PREDICTION OF PARTICLE COLLECTION EFFICIENCY, THE POROSITY AND THE PRESSURE DROP ACROSS FILTRATION MEDIA USING FEMLAB

By

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CERTIFICATION OF APPROVAL

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Approved:

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CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

Zainina Dini Mohd Zainuri

ABSTRACT

This report consists of a research project on the prediction of particle collection efficiency, the porosity and the pressure drop across filtration media at stationary phase. Two types of model were compared in this project. The first one is the model developed by Awni Y. Al-Otoom, which simulates particle distribution on the filter cloth and predicts whether each particle was trapped on or escapes the filter cloth. The filtration parameters will be calculated by the number of particles trapped and the geometry of the cake simulated on the filter cloth. The second model is developed based on flow through porous media using Darcy's Law and FEMLAB software. In this model, the pressure drop will be simulated using the software and other parameters will be calculated from it. From the project, it can be concluded that the pressure drop shown by both models agree with the theory. This result was the same for porosity and efficiency predicted by Al-Otoom. However, the FEMLAB model needs more experimental information as the porosity prediction is only applicable to the filter cloth porosity, while efficiency prediction requires the pressure drop contributed solely by the filter cake.

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Δp	Pressure drop
p	Pressure
η	Efficiency
G	Flux of particles
P	Penetration
k	Permeability of the porous medium
u	Superficial velocity
μ	Fluid dynamic viscosity
L	Porous media thickness
Q	Volumetric flow rate
A	Cross sectional area of filter
M	Mass of aerosol
N	Number of particles collected
C	Cunningham slip correction factor
d_p	Particle diameter
W	Mass of particles collected per unit area
E	Porosity
ρ_p	Particle density
r_p	Mean particle radius
ρ	Fluid density
W_{in}	Mass of particles at the inlet of filter
V	Volume of particle

CHAPTER 1
INTRODUCTION

1.1 Background of Study

Pich (1987) defined filtration as "the process of separating dispersed particles from a dispersing fluid by means of porous media. The dispersing medium can be a gas or liquid." The filtration process which uses gas as the medium is known as aerosol filtration.

In filtration processes, the trapped particles build up on the filter media and form cakes. Having a porous structure, the cakes may also act as a filter for incoming particles. Addition of the cakes on the filter media alters the filtering performance, resulting in change of the collection efficiency and pressure drop. As the cakes become thicker, these properties change accordingly.

However, Al-Otoom (2005) points out that "the diversity and complexity of filtration media makes the evaluation of the performance of such media extremely difficult to perform experimentally" (p.52) and "theoretical approaches are generally considered the key to predicting the cake filtration performance" (p.52). A new approach to predict filtration performance was introduced by Al-Otoom, which is a model that predicts the collection efficiency, cake thickness and porosity and the pressure drop across it with respect to filtration time. The cake thickness was predicted by determining whether randomly distributed particles pass through the filter media or trapped and contribute to the formation of the cake. This prediction was done using the geometry of the particles and filter pores.

As an air filtration model can act as a guide in research done in UTP, it may be useful to verify the model by Al-Otoom by developing another model using resources available in the university. The FEMLAB software is suggested as a good platform to develop the model.

1.2 Problem Statement

Filtration is a well-known solution for particulate emission treatment. Having a model for research on this subject may help in predicting the properties associated with this process. Several models have been designed for this purpose. Thus, for model verification purpose, a study on comparison between models is required.

1.3 Objective of Study

The following are the objectives of the study:-

i. To predict the collection efficiency, the porosity, and the pressure drop across filter cakes in particulate air filtration at stationary phase using FEMLAB
ii. To compare the model with the model developed by Al-Otoom A.Y

1.4 Scope of Study

The scope of this study is the prediction of the collection efficiency, cake porosity and the pressure drop across filter cake for particulate air filtration at stationary phase using the FEMLAB software. It also includes the comparison between the FEMLAB model and model by Al-Otoom A.Y.

1.5 Relevancy of the Project

Using experimental method to determine the filter parameters is a difficult task. With models developed in this project, these parameters can be predicted and the value can be obtained without having to do experimental work. This may save time and resources and may be very beneficial in research and design purposes. Models may also serve as an education aid. This project may also promote FEMLAB usage among UTP students, as for now the software is found underutilized due to lack of modelling projects and assignments. Also, this project may contribute to the development of models by verifying whether the approach by Al-Otoom agrees with the FEMLAB model.

1.6 Feasibility of the Project within the Scope and Time Frame

This project is feasible within the scope because both of them were based on the air filtration system. In terms of time frame, this project was feasible because it involves mainly computer based activities that are compatible with the daily schedule. Also, all the resources needed for this project is available in the university so that there is no need for time consuming travel to other location to get its resources or to use equipments.

CHAPTER 2

LITERATURE REVIEW / THEORY

2.1 Filtration Parameters

The filtration process can be characterized by several parameters. All the parameters will be described according to Pich (1987). First, the pressure drop across the filter, Δp is defined by

$$\Delta p = p_1 - p_2 \tag{1}$$

where p_1 is the gas pressure before the filter and p_2 after the filter. This quantity is dependent on the property of the fluid and filter media in the case of a clean filter. However, as the filtration process proceeds, the pressure drop will become dependent on the properties of particles that deposits on and inside the filter.

The filter efficiency is defined by

$$\eta = \frac{G_1 - G_2}{G_1} \tag{2}$$

where G_1 is the flux of particles into the filter and G_2 is the flux of particles coming out of the filter. Other than flux, G_1 and G_2 can be expressed in terms of number, weight, activity etc. The penetration of the filter P is defined by

$$P = 1 - \eta \tag{3}$$

which represents the fraction of particles that escapes the filter. Other parameters include the filter capacity and filter quality (p 1-2). However, they will not be discussed further as they are not directly related to this study.

Pich (1987) also states that the three elements that participate in the filtration process, namely the dispersed particles, the dispersing medium and the porous substance can be characterized by a number of factors (p. 2). Table 1 lists the respective factors corresponding to each filtration element.

Table 1 Characterizing Factors on Filtration Process

Filtration element	Characterizing factors
Dispersed particles	Diameter, size distribution, shape, mass, density, electric charge, electric constant, chemical composition and concentration (number, weight volume, active concentration)
Dispersing medium	Velocity, density, absolute temperature, pressure, dynamic viscosity, kinematic viscosity and humidity
Porous substance	Surface area, thickness, size of structural units and their arrangement and distribution in the filter, porosity, specific surface, electric charge, dielectric constant and chemical composition

The pressure drop Δp and filter efficiency η depend on nearly all factors mentioned above. The determination of their dependence on these factors is the basic problem of filtration (Pich, 1987, p. 3)

Porosity is defined by Schlumberger (2005) as the percentage of pore volume or void space, or that volume within porous medium that can contain fluids. Porosity can be divided into two types. Total porosity means the total pore volume per unit volume of porous medium and is measured in volume/volume, percent or porosity units (Schlumberger, 2005). On the other hand, effective porosity means the interconnected pore volume or void space in a porous medium that contributes to fluid flow or permeability in a system (Schlumberger, 2005). However, in this study, all void space in the porous media is assumed to be interconnected. This means that the effective porosity is equal to total porosity.

According to Pich (1987), there are two different phases of filtration. The first one involves the deposition of particles on a clean filter with a definite structure. The amount of deposited particle is small and the structural change was assumed to have only a little influence on both pressure drop and efficiency. This phase, where Δp and η are independent of time, is known as stationary filtration. Practically, filtration process can be treated as a stationary phase in the initial stage of the filtration process or for low concentrations of the inlet aerosol. The second phase is more complex. At this point, structural changes due to the particle deposition may change Δp and η with time. These two parameters may increase or decrease. Besides, the filter media may become clogged. This phase is known as nonstationary filtration (p.3).

2.2 Governing Equations for Fluid Flow in Porous Flow Region

Bird, Stewart and Lightfoot (2002) states that the flow characteristic in the filter media can be described using Darcy's equation,

$$\Delta p = \frac{1 \mu u L}{k} \tag{4}$$

where k = permeability of the porous medium

u = superficial velocity

μ = fluid dynamic viscosity

L = porous media thickness

Superficial velocity u is defined as the volumetric flow rate through a unit cross-sectional area of the filter medium, averaged over a small region of space – small with respect to the macroscopic dimension of the flow system, but large with respect to the pore size (p. 149). Superficial velocity is also known as face velocity and can be calculated using the following equation

$$u = Q/A \tag{5}$$

where Q = volumetric flow rate

A= cross sectional area of filter

According to Schlumberger (2005), the permeability of the porous media is the measurement of a medium's ability to transmit fluids. This parameter may be applied to the filter cloth of filter cakes. Permeability can be divided into three types, absolute, effective and relative permeability. Absolute permeability is the measurement of the ability to flow or transmit fluids through a medium, conducted when a single fluid, or phase, is present in the medium (Schlumberger, 2005). Effective permeability is the ability to preferentially flow or transmit a particular fluid when other immiscible fluids are present in the system, while relative permeability is the ratio of effective permeability of a particular fluid at a particular saturation to absolute permeability of that fluid at total saturation (Schlumberger, 2005). Any 'permeability' terms found in this report will be referring to absolute permeability. According to de Nevers (2000), the resistance of the filter cloth can be assumed as a constant with time. For a filter cake, a uniform cake will have a resistance that is proportional to its thickness (p.283).

The Darcy equation is used for low speed, incompressible, Newtonian flow, as how filtration process usually is (Pich, 1987, p. 13). According to Nassehi et al (2004), the Darcy equation is suitable for low-permeability system. This equation also "does not account for viscous effects" ("FEMLAB 3 User's Guide", 2004, p.545). Thus, it is suitable for low viscosity system.

2.3 Filtration Model by Novick and Klassen

Novick and Klassen (1998) has studied various models that predicted mass loading as a function of the increase of Δp across the filter. One of the approaches studied models physically the relationship between Δp and mass loading, and then determining factors that are necessary to make the model fit the data. All the description of this model in this chapter, unless indicated, is according to Novick and Klassen (1998, p.338-343).

The model describes the total pressure drop across the filter as the summation of the pressure drop across a clean filter Δp_0 and the pressure drop across the filter cake Δp_{cake}, which is due to particle loading.

$$\Delta p = \Delta p_0 + \Delta p_{cake} \tag{6}$$

Assumptions for this model are that both filter and filter cakes are rigid, porous bed superimposed on each other and that the flow through them is laminar. Each component of the pressure drop is then described using Darcy's Law.

$$\Delta p = K_1 u + K_2 u M/A \tag{7}$$

where $\Delta p_0 = K_1 u$, $\Delta p_{cake} = K_2 u M/A$ and M/A is the mass loading

K_1 is a parameter that only depends on the properties of the filter cloth and is determined from the slope of Δp versus u graph. On the other hand, K_2 is modeled by considering that Δp_{cake} can be determined using Stokes Law

$$\Delta p_{cake} = 3\pi\mu u d_p N/C \qquad (8)$$

where N = numbers of spheres (particles) per unit area

C = Cunningham slip correction factor

The cake is assumed to be comprised of isolated spheres of porosity approaching 1.

The Cunningham slip correction factor is defined by Sioutas and Koutrakis (1998) as

$$C = 1 + \frac{2}{pd_p}[6.32 + 2.01\exp(-0.1095Pd_p)] \qquad (9)$$

where p is the absolute pressure in mmHg and d_p is particle diameter expressed in microns (p. 456).

