Packed Bed Consisting of Different Sizes of Glass Spheres

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by

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ABSTRACT

The aim of this research is to study the packed bed using theoretical methods and experiments.

Five types of glass spheres were used which represent the packed bed with diameters of (d_1= 7.972, d_2 = 10.164, d_3= 14.772, d_4 = 20.614, d_5 = 25.448 mm).

The theoretical methods which was given by latif consist of calculating the pore diameter, mean pore diameter and the probability due to (number, length, area, and volume). The results obtained using computer program and these results showed that the probability of finding pore size in any packed bed is different for each distributions.

An experimental apparatus was built, which consists of glass cylinder in which five types of spheres put in, sieve, and impurities passed through the packed bed.

Results obtained from the experimental work showed that the percent output of impurities decreased with the increase of the number of layers; and also decreased with increase of size of impurities for each value of number percent of spheres.

Experimental results are related with theoretical results in order to find the relation between mean pore diameter and percent output of impurities for each bed, the increase in size of spheres lead to increase the mean pore diameter.

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NOMENCLATURE

a_k	Ratio between diameter of small and large particles.
a_m	Ratio between diameter of medium and large particles.
A_g	Area function of large spheres.
A_K	Area function of small spheres.
A_m	Area function of medium spheres.
d	Particle mean diameter (mm).
dc	Mean value of pore diameter (mm).
dc_I	Pore diameter of three equal sizes of diameter (mm).
dc_{II}	Pore diameter of two equal and one different size of diameter (mm).
dc_{III}	Pore diameter of three different sizes of diameter (mm).
$dc_m a$	Mean pore diameter due to area.
$dc_m l$	Mean pore diameter due to length.
$dc_m n$	Mean pore diameter due to number.
$dc_m v$	Mean pore diameter due to volume.
d_g	Large particle diameter (mm).
d_K	Small patrticle diameter (mm).
d_m	Medium particle diameter (mm).
K_1 to K_5	constants.
L_g	Length function of large spheres.
L_k	Length function of small spheres.
L_m	Length function of medium spheres.
n	Number of repetition.
n_g	Number of repetitions for large particles.
n_K	Number of repetitions for small particles.

$\mathbf{n_m}$	Number of repetitions for medium particles.
$\mathbf{N_g}$	Number function of large spheres.
$\mathbf{N_k}$	Number function of small spheres.
$\mathbf{N_m}$	Number function of medium spheres.
$\mathbf{P_i}$	Probability of finding the pores.
$\mathbf{P_r}$	Probability for diameters.
$\mathbf{P_{ra}}$	Probability of diameters due to area.
$\mathbf{P_{rl}}$	Probability of diameters due to length.
$\mathbf{P_{rn}}$	Probability of diameters due to number.
$\mathbf{P_{rv}}$	Probability of diameters due to volume.
$\mathbf{r}$	Type of distribution.
$\mathbf{r_g}$	Type of distribution for large particles.
$\mathbf{r_K}$	Type of distribution for small particles.
$\mathbf{r_m}$	Type of distribution for medium particles.
$\mathbf{V_g}$	Volume function of large spheres.
$\mathbf{V_k}$	Volume function of small spheres.
$\mathbf{V_m}$	Volume function of medium spheres.

CHAPTER ONE

Introduction

The study of pore size in packed bed is necessary to study the properties of the packed bed. To purify materials from impurities, and the packed bed is used in many industries such as adsorption, desorption distillation, filtration etc.

Pore size among the many that are required in the evaluation of porous media and membranes and it affect factors such as adsorption capacity, adsorption kinetics, exclusion phenomenon, adsorption competition and others, which are fundamental knowledge in further investigation and design of adsorbent or absorber [1].

The pore concept refers generally to models representing the voids in a porous medium as a set of elementary units with simple geometrical shapes (eg. A bundle of cylindrical tubes of various apertures).

The pore size among the most commonly used parameters for the characterize of particles or surface shape and these parameters are: -particles size distribution, specific surface area, specific pore volume, pore size distribution and density [2].

Enumerations all most all proposed space models is presented and classified with reference to the pore space inter connectivity. This inter connectivity may be one – dimensional models (transport is possible in one direction only) such as; tubes in parallel, in series; tubes with constrictions;

random adjacent silices models, two dimensional models (transport in plane containing the macroscopic transport direction) such as network models, three dimensional models (transport also in a plane perpendicular to the macroscopic transport direction) such as regular spheres packing; tetrahedral networks; tubes and /or junctions randomly in space , and strictly zero dimensional such as simple capillary elements used in ad hoc explanation ; independent domain in theory.

All the models have been given a number that refers to their place in the classification scheme. As it usual in such cases, some models fit in adopted structures better than others. The policy has been that; in order to get a general view; it is better to force the existing models in the best possible scheme then to admit exceptions or intermediate cases [3].

A large variety of standardized methods are concerned with the determination of particle size distribution: sieve analysis, sedimentation in the gravitational field or in a centerifuge, optical methods and electrical sensing (which allow simultaneously counting and size determination of individual particles), laser diffraction, small X-ray scattering and image analysis, many of these techniques are currently under discussion [4].

Many models have been published (Perrier et al; 1995) which represents a porous media in a simplified approach as a connected set of individualized voids, cylindrical pores or parallel piped fractures, where simple, integrated forms of the Navier – stokes equations are available (namely, the poiseuille law in cylindrical tubes). In saturated conditions, i.e. a soil partially filled with water, the active network is reduced to the smaller, water filled pores according to the Lap lace law and displacement of the air – water boundaries with varying capillary pressures [5].

Ground water among the important substances that are contained in the pore spaces provided by various geological formations.

