the large volume of air used in operation. Typically, 20-25m3/sec of air is used for this sort of operation. The air is drawn and subsequently disposed of from and to the surrounding.

The drying chamber takes air from three inlets of which two are heated to high temperatures ranging in 200s depending on the operation. There is also an auxiliary input of air which helps cool down the dried product from operating temperature close to room temperature and draws air at room temperature and is heated to not a large degree. Thereafter, the product-dried powder is removed from the spray chamber and collected. Inevitably, the exhaust hot air with residual dry powder is then diverted to a bag filter to recover the residual powder and clean the exhaust air to the standards of the exhaust [1], [2]

## 1.2 Spray drying

In its modern form spray drying came to popularity during World War II [3], with the need to reduce the transport weights of foods and other materials. The flexibility of feed, for example, liquid solutions, suspensions, dispersion, or emulsion, is the main advantage of this type of drying. In spray drying, all starting materials are sprayed for drying. For liquids, this is naturally not an issue. However, other materials such as waxes and meltable raw materials are transformed into an atomized state with suitable methods before spray drying. The dried product can be in the form of powders, agglomerates, or granules depending upon the properties of the feed. The procedure for spray drying is demonstrated in Figure 1.

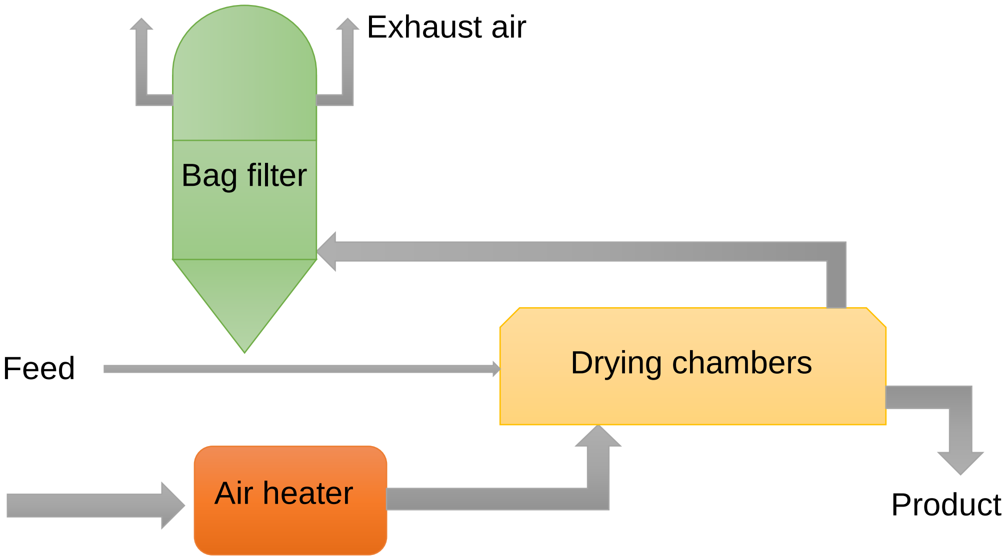



*Figure 1 Spray drying procedure*

The feed is finely atomized in a spray tower, during the spray drying process and then brought into contact with a hot air stream. It free falls through the hot air, the atomized particles will go on to dry in a split second into a fine powder. The flow of the air can be modified to achieve different results in a product; air can be flown against or with a spray jet, for example. The dry particles are separated from the air stream by a cyclone separator and further air filtration is done in filter bags.

Spray drying's most important advantages are:

- Spray drying can be designed for virtually any capacity
- Operations are continuous and most importantly adaptable to fully automatic control [4]

- the temperature in the spray drying technology is defined precisely, allowing finer parameter control
- The heat exchange time is quite short yet intensive, leading to the creation of powdered particles of size between 20-200 µm enabling us to create hollow spheres-granting us the desired good solubility of powder for further industrial products.
- Improved dissolution behavior and re-dispersibility in water
- Defined distribution of particle sizes
- Brief thermal loading of the droplets or created particles

## 1.2 The filter and its function

The drying process in fluidized beds and spray dryers inevitably produces dust-which is harmful to the environment and detrimental to human health[5]. Thus, de-dusting the air is a critical part of the process. The common de-dusting methods used for industrial-scale operations usually include cyclone de-duster, electrostatic precipitation, and a bag filter [6]. With modern standards of emissions, however, cyclone and electrostatic precipitators do not suffice the level of filtration. In contrast, bag filters and bag filters can achieve efficiency greater than 99.99% [7] It not only has excellent separation efficiency but also has a good level of fine particle collection efficiency. So, dust can be collected, recycled, or reused.

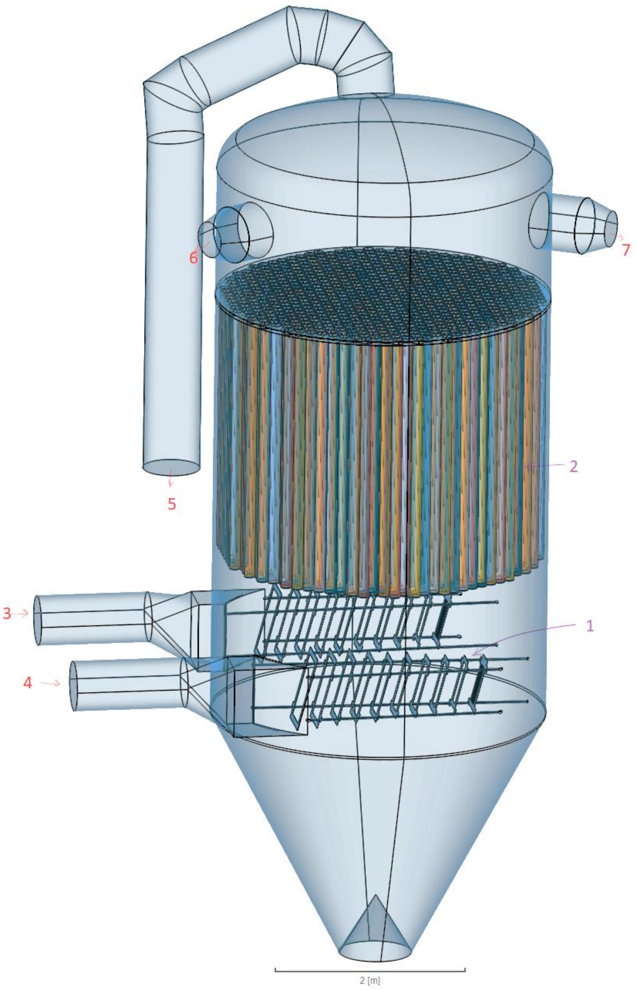



*Figure 2 Filter CAD Model*

# 1. Introduction

In the Genthin drying plant’s operation, the air is drawn from the surroundings and must be subsequently disposed off to the surrounding. The inlet conditions change depending on the time of the year. Certainly, the operation is easier to run when the air is dry and hot enough in summer; requiring less effort to remove moisture and less energy required to heat the air to obtain the desired temperature. In winter, the situation is the opposite. However, after adequate treatment and the process of drying, the parameters of inlet air could be considered controlled. The large volume of air, however, needs to be treated before it is allowed to be disposed of in the surrounding area.

The adjacent image shows a 3D CAD model of the entire filter. In-image location 1 indicates the diffuser manifold. Location 2 shows bags of the filter. 3 &4 show inlets, whereas 5,6 & 7 show outlets. The filter is 16 m in height and 6 m in diameter and contains 762 filters.

The vital functions that a filter needs to fulfil are:

- Filter large amounts of air in a relatively short time
- Recollect useful residual products that inevitably flow away with an air
- Filter air to the regulatory standards of the EU and Germany
- Function reliably for a variety of different products are operating conditions.

To ensure all these requirements, it makes the most sense to use a passive bag filter, as a bag filter provides required flexibility at the same time, robust operation by avoiding the complexity of active filters such as cyclone filters. This, however, isn’t free of the challenges that are part and parcel of most bag filters. Some of the specific problems that are frequently encountered at Inprotec AG and with bag filters, in general, are mentioned below:

- Heterogeneous filtering load on individual filters, thus efficiency of operation drastically reduces once most stressed filter clogs. Some filters remain underutilized.
- Down-time required to replace the filter bags- intern halting the operation of the entire plant.

The effects of the above-mentioned drawbacks, however, provide a good opportunity for CFD engineers to optimize the flow of the air and minimize the heterogeneity of the flow. The downtime to replace the filter bags is an integral part of the bag filter but unscheduled downtime due to heavy clogging of stressed filters, thus causing a substantial drop in efficiency of operation, could be avoided if the flow is better designed.

## 1.3 Motivation

Optimal filter performance necessitates proper gas flow distribution in the filtration area. The filter had been commenced without considering many of the fluid flow characteristics. It had some inherent flaws, at least in terms of flow behavior. Fabric filters are especially sensitive to uneven flow [8]. As premature wear of bags results in particle emissions. The focus of the design was to get the required filtering capacity. However, reliability and redundancy were not on par with desired expectations. This was quickly discovered by the frequent shutdown of operation to clean and inspect the filter. Subsequently, the engineers at the plant designed the inlet diffuser which has solved the issue to some extent, giving confidence in the diagnosis of the problem at hand. Thus, to further improve the design, the diffuser needed to be designed using computational fluid dynamics (CFD) tools-which wasn't the case in the initial deployment of the diffuser. The CFD is increasingly becoming a very valuable tool for engineers designing, testing, and comparing different solutions. In the present study, the area of attention has been the inlet diffuser. Which has been shown to make a tremendous difference in flow patterns inside the filter housing. [9]

The following picture shows the current design of the inlet diffuser which has 10 plates equidistantly placed on the supporting structure. At the end of the manifold, the last plate is a semi-oblique plate that diffuses residual velocity at the end.

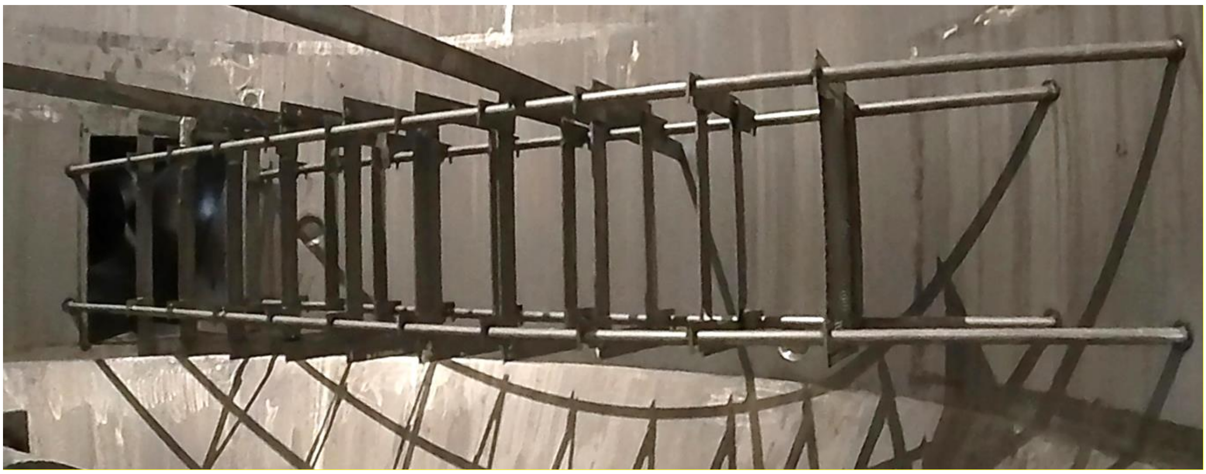


*Figure 3 Inlet manifold to diffuse the flow homogenously*

Furthermore, when dust particles accumulate to a critical extent, under certain conditions with sufficient air and high temperature (fire source) or strong vibration or friction a dust explosion can occur [10], [11]. Thus, identifying the flow pattern and positions with potential for dust accumulations is indispensably important.

## 1.4 Problem statement

The first objective is to understand the flow inside the filter housing, to get an idea about flow, which is, by large, treated as a black box until now. In addition to that, we also decided to simulate an unmodified design of the filter to compare the current diffuser to the state without any. This would then provide us with a guide way to identify the problem areas and try out different ideas to implement in the frame of possibility. Changing the inlet diffuser or inlet manifold is required. Auxiliary to all of this is, of course, the creation of CAD models at each stage.

We have been able to get limited data from the manufacturer of the filter bags about the characteristics of the material which need to be modeled in the simulation to get close to reality pressure drop behavior. The required Darcy and Forchheimer coefficients are to be obtained from the given data.