The mass of particles collected per unit area W is

$$W = N\rho(\pi/6)d_p^3 \qquad (10)$$

2.4 Filter Cake Buildup Model by Al-Otoom

A model developed by Al-Otoom A.Y. uses random distribution to predict the falling coordinate of each particle. Then, using the location and geometry of the filter media pores and particles that are already deposited on it, the model determines whether the falling particle will pass the filter cake or not. If not, it will contribute to the increase of the cake thickness. The efficiency of the filter is then calculated using the following equation

$$\eta = \frac{\text{no. of particles trapped on the filter media}}{\text{no. of particles exposed to the filter media}} \times 100\% \qquad (11)$$

The porosity of the cake ε will be calculated using

$$\varepsilon = 1 - \frac{\text{Particles volume}}{\text{Filtration area x Cake thickness}} \tag{12}$$

The pressure drop across the filter media is determined using either Ergun's equation (13) or Rudnick-Happel equation (14)

$$\Delta P = \frac{150 Q \mu V}{A \rho_{\mathrm{p}} d_{\mathrm{p}}^{2}} \frac{(1-\varepsilon)}{\varepsilon^{3}} t, \tag{13}$$

$$\Delta P = \frac{150 Q \mu V}{A \rho_{\mathrm{p}} d_{\mathrm{p}}^{2}} \times \left[\frac{3 + 2(1-\varepsilon)^{\frac{5}{3}}}{3 - 4.5(1-\varepsilon)^{\frac{5}{3}} + 4.5(1-\varepsilon)^{\frac{5}{3}} - 2(1-\varepsilon)^{2}} \right] t, \tag{14}$$

where ρ_p = particle density

d_p = particle mean diameter

ε = porosity

Another variation of Ergun equation is stated by Tardos (1998) which in dimensionless form f_0 is

$$f_0 \left[\varepsilon^3 / (1 - \varepsilon)\right] = 180(1 - \varepsilon)/Re_0 + 1.8 \tag{15}$$

The actual pressure drop can then be calculated by

$$\Delta p = \frac{f_0 \rho u^2 L}{2 r_p} \tag{16}$$

where the Reynolds number is expressed as

$$Re_0 = \frac{2 r_p u \rho}{\mu} \tag{17}$$

where r_p = mean particle radius

ρ = fluid density

L = filter thickness in the direction of the flow

The model is based on the following assumptions:-

i. Filter media has a uniform surface porosity with an average pore diameter, p_d and a constant distance between all successive pores.
ii. Pores in filter media are cylindrical.
iii. Particles that enter pores escape from the filter cake.
iv. Particles that come into contact with other particles adhere to the surface with these particles
v. Particles have uniform spherical shapes.
vi. Particles are incompressible.
vii. Particle size distributions and the particle falling location are randomly distributed.

The flow diagram for the model by Al-Otoom is shown in Figure 1. The filter porosity, dimension and mean pore diameter are used to assign pore locations on the filter cloth. The mass mean particle diameter will be used to generate varieties of particle diameters within a specified range. The explanation for each model stage will be included in the later sections.

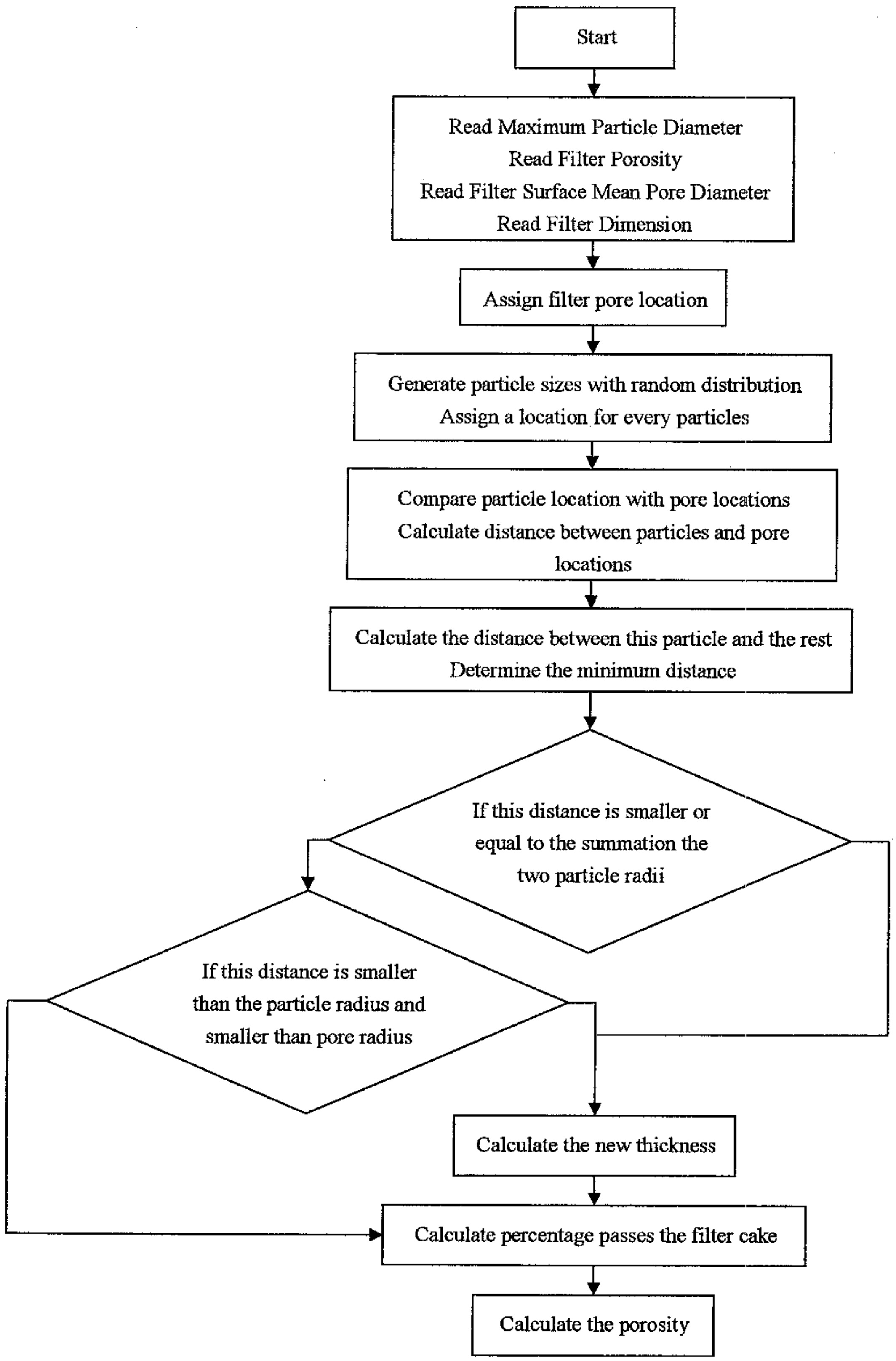

Figure 1 Flow Diagram for Model Calculation by Al-Otoom

Source: Al-Otoom (2005)

2.4.1 *Pore location assigning*

The location of each pore is represented by its center coordinate. To determine the coordinate of each pore center, the distance between two successive pores S is calculated. The number of pores in the x-direction is

$$x = \frac{L}{S} \tag{18}$$

where L is the length of the filter cloth. The number of pores in the y-direction is

$$y = \frac{W}{S} \tag{19}$$

where W is the width of the filter cloth. Thus, the total number of pores is

$$xy = \frac{LW}{S^2} \tag{20}$$

The total number of pores can also be calculated alternatively using

$$\frac{\text{Total pore volume}}{\text{Volume of one pore}} = \frac{LWH\varepsilon}{(\pi/4)d_p^2H} = \frac{LW\varepsilon}{(\pi/4)d_p^2} \tag{21}$$

where H is the thickness of the filter cloth. Equating equation (20) and (21) will result in the equation to find S

$$S = \sqrt{\frac{\pi/4p_d^2}{\varepsilon}} \tag{22}$$

The pore x and y coordinates were then determined by the following equations

$$P|x(a,b) = P|x(a-1,b) + S \tag{23}$$

$$P|y(a,b) = P|y(a,b-1) + S \tag{24}$$

where a and b are integers generated for every pore location an x and y coordinates. P|x(a-1,b) is the x-coordinate of the previous pore and P|y(a,b-1) is the y-coordinate of the previous pore.

2.4.2 Particles Radii

The particles radii r_p are generated randomly using the maximum particle diameter d_{pmax} and the following equation

$$r_p(i) = \frac{d_{pmax} \text{ x Random number}}{2} \qquad (25)$$

Al-Otoom (2005) stated that the mean particle diameter generated is around the half the value of the d_{pmax}. A typical particle size distribution is shown is Figure 2. The mass mean diameter obtained in this sample is around 15 μm, which is a normal distribution found in practical situations.

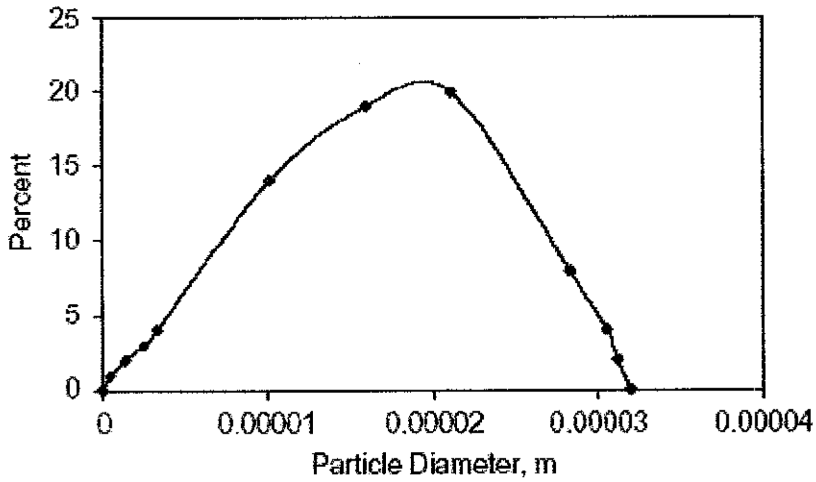

Figure 2 Sample of particle size distribution generated for $d_{pmax} = 31$ μm

Source: Al-Otoom (2005)

2.4.3 Particle Falling Locations

The coordinates of the particle falling locations are also randomly generated. In this case the length or width of the filter cloth is used to get the location as a fraction of the filter cloth length and width. The equations for the x-coordinate $x_0(i)$ and y-coordinate $y_0(i)$ are

$$x_0(i) = L \text{ x Random number} \qquad (26)$$

CHAPTER 3
METHODOLOGY / PROJECT WORK

The general procedure for this project is illustrated in Figure 3:

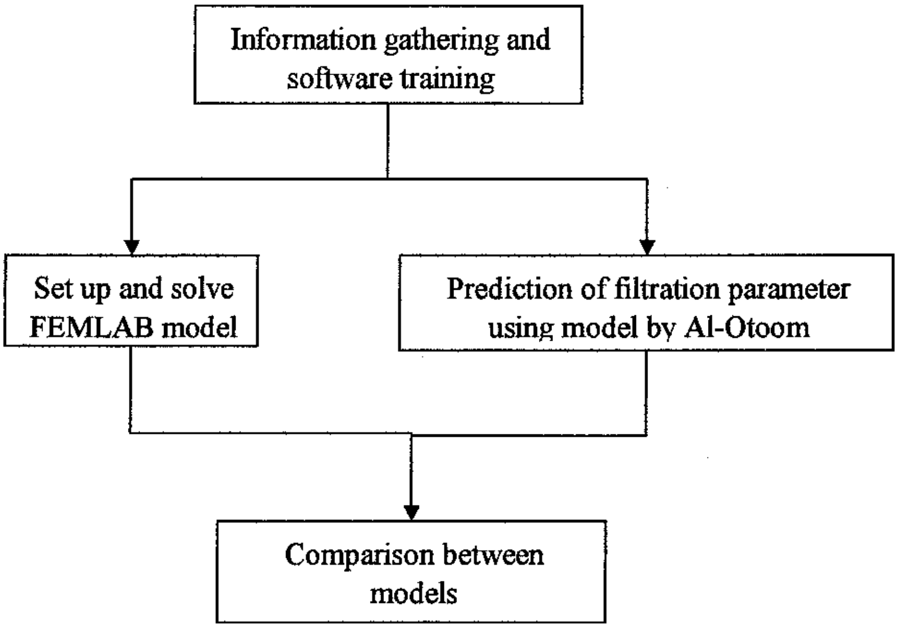

Figure 3 General Procedure of the project

3.1 Information Gathering and Software Training

Information regarding the research subject is gathered from various sources, including books, journals, manuals, online articles etc. Copies of relevant documents were obtained from the library and the supervisor in charge. The software was accessed from computer laboratories or personal computer to familiarize with its features. Guide on software usage was obtained from the FEMLAB help file and from the internet.