Beside the importance of porous material in industry their life functions would not be possible without pores in them, pores make breathing possible as well as the circulation of natural fluids in both plant and animal life [3].

The aim of this research is: -

1. Description of pores using spherical particles.
2. Calculate the probability of the pore diameter due to different particle size distribution (number, length, area, and volume) in different number of packing layers.
3. Weight percent of output impurities in four, five, and six layers.

CHAPTER TWO
LITERATURE SURVEY

2.1 Description of porous medium

Porous medium consist of pores between some particulate phase, contained within a vessel, or some control volume [6].

To describe the structure of porous media we have many models of them, and these models may be one-dimensional models as in fig. 2.1 , two-dimensional models as in fig. 2.2, three-dimensional models as in fig.2.3 [3].

Many models (eg. soil, sand, packed catalyst beds) consist of a large number of particles or fibers packed closely together .In between the solid particles or fibers, there is open space, giving rise to pores through which fluid can flow [7].

The concept of local porosity distribution for the geometric characterization of arbitary porous media has been evaluated using computer generated pore space images [8].

The study of low speed flow in porous media is important in a wide range of areas, including oil recovery, geothermal development, chemical and nuclear industries and civil engineering [9].

Porous media are often characterization terms of “pore size distribution “ but this does not provide a sufficient description for the calculation of important physical properties such as permeability, a variety of models for the pore space geometry of porous media have been developed. However, simple models that can be used to calculate microscopic physical properties have not yet been developed [10].

The pores in a porous system may be interconnected or non-interconnected. Flow of interstitial fluid is possible only if at least part of the pore space is interconnected. The interconnected part of the pore system is called the effective pore space of the porous medium [3].

The term porous media is useful in modeling of several chemical engineering operations, including towers packed with pebbles, bert saddles, raschig rings, etc; beds formed of sand, granules, lead shot, etc; porous rocks such as limestone, pumice, dolomite, etc; fibrous aggregated such as cloth, felt, filter paper, etc and finally catalytic particles containing extremely fine “micro” pores [11].

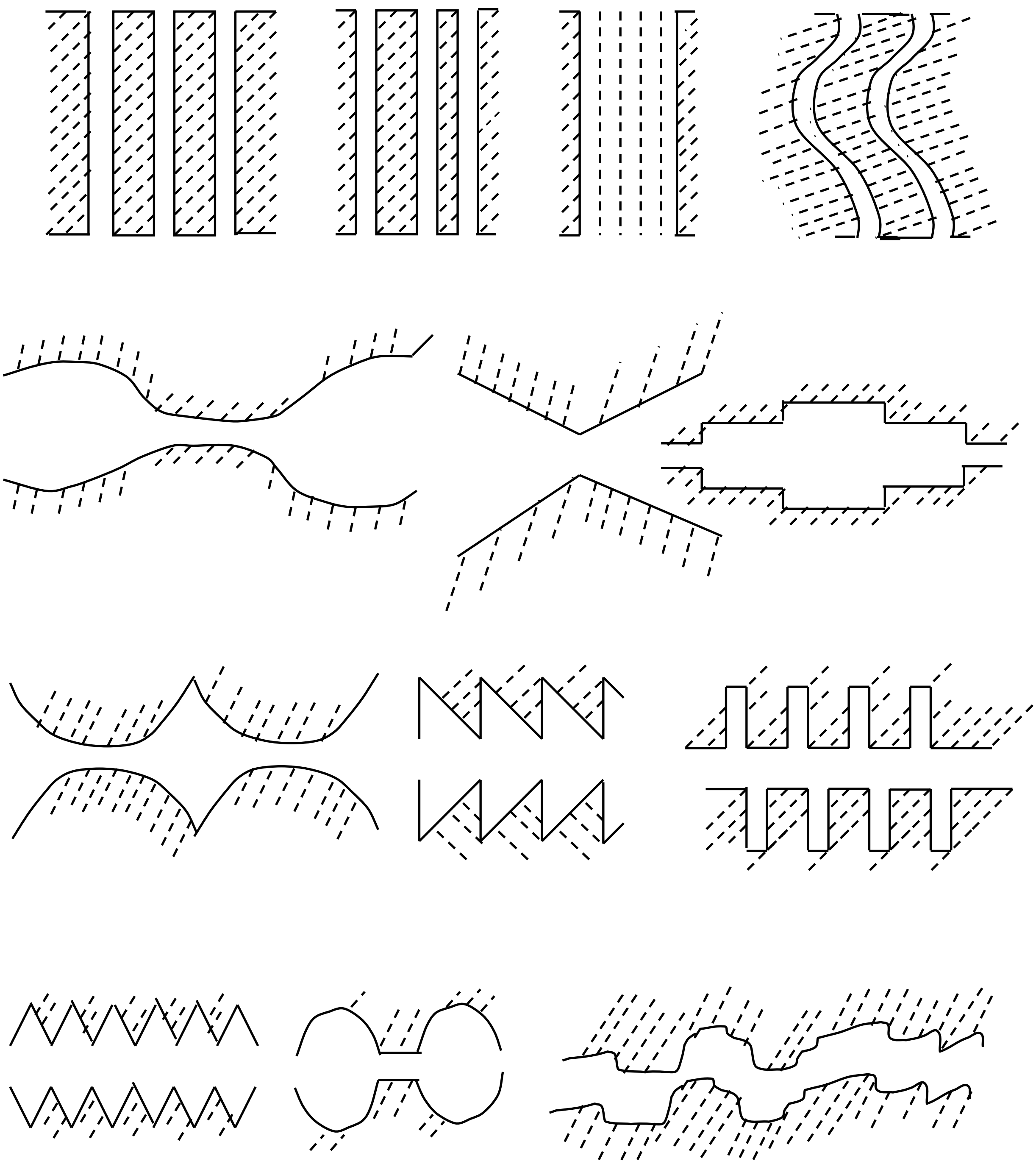

Figure 2-1 Elements of pore space models with

One – dimensional connectivity[3]