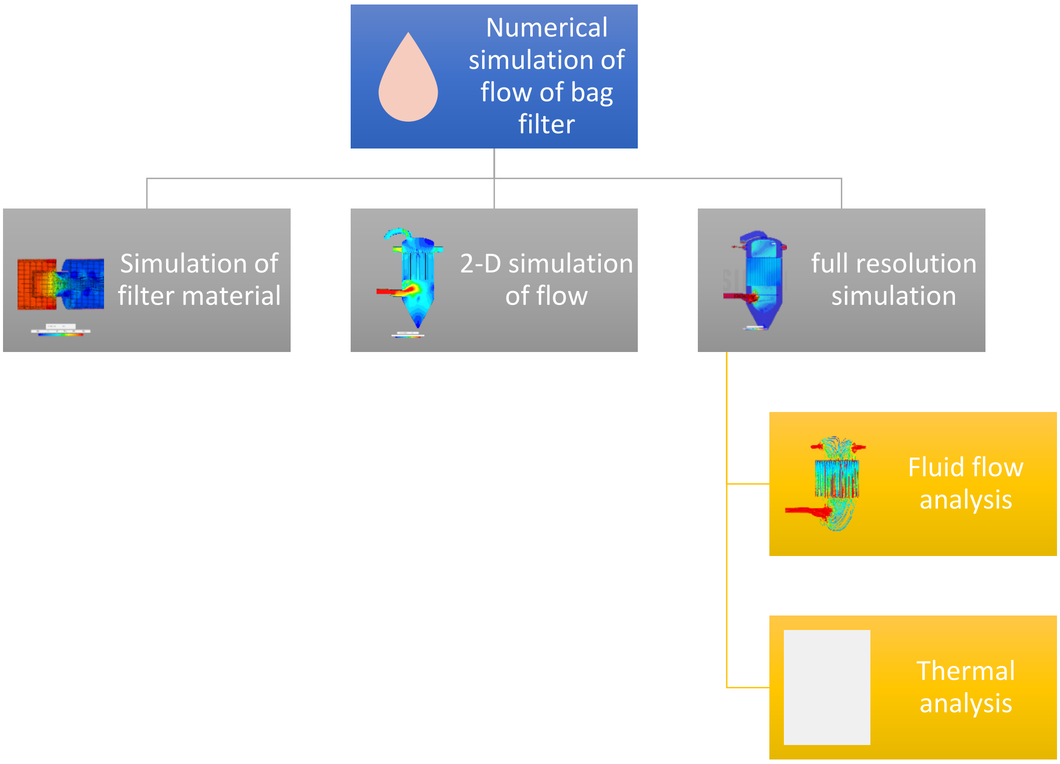
Since the restriction on the degree of modifications that could be done without hindering the entire operation for a long period needs to be investigated.

In addition to this, the understanding of the flow will also help place pressure sensors and fire safety sensors—as the current placements occasionally give false alarms. Thus, halting operations unnecessarily.

# 2. Methods and materials

## 2.1 Simulation scheme

In CFD compromises and assumptions are made to make the model close to reality yet computationally less expansive. In our case, the size of the filter and complexity of geometry provides the challenge of simplification and optimisation of the domain to reduce computation. Thus, the problem was divided into three schemes of increasing complexity. Following Figure shows the method of problem solving.




| | | | |
|---|---|---|---|
| **Aim** | To find out appropriate approximation to model porosity of filter material | To optimize meshing<br>Reduce simulation complexity<br>To get an idea of pressure and velocity range across domain | Get full resolution of flow<br>Change design configuration and observe changes in flow<br>Identify low pressure zones to prohibit moisture formation inside the filter |

2. Methods and materials

### 2.1.1 Simulation of filter material

Simple geometry was considered for this simulation. In which the relationship between flow rate and pressure drop is verified for different lengths of the filter and varying parameters. Since the role of the filter is vital in flow characterization, this simple simulation provides a quick peek in. Both steady-state and non-steady flows were simulated for this geometry. However, since flow rate vs pressure characteristics are known to be approximately linear in the later stage of the project, it becomes redundant over time. Initially, we did not have this data from manufacture, so approximation was made by some pressure loss data from the plant operation. And by varying the flow rate of the inlet, we got some relationship between flow rate and pressure drop, but it was approximate and thus led to too much error.

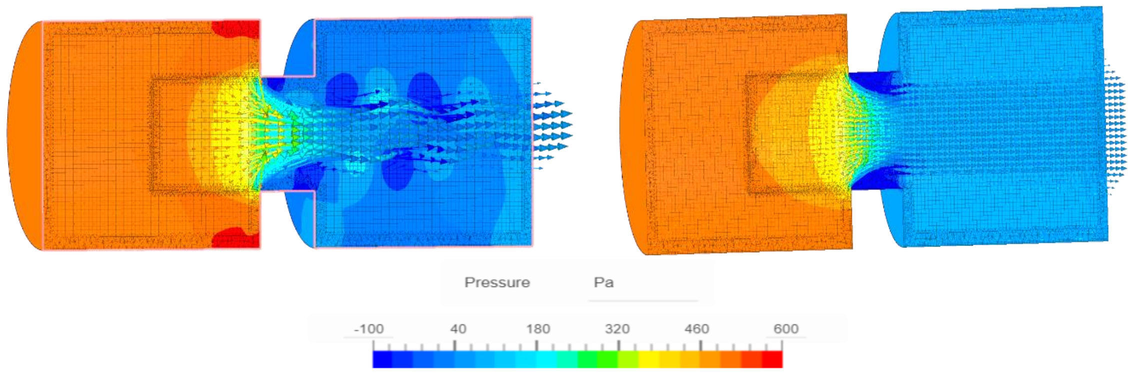



*Figure 5 Single filter bag simulation 20cm length*

*Figure 4 Single filter bag simulation only Darcy coefficient*

One of the more important roles of this simulation was to decide the resolution of mesh required in the porous cell zones to properly resolve source and sink terms using the Darcy equation. It has been suggested in various literature that a minimum of 4 cells are suggested in this area to obtain proper pressure drop characteristics.

Since the thickness of the martial is very thin 1.6 mm with respect to domain size, this leads to a very fine mesh close to the filter region. Since the growth factor is unable to make any substantial difference in reduction of total fineness of the entire mesh, 10mm thickness was modelled. Thus, this part of simulation is important to validate the validity of assumptions and to verify whether it did make much difference in the outcome of pressure drop, and subsequently flow behavior.

### 2.1.2 2-D simulation

Since the geometry is not symmetrical, using other methods such as symmetry or wedge would not work. Thus, the slice size of the original geometry with simplified inlet and outlets was assumed. The adjacent diagram shows 2-D geometry is shown. In this geometry, the following substantial changes are made.

- Two inlets are integrated into one
- Outlets are moved in a single plane
- Filtering is only considered in a single direction (no isotropic)

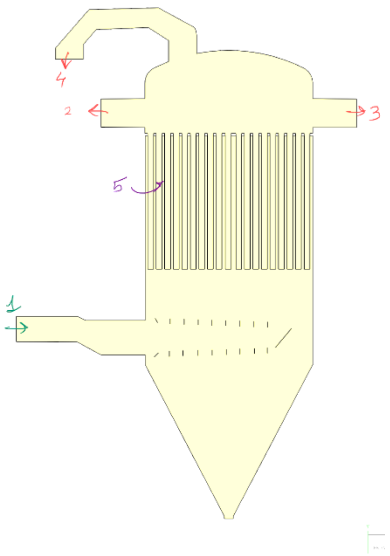



*Figure 6 2-D slice of filter housing*

In Figure 6 position 1 shows the inlet position 2,3 & 4 show outlets and 5 shows filters arranged in series.

Despite compromises, this stage of simulation provides general direction of flow development and indicates a path forward without costing many computational resources. The fineness of the mesh could also be improved in this simulation to test the effect of fineness on the results.

Finally, before making geometrical changes to improve the flow and low-pressure zones planned changes in 3-D geometry could be tested with 2-D geometry. As can also be seen in Figure 6, the first two diffusers are inclined forward slightly and the last diffuser sieve is inclined backwards. This saves efforts to do modifications directly in 3-D geometry and the freedom to do more trial and error.

### 2.1.3 Full-resolution simulation

With confidence gained from previous methods, finally, simulation of full geometry is done. This was done in multiple stages.

1. Simulation of the present filter configuration.
2. Simulation of original configuration.
3. Simulation of different modifications based on results of previous stages.

As before mentioned, the present configuration has been modified upon initial commencement arrangement. By comparing the first two simulations, the path to further modification becomes clear. The criteria of comparison are

1. How well flow is distributed across all filters.
2. Reduction of flow eddies disturbing settled dust at the bottom.

In addition, thermal analysis was also done, since very high flow rates of heat transfer can be assumed to be negligible, so only temperature changes due to porous media and pressure drop are of importance to us. Low pressure zones create a perfect place for condensation and if these places are near metal bodies, they start depositing dust particles and pile up eventually. Thermal analysis is thus of quite a bit of importance.

## 2.2 Simulation Model

Present simulation is based on open source CFD solver OPENFOAM and Commercial Simscale. Modelling of fluid flow was done with commercial software Creo Parametric. Following four steps were performed

Step 1: 3-D/2-D CAD model generation via Cero

Step 2: extraction of internal flow volume via Simscale geometry edit

Step 3: Mesh generation via Simscale unstructured/ structured meshing.

Step 4: Simulation run either with Simscale/Openfoam8

Step 5: Post processing with Simscale/Paraview & MS Excel

### 2.2.1 Simscale

Most simulations in this project are done partially or completely with OpenFoam based, Cloud-Native CFD Software called Simscale. Some advantages of Simscale are as follows: since it is OpenFoam based, it provides great flexibility and the ability to run simulation both online and on your own machine (with some changes required relevant to the version of OpenFoam used). It also gives the ability to run multiple simulations simultaneously, resulting in a tremendous saving of time. In addition to this, the ability to share results and progress across the team is also easier as data is saved in the cloud and can be easily accessed even with mobile devices on the internet. They have also kindly provided me with an academic license with which I could use a higher number of cores, up to 96 cores, considerably higher than my personal 32 core machines.

Simscale provides a good GUI for selecting volumes of filters, which is quite difficult to manually do each time in OpenFoam since there are over 700 individual filter bag volumes. Which also needs to be their separate cell zones in Polymesh. GUI of Simscale is quite powerful to handle multiple volumes and mesh regions. Alternatively, for offline simulations, Simflow can also be used for this kind of workload, but it does not provide an academic license.

## 2.2 Numerical Methods

### 2.2.1 numerical scheme

The air flow around a bag filter in a housing is assumed to be incompressible, turbulent, isothermal and steady. Undoubtedly, complex flows, such as the present case of large filters, suggest the need for unsteady calculations. [8] However, comparing some results of steady state and unsteady results indicates that steady state calculations could provide a decidedly accurate solution. The governing equations were solved with Reynolds-averaged Navier-Stokes (RANS).

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

Where $u_i$ is the mean velocity and fluid and $x_i$ is the *a* th-direction. The momentum equation is written as follows.

$$\frac{\partial u_i u_j}{\partial x_i} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \vartheta\frac{\partial}{\partial x_i}\left(\frac{\partial ui}{\partial u_j} + \frac{\partial u_j}{\partial x_i}\right) + g_i \tag{2}$$

Where $u_i$ is the mean velocity of the fluid, and $\rho$ is the density of the fluid. And $p$ is the pressure, and $\vartheta$ is the kinematic viscosity of the fluid. $g_i$ is the gravitational acceleration.

### 2.2.2. Porous Media Model

In many engineering applications, different objects can be inserted into the flow, such as honeycombs, perforated plates, and filters. The main effect on the flow of these objects is a pressure drop and, in most cases, an additional velocity direction correction. For example, through perforated plates with a large thickness or honeycombs, the fluid can only pass in one direction. However, for filters, a flow direction correction might happen or not. Nevertheless, the central aspect is the pressure drop in the fluid flow. As is also the case in our project.

2. Methods and materials

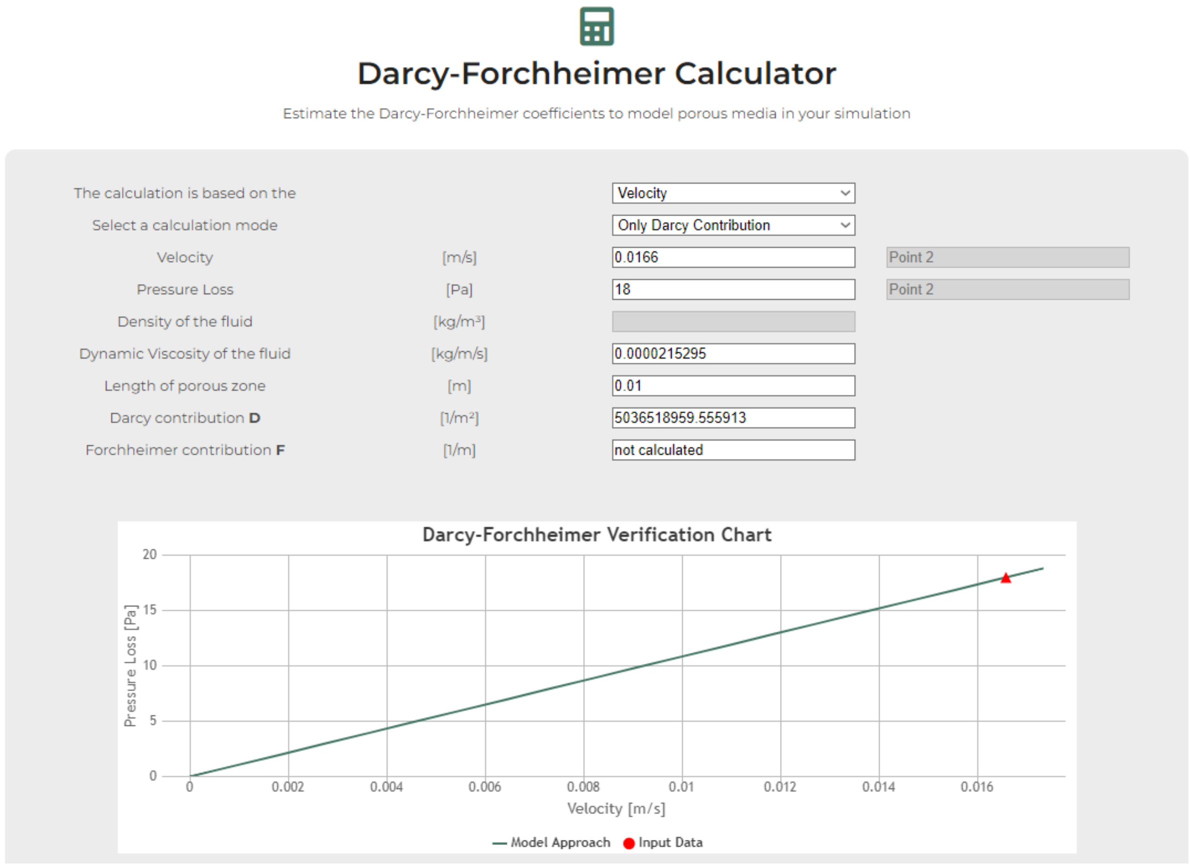



*Figure 7 Calculation of Darcy Coeff for the filter martial based on lab data for the filter media* [12]