To get the suitable equation for the model, all equations for momentum balance and fluid flow in the FEMLAB was listed. Then, their properties are looked up in books. This is to get information on the suitability of the equation with the system to be simulated. The FEMLAB model will require an equation to govern the fluid flow in the porous region. The porous region is the flow region in the filter media. Then, trials were done using these equations to find the solution for the flow system.

To obtain the properties needed for the modelling, a pulse jet bag filter which is available in the university was selected. From this equipment, the following properties for the model can be determined: filter dimension, pore size, porosity and permeability. The vendor for this equipment is contacted to obtain these information. The properties and their values are listed in Table 2.

Properties	Value
Filter dimension	1 m x 0.4241 m x 0.002 m
Pore diameter (Average)	15 μm
Porosity	0.6
Filter Permeability	$2.9115306 \times 10^{-12}$ m^2

Table 2 Properties of the Filter Cloth

3.2 Set Up and Solve FEMLAB model

Once the FEMLAB features and model equations are identified, the project can proceed by setting up the model using the software.

The first step in setting up models in FEMLAB is the specification of the constants. The constants are the values or properties for the model. A menu is opened from the 'Options' > 'Constants' drop-down menu to key in the needed data, as shown in Table 3. When all the constants are gathered in here, it will be easier to be accessed as the subsequent steps will require changing of some values, including the volumetric air flow rate and total filtering area.

Table 3 Constants for FEMLAB Model

Properties	Variable name	Value/ expression	Unit
Dynamic viscosity of air	Eta	1.8×10^{-5}	kg/m.s
Density of air	Rho	1.2	kg/m^3
Filter cloth permeability	Perm	$2.9115306 \times 10^{-12}$	m^2
Air flowrate	Q	Ranged from 130 to 10	m^3/hr
Total filtering area	A	0.4214 x (1 to 4)	m^2
Superficial velocity	v0	Q/A	m/s

The dynamic viscosity and density of air is obtained form literature, whereas the filter cloth permeability was calculated from the information obtained from the pulse-jet bag filter operating manual. A set of result from an experiment of filtration using atta flour as the dust sample is used to calculate the permeability. The equation used is the Darcy equation. The data from the early stages of filtration is used because the will be none or very little cake deposited on the filter cloth surface. This will ensure that the calculated permeability is the permeability of the filter cloth, not the cumulative permeability of the cloth and the filter cake.

These data were used to construct a model based on Darcy's equation. First, the geometry of the model was made. This means that the shape of the filter cloth was drawn. Then, the properties of the model, including the constants used, subdomain and boundary condition were assigned. The fully specified model was then divided into meshes before solved using the FEMLAB solver. From the solution, many properties of the filtration process can be obtained.

3.2.1 Model Specifying Steps

Before the model is constructed, the FEMLAB file must be created. When the FEMLAB programme was opened, the 'Model Navigator' menu was shown on the screen. Refer to Figure B-1 in Appendices for a view of the 'Model Navigator'. In this menu, the space dimension and equations used in the model were specified. Space dimension determines the number of dimensions that the model has, either 1, 2 or 3. The coordinate system of the model can also be determined, whether Cartesian or Cylindrical. For this model, the space dimension is set to '3D' and 'Darcy's Law', 'Steady-state analysis' was selected from 'Chemical Engineering Module', in 'Momentum balance' folder. The 'OK' button was used to confirm these selections.

The first step was to draw the geometry of the model. The geometry of the model consists of a fraction of the filter cloth, with the dimension of 0.1 m x 0.08482 m x 0.002 m. The geometry of the model (See Figure 4) is drawn smaller than the original filter cloth dimension to fasten up the simulation process. However, the thickness of the filter cloth is maintained at the original so that the geometry drawn is representative for the actual filter cloth. To do this, the 'Block' menu was opened from 'Draw' > 'Block' drop-down menu. In this menu (Refer Figure B-2 in Appendices), the length of the block was specified as follows: X=0.1, Y=0.08482 and Z=0.002. Other parameters were left as they were, which were: 'Style' = 'Solid', 'Base' = 'Corner', 'Axis Base Point' = (0,0,0), 'Rotation Angle' = 0, 'Axis Direction Vector' = 'Cartesian Coordinates' at (0,0,1) and 'Name' = 'BLK1'. 'OK' button was then clicked and the specified block was shown on the coordinate system.

Then, the program will divide the geometry into subdomains, which are defined by as "a topological part of the modeling space in a geometry model" ("FEMLAB 3 User's Guide", 2004, p.545). In the case of this model, only one subdomain is present. Darcy equation was assigned to the existing subdomain. This indicates that the subdomain is assigned as a porous media and the calculation for the flow passing through the subdomain will be based on the Darcy equation. To assign properties on the subdomain, the 'Subdomain Settings' menu (Refer Figure B-3 in Appendices) was opened from 'Physics' > 'Subdomain Settings'. For subdomain 1, in the 'Physics' tab, the following values were put inside the text box: 'rho' for 'Density', 'perm' for 'Permeability' and 'eta' for 'Dynamic Viscosity'. For 'Source Term' the text box was left as it was. Using the names of the variable specified in the text boxes, the programme would find values corresponding to each name from the values specified in 'Constant'.

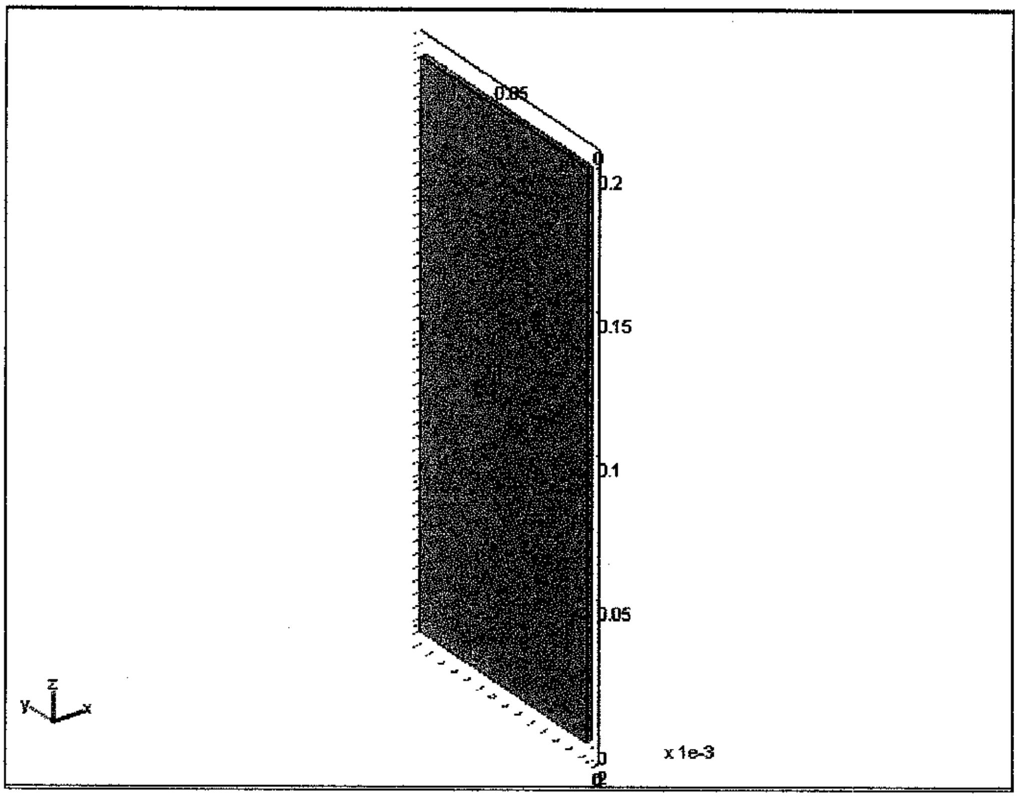

Figure 4 Geometry of the model for FEMLAB simulation

The next step involves the setting of the boundary condition at the boundary of the subdomain. In Darcy models, the boundary condition may be the flux, pressure condition and insulation/symmetry. Flux condition is used to specify the rate of flow entering of exiting the boundary. The pressure condition is used to specify pressure at the boundary of the subdomain, while insulation/symmetry indicates that there will be no flow passing through the respective boundary, where flux and pressure is not specified. The model consists of 6 boundaries and the condition for each of them is summarized in Table 4. The term v0 in the first boundary condition corresponds to the inlet superficial velocity. Its value has been specified in the 'Constant' menu. To open the 'Boundary Settings' menu (Refer Figure B-4 in Appendices), 'Boundary Settings' was selected from 'Physics' drop-down menu. Then, the 'Boundary Condition' was set to 'Flux', 'Pressure Condition', or 'Insulation/Symmetry', according to Table 4 below.

Table 4 Boundary Conditions for FEMLAB Model

Boundary	Location	Boundary Condition
1	Inlet of the filter cloth	Flux at v0
2	Sides of the filter cloth	Insulation/symmetry
3		
4		
5		
6	Outlet of the filter cloth	Pressure at 0 Pa

Then, the model was divided into small sections called mesh. The mesh used in this model is the default type, which is tetrahedron of normal size. The actual dimension of the mesh will be determined by the software based on the geometry drawn. The mesh should be small enough to fit the geometry, but not too small as it can result in longer time taken to solve the model. The mesh size should also fit the capability of the computer used to solve the model. If the mesh size is too small, the program may run out of memory. The mesh was started using 'Mesh' > 'Initialize Mesh' was selected. This action divided the model into meshes using default setting. If other mesh setting was needed, it can be set from 'Mesh' > 'Mesh Parameters'. The menu for this feature is shown in Figure B-5 in Appendices.

3.2.2 Model Solving to Obtain Pressure Drop

The next step is to solve the model. The FEMLAB solver was used to find the solution of the model, yielding the properties that is needed. 'Solve Problem' was selected in 'Solve' drop-down menu. The solver used in this model was stationary nonlinear solver. The type and properties of solver may be changed through 'Solver Manager' (Refer Figure B-6 in Appendices) and 'Solver Parameters' (Refer Figure B-7 in Appendices), also in the 'Solve' drop-down menu. By default, the solved model displayed the solution in terms of velocity field. The parameter to be displayed in the solved model was changed to pressure, as this will show the pressure drop across the filter cloth. This was done by selecting 'Plot Parameters' (Refer to Figure B-8 and Figure B-9 in Appendices) in 'Postprocessing' drop-down menu. The type of display chosen was slice, which shows the parameter value using colour scale. The red colour will indicate the highest value, while blue colour will indicate the lowest value.

As the numerical number is not shown directly on the solution plot, it is difficult to obtain the exact pressure drop across the filter cloth. To overcome this problem, another feature of FEMLAB is used, which is the cross-section plot. The 'Cross section Plot Parameters' (Refer to Figure B-10 in Appendices) was selected from 'Postprocessing' drop-down menu. From 'Line/Extrusion' tab, 'Line Plot' was chosen as the 'Plot Type' and for 'y-axis data', 'Pressure' was chosen as the 'Predefined Quantities'. The coordinates for the line along which the pressure value would be measured was specified in the 'Cross-section Line Data' as (0, 0.04241, 0.1) to (0.002, 0.4241, 0.1). A line was drawn perpendicular to the filtering surface and passing through the center of the filter cloth geometry. The pressure along this line was then plotted on a graph of pressure versus distance in the x-coordinate. The sample of this kind of plot is shown in Figure B-11 in the Appendices. The same approach can be used to obtain the outlet velocity of the filter cloth.

3.2.3 Determination of Porosity

In this model, there was no filter cake taken into consideration. As a result, the porosity that can be determined from this approach is the porosity of the filter cake itself. This can still be a beneficial information, as the porosity obtained can be compared with the porosity value obtained from the equipment supplier.

The variant of Ergun equation 15 is used to calculate the porosity. As the value of porosity cannot be determined directly from the equation, interpolation method is used. Values of porosity, which is known as in the range of 0 to 1 is used to find the corresponding value of dimensionless pressure drop f_0. Then, the dimensionless pressure drop whose porosity is to be found was calculated using equation 16. The dimensionless pressure is used to get the porosity from interpolation.