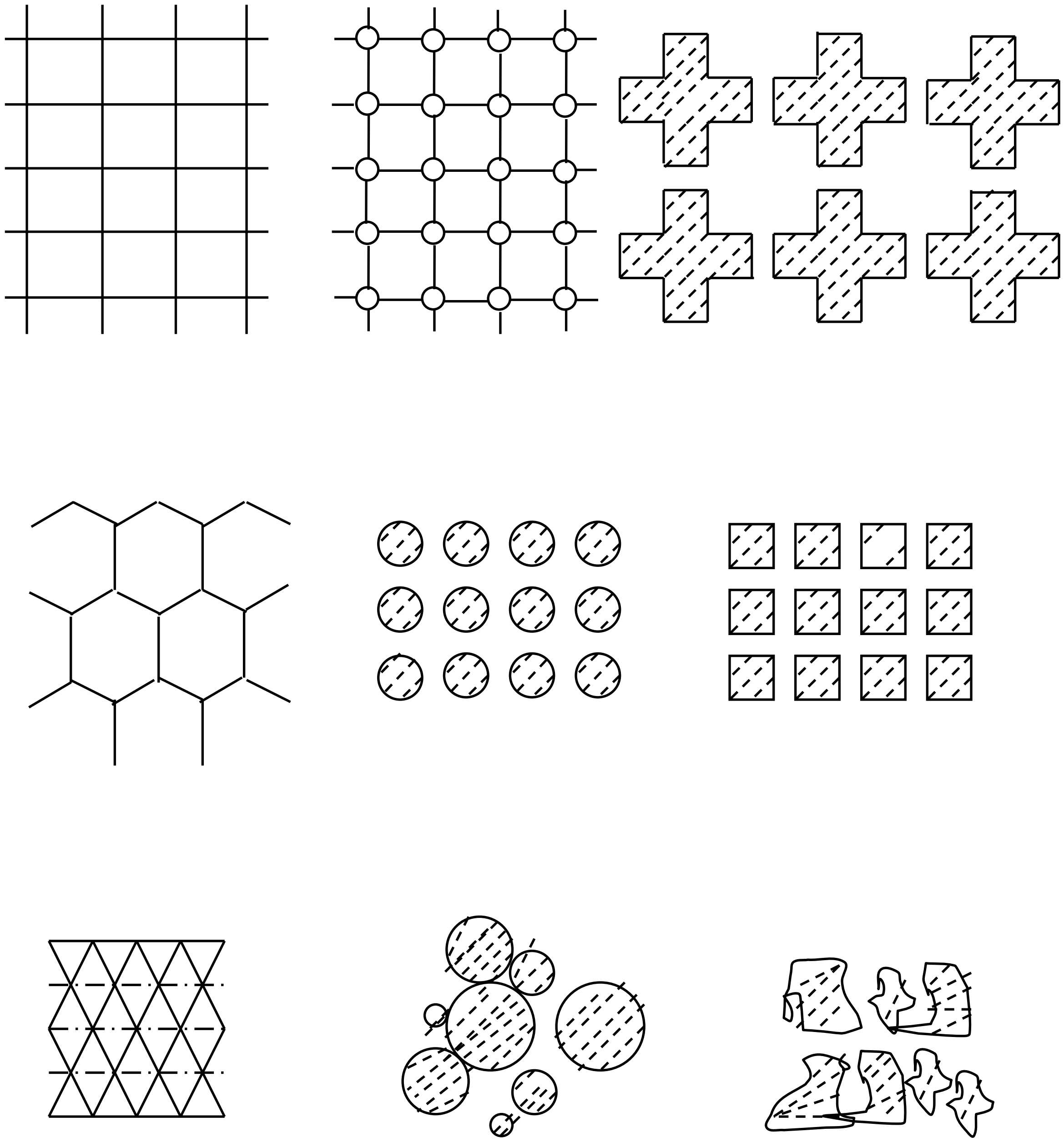

Figure 2-2 Elements of pore space models with

Two – dimensional connectivity[3]