If we consider resolving each of these narrow channels, we will end up in a large mesh. Additionally, the time-step will reduce due to the small cells and the increase in velocity (Courant number definition). Hence, in computational fluid dynamics, we are modelling these zones with so-called "porosity models". One of these models is the famous "Darcy-Forchheimer" or "Power Law" model. These models are commonly applied to a defined cell zone in which the momentum equation gets a new sink/source term $\boldsymbol{s_m}$[13], [14]

$$\frac{\partial \rho \mathbf{U}}{\partial t} + \nabla(\rho \mathbf{U}\mathbf{U}) = \nabla \boldsymbol{\sigma} + S_m \tag{3}$$

$$\Delta p = \left[\mu D + \frac{1}{2}\rho F u\right] u \Leftrightarrow \nabla p = \frac{\Delta p}{\Delta x} = rU + fU^2 \tag{4}$$

From the above expression following coefficients are derived.

$$D = \frac{r}{u} \quad \& \ F = \frac{2f}{\rho} \tag{5}$$

The Darcy-Forchheimer model is a tensor model of rank 1. Hence, one can apply flow-directed pressure drops. The calculator created by Tobias Hollmann can be used to estimate the model parameters for the Darcy-Forchheimer model. Based on the equation — mentioned below — three different modes can be used.

1. Linear velocity-pressure drop relation (F = 0 » only Darcy contribution)
2. Parabolic velocity-pressure drop relation (D = 0 » only Forchheimer contribution)
3. A mixed formulation based on (1) and (2)

The choice of the calculation mode depends on the pressure-velocity relation of the porous media. In our case, the filter material shows linear characterizes of pressure drop-pertaining to information acquired from the manufacturer. Thus, in our case, only the Darcy coefficient was considered.

```
DarcyForchheimerCoeffs {
    d d [0 -2 0 0 0 0 0] (5036518959.555913 5036518959.555913 5036518959.555913);
    f f [0 -1 0 0 0 0 0] (0.0 0.0 0.0);
    coordinateSystem {
        type cartesian;
        origin (0 0 0);
```

*Figure 8 Darcy coefficient setup in FvOptions in the system directory.*

Porous media is considered isotropic in our case as all three directions contribute to flow. Although upward flow doesn’t contribute much computationally, it’s not extensive to eliminate it. I have also done a couple of simulations considering only *x* and *y* coordinate. In such a case, the third coefficient is set to a high value as the Darcy coefficient is the reciprocal of the permeability κ.

$$D = \frac{1}{k}$$

for low permeability in *z* direction *D* must be set high.

```
DarcyForchheimerCoeffs {
    d d [0 -2 0 0 0 0 0] (5036518959.555913 500000000000.0 5036518959.555913);
    f f [0 -1 0 0 0 0 0] (0.0 0.0 0.0);
```

*Figure 9 Darcy coefficient setup for bidirectional flow in FvOptions in the system directory.*

### 2.2.1 Model Approximations

pressure loss due to filtration. Hence, particle movement calculation and concentration of dust are not included in the present analysis. Part of the reasoning is also that the size of dust particles is very small. Thus, dust particles follow an approximate path of the gas flow, and the effect of gravity only affects once dust deposited on a filter reaches critical mass.

Dynamic deposition of the dust is neglected, however, to simulate additional pressure drop. Some simulations are done with added filtering resistance by altering the value of Darcy’s coefficient.

The geometries which do not substantially affect flow are neglected. For example, sensors, internal supporting structure of filter bags, welds on inlet and outlet pipes etc.

Air parameters are assumed at 80˚c, which is the mean operating temperature of the filter housing. This value changes by a couple of degrees depending upon the operational temperature of the spray dryer. The assumed fluid parameters are thus as follows.


*Figure 10 Fluid parameters assumptions*

The thickness of the porous media in the modeling is assumed to be 10mm whereas the filter material is of thickness of 1.6mm. This was done to reduce the fineness of mesh in the filtering region, which often resulted in 100M+ cells. However, to compensate for that, Darcy’s coefficient was calculated accordingly.

## 2.3 Statistical analysis of results

To be able to differentiate and judge the CFD solutions from one another, it is vital to derive a unidimensional index that will provide a quick account of how well the flow is homogeneous. Since CFD results are large and qualitative analysis, although vital, does not provide quantitative difference. One very important tool that we must measure how much homogeneity is present is standard deviation, and in addition to that, the slandered deviations from each model can be then converted into an index to get a single number in the range of 0-1. Whereas 0 is very heterogeneous flow and 1 is maximum possible homogeneity.

$$Homoeneity\ index\ = \frac{S_O^2 - S^2}{S_O^2 - S_R^2}$$ Equation 6

Were,

$S_o^2$ is variance of the heterogeneous flow

S is variance of the real sample flow

$S_R^2$ is variance of perfectly homogeneous flow

Above-mentioned index is derived from well known ‘mixing index’ [15]. To obtain values so, case -1 mentioned in section 3.3.1 is used. To get theoretically maximum possible homogeneity, SR is obtained by maximizing the inlet area to the filter as much possible.

Since it is of importance to us to have a homogeneous velocity distribution area close to filter bags, the slice data is derived from this area in Paraview. However, this data cannot be directly used as the mesh used in the present study is unstructured. This data must be transferred to the structured mesh. To achieve this, structured mesh is created using Ansys with an edge length of 50mm and the slice data is transferred on to the mesh as shown in Figure 11, afterwards using the ‘Resample with dataset’ filter in Paraview. Then this data is exported in CVC format and variance is calculated using ‘MS Excel’ software.

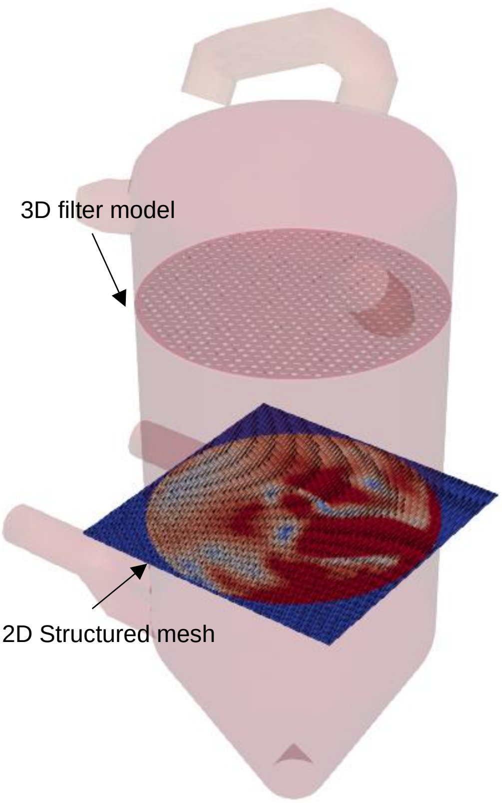



*Figure 11 Resample slice data on 2D structured mesh*

# 3. Results and Discussion

Multiple retrofit modeling cases (sections) are presented each case includes following:

- Motivation and Problem description
- CFD model and Modelling data
- Results presentation & Discussion of findings

The results are presented in order of increasing complexity of the model, from filter material simulation to 2-D model to 3-D model. However, the simulations were performed at different orders - as problems presented themselves during the process of simulation.

In addition, the colour map used in the result presentation is consistent in all result presentations and is shown in the figure below. If some other colour map is used, it is mentioned in the respective figures.

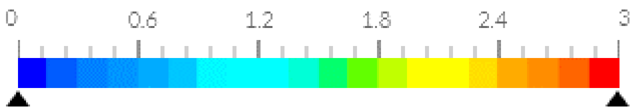



*Figure 12 Velocity (m/sec) colour map used in results presentation.*

## 3.1 Simulation of single bag with different lengths

*Problem description:*

Length of filter considerably affects filtration velocity and pressure drop (filtration resistance), [16] as height increases filtration velocity reduces, hence longer bags are suitable. Furthermore, validating models to lab values of filtration resistance is important. Since lab values are for the material, not for the value of the entire bag length. It is important to validate and compare the results of single bag to multiple bags configuration.

*Model and Modelling data:*

The filter model is a single filter with varying lengths, with inlet and outlet on either side. Around 500k-1M individual cells were created. With mesh quality of 0.25 unstructured mesh was used for the large parts. Following figures show the mesh and CAD model of the geometry used. Same numerical model of K-omega SST for turbulence and

SIMPLE algorithm for solving are used. For porous media only Darcy coefficient (5.037e+9) is used. Porosity is treated isotropic in all Cartesian coordinates. 500-time

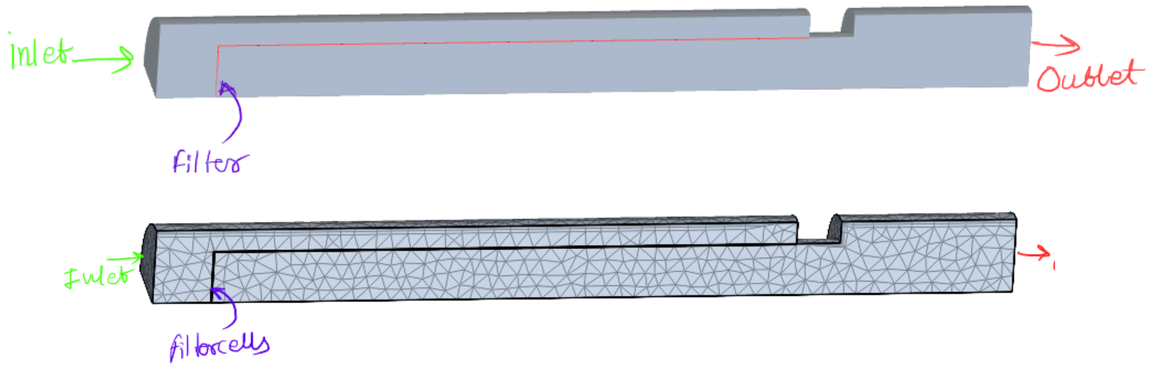



*Figure 13 CAD model and mesh of single filter model*

steps were simulated, resulting in very good convergence.

### *Result presentation*

Length of filter is one of the vital parameters to calculate the filtering resistance. With these results we can clearly see filtering resistance drops drastically for the first few meters up-till 3m of length, and then slowly decreases with an increase in length of bag. Furthermore, in the present simulation the channel of flow is restricted in *y* direction. This was done to simulate the condition in the filter, where the area available

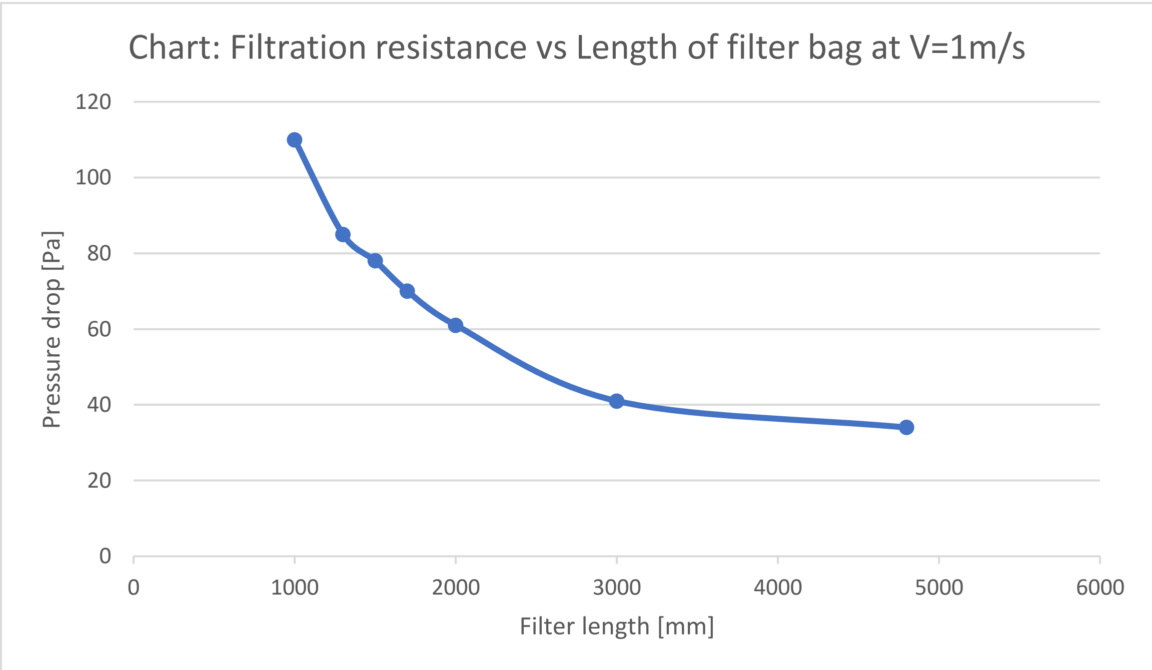



*Figure 14 Filtration resistance vs length of filter bag at velocity of 1m/s*

for the flow is restricted due to neighboring filters. And, to avoid large domains resulting in larger computational time.