To simulate the changes caused by flowrate and total filtering area change, the Q and A in the constant dialog box is varied among these values: 130, 90, 50 and 10 m^3/hr for flowrate and 0.4241, 0.8482, 1.2723 and 1.6964 m^2 for total filtering area. The results were then plotted in to graphs to be compared with different model approach.

3.2.4 Determination of Efficiency

The pressure drop obtained from the FEMLAB model is assumed as the total pressure drop of the filter cloth and filter cake. The pressure drop from the filter cloth is calculated as the slope of Δp versus u graph, multiplied by the u value. From this data, the Δp_{cake} can be calculated.

The efficiency of the filtration process is modeled using the combination of equation 8 and 10 to yield the relationship between the pressure drop across the cake Δp_{cake} with the mass collected per unit area W

$$W = \frac{\Delta p_{cake} C \rho d_p^2}{18 \mu u} \tag{28}$$

This W will be used to calculate the efficiency using

$$\eta = W/W_{in} \tag{29}$$

where W_{in} is the mass at the inlet of the filter.

3.3 Prediction of Filtration Parameter using Model by Al-Otoom

The process of prediction of filtration parameter using Al-Otoom's approach is done using Microsoft Excel. The reason why the respective software is used is because it is easier to use. Although there are a lot of programming software available in the university, such as MATLAB and C++ programming, they are more difficult to handle. Even though they do have an advantage of the ability to produce better user interface, time constraint will be interrupting the process of studying the features of these software. Furthermore, as they were a lot of particles and parameters to be considered in this approach, it would be preferable of each of the calculating step can be easily monitored so that mistakes can be easily detected and corrected. This advantage is found on Microsoft Excel.

3.3.1 *Determination of Filtration Efficiency*

In his paper, Al-Otoom uses 4000 particles deposited on 0.05 cm x 0.05 cm of filter cloth. In this study, the number used will be at most 1000 particles deposited on 68.6468 μm x 68.6468 μm. This is to simulate 0.1 kg of dust sample on 1 to 4 filter bags, each having the filtering area of 0.4241 m^2. The number of particles will be varied to 500, 333 and 250 to simulate the increase in the filtering area. The particles used in this simulation is a hypothetical particle of 2000kg/m^3 density as stated in de Nevers (2000) for unspecified particle and diameter range 1-40 μm, which is inside the range of milled flour particle diameters (de Nevers, 2000, p. 210). The pore diameter used is 15 μm. The distance between the successive pores is calculated using the equations specified in section 2.3.1.

After that, the particle diameter and falling location is specified using equations specified in section 2.3.2 and 2.3.3, respectively. In Microsoft Excel, the RAND() function is used to generate random numbers between 0.025 and 1 to obtain the particle diameter within the range specified. For the falling locations, the same function was used, but the range of the random number would be within 0 to 1.

To find the distance between the falling particle and the particles that are already deposited on the filter cloth the equation shown below is used. (x_1, y_1) is the coordinate of the falling particle, while (x_2, y_2) is the coordinate for other particles deposited on the cloth. The MIN() function is then used to find the minimum among the distances. If this distance is smaller than or equal to the summation of the radii of the falling particle and the particle closest to it, the particle will be trapped on the cloth and a constant TRUE is assigned on the particle. If not, the constant FALSE will be assigned.

$$\text{Distance} = ((x_1 - x_2)^2 + (y_1 - y_2)^2)^{1/2} \qquad (30)$$

The same equations were used to find whether the particle escapes the cloth through the pores on the cloth. But in this case, the coordinates used are the falling particle's and pores' coordinates. If the minimum distance is bigger than or equal to the particle and pore radius, the particle will be trapped on the filter cloth and the constant TRUE is assigned on the particle. If not, a FALSE will be assigned to it.

After determining whether the particles pass through the filter cake and cloth separately, the TRUE and FALSE constant for each condition of each particle will be combined to determine whether the particle pass through the whole filtration system or not. The conditions and decision on whether the particle passes through or trapped on the filter system is shown in Table 5.

Table 5 Determination of the Particle Entrapment on the Filter System

Constant at Filter Cake Region	Constant at Filter Cloth Region	Particle Trapped
TRUE	TRUE	TRUE
TRUE	FALSE	TRUE
FALSE	TRUE	TRUE
FALSE	FALSE	FALSE

The particle with the constant TRUE assigned on the last column in the table above are the particles that are trapped on the filter cloth and contributes to the formation of filter cake. From the number of particles trapped and the total number of particles, the efficiency can be calculated as the number of particles trapped over the total number of particles. The efficiency of the filtration is expressed in terms of percentage.

3.3.2 Determination of Cake Porosity

To get the porosity of the cake, the volume of the particles trapped and the cake volume is needed. The volume of particles trapped can be directly calculated using the equation of volume of sphere

$$V = (4/3)\, \pi r_p^{\,3} \tag{31}$$

where V is the volume of the sphere and r_p is its radius. To calculate the volume of the cake, the height of the cake is needed. Al-Otoom states in his paper that a geometrical analysis is used for this purpose, but no further explanation on how the analysis was done was present in his literature. Due to this reason, an additional assumption is made to facilitate the height calculating process, which is that all particles located at the same 17.16171 μm x 17.16171 μm squares on the filter cloth will be stacked on top of each other. This means that the height at each 17.16171 μm x 17.16171 μm squares is equal to the summation of the diameters of the particles inside the region. After the height of each square is obtained, the highest value is taken as the height of the cake. From this height, the volume of the cake and its porosity is calculated. The simulation is repeated for smaller particle number, which denotes the increase in total filtration area.

3.3.3 Determination of Pressure Drop

The pressure drop is determined using the variant of Ergun equation, or equation 15. The pressure drop is calculated using varied superficial velocity, which is the same as the velocity used in the FEMLAB model.

Finally, all the filtration parameters obtained is plotted as graphs to show the trends and to facilitate the comparison between the models. Initially, an experiment of atta flour filtration was planned to be done, but it was cancelled due to equipment malfunctioning. An experimental data would be useful to verify both models.

CHAPTER 4
RESULTS AND DISCUSSION

This discussion will be in terms of comparison between the two models, the first one is the FEMLAB model using Darcy's Law, and the other one is the model developed by Al-Otoom based on the size and distribution of particles to determine the pressure drop, porosity and particle collection efficiency.

4.1 FEMLAB Solution

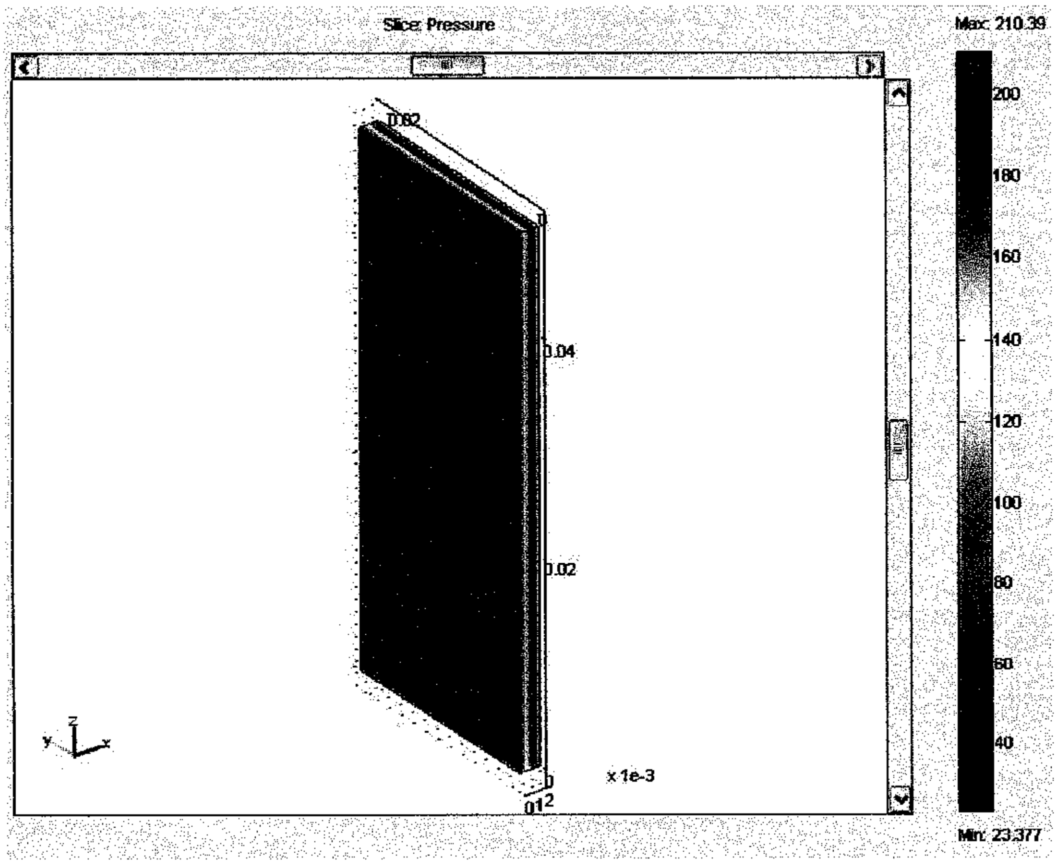

Figure 5 Sample of Solution to Find Pressure Drop using Darcy's Law in FEMLAB

The plot of pressure distribution of the filter cloth was obtained using FEMLAB and was shown in Figure 5. The dark red surface is the inlet surface of the filter cloth, while the back side, which is in dark blue, is the outlet surface of the filter cloth. Using the colour scale in the figure, it can be interpreted that the pressure at the inlet is higher than the outlet. This indicates that there is a pressure drop across the porous media, which is expected.

4.2 Pressure Drop

According to Nassehi et al, "the maximum contribution to the pressure drop value is by virtue of the flow through the porous medium". An expected rise in the pressure drop is noted across the porous media along the flow direction. For the FEMLAB model, this is a result of low permeability. In this case, the permeability is as low as $2.9115306 \times 10^{-12}$ m^2. The air flow will be hindered due to this low permeability. The resistance to the flow through the porous media is also due to the friction between the flow and the structure of the porous media. As a result, pressure will build up at the inlet of the filter cloth. Also, as the outlet of the filter cloth has a zero pressure condition, a differential pressure will exist across the filter media.

In case of the model by Al-Otoom, the facts above are also true. But as this model considers only the pressure drop resulting from the filter cake, the factors contributing to the increase of pressure drop across the filter media are the properties of the cake, such as thickness and porosity.

The result of pressure drop for Al-Otoom's model is shown in Figure 6 while the pressure drop from FEMLAB model is in Figure 7. It is found that the pressure drop of Al-Otoom's model is significantly less than the pressure drop simulated using FEMLAB model. This is due to small amount of mass sample simulated; so the cake thickness for Al-Otoom's model is very small compared to the thickness of the filter cloth present in the FEMLAB model. As the Ergun's equation used considers the thickness of the porous media, the pressure drop will be less as the thickness of the porous media decrease.