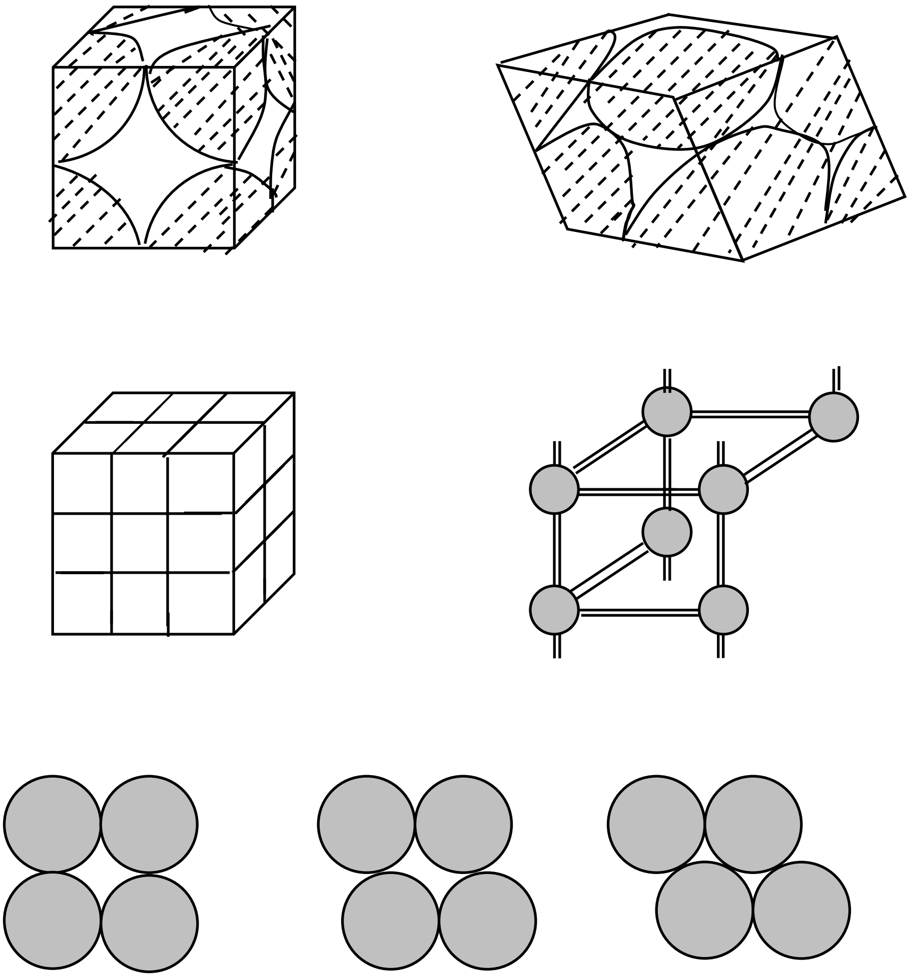

Figure 2-3 Elements of pore space models with Three – dimensional connectivity [3]

2.2 Packed bed and its theories in packing of spheres and natural materials

Packed beds play a major role in many chemical engineering processes, packed bed situations include such diverse processes as filtration, wast water treatment, the flow of crude oil in petroleum reservoir and other processes [12].

Now in order to relate the packed bed with the theories of packing of spheres we must know something about the packing of grains as well as about their shape.

A qualitative visualization of the conditions involved can be obtained by the procedure of assuming “model “ grains, usually spheres, and by studying their models of packing. Thus, one arrives at a theory of models of porous media that are composed of spheres [13,18].

Such models are constructed in the following way:- Firstly the average size of the grains is measured in one way or another and spheres of the models are investigated as being of the same diameter. The porosity of the original specimen is determined and the packing of the model-spheres is assumed to be arranged in such fashion that the model have the same porosity as the original [14,19].

The first study of the models of packing of spheres and the porosity calculated therefore appears to have been under taken by Slickter (1899). Since then the theory has been reviewed, refined, and extended by Smith, Foote and Busang (1929), Graton and Fraser (1935), Manegold (1937), Manegold and Solf (1939), Hrubisek (1941), and others [15,20].

All the above is about the packing of spheres; Now we must take the packing of natural materials (natural materials are composed of grain whose shape may deviate appreciably from that of spheres). It will often be found that the grains are somewhat cemented together without being fully consolidated, but it will still be desirable to apply some correlation between "grain size " and pore size distribution and other characteristics of the porous medium, such as specific area. Furthermore, the size of the grains will seldom be very uniform. Non- uniformity in size will, in general, permit the smaller particles to fill the spaces between the larger ones and thus appreciably reduce porosity. Contriwise, angularity of particles permits bridging with a resulting increase of porosity [16,21,22,23,24].

It is only reasonable, therefore, to expect that spherical models as discussed before will not be entirely adequate to represent even the geometrical properties of porous media (not speak of hydraulic ones). They will help us to understand some of the features better, but actual correlations between grain sizes and pore sizes, such as have been proposed, are based on experimental investigations rather than on theory. A true understanding of the effects, of course, cannot be obtained in the manner either [17,25,26,27].

Theoretical and experimental studies of the effect of grain- size on pore – size have been conducted by Tickell, Mechem and Mccurdy (1933), Nissan (1938), cloud (1941), Hrubisek (1941), Rosenfeld (1949), Griffiths (1952), and Gaither (1953). Kiesskalt and Matz (1951) and Wise (1954) discussed the dependence of specific area on the grain distribution [28].

2.3 Pore structure analysis [29]

The structure of most porous media is far too irregular and complicated to allow a rigorously correct geometrical description. Even if it were possible somehow to enter all pores with a tiny probe and determine the coordinates of every point on the bounding surfaces of the pores and store this information in the memory of some giant computer, this kind of three – dimensional map of the pore structure would only be of limited usefulness without appropriate equations capable of giving the mass transport and the capillary behaviour for such highly irregular channels. Such equations, however, have not been developed, much the same way as an accurate mapping of the pore structure has not been possible up to the present time.

The development of improved mathematical models of the pore structure and the experimental determination of the parameters that are necessary to compare different samples in terms of the models is the more realistic aims of pore structure analysis.

The ideal aim of pore structure analysis is to develop mathematical models that will account for all the important properties, such as effective diffusivity, permeability, relative permeability, capillary hysteresis, dispersion coefficient, etc, or real porous media, quantitatively. It can be expected that different types of porous media will require quite different models to achieve this aim.

The model of pore structure that is used almost universally at the present time consists of straight, nonintersecting cylindrical tubes, the diameters of which are distributed according to some distribution function. Whereas this model can be fitted to account for certain properties of porous samples, it cannot even qualitatively account for two- phase flow behaviour and capillary hysteresis.

To develop more accurate models of real porous media, a great deal more information is required on the shape, true size, and degree, as well as the type of interconnectedness of the pores in such materials. The best way this kind of information can be obtained, and suitable mathematical models developed, is by a combination of properly designed experiments and a careful mathematical analysis of the problems.

The different contributions to pore structure analysis can be divided roughly into two categories: -

1- Development of mathematical models to be used in correlating certain properties of certain types of porous media.