In literature length of more than 10m are studies and shown to improve filtering capacity. However similar results could be achieved with multiple parallel filters, as is the case in the present project; where 786 individual works in parallel.

Furthermore, it is interesting to see the pressure drop with respect to velocity. It is more to validate the model than to acquire results, as porous media is modeled to behave linearly with respect to pressure. So, this result is to be expected, does validate the

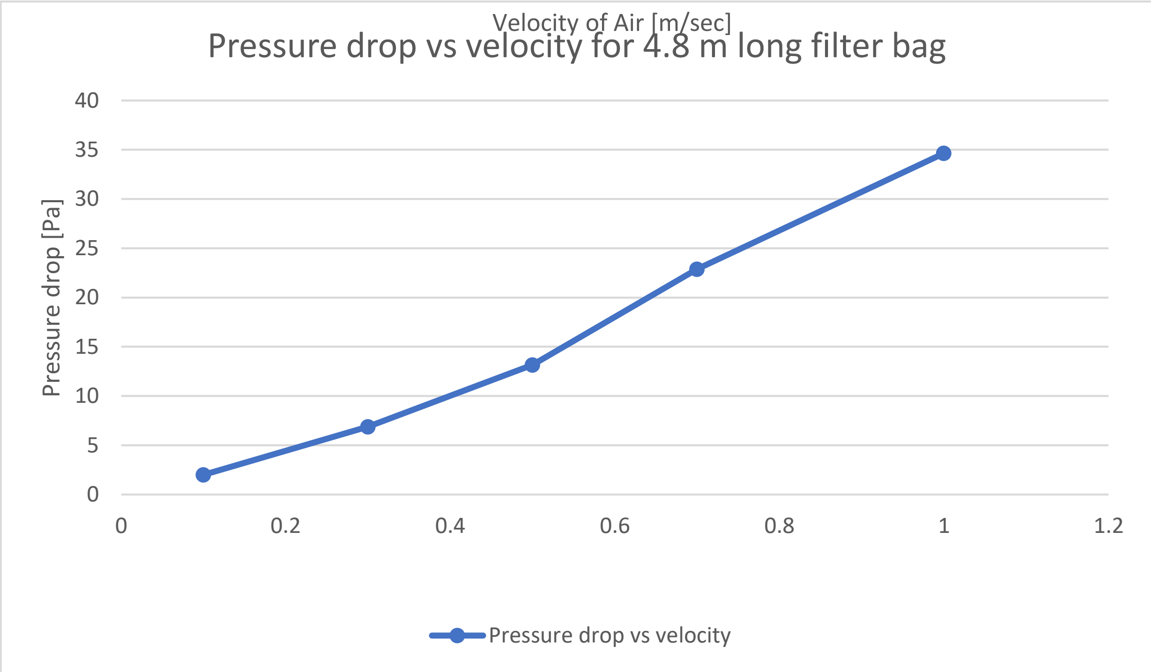



*Figure 15 Pressure drop vs velocity for single filter bag length of 4.8m*

numerical scheme and gives confidence in the results. Fineness of mesh requirements are also checked with these simulations. Simulations with both coarse mesh and fine mesh are done to validate the pressure drop characteristics of porous media cells. It was found that porous media is resolved with relatively coarse mesh, however for better resolution of flow field the fineness is vital especially close to porous media [17], [18]. Following figures show 1m length filter bag simulated with 30k cells and 670k cells.

## 3. Results and Discussion

### *Discussion of findings*

To summarize following take away findings are obtained in this simulation.

- Coarser mesh is a viable option to get similar pressure drop in expanse of less resolution of fluid flow in the porous media region.
- Longer filter bag length is desirable, however the law of diminishing return plays

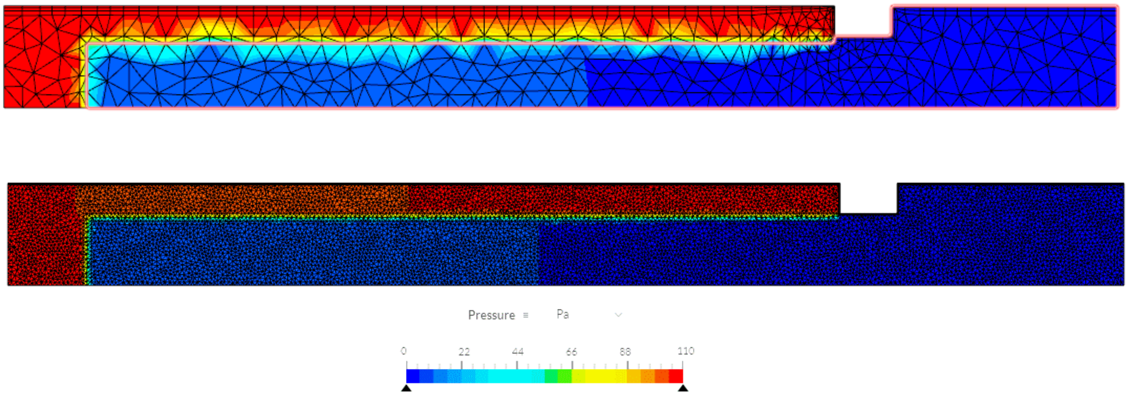



*Figure 16 Filtering resistance for coarse mesh vs fine mesh*

an important role for any additional length increase after 3m.

- For lesser pressure drop across whole domain of filter lesser velocity is preferred[19], hence parallel configuration of multiple filters is desirable. This leads to less amount of fluid flow through each filter reducing overall pressure drop due to filtration.

## 3.2 Simulation of 2-D slice of filter housing

*Problem description:*

Initial investigation for the flow modification due to manifold of inlet diffuser did could be explored using a 2-D modified slice of the filter housing, in which 2 inlets are combined into one and outlets moved to a plane of interest. With slight modification of inlet diffuser, the flow needs to be modified to get general direction to move forward with full domain simulation. Also, a considerably finer mesh was used in this simulation compared to the 3-D model, again the purpose being the validation of the results of the 2-D model with 3-D modeled, to verify the integrity of results in the coarser 3-D model.

*Model and Modelling data:*

Model has 18M cells and 3.7 nodes. K-omega SST turbulent model is used. And SIMPLE algorithm is used for simulation solving. Different angles for the diffuser plates mainly the first plate (Figure 17 position marked as 2) and the last one is considered. Last plate marked as 3 in Figure17 is modeled as porous zone, with 50% porosity. Whereas position 1 is inlet with 18 m/sec. Apart from Darcy coefficient modeling, Simscale's own porosity model of perforated plate with 10-75% porosity was examined to explore the possibility of simpler modeling methods, in absence of accurate pressure characteristics data for the filter material.

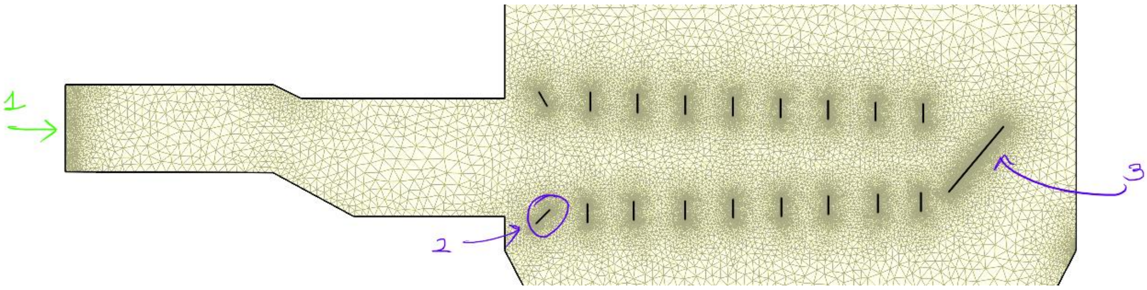



*Figure 17 Mesh of 2-D domain at inlet*

## 3. Results and Discussion

*Result presentation & Discussion of findings:*

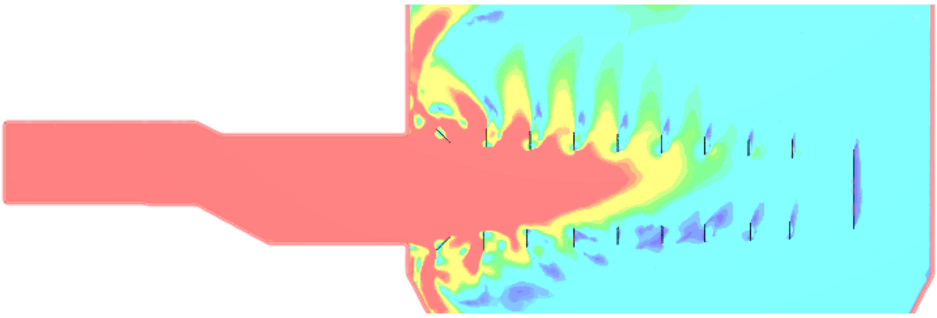


*Figure 18 Velocity results for 2-D slice with diffusers*

comparing the results of 2-D to 3-D simulation it becomes apparent that the general direction for shape of inlet diffuser could be estimated using the 2-D simulation. Although pressure drop characteristics vary from 2-D to 3-D due to differences in number of filters, the flow of interests close to diffuser gives satisfactory results with some modification to Darcy's coefficient to reduce the pressure drop. In addition to the model shown above the model with much less cell numbers was also simulated with 1M cells and 220k nodes. As shown in Figure 19 the simulation demonstrates the necessity of the diffuser, as we can clearly see lack of flow diversion to the filters close to inlet. This knowledge helps to evaluate need of flow diversion especially close to the inlet.

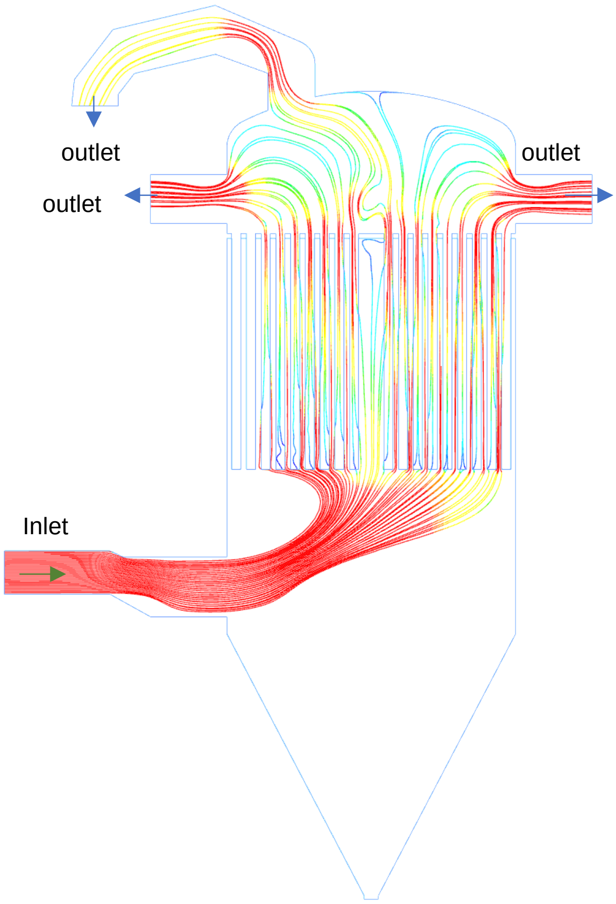



*Figure 19 2-D Simulation with no inlet diffuser*

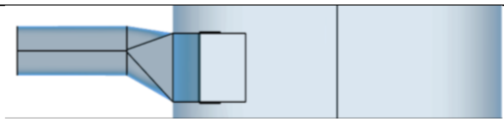
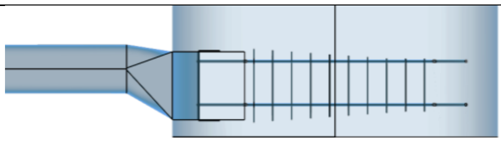
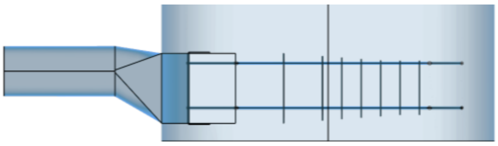
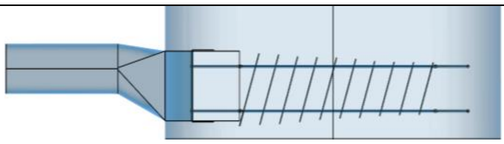
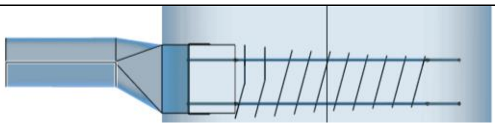
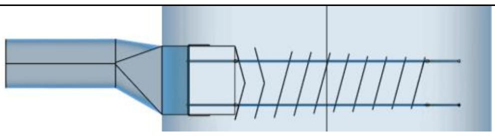
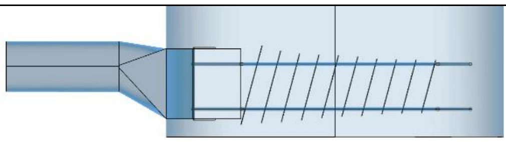
## 3.3 Full scale 3-D domain simulation

Following table shows the case that is discussed in this section. The cases are based on modifications done to the inlet diffuser manifold. Short sketch of modifications is also shown in the table.