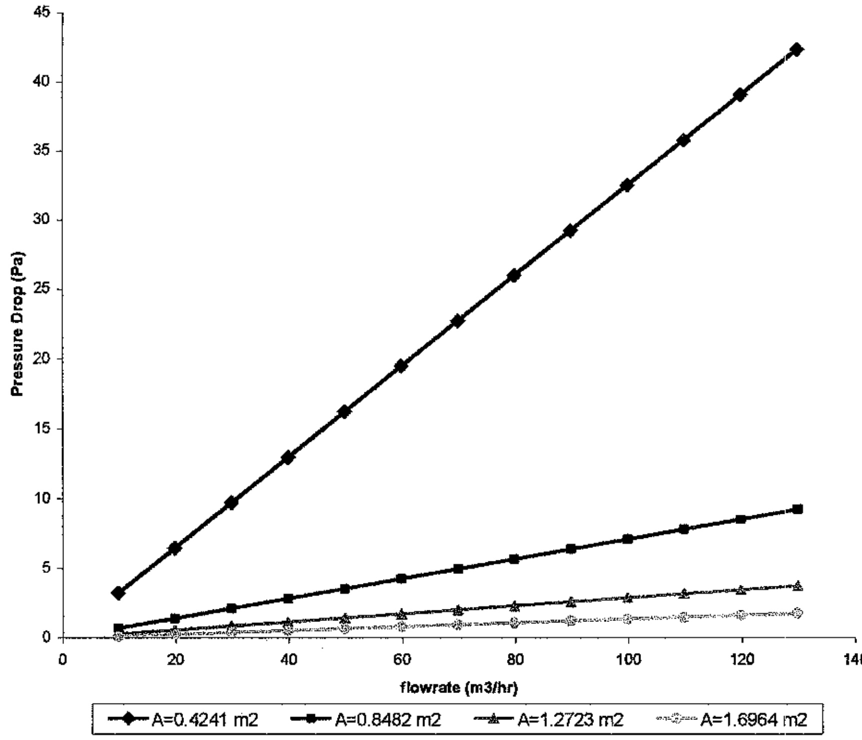

Figure 6 Pressure Drop Simulated using Al-Otoom's Model

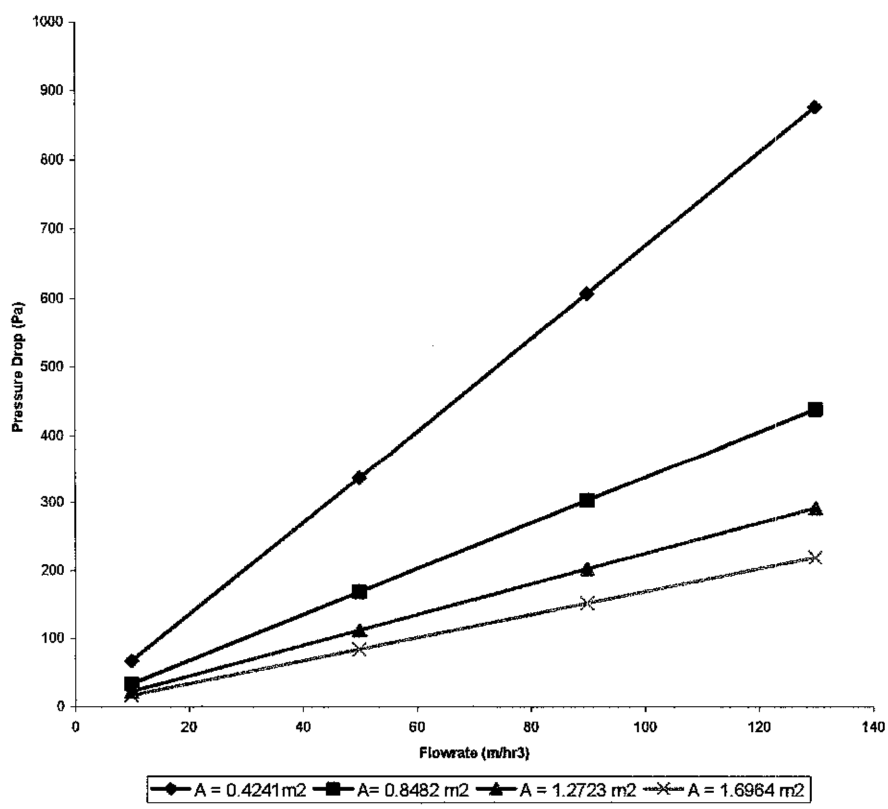

Figure 7 Pressure Drop Simulated using FEMLAB Model

As the gas flowrate increases, the pressure drop will also increase. This is due to more gas molecules become in contact with the filter at its inlet side. As there is a resistance to the flow introduced by the porous media, larger amount of molecules will exert more pressure on the filter cloth, resulting in higher pressure drop across it. The trend of change of pressure drop due to the increase of flowrate is found to be the same in both of the models used.

For fixed flowrate, change of pressure drop is also found as the area of the filter cloth increase. The pressure drop of smaller filter area would be smaller than that of larger filter area. For FEMLAB model, this change is due to less flowrate per unit area, or superficial velocity u. Larger filtering area provides more space for the air molecules. This will result in less force exerted by air molecules per unit area and lower pressure drop.

4.3 Filter Media Porosity

The pressure obtained from FEMLAB model is used to calculate the porosity of the filter cloth. As no filter cake is considered for this calculation, the porosity of filter cloth is obtained at the range from 0.6023 to 0.6026, which complies with the value specified by the supplier. This shows that the pressure drop simulated using FEMLAB and Ergun equation can be used to determine the porosity of a porous media if the value is unknown.

The model by Al-Otoom yields the filter cake porosity value as shown in Figure 8. It is found that the porosity of the cake is within the range of 0.84 to 0.875 and they increases as filter area increases. The decrease in the filter area, which is the total filtering area, will result in larger amount of particles per unit area. More particle per unit area means that there will be some particle that occupies the spaces between the particles that forms the cake. This results in less volume of voids per volume of cake, which means less porosity. It can be said that the result complies with the theory.

However, the values obtained for the porosity is quite high, which is more than 0.8. This condition may be due to the additional assumption to the model, which is that all particles located at the same 17.16171 μm x 17.16171 μm squares on the filter cloth will be stacked on top of each other. This assumption may not be suitable to be used as assumption for the arrangement of particles in the cake as it may increase the number of voids present in the cake. However, as the geometrical analysis mentioned by Al-Otoom is not explained further and there were lack of suitable software to do this analysis, the fact that the porosity follows the actual trend of porosity as filter area increases is satisfying enough for the time being.

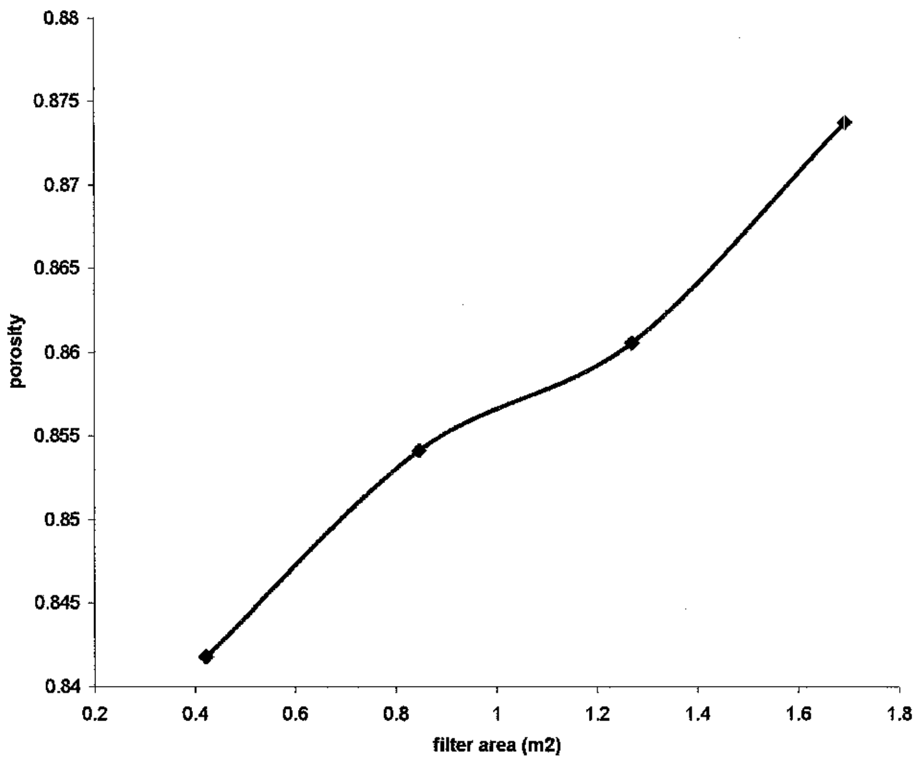

Figure 8 Filter Cake Porosity Simulated by Al-Otoom's Model

4.4 Filtration Efficiency

As the FEMLAB model does not include the mass or amount of particle entering the filter system from the start, the amount of pressure drop contributed by the filter cake will be very small. This value is calculated by subtracting the pressure drop contributed by the filter cloth from the simulated pressure drop. As shown in equation 7, the pressure drop by the filter cloth is defined as $\Delta p_0 = K_1 u$, it is calculated using the slope of Δp versus u graph as K_1 (Figure 9) and superficial velocity u. The value of K_1 is found to be 10301 Pa.s/m.

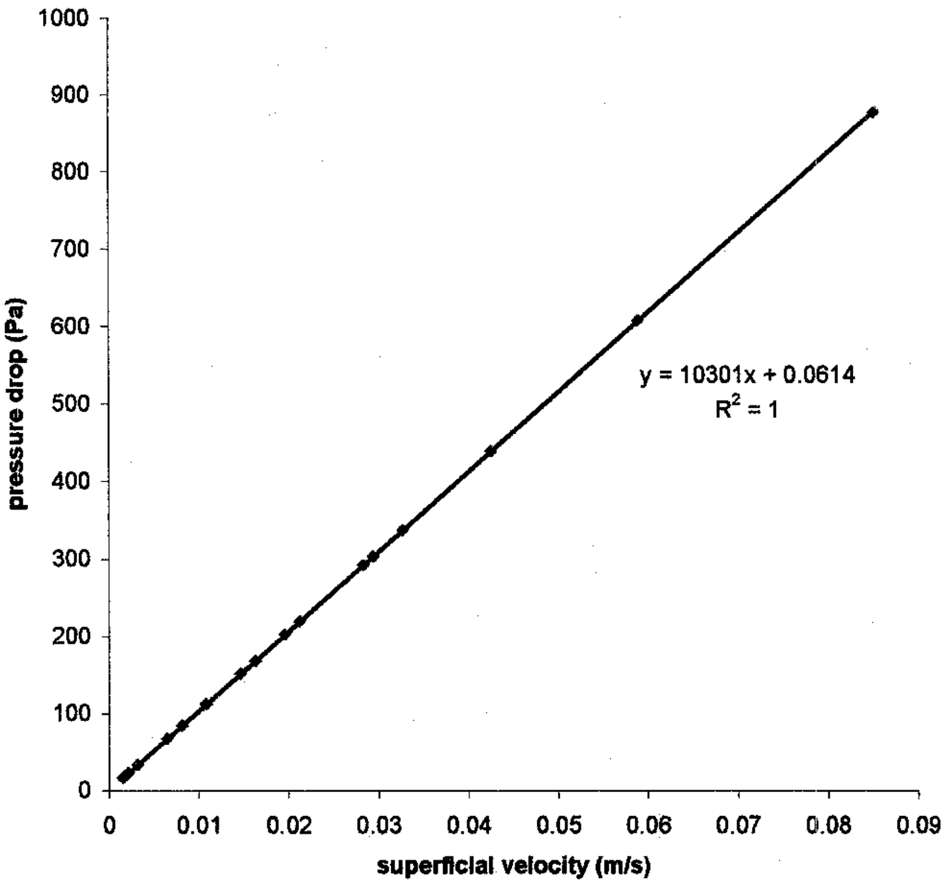

Figure 9 Graph to Determine the Value of K_1.

As the filter cake is unable to be taken into account, the pressure drop obtained from the filter cloth made up almost all of the total pressure. The residual pressure drop, which is the pressure drop contributed by the cake is too small and leads to low and inconsistent efficiency. However, this method may yield better result if experimental data on the filter cake is used in the prediction of the pressure drop. The new pressure drop calculated may consist of the pressure drop from the filter as well as the pressure drop from the cake

For the model by Al-Otoom, the efficiency is as shown in Figure 10. The efficiency is found to be high, but decreasing with filtering area. However, the range is very small, which is 99.6% to 99.9%. The decrease is due to the reason that larger filtering area means less particle per unit area, thus there will be less cake formed. The cake formed on the filter cloth will also act as filter and less cake formed may result in less efficiency.