2- Basic studies aimed at an improved understanding of pore structure.

In some contributions, both objectives have been pursued simultaneously; however, in the vast majority of cases the contributions fall quite naturally into one or the other of the above categories.

The models of pore structure investigation can be conveniently classified as follows: vapor sorption, diffusion, fluid flow, capillarity, micrography, radiography and miscellaneous methods.

There are very few instances where the pore structure of one and the same substances has been investigated by a variety of different methods. In the majority of the cases individual research groups have used only one method, and often little attention has been paid to results obtained by others, using different methods.

The fact that different researchers are interested in different applications of porous media is at least partly responsible for this state of affairs. another important factor is that often so porous materials are more readily investigated by a certain method, while in other cases different methods are more convenient to apply.

2.4 Methods of determining the pore size distribution

The pore size distribution can be obtained by several methods; such as, mercury porosimetry, water displacement, and nitrogen adsorption at 77 k, x-ray scattering and others; however, due to the more complex structure of the activated carbon, some of the above techniques are not so successful in adsorption of nitrogen at its normal boiling point (77k) which is currently widely used throughout the industry [1].

The most widely used method is that of injection of mercury into the pore system. In this manner, a capillary pressure curve is obtained which, in turn, can be interpreted in terms of pore size distribution.

Surface adsorption is also used to determine indirectly a curve of pore size distribution. In similar fashion capillary condensation is small spaces that has been used for obtaining pore size distribution curves.

If the size and frequency of the maximum pore that permit the passage of a fluid through the porous medium is only required, a method for forcing gas bubbles through the porous medium and measuring threshold pressure can be employed (Knoll, 1940).

(Brusset, 1948; Ritter and Erich, 1948; Shull, Elkin and Roess 1948; Avgul et al., 1951; Luk'yanovich and Radushkevich, 1953; Clark and Liu, 1957) have employed more direct methods using the principles of x-ray scattering [11].

A new method has been developed for finding the pore size by using pore size meter (PSM) 160/165 which is shown below [30].

2.4.1 Pore Size Meter (PSM) 160 [30]

The pore size meter series PSM /160 enables to measure the pore size of porous materials such as chemical filters membranes, pore size distribution, smallest pore diameter and pressure drop in certain liquid or gas flows can be determined very easily.

The high-pressure pore size meter PSM 160 has been especially designed to investigate manometer pore size . .

- **Applications**

Porous materials serving as filter media are widely used in production and research, particle filtration efficiency and pressure drop are key properties depending on pore size distribution as well as permeability.

The pore size meter PSM 160 allows the measure of pore size distribution and permeability of samples with a maximum diameter of 90 mm up to testing pressure of 50 bars [30].

- **Principles**

The basic principle of pore size measurements is that liquid filled pores will become gas permeable at a certain pressure, because the liquid has to be displaced by the gas first. The opening pressure, the so-called bubble point depends on the surface tension of the liquid and the pore size meter.

Because real materials almost always show a distribution of pore sizes, the pressure where a former liquid filled pore becomes gas permeable corresponds to the opening pressure of the biggest pore. Based on further increasing the pressure drop across the material under testing and measuring the volumetric flow rate, from the obtained data, it is possible to calculate the pore size distribution [30] .

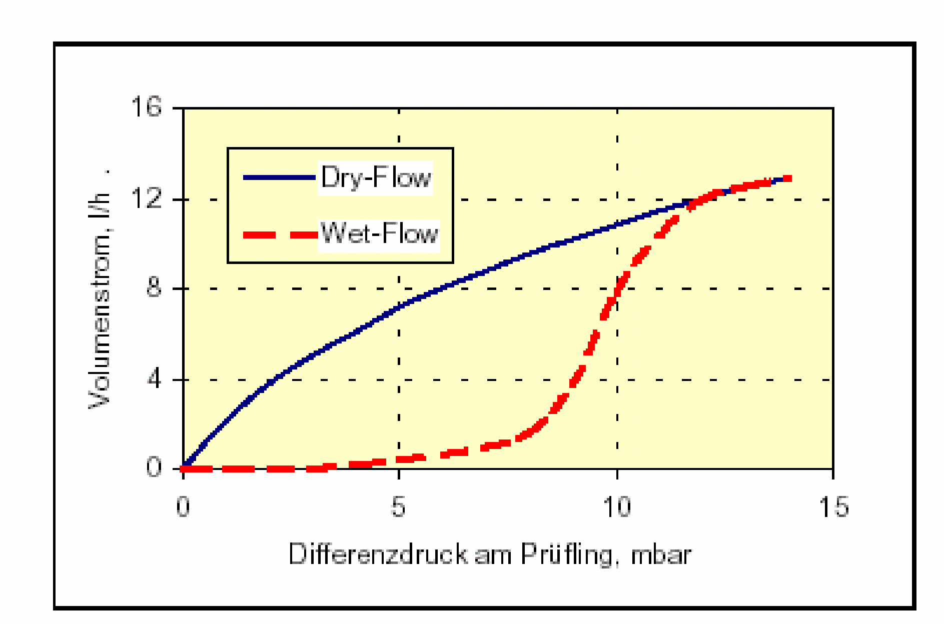

Figure 2-4 obtained pressure drop vs. flow rate for wet and dry sample of woven filter material [30]

- **Specifications**

Gas flow rate	Max. 1300 l/hr
Pressurized supply	Gas max.50 bar (nitrogen)
	Liquid max. 50 bar (water)
Free sample diameter	25,90 mm (exchangeable)
Pore size range	0.8 …. 1.3 mm<5µm
Material	Stainless steal
Dimensions (W*H*D)	1000*450*300 mm
Weight	26 Kg

2.4.2 Pore Size Meter (PSM) 165 [31]

The newly developed pore size meter PSM 165 enables investigations of porous materials with regard to pore size distribution. This pressure drop across the filter media at a definite flow rate is measured. The material under testing is investigated in both dry and wetted states with a known liquid.