Following qualitative parameters are used to judge the difference between the different configurations.

- How homogeneous the flow is?
- The relative amount of flow that is diverted in undesired downwards direction
- Average velocity in filter region. (Lower is better)

*Table 1 Case presentation of modifications of inlet manifold*

| Case | Modification | Results |
|---|---|---|
| Case 1- Without inlet diffuser |  | Appendix A- Case 1 |
| Case 2- With unmodified inlet diffuser |  | Appendix B Case-2 |
| Case 3- Elimination of three diffuser plates |  | Appendix C Case-3 |
| Case 4- Inclining diffuser plates by 15° |  | Appendix D Case-4 |
| Case 5- Inclining only lower half the diffuser plates |  | Appendix E Case-5 |
| Case 6- Inclining lower half and decline upper half of the plates |  | Appendix F Case-6 |
| Case 7- Modification to case 5 by increasing size of first three plates. |  | Appendix G Case-7 |

### 3.3.1 Filter without inlet diffuser – Case 1

*Problem description:*

To understand the role of the diffuser in modifying the flow pattern, it is vital to compare the flow with and without the manifold. Clearly, diffusers in operation currently provide significant improvements. However, it's imperative to quantify these improvements. Furthermore, it will help us to identify any problems besides inlet diffuser and potential improvements.

*Model and Modelling data:*

For this simulation, 27.7M cells and 5.3M nodes were meshed. With a meshing quality of 0.28. With a global growth rate of 1.22. Inside the porous media cell zones, on average 4 cells were created. The mesh was largely unstructured with a few hexagonal cells at the center of the filter. As for boundary condition, initially one inlet was assigned as a pressure outlet and subsequently all the outlets were assigned as pressure outlets. All the surfaces except for porous media are treated as no-slip wall.

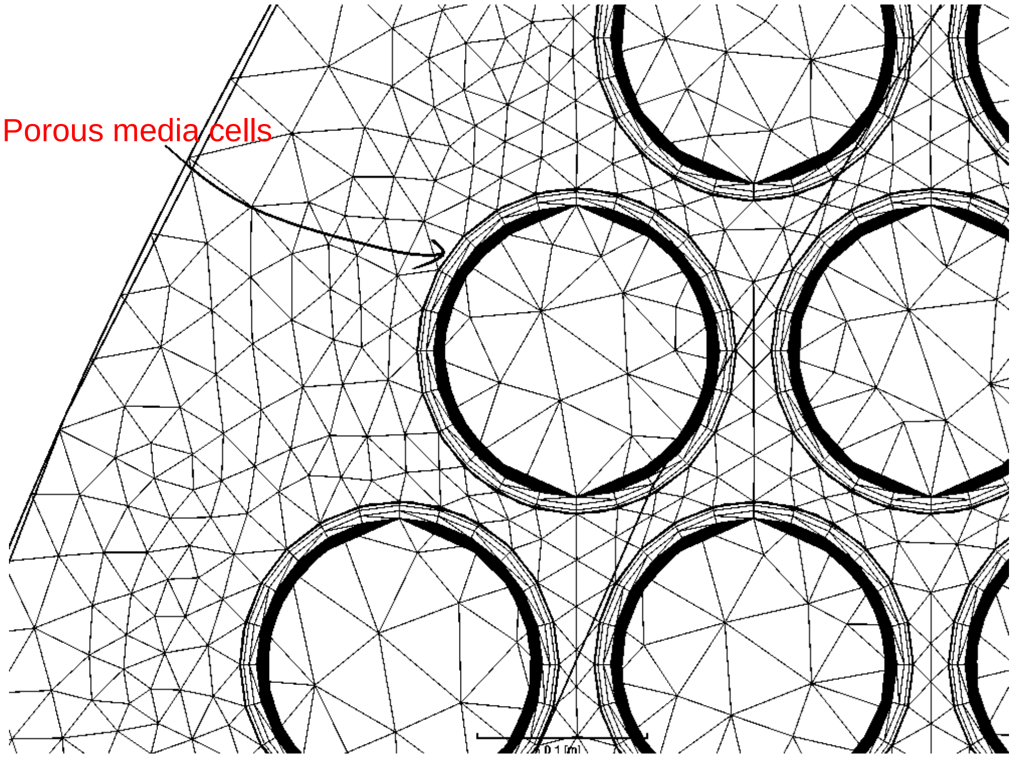



*Figure 20 Quality of mesh in porous media*

*Result presentation & Discussion of findings:*

The following figure shows particle trace for the right-side inlet and three outlets. From the results, it is evident that the additional outlet at the top helps distribute flow evenly, although due to its position at the top, it contributes more for the capacity than the other two. The capacity of the motor at the top is also the highest, which, in retrospect, is a better decision. This result also shows developed and streamlined flow development across the domain. It comes with the drawbacks of overload of a few filter bags and filter bags hanging in the same position for longer time, hence less frequency of dust dropping off to the bottom, leading to more pressure loss over time. In Figure 22, it can be seen that filters are free to move laterally. Thus, with disturbance in the flow patterns, the filters can easily shed the dust off. This ability, however, is hindered lightly with streamlined flow. Henceforth, introduction of diffusers not only cares for homogeneous gas distribution but also induces disturbance in developed flow.

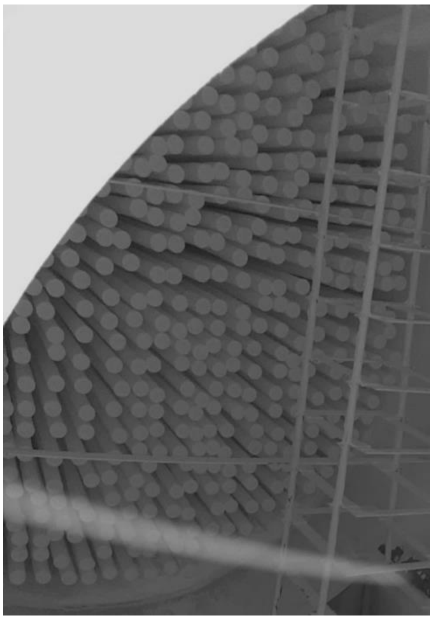


*Figure 22 Filter bags locomotion during operation*

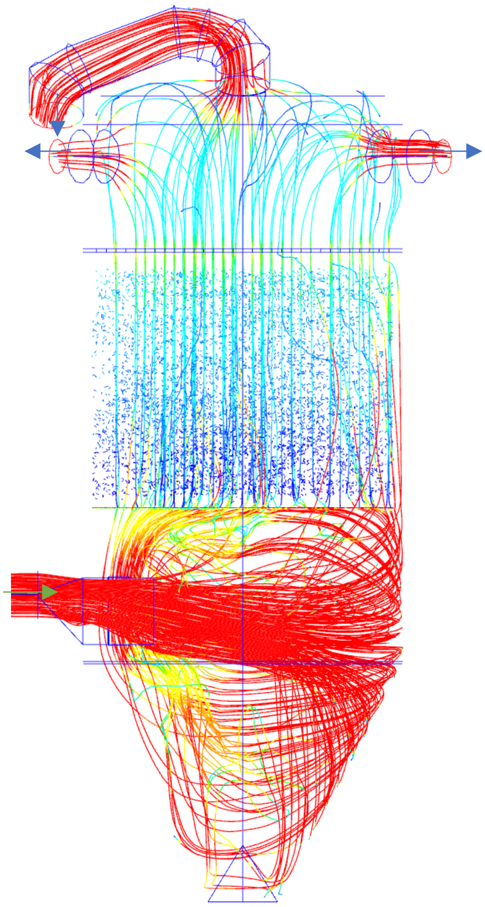


*Figure 21 Side view- Particle trace for inlets, for model without inlet diffuser*

Furthermore, from the bottom view shown in Appendix A it is visible that there are multiple zone formations where there is a clear lack of fluid flow. Moreover, as discussed before, high velocities are unfavorable in the filtering operation as it reduces filtering efficiency. Thus, it is evident from the results that a filter without an inlet diffuser is not the ideal design.

### 3.3.2 Filter with present unmodified inlet diffuser – Case 2

*Problem description:*

To further our understanding of the effects of the inlet diffuser on the overall flow, the ensuing step is to simulate flow with the present state of the filter housing and inlet manifold. Interesting to us is the magnitude and homogeneous nature of the velocity vector in the filtering region. As understood from previous simulations, turbulence is quite absent in the inner region.

*Model and Modelling data:*

Meshing is done with 32.5M cells and 6.6M nodes. A slight increase (compared to Case-1) in cell numbers due to fine meshing in the region of the inlet manifold, however, results in fewer cells in the filtering region. On average, there are 2 cells across porous media-down from 4 in the previous simulation. Nevertheless, as shown before, this does not affect pressure drop characteristics, just flow formation in the porous region. Since the area of interest here was inlet, manifold priority of fine meshing was given to this area. This is also the case for simulation later on.

Furthermore, more types of boundary conditions were tested for this model, the reason being, this configuration is in operation at the moment. In addition, changes were also tested for higher Darcy's coefficient (simulating extra pressure drop due to dust build-up).

*Result presentation & Discussion of findings:*

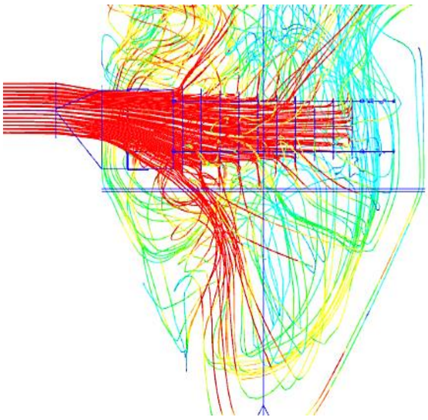


*Figure 23 Simulation with present inlet manifold*

One of the most visible changes in the flow that ensued from the introduction of the inlet manifold is the reduction of higher velocity magnitude through the length of the filter housing at the inlet. And fluid is better distributed compared to Case-1 from the pictures in Appendix B the bottom view demonstrates a more homogeneous filtering load on individual filters. Furthermore, unlike configuration without a diffuser, flow is not smooth. Also, there is a jet of flow directly going downwards. This is clearly unwanted, as this is going to disturb settling dust particles as well as reduce the efficiency of the filtering operation. Also, there is more mixing of the flows from both inlets.

### 3.3.3 Modified inlet diffuser- elimination of three diffuser plates – Case 3

*Problem description:*

From the results obtained from simulation without diffuser, and equidistant diffuser, it seems beneficial that plate configuration could be made non-equidistant, by eliminating a few diffusers. Investigate elimination of few diffuser plates close to the inlet-this is decided by observing the flow near the diffuser. However, it is not apparent how much contribution is made by the individual diffuser plate. By eliminating a few plates, it is possible to evaluate their role and focus the modification on a few plates rather than the entire manifold.

*Model and Modelling data:*

Meshing is done with 32.6M cells, with 5.5M nodes. Equivalent turbulence model and inlet boundary conditions have been used in cases before. In addition, the different outlet boundary conditions are also simulated to evaluate the difference it makes in flow patterns.

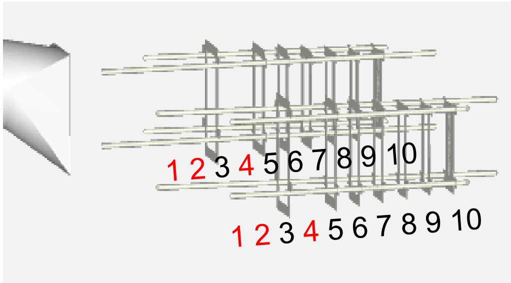



*Figure 24 Eliminated diffuser plates positions*

*Result presentation & Discussion of findings:*

In addition to the very high downward flow marked by the black circle in Figure 22. The flow is very turbulent. The images in Appendix C show that in detail. Since the flow of motors could also be adjusted if it helps to improve flow, different outlet conditions are simulated in which flow rates of outlets are adjusted by a range of ±1-2 m3/sec does not seem to make any noticeable difference in the flow development.

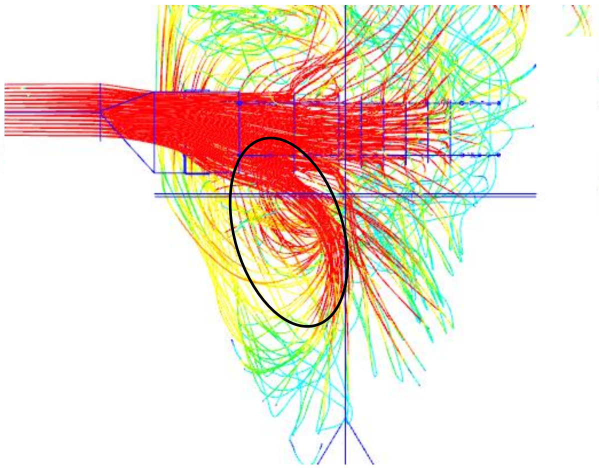


*Figure 25 Front view- inlet diffuser with elimination of three diffuser plates*

These results demonstrate the importance of the first few diffusers close to the inlet. Hence, after this simulation, the focus is paid to the plate number 1-4(as the positions marked in Figure 24)

### 3.3.4 Modified inlet diffuser- Inclined diffuser plates 15 degrees – Case 4

*Problem description:*

With placement of the diffuser, the problem is identified to be undesired downward stream of flow. This could also be eliminated by increasing inclination angle-Since the desired flow direction is upwards, to avoid undesired downward diversion of the flow, it is decided to investigate inclined diffusing plates. This is inspired by a few results from 2-D simulation, where 5,15 & 18 degrees of inclination were simulated. Giving confidence in the method. In addition, the position of the entire manifold is shifted downwards by 100 mm. By trial and error, this new placement was found to optimum greater angle of inclination, which leads to heterogeneous flow and even lower placement of the manifold seems to not substantially help. With limitation on the extent to which modification can be made in this particular regard, this seems to be the optimum modification in terms of inclination and position displacement.