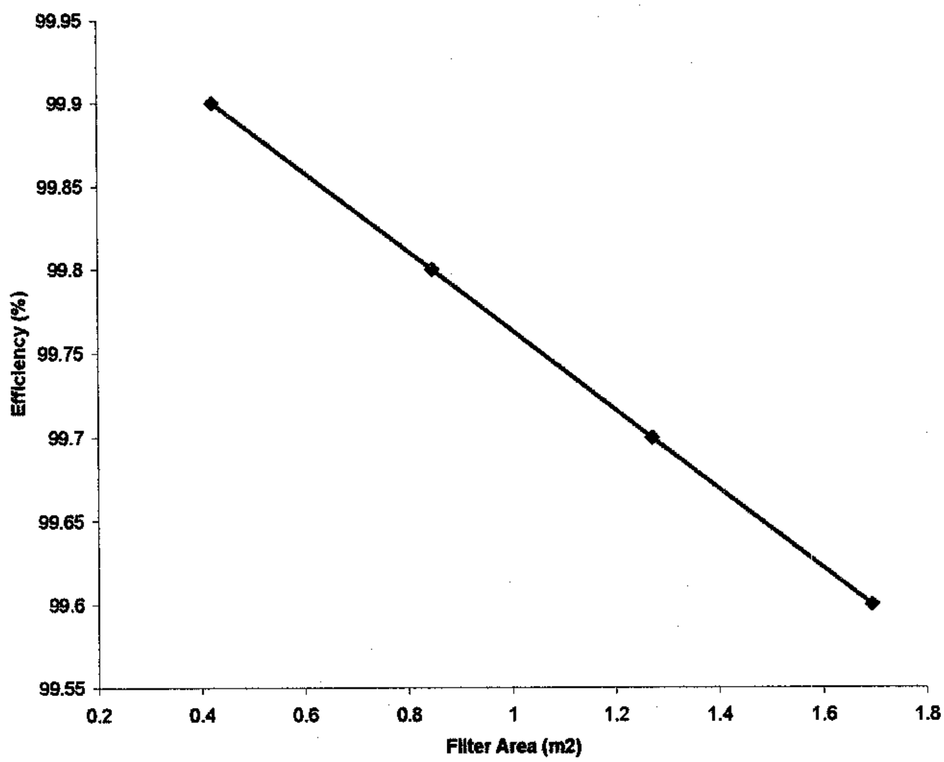

Figure 10 Filtration Efficiency modeled by Al-Otoom's Approach

CHAPTER 5
CONCLUSION AND RECOMMENDATION

5.1 Conclusion

From the project, it can be concluded that the model by Al-Otoom agrees with the filtration theory in terms of pressure drop, porosity and efficiency. The porosity is found to be high possibly due to the additional assumption used in determining the height of the cake. The FEMLAB model developed using Darcy's Law, Ergun equation and approach stated by Novick and Klassen agrees with the filtration theory in terms of pressure drop and porosity. The porosity calculated by this approach is the filter cloth porosity. The efficiency calculated by this model is low and inconsistent possibly due to no incorporation of particle mass or amount in the flow model by FEMLAB

5.2 Recommendation

It is recommended that improvement is done to the FEMLAB model in terms of the consideration of the inlet mass or amount of particle in the pressure drop modelling using FEMLAB. The filter cake simulated will help the calculation of pressure drop contributed separately by filter cloth and filter cake, which will help in the calculation of porosity and efficiency. Also, to further verify the model by Al-Otoom, it is suggested that suitable software is used for the geometrical analysis instead of using assumptions.

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APPENDICES

APPENDIX A

PORE AND PARTICLE COORDINATE ASSIGNMENT

pore coordinates		
pore no.	x	Y
1	0.000000	0.000000
2	0.000000	17.161711
3	0.000000	34.323421
4	0.000000	51.485132
5	0.000000	68.646842
6	17.161711	0.000000
7	17.161711	17.161711
8	17.161711	34.323421
9	17.161711	51.485132
10	17.161711	68.646842
11	34.323421	0.000000
12	34.323421	17.161711
13	34.323421	34.323421
14	34.323421	51.485132
15	34.323421	68.646842
16	51.485132	0.000000
17	51.485132	17.161711
18	51.485132	34.323421
19	51.485132	51.485132
20	51.485132	68.646842
21	68.646842	0.000000
22	68.646842	17.161711
23	68.646842	34.323421
24	68.646842	51.485132
25	68.646842	68.646842

particle no	Radii	x	y
1	12.366976	5.993476	31.992565
2	15.827181	43.978965	14.722303
3	2.294085	48.050898	64.550841
4	2.326461	40.586204	0.794943
5	16.926149	61.086532	60.313603
6	15.396783	34.806966	30.920557
7	14.634179	8.131206	19.503218
8	11.077997	30.076468	45.518097
9	17.514760	4.076640	3.512038
10	12.833509	66.527871	63.025922
11	7.646799	18.381486	26.664044
12	4.054427	30.238277	7.515275
13	12.049835	31.553567	18.683028
14	16.428768	12.143021	36.571068
15	14.483383	37.674790	55.102853
16	12.821287	6.929252	27.040687
17	12.878699	65.752293	59.512448
18	13.770213	23.001666	16.940872
19	17.810880	41.820849	7.290611
20	6.960309	51.860120	63.012328
21	18.588518	8.084014	54.147943
22	17.763717	3.410369	34.596565
23	19.564519	46.488041	64.965263
24	17.219778	26.872054	5.184581
25	16.852215	14.071730	17.941872
26	6.942341	46.922494	41.771405
27	5.569323	62.093709	28.213616
28	11.442414	32.961760	26.597591
29	16.236108	59.373255	65.383836
30	10.506325	5.771155	42.083787
31	5.281782	25.532856	11.340266
32	17.027712	29.141606	44.531704
33	2.196915	46.469692	16.072611
34	15.375428	65.616523	34.515800
35	11.548646	24.916857	42.772634
36	9.131853	36.725478	11.836612
37	4.779301	48.259853	25.652300
38	7.794894	56.040677	7.787774
39	15.070224	45.109419	63.634470
40	6.638372	37.188861	45.249989
41	14.053510	54.851283	48.561283
42	14.177368	45.221135	29.437522
43	13.119087	53.153580	34.433283
44	4.982232	61.164700	44.925484
45	9.784427	34.331667	35.210728
46	17.312103	59.478241	48.783934
47	14.779319	7.364840	32.226476
48	10.647150	0.845039	66.544716
49	15.020876	16.235918	66.044945
50	6.189634	9.051969	24.798074
51	18.840604	0.663476	33.510157

52	6.944529	50.478938	56.276828
53	2.118453	8.971578	67.700483
54	13.262804	40.400490	58.957404
55	19.931386	32.917613	59.767331
56	8.290837	40.885225	22.295086
57	1.306503	27.193015	34.152964
58	8.614569	38.738773	42.751628
59	15.733479	13.352989	40.753420
60	4.245862	0.601005	12.731101
61	1.498689	60.635114	36.081176
62	13.510933	13.362208	51.999332
63	12.243396	17.809898	25.181083
64	11.734968	32.335159	40.171477
65	16.450577	54.948646	48.728521
66	9.986135	29.759704	43.675766
67	10.549370	6.760691	28.318657
68	7.358663	10.798455	19.558871
69	10.382317	57.322986	5.438580
70	16.930940	21.393153	42.566969
71	17.501457	4.110705	34.881968
72	2.512665	25.036411	38.208331
73	19.882638	20.676906	68.411603
74	17.394538	42.987909	10.217589
75	8.356102	53.719526	44.832151
76	11.401001	67.895937	4.714214
77	12.443721	68.624319	15.299679
78	13.269812	17.452055	20.759792
79	4.817447	41.351967	28.952395
80	12.566154	13.353255	61.078358
81	5.710869	28.727968	58.453464
82	3.512177	1.175735	54.629775
83	5.886660	13.174419	48.205758
84	17.706829	15.118805	25.229626
85	4.184511	61.992614	40.101584
86	9.085436	19.974699	41.836569
87	8.321501	51.389579	36.545466
88	5.511883	40.167156	23.956294
89	10.642235	32.141721	45.819112
90	9.254864	8.871854	23.670657
91	6.784710	11.896069	6.396602
92	4.963717	31.516750	59.936724
93	18.455284	14.722254	66.722283
94	13.546414	58.679407	34.192437
95	9.914360	64.751031	12.492780
96	5.861500	59.299604	52.737849
97	6.236355	68.329872	38.468772
98	10.453682	36.254592	30.002669
99	19.819910	12.884419	47.609117
100	1.216342	34.941853	40.718965