Three main parameters describing the inner structure of the material can be obtained with this compact measuring device: -

1- **Bubble point:** pressure drop value where the liquid wetted sample is starting to become gas permeable. Whereby the sample is immersed in a suitable liquid and then pressurized with compressed air to permit observation of the pressure at which bubbles of gas being to appear [32].

2- **Pore size distribution:** permeability weighted pore size distribution calculated from wet flow curve (pressure drop vs. volumetric flow rate of the wet sample). And dry flow curve (similar to wet flow; but obtained from dry samples).

3- **Mean flow pore size: -** pore size diameter corresponding to the pressure drop where the wet flow value is half (50%) of the dry flow.

The operator is guided through the test procedure by a special instrument soft ware running on a PC under Windows . Data acquisition as well as processing fully computerized. Special instructions are given to the operator eg. For inserting the filter sample. That way subjective errors through the instrument operation can be reduced to the minimum [31].

2.5 Theoretical method to calculate the pore size

This method is given by latif (1981) [33] who gives a mathematical procedure to find the pore size and the mean pore size of packing, so the calculation of this procedure is as follows:-

i. The diameter of the (dc_{III}) which may be able to pass through the pore, as shown in fig 2-7.1, which represents the general case.

$$d_{cIII} = \frac{K_4 - \left(K_4^2 - 4K_5\right)^{1/2}}{2} \times d_g \qquad \ldots (2\text{-}1)$$

Where:

$$K_1 = \left[\frac{\left(a_m + 1\right)}{\left(a_m - 1\right)}\right]^2$$

$$K_2 = \frac{4d_m}{\left(a_{m+1}\right)}$$

$$K_3 = \left(a_k^2 + a_k K_2\right)^{1/2} - a_k$$

$$K_4 = \left(K_2 + 2K_3\right) \times K_1$$

$$K_5 = K_3^2 \times K_1$$

$$a_m = \frac{d_m}{d_g} \qquad (=1)$$

$$a_k = \frac{d_k}{d_g} \qquad (\le 1)$$

ii. The diameter (dc_{II}) as shown in fig. 2-7.2.a, 2-7.2.b may be calculated by equation 2.2.a and 2.2.b for case (a) and (b) respectively.

$$d_{cII} = \frac{\left[\left(2a_k + a_k^2\right)^{1/2} - a_k\right]^2}{2 + 2\left[\left(2a_k + a_k^2\right)^{1/2} - a_k\right]} \times d_g \qquad \text{..... (2-2.a)}$$

Equation (2.2.a) is used if pore by two different sphere diameters $d_g = d_g > d_K$

$$d_{cII} = \frac{\left[\left(2/a_k + a_k^{-2}\right)^{1/2} - a_k^{-1}\right]^2}{2 + 2\left[\left(2/a_k + a_k^{-2}\right)^{1/2} - a_k^{-1}\right]} \times d_k \qquad \text{.. .. (2-2.b)}$$

Equation (2.2.b) is used if pore by two different sphere diameters
$d_K = d_K < d_g$

Where:

$$a_k = \frac{d_k}{d_g}$$

iii. The diameter (dc_I) can be calculated by the equation written below

When $dc = d_m = d_g$ as in fig. 2-7.3

$$d_{cI} = 0.155 \times d_g \qquad \text{..... (2-3)}$$

To calculate the probability that the diameter dc will occur is:

$$P_i = \frac{3!}{n_g!n_m!n_k!} P_{r_{dg}}^{ng} \times P_{r_{dm}}^{nm} \times P_{r_{dk}}^{nk} \qquad \text{….. (2-4)}$$

Where $r_g + r_m + r_k = 3$

Equation (4) is the general equation to calculate the probability due to number, volume, length and surface area, so we must have the percent due to one of it and depend on it to find the probability due to other. In this research we depend on the number percent to find the other as follows:

1. To calculate the probability due to length:

We have the number percent of each type of diameters (d_1, d_2, d_3, d_4, d_5) and to find the percent of length as below:

$$L = (d_1 \times N_1) + (d_2 \times N_2) + (d_3 \times N_3) + (d_4 \times N_4) + (d_5 \times N_5)$$

$$L_k = (d_k \times N_k)/L$$

$$L_m = (d_m \times N_m)/L$$

$$L_g = (d_g \times N_g)/L$$

Where N: number percent.

d_K, d_m, and d_g: the choice diameters.

Then we sub L_K, L_m, and L_g in eq. 4 to find the probability due to length.

2. To calculate the probability due to area:

$$A=\left(d_1^2\times N_1\right)+\left(d_2^2\times N_2\right)+\left(d_3^2\times N_3\right)+\left(d_4^2\times N_4\right)+\left(d_5^2\times N_5\right)$$

$$A_k=\left(d_k^2\times N_k\right)/A$$

$$A_m=\left(d_m^2\times N_m\right)/A$$

$$A_g=\left(d_g^2\times N_g\right)/A$$

Then we sub A_K, A_m, and A_g in eq. 4 to find the probability due to area.

3. To find the probability due to volume:

$$V=\left(d_1^3\times N_1\right)+\left(d_2^3\times N_2\right)+\left(d_3^3\times N_3\right)+\left(d_4^3\times N_4\right)+\left(d_5^3\times N_5\right)$$

$$V_k=\left(d_k^3\times N_k\right)/V$$

$$V_m=\left(d_m^3\times N_m\right)/V$$

$$V_g=\left(d_g^3\times N_g\right)/V$$

Then we sub V_K, V_m and V_g in eq. 4 to find the probability due to volume.