*Model and Modelling data:*

Mesh size of 30M cells is used, other modeling parameters are the same as the Case-3. Since, since this model has shown promising results, more than 100 more-time steps are simulated. Also, simulation with additional pressure drop due to dust build-up is simulated by increasing Darcy's coefficient by 1-2E9.

*Result presentation & Discussion of findings:*

Although not the perfect homogeneity, absence of downward jet of flow and desired level of flow diversion is observed. Also, as discussed before, the flow going down, if close to the walls is highly desired as it de-dusts the walls effectively, hence reducing the number of maintained hours and frequency.

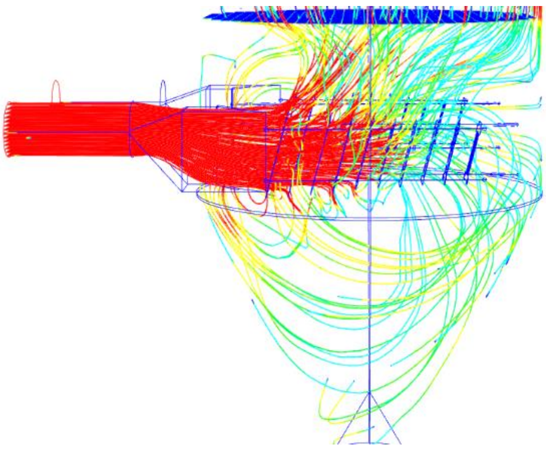


*Figure 26 Front view- inlet manifold with inclined diffuser plates*

With promising results from this case, modifications were done to form the Case-7 mentioned later in this chapter.

### 3.3.5 Modified inlet diffuser- Lower half of the diffuser inclined – Case 5

*Problem description:*

If we compare results from straight diffusers with inclined diffusers, it is apparent that the function of the lower half of the diffuser plate is to change the direction of flow upwards as much aerodynamic as possible. This can be best achieved with the 3-D shape of the diffusers, however with limitations on ability to manufacture and deploy them it is decided to make aerodynamic shape with limited capacity by inclining plates in the lower half and maintaining shape in the upper half- as to direct flow towards filter bags in rectilinear fashion possible.

*Model and Modelling data:*

Two models are tested in this simulation. Both have a similar structure of the inlet manifold, however in the second on the whole manifold was shifted downwards by 100 mm. The results shown are of a second case. 30M cells are meshed with 6.2M nodes. Outlet boundary conditions are all set to pressure the outlet at a fixed value of 1000 Pa (gauge value take for convenience)

*Result presentation & Discussion of findings:*

As compared to Case-4, there are many more flow disturbances, however with a slight increase in homogeneity of the flow. The area marked in the black circle in Figure 25 is the area where we would like to divert part of flow. Due to the poor flow pattern in the shown region, this modification seems not viable. Even with a slight increase in size of the first few plates, there seems to not be a difference in flow diversion.

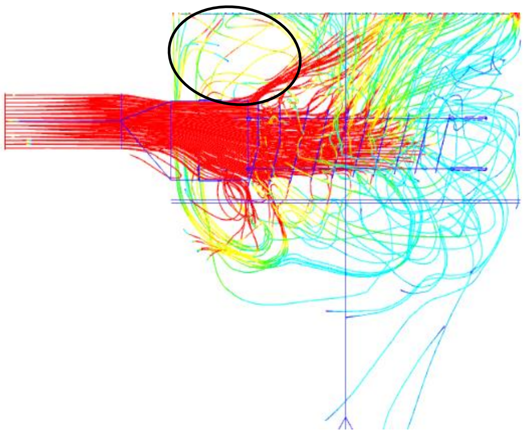


*Figure 27 Front view- inlet diffuser with lower half inclined upper half straight*

### 3.3.6 Modified inlet diffuser- Lower half of the diffuser inclined upper half declined – Case 6

*Problem description:*

With before mentioned modification, the problem of heterogeneity of the flow persists. Especially the region just above the filter. This is partly resolved with stronger motors on the side of the inlets. However, it seems that the diversion of flow could help a few filters that are underutilized. To resolve this issue, flow diversion plates are to be configured in a way that the lower half reduces downward flow stream-hence inclining them. Whereas the upper half of the plates are to be declined with respect to flow direction to divert flow slightly in the opposite direction towards underutilized filters.

*Model and Modelling data:*

Similar boundary conditions and mesh sizing are used for this case as Case-5 Finer mesh was used close to the inlet for one of the inlets with a refinement box of 50 cm size. As more resolution is desired to understand flow better in this region.

*Result presentation & Discussion of findings:*

The results of this case show huge variation to what was expected from 2-D simulation results. As even with declining diffuser plates, the flow is not diverted efficiently upwards. Additionally, there is a higher-pressure zone created close to the plates, marked in Figure 28 by a black circle, this is highly undesired. Although the flow is more homogeneous, qualitatively the flow could be better.

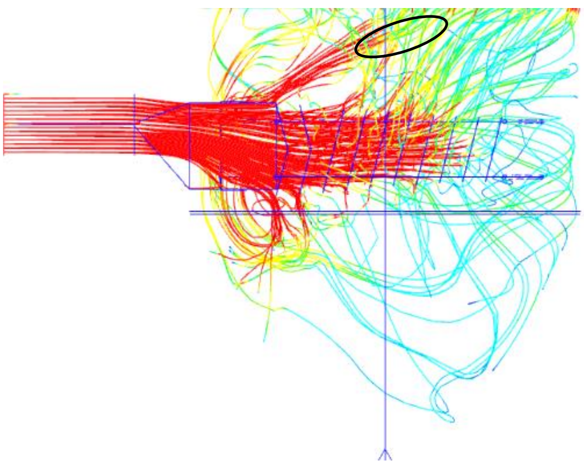


*Figure 28 Front view- inlet diffuser with lower half inclined lower half declined*

### 3.3.7 Modified inlet diffuser- inclined diffuser plates with increased plate size for three plates – case 7

*Problem description:*

Considering multiple modifications, the most feasible and viable option seems to be inclining diffuser plates by 15° with respect to flow direction. To further improve flow, some improvements would be interesting to test out, namely changing the size of the diffusers where flow diversion is lacking. This area is identified as shown in Figure 27 to achieve better flow diversion to this area. The size of the first three plates to be increased (counting from inlets) and studying the changes produced by these changes.

*Model and Modelling data:*

All the modeling parameters are kept the same as in the Case-4. As this is just an additional modification of the Case-4.

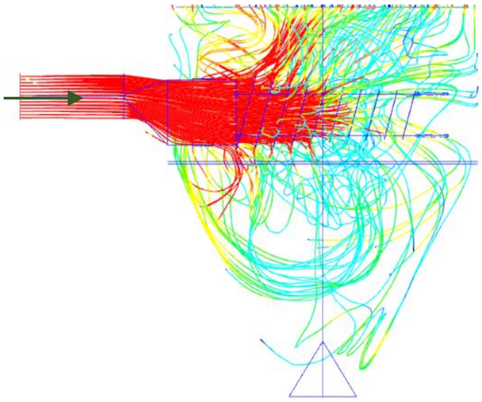


Figure 29 Back view- case 7

*Result presentation & Discussion of findings:*

It is quite apparent from the results that this modification is very viable. Flow is optimally diverted and is streamlined as well as there is enough flow diversion downwards to avoid dusting problems on walls.

Also, statistically speaking, flow is homogenous enough with a variance of 0.3 for velocity magnitudes close to the filter bags. In Figure 30, it is shown how two streams from two inlets mix. Compared to other cases (shown in the Appendix G) flow is qualitatively better in this case.

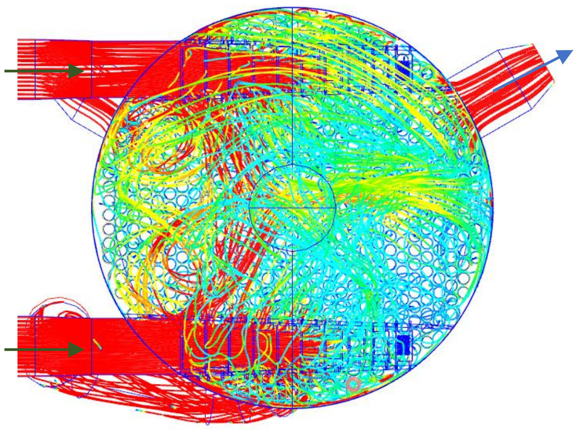
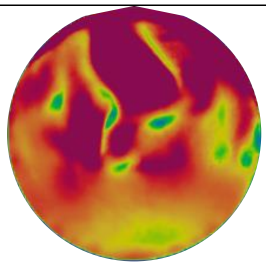
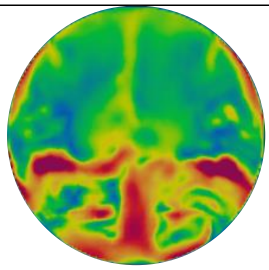
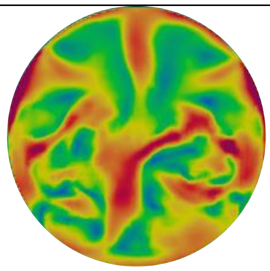
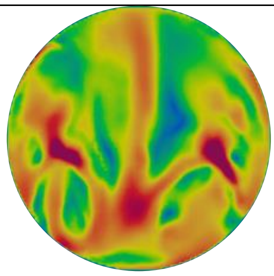
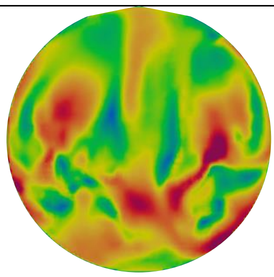


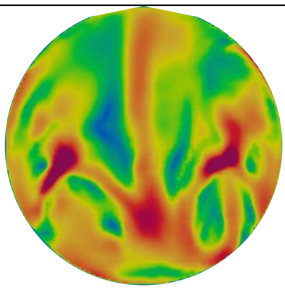
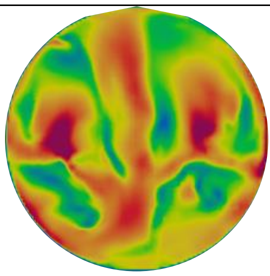
Figure 30 Down view- case 7

## 3.4 Comparison of results & discussion

To evaluate and compare the results statistically, cut plane just below the filter bags was analysed. As mentioned in the methods chapter. The table below shows the homogeneity index from 0-1, with 0 being totally unmixed and 1 being fully mixed.

*Table 2 Homogeneity index for the simulation cases*

| Case | Slice image | Average velocity | Variance | Homogeneity index |
|---|---|---|---|---|
| Case 1- Without inlet diffuser |  | 2.65 | 1.208 | 0 |
| Case 2- With unmodified inlet diffuser |  | 1.38 | 0.443 | 0.640 |
| Case 3- Elimination of three diffuser plates |  | 1.542 | 0.388 | 0.686 |
| Case 4- Inclining diffuser plates by 15° |  | 1.89 | 0.509 | 0.585 |
| Case 5- Inclining only lower half the diffuser plates |  | 1.55 | 0.277 | 0.779 |

| | | | | |
|---|---|---|---|---|
| Case 6- Inclining lower half and decline upper half of the plates |  | 1.56 | 0.304 | 0.756 |
| Case 7- Modification to case 5 by increasing size of first three plates. |  | 1.65 | 0.323 | 0.740 |

Looking at statistical data, it is evident that Case 7 gives the most homogenous mixture quantitatively speaking. At the same time, the qualitative analysis by studying the practical traces is also equally vital. Thus, comparing qualitative and statistical results, Case-7 is most promising to be implemented in a filter to achieve better operation.

## 3.6 Further scope for investigation and implementation

With knowledge obtained from this project, some interesting opportunities come to attention. To verify the results of heterogeneous flow, the inspection of filter bags at over-haul can be undertaken to identify regions where filter bags are most damaged or clogged. This would be then useful to modify flow in a particular way so to avoid selective damage to bags.

The filter material properties are assumed to be linear, although they are close to linear in the low velocity region, as is the case in this thesis, the correct pressure drop model can help to get more exact model and hence more freedom to make geometrical modifications. This can be done by implanting a few pressure sensors close to the inlet and right after the filter bags.

In addition to inlet diffuser modification, the inlets can also be modified into different shape. As seen in the Figure below, the present shape is not optimal for flow diversion, with these inlets turned upside down, will solve some issues. As the flow expands

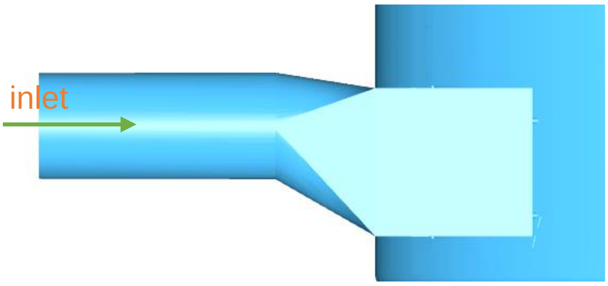



*Figure 31 Present design of inlets*

downward even before being administered into the filter housing. If, however, this was turned upside down, it would help direct flow better right from the inlet and the role of the diffuser in flow behavior would minimize.