APPENDIX B

FEMLAB FEATURES MENU

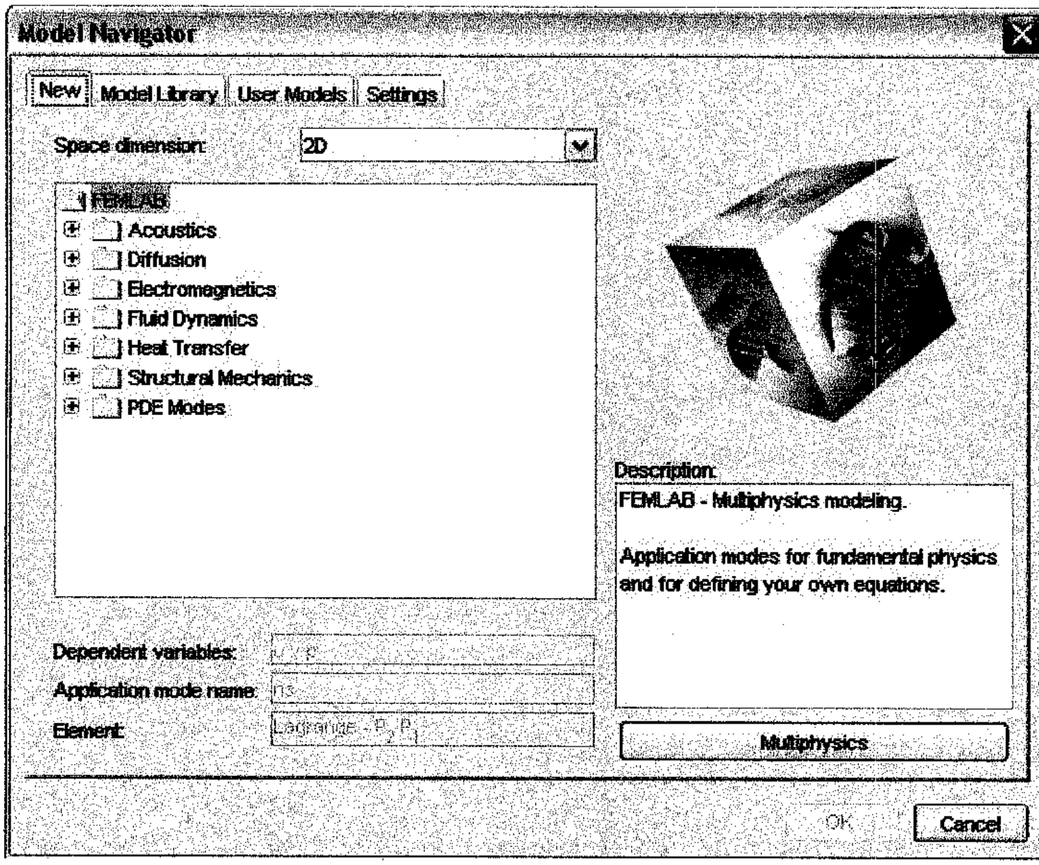

Figure B-1: Model Navigator

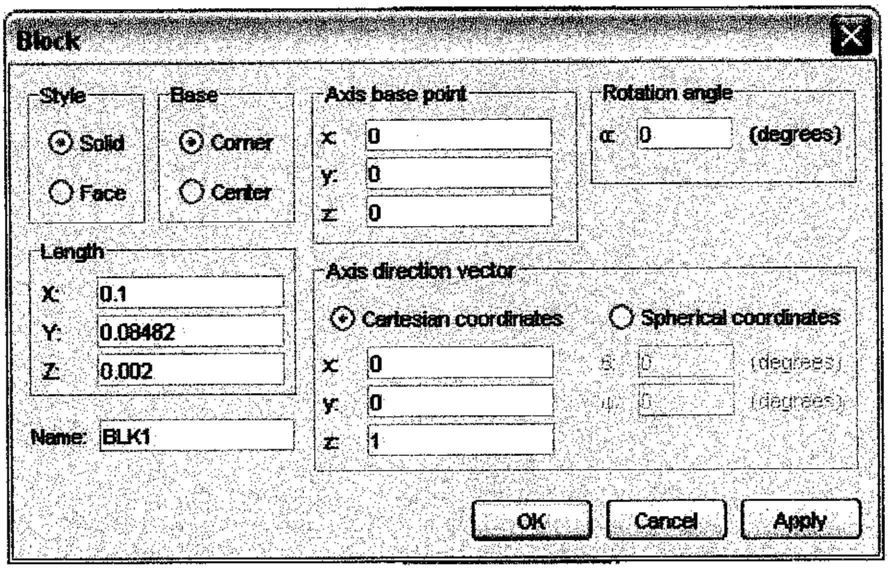

Figure B-2: Block

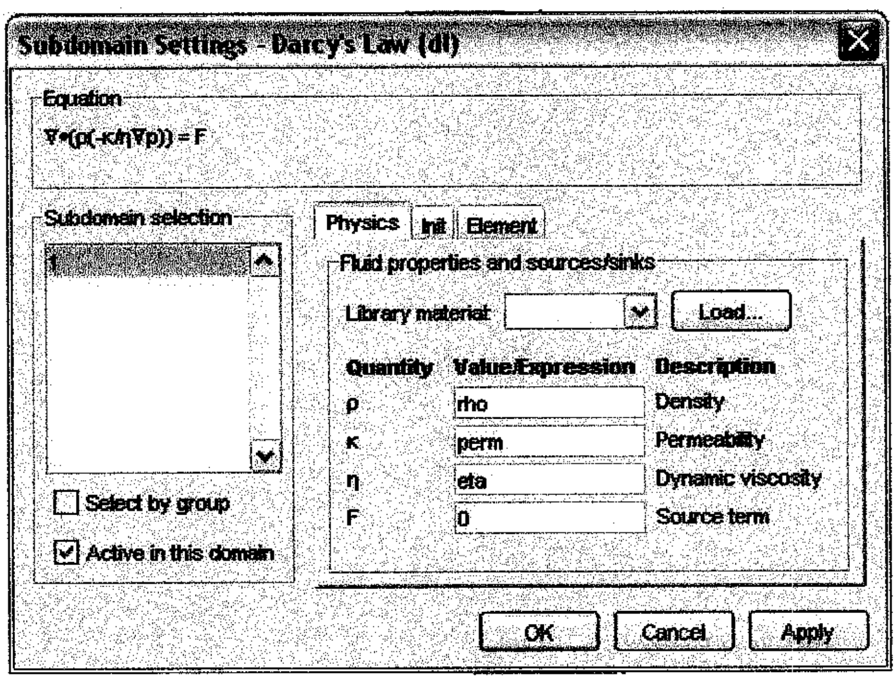

Figure B-3: Subdomain Settings

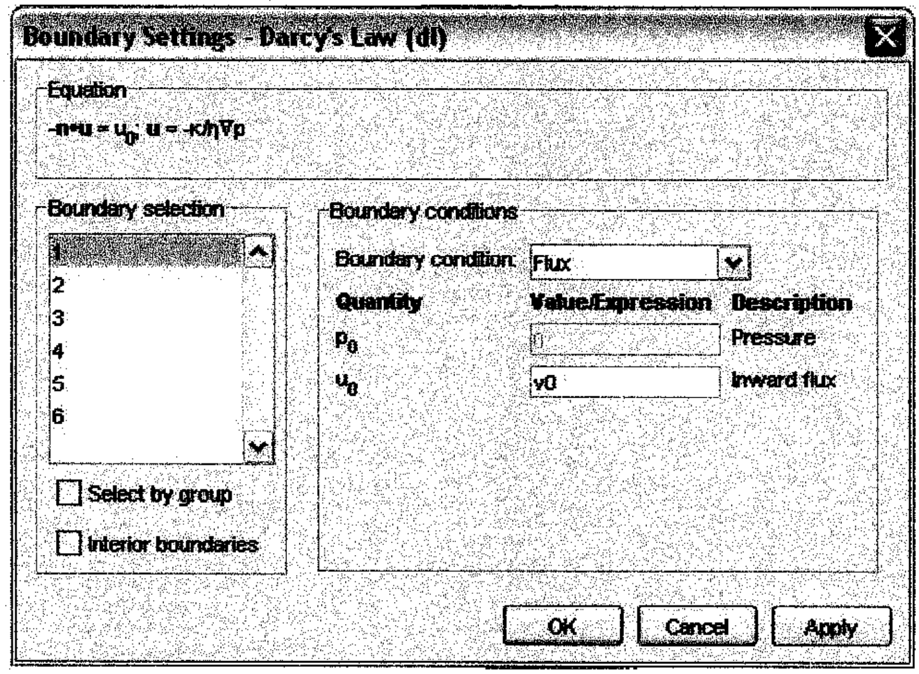

Figure B-4: Boundary Settings

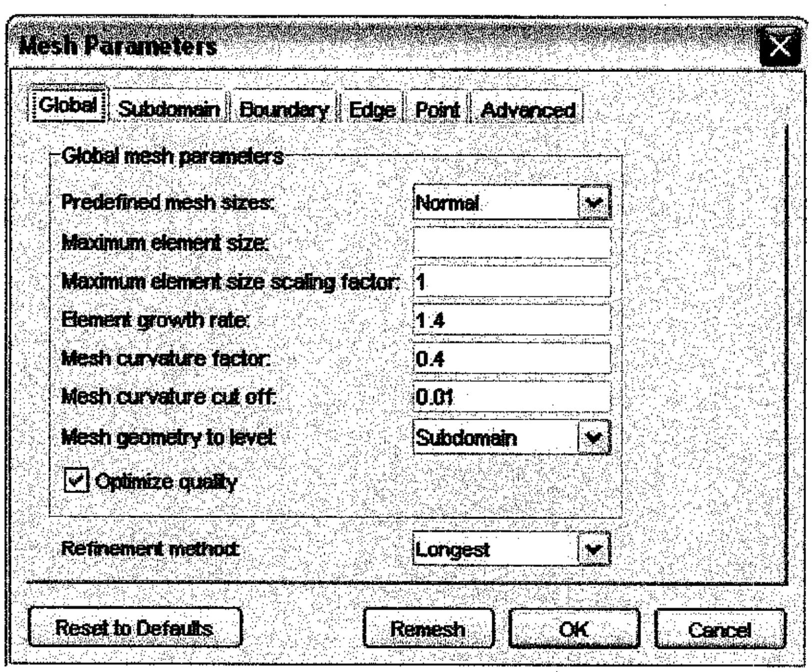

Figure B-5: Mesh Parameters

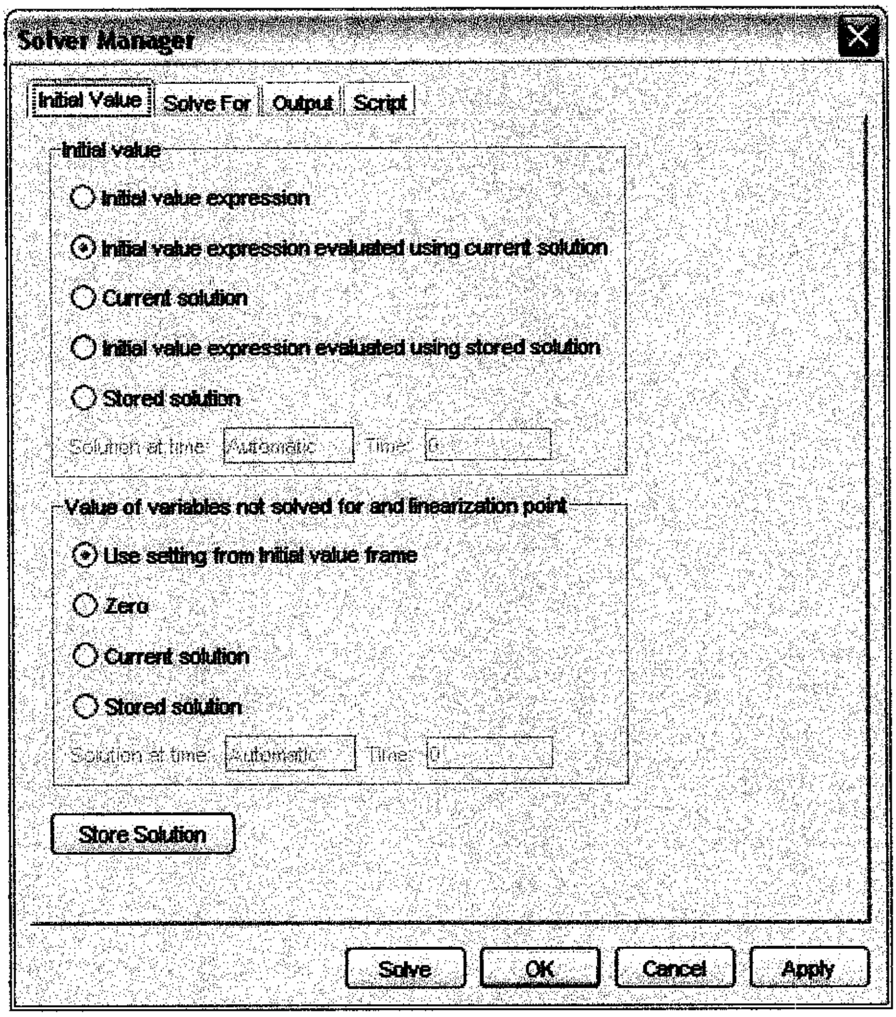