To calculate the mean diameter dc_m as in the below equation :

$$d_{cm} = \sum_{i=1}^{n} p_i d_{ci} \quad \ldots.. \; (2\text{-}5)$$

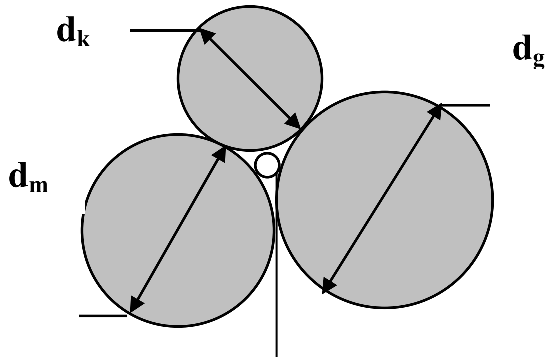

Figure 2-5.1
General case

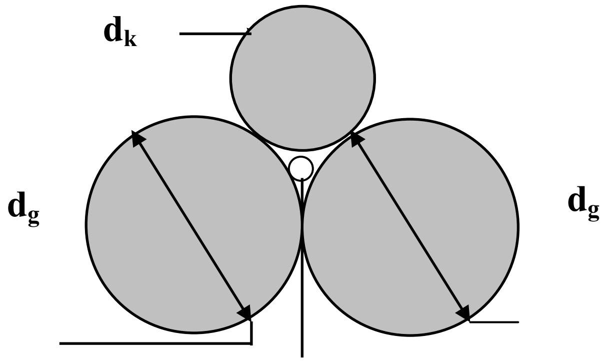

Figure 2-5.2.a pore by two different sphere diameters
$d_g = d_g > d_k$

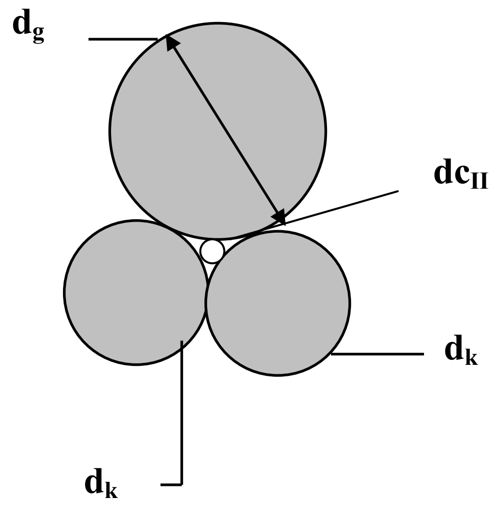

Figure 2-5.2.b pore by two different sphere diameters
$d_k = d_k < d_g$

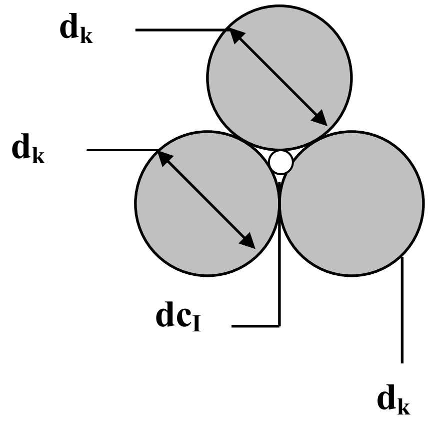

Figure 2-5.3
Three equal sphere diameters

2.6 Relationship between pore size and filteration efficiency [34]

Users of filters are often confused by the “pore size” printed in the specifications for a particular catalog number. For filters used for air sampling, pore size has nothing to do with the collection efficiency of a filter .

The force velocity governs the efficiency, through the filter and the aerodynamic diameter.

Pore size is an indicator of the pressure drop across a filter, not its collection efficiency. The one exception, are filters which are manufactured by bombarding a solid surface, such as Mylar, with neutrons.

An imperfection is created on the surface, which is subsequently acid etched to form a microscopic hole through the membrane. Filters of this type will have significantly reduced efficiencies when a combination of large pore size (3 – 5 mm) and small diameter (1mm) is encountered [32].

Historically, filters selected for use in a particular application have had a smaller pore size than was required .

This was only a minor problem, prior to the advent of battery operated sampling equipment. Too small a pore size would only result in a too rapid, plugging or blinding, of the filter so that the requisite quantity of air could not be drawn through it. With battery operated equipment, to small a pore size would lead to high power consumption, premature shutdown and with unregulated equipment, an incorrect flow rate .

When selecting a filter for an application, the important points to consider are: -

- If a regulating body has recommended a type and pore size, use it.

- If ranges of pore size have been recommended, uses the largest.

- Consult the manufacturer of the sampling equipment for the correct type and pore size to use.

- Many manufactures provide application notes regarding correct filter applications.

- Avoid small diameter filters and small pore size membranes.

The physics of the filtration of particulate material from a gas stream is complex. Several mechanisms act in concert or opposition .

2.7 Proprietary Packed Bed Filters [35]

Packed bed filters (PBF_S) are packed with filter media such as sand, gravel, peat, plastic foam, or geotexile, for the aerobic biological and physical treatment of wastewater constituents. PBF_S come in different configurations and sizes, but incorporate the following common elements: a container for holding the filter medium, the filtering media, a distribution or dosing system applying the waste water to be treated to the filtering media, and an under drain system for removing the treated waste water. In respect to waste water distribution, it can be gravity flow, intermittently dosed (single-pass) or recirculating (multi-pass). Other alternative waste water treatment technologies, such as public domain sand filter systems and aerobic treatment units, may also be described by these characterizations, however the Washington state Department of health (DOH) does not categorize them as proprietary packed bed filters or systems .