# 4. Conclusion

CFD modelling of air bag filters allows simulation of flow behavior and pressure losses and enables testing of different design modifications of inlet diffusers. It also allows us to visualize and quantitatively understand the flow in detail and helps us choose better solutions without undergoing the tedious process of trial and error or making traditional scaled models.

In this thesis, has presented solutions to the flow problems occurring at the industrial plant at Inprotec, AG. Seven different configurations of the inlet manifold have been tested.

1. Filter without inlet diffuser
2. Filter with present inlet diffuser
3. Filter with diffuser plates elimination
4. Filter with inclined plates diffuser
5. Filter with diffuser plates half straight and half inclined
6. Filter with diffuser plates half declined and half incline
7. Filter with inclined plates diffuser, and increased size of plates.

With qualitative analysis and with statistical analysis of results, Case-7 was chosen to be the optimum solution considering flow behavior and pressure losses. The promising perspectives of this model are:

- With a more than 10% increase over homogeneity of the velocities in the filter region the improvement is substantial to be implemented
- Lower gas & dust velocities approaching the bags
- Better de-dusting of walls below inlet—reducing maintenance requirement
- Lesser degree of modification to be done to present inlet diffuser manifold-saving modification cost, and downtime
- Long bag lifetime

In addition to modifications of the inlet diffuser, CFD analysis also sheds light on the overall flow behavior of the filter, hence enabling optimal location choices for retrofitting pressure and fire safety sensors to better monitor operation.

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# Appendix

## Appendix A- Case 1

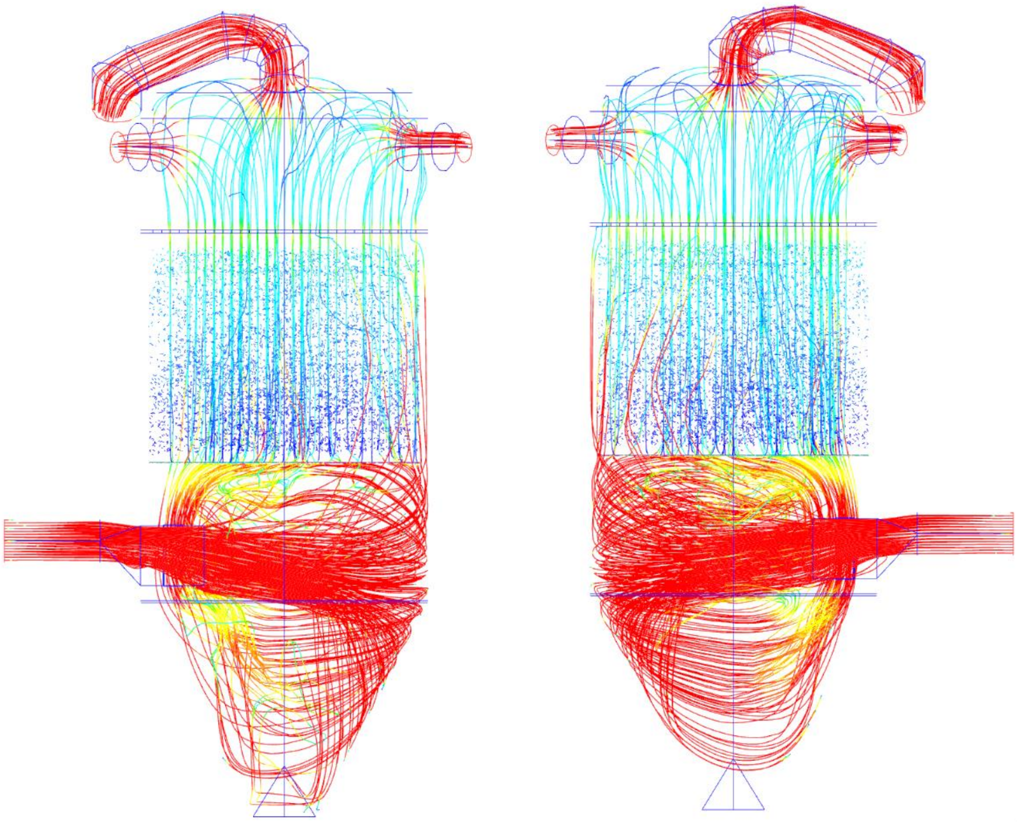


Figure 32 Particle trace for inlets, for model without inlet diffuser

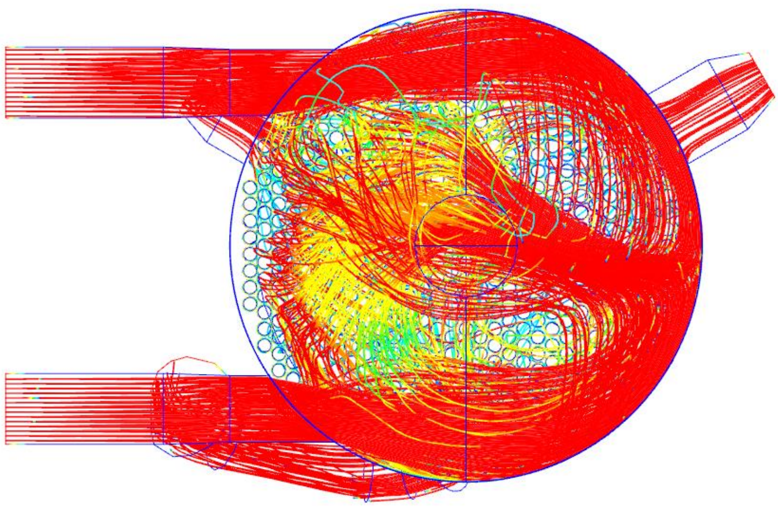
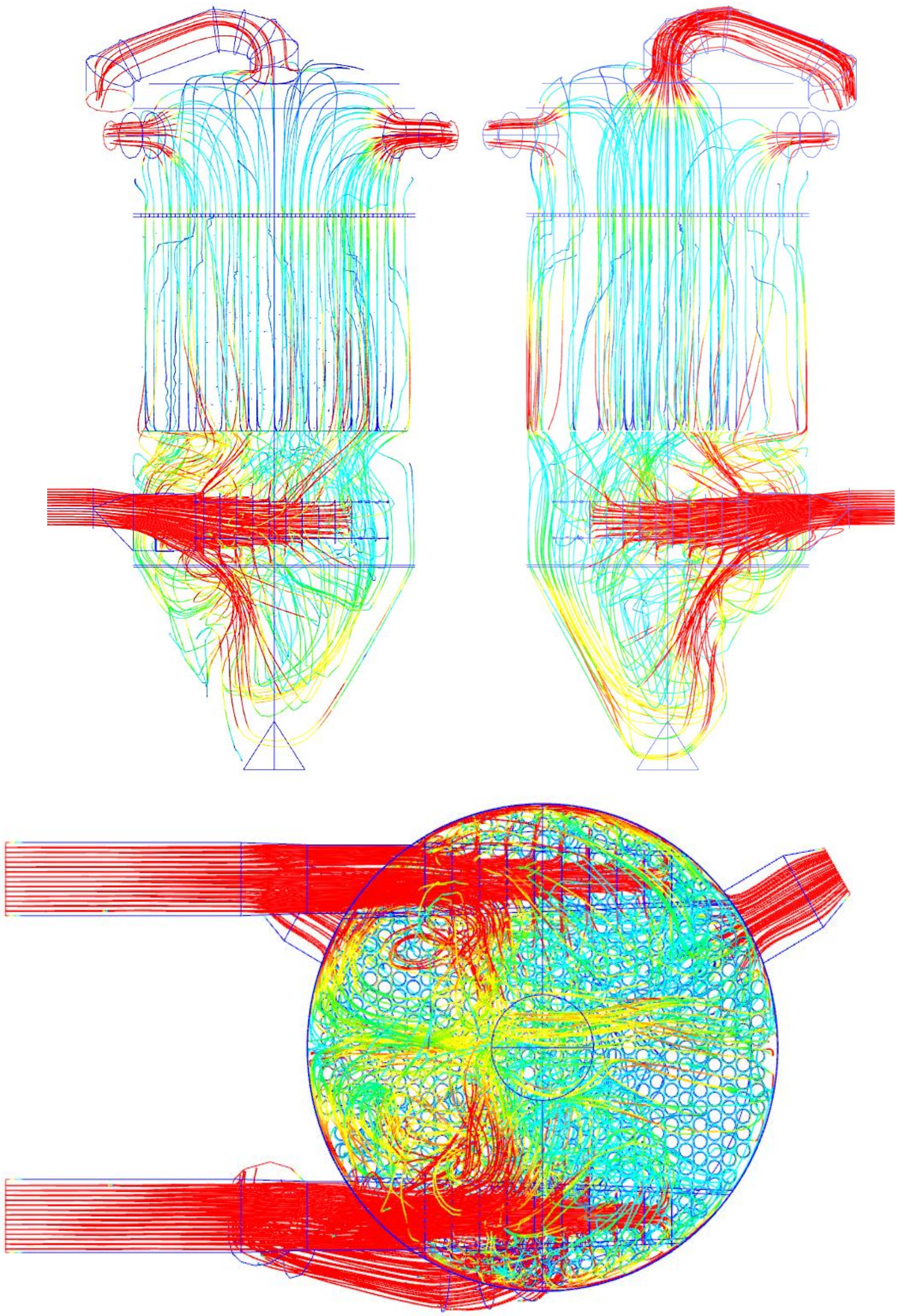
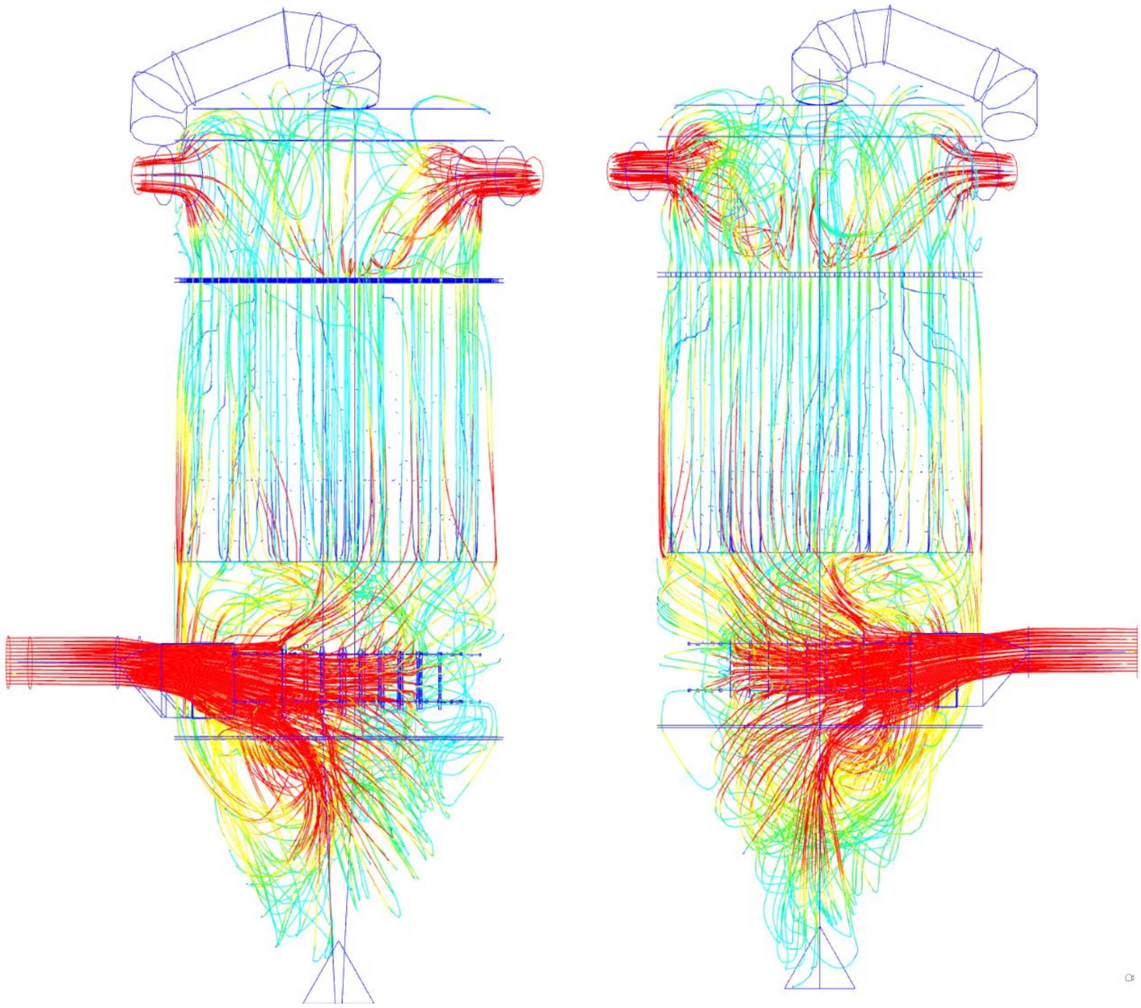