Figure B-6: Solver Manager

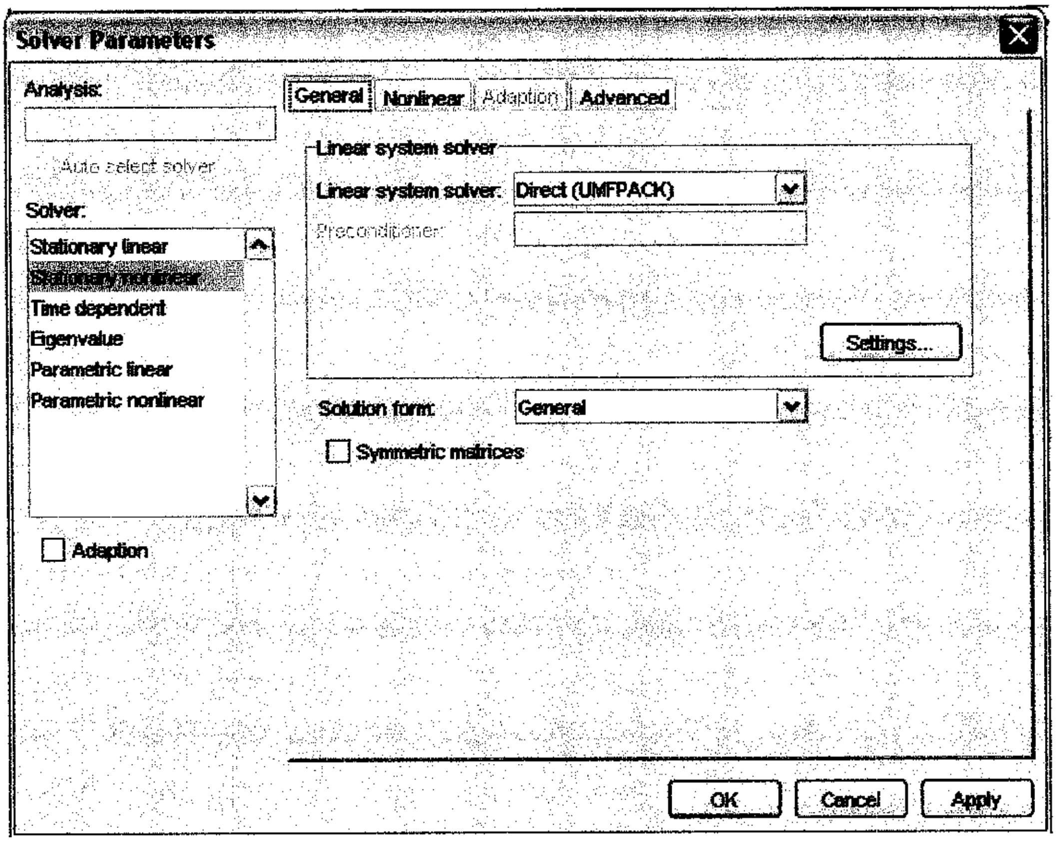

Figure B-7: Solver Parameter

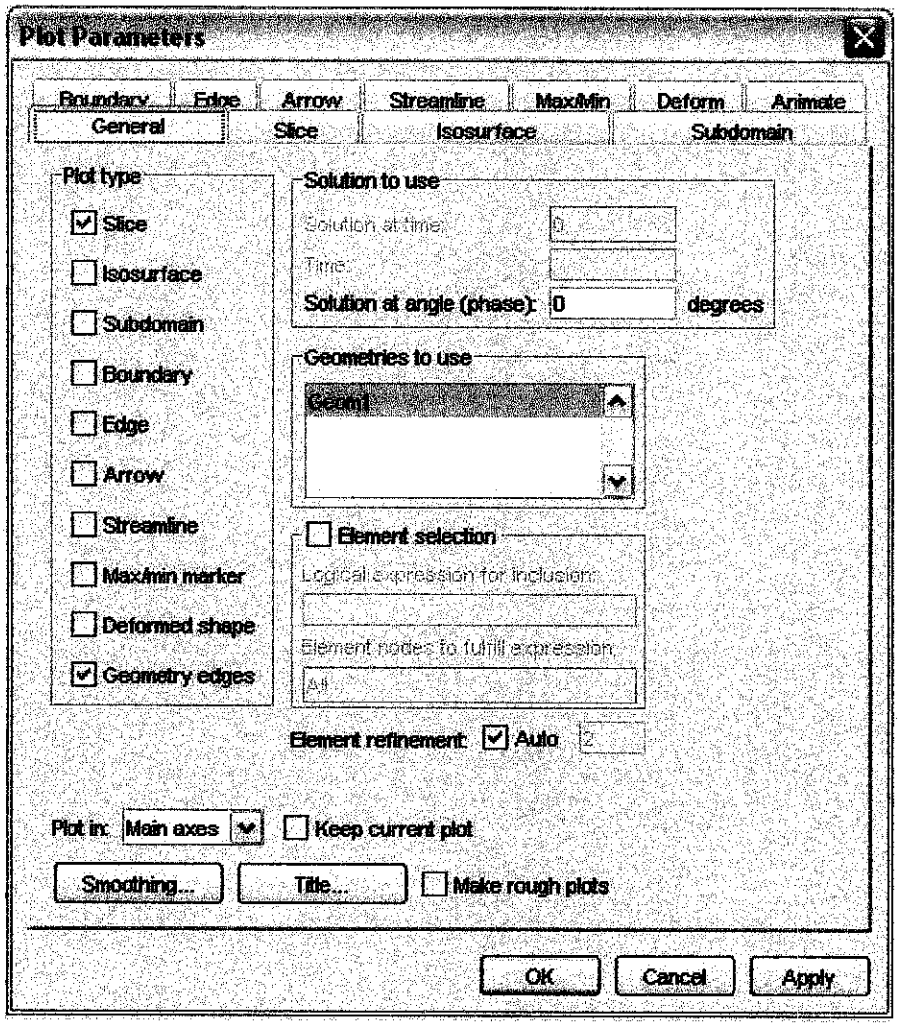

Figure B-8: Postprocessing (General tab)

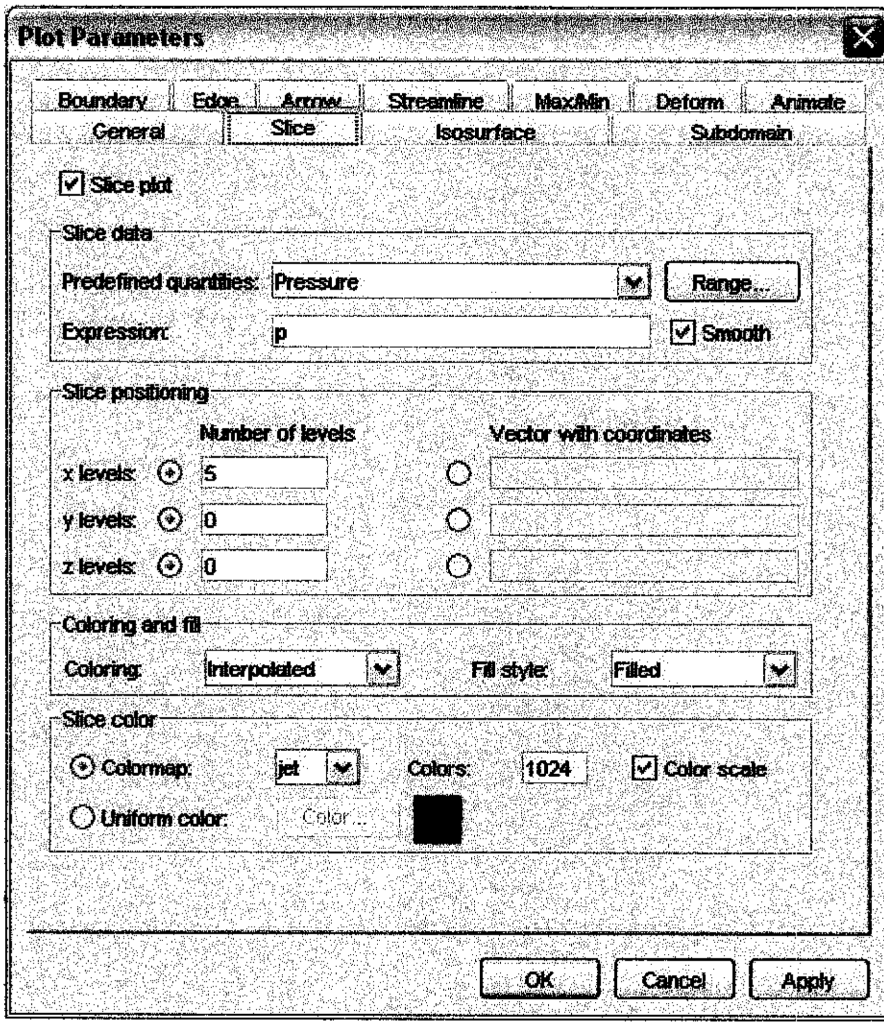

Figure B-9: Post processing (Slice tab)

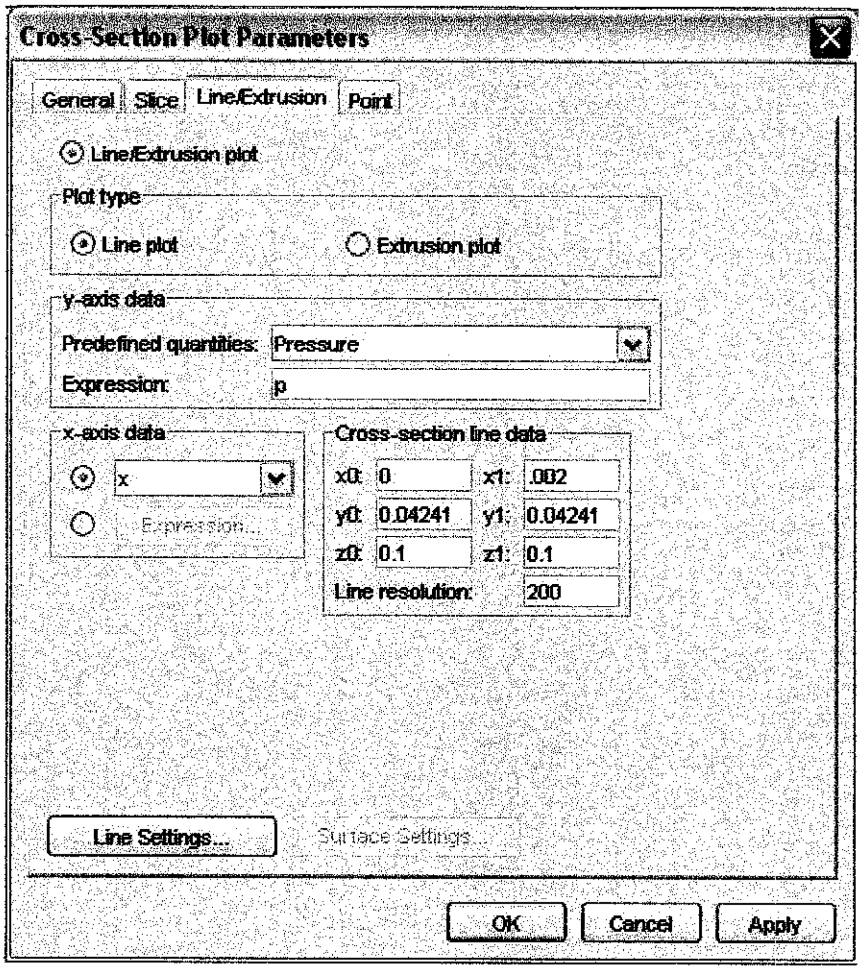

Figure B-10: Cross Section Plot Parameters

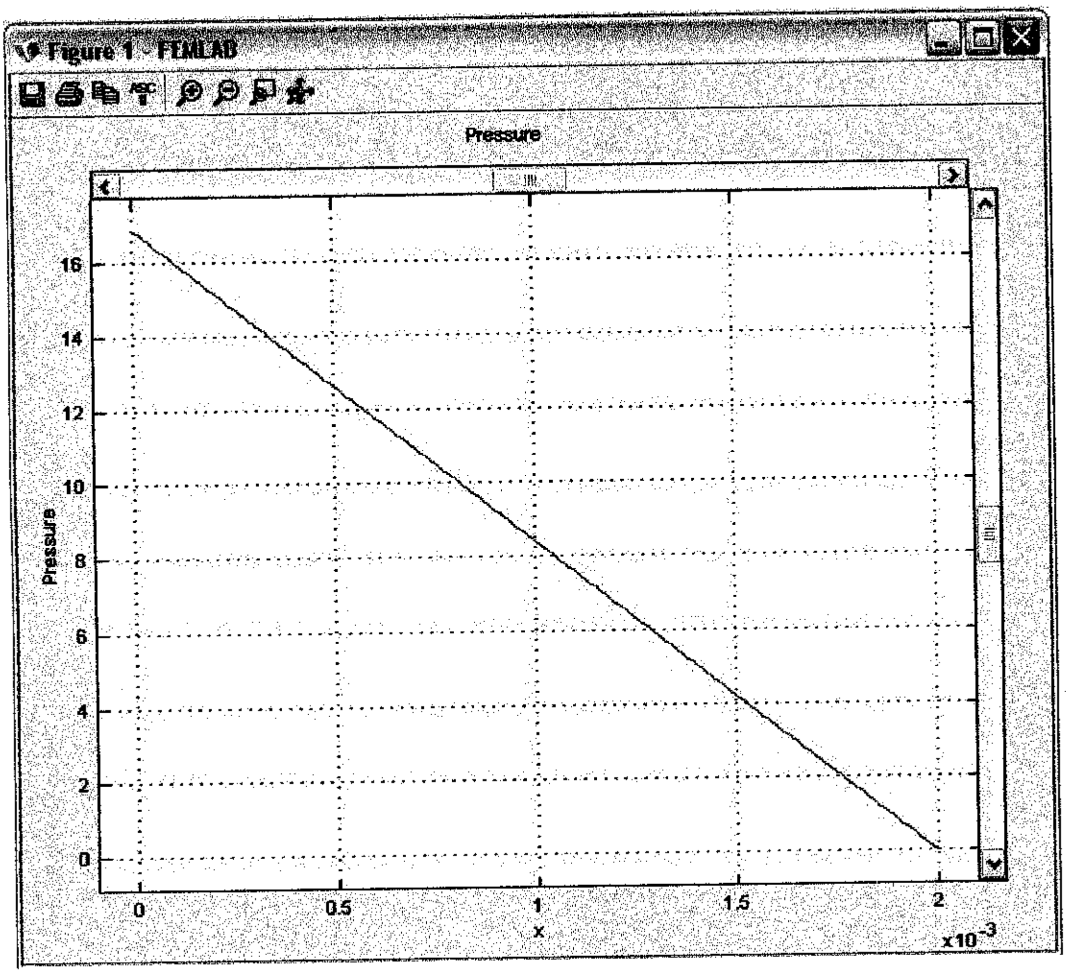

Figure B-11: Cross Section Plot Sample