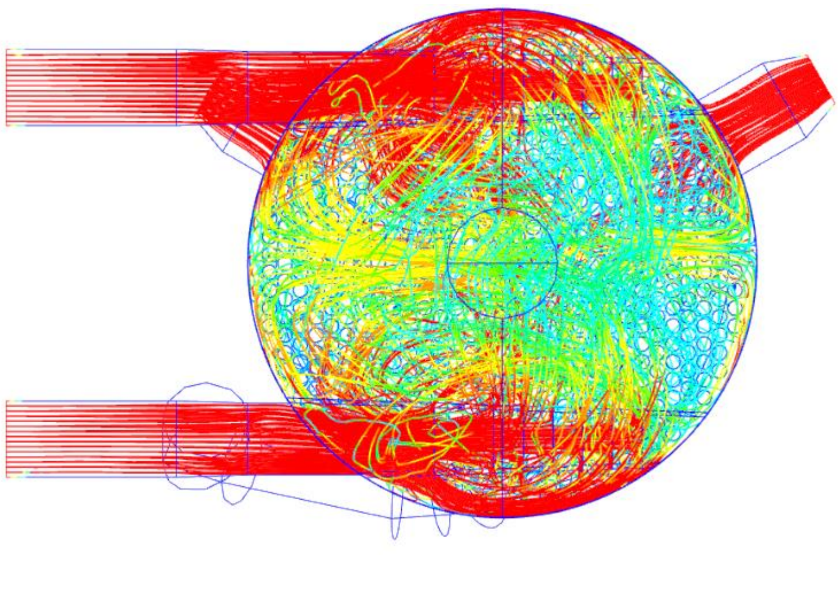
*Figure 33 Down view- Particle trace for inlets, for the model without inlet diffuser*

## Appendix B Case-2

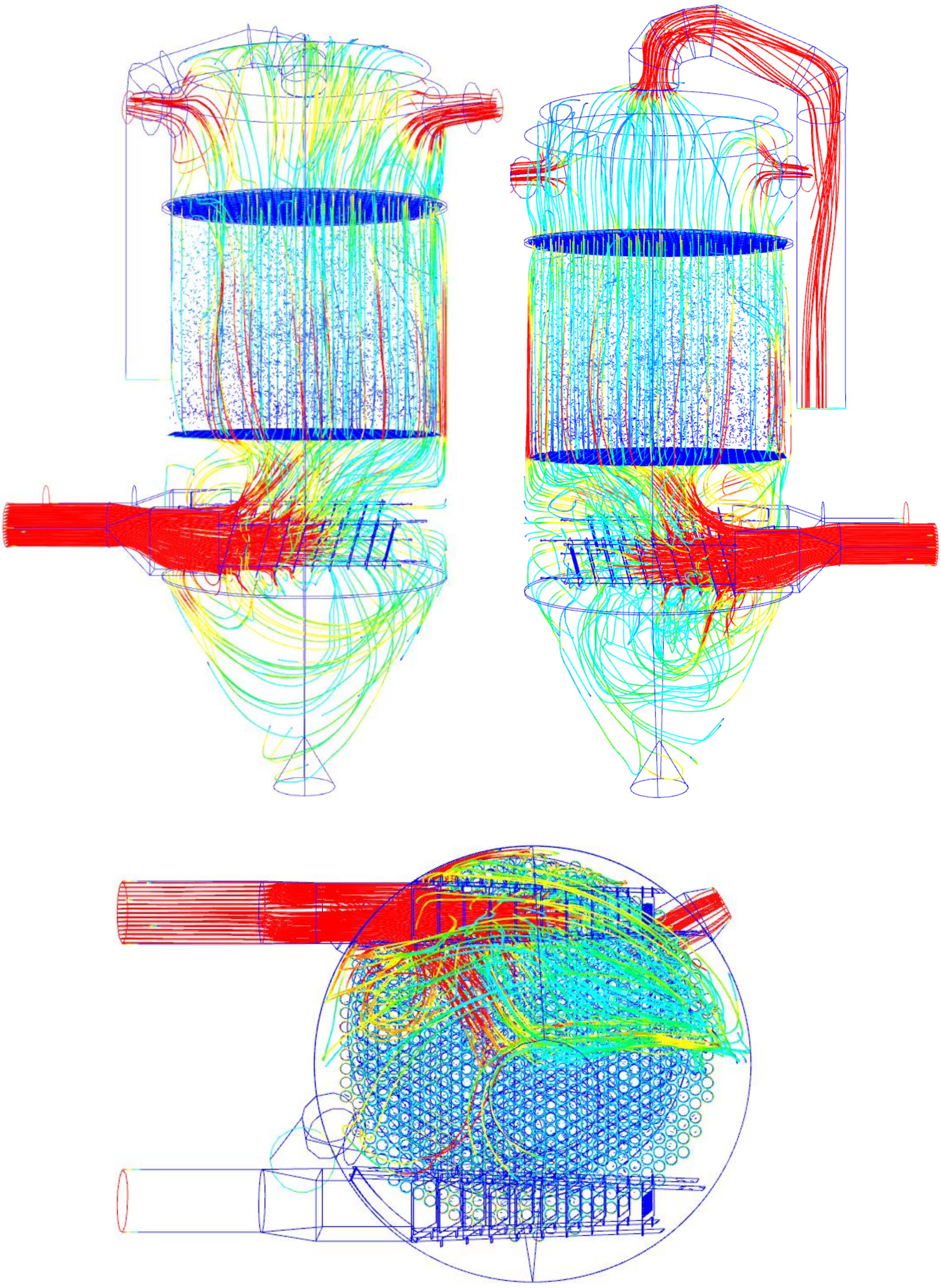


# Appendix C Case-3

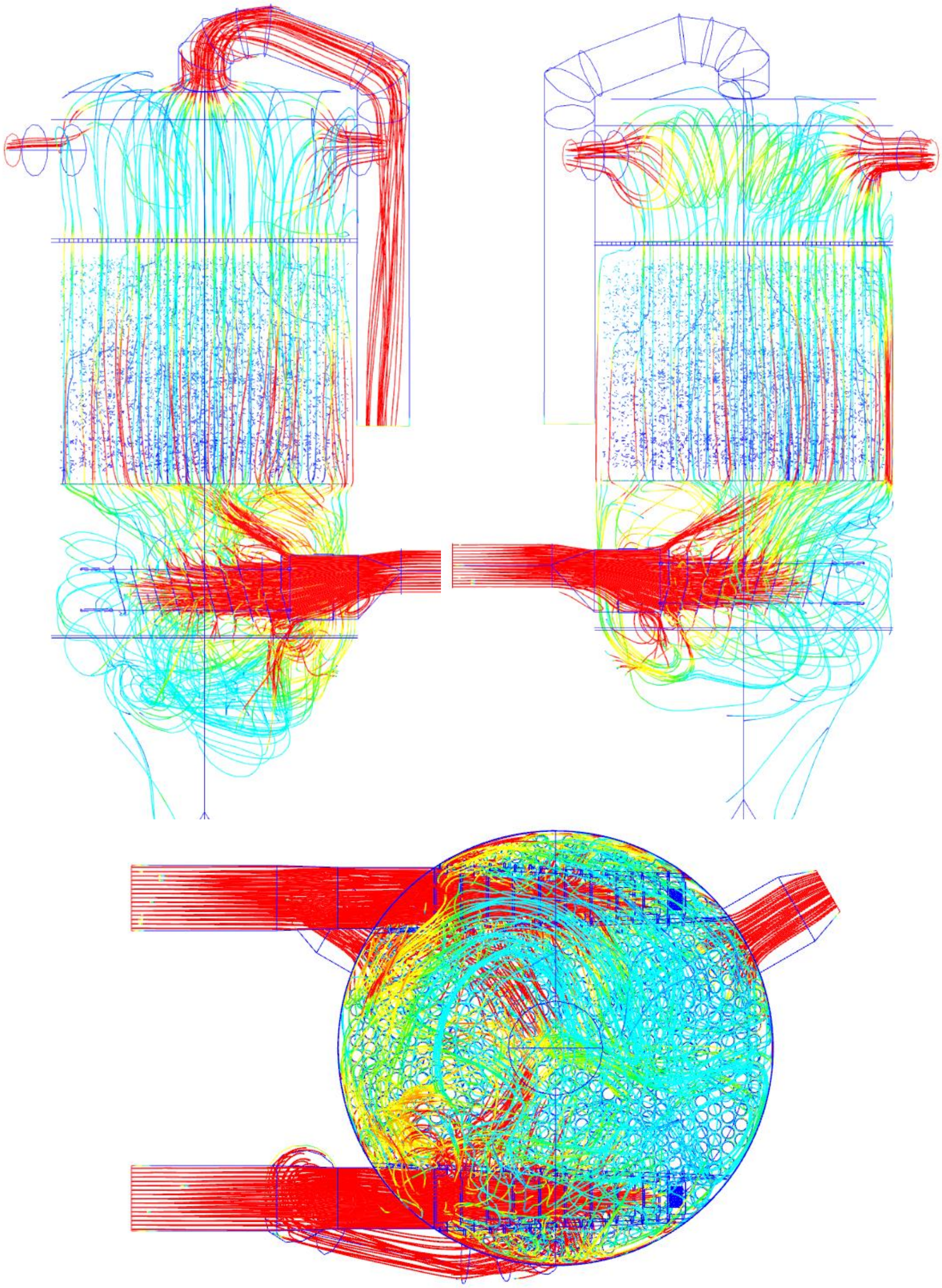




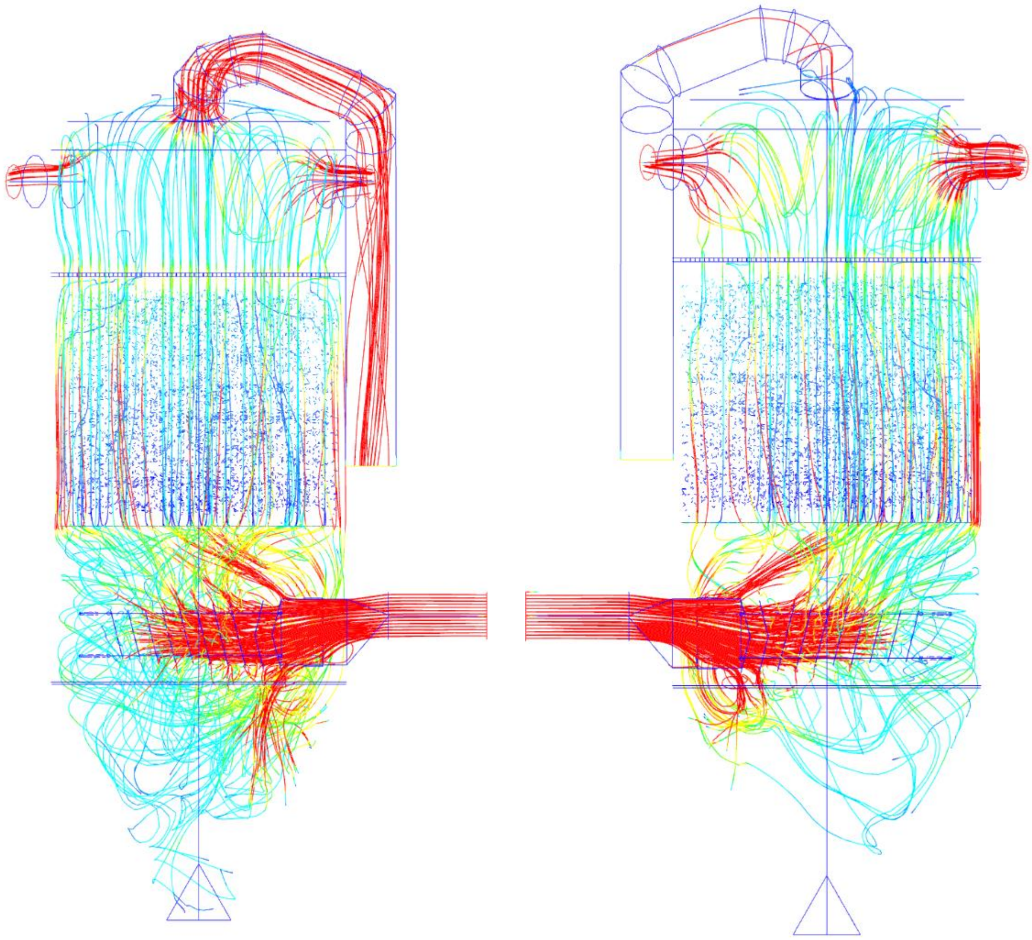
## Appendix D Case-4

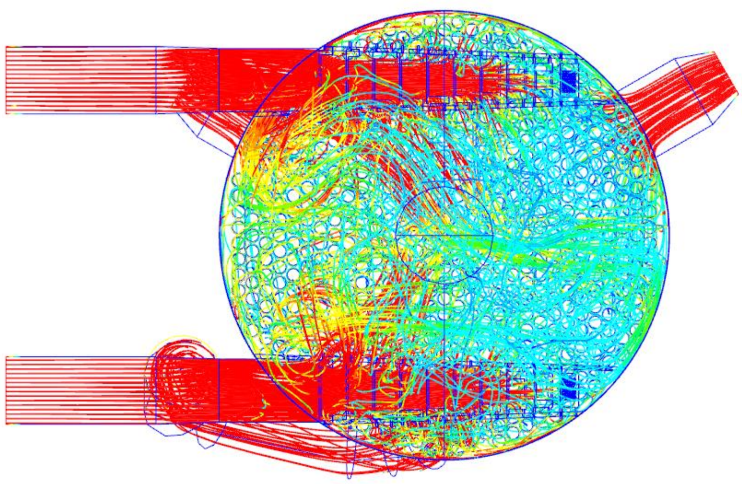


# Appendix E Case-5



## Appendix F Case-6





## Appendix G Case-7