CHAPTER THREE
THEORETICAL RESULTS

3.1 Theoretical Results

To apply the equations in chapter two, we will take the following five diameters to calculate their pore size diameters and their diameter are taken in a different ratios to find the probability, i.e. its diameters (dc) occurred, the diameter are:

Sphere of group 1 (d_1) = 7.972 mm.
Sphere of group 2 (d_2) = 10.164 mm.
Sphere of group 3 (d_3) = 14.772 mm.
Sphere of group 4 (d_4) = 20.614 mm.
Sphere of group 5 (d_5) = 25.448 mm.

The pore diameter (dc) is calculated on the basis of the pore distribution due to number, area, and length and volume ratios for the sphere the packing consists of.

To find the pore sizes and their probabilities for any three sizes of spheres chosen from the five diameters, a computer program was made listed in appendix [B] and the following tables show the results of the computer program for the above five diameters and for different relations.

Figures from 1 to 12 show the relationships between the probability and the diameter of the pore (dc) for each distribution, and show the difference between the distributions of each case.

Table 3-1 Arrangement of paticles to determine the diameter of the pore.

No. of small spheres	No. of medium spheres	No. of Large spheres	Araangement	d_c (mm)
3	0	0	d_1, d_1, d_1	1.23566
2	0	1	d_1, d_1, d_2	1.33094
1	0	2	d_1, d_2, d_2	1.443092
2	0	1	d_1, d_1, d_3	1.469858
0	3	0	d_2, d_2, d_2	1.57542
2	0	1	d_1, d_1, d_4	1.578567
1	1	1	d_1, d_2, d_3	1.603311
2	0	1	d_1, d_1, d_5	1.638988
1	1	1	d_1, d_2, d_4	1.728805
2	0	1	d_2, d_2, d_3	1.761223
1	1	1	d_1, d_2, d_5	1.798794
1	0	2	d_1, d_3, d_3	1.803303
2	0	1	d_2, d_2, d_4	1.913525
1	1	1	d_1, d_3, d_4	1.964144
1	0	2	d_2, d_3, d_3	1.994477
2	0	1	d_2, d_2, d_5	2.000081
1	1	1	d_1, d_3, d_5	2.055709
1	0	2	d_1, d_4, d_4	2.157553
1	1	1	d_2, d_3, d_4	2.185808
1	1	1	d_1, d_4, d_5	2.269556
0	3	0	d_3, d_3, d_3	2.28966
1	1	1	d_2, d_3, d_5	2.295495
1	0	2	d_1, d_5, d_5	2.394654
1	0	2	d_2, d_4, d_4	2.417959
2	0	1	d_3, d_3, d_4	2.531036
1	1	1	d_2, d_4, d_5	2.553441
2	0	1	d_3, d_3, d_5	2.675837

1	0	2	d_2, d_5, d_5	2.705573
1	0	2	d_3, d_4, d_4	2.827882
1	1	1	d_3, d_4, d_5	3.004799
0	3	0	d_4, d_4, d_4	3.19517
1	0	2	d_3, d_5, d_5	3.205215
2	0	1	d_4, d_4, d_5	3.408748
1	0	2	d_4, d_5, d_5	3.656557
0	0	3	d_5, d_5, d_5	3.94444

Table 3-2 Results obtained from computer program for:

$d_1 = 7.972$, $d_2 = 10.164$, $d_3 = 14.772$, $d_4 = 20.614$, $d_5 = 25.448$

$N_1 = 0.2$	$N_2 = 0.2$	$N_3 = 0.2$	$N_4 = 0.2$	$N_5 = 0.2$
$L_1 = 0.1010$	$L_2 = 0.1287$	$L_3 = 0.1871$	$L_4 = 0.2610$	$L_5 = 0.3222$
$A_1 = 0.0436$	$A_2 = 0.0709$	$A_3 = 0.1497$	$A_4 = 0.2915$	$A_5 = 0.4443$
$V_1 = 0.0169$	$V_2 = 0.0349$	$V_3 = 0.1075$	$V_4 = 0.2918$	$V_5 = 0.5489$

Diameter of the pores (dc)	Probability Due to Number (P_{rn})	Probability Due to Length (P_{rl})	Probability Due to Area (P_{ra})	Probability Due to Volume (P_{rv})
1.23566	0.008	0.001029	8.29E-05	4.81E-06
1.33094	0.032	0.004964	4.87E-04	3.47E-05
1.443092	0.056	0.009981	1.14E-03	9.66E-05
1.469858	0.08	0.0157	2.00E-03	1.88E-04
1.57542	0.088	0.017832	2.35E-03	2.31E-04
1.578567	0.112	0.025812	4.02E-03	4.81E-04
1.603311	0.16	0.040395	6.79E-03	8.61E-04
1.638988	0.184	0.050247	9.33E-03	1.33E-03
1.728805	0.232	0.070597	1.47E-02	2.36E-03
1.761223	0.256	0.084107	1.70E-02	2.76E-03
1.798794	0.304	0.109229	2.52E-02	4.70E-03
1.803303	0.328	0.119826	2.82E-02	5.29E-03
1.913525	0.352	0.132799	3.25E-02	6.36E-03
1.964144	0.4	0.162374	4.40E-02	9.53E-03
1.994477	0.424	0.17167	4.87E-02	1.07E-02

2.000081	0.448	0.187685	5.54E-02	1.28E-02
2.055709	0.496	0.224196	7.28E-02	1.87E-02
2.157553	0.52	0.244832	8.39E-02	2.30E-02
2.185808	0.568	0.28254	1.03E-01	2.96E-02
2.269556	0.616	0.33349	1.36E-01	4.58E-02
2.28966	0.624	0.340036	1.40E-01	4.71E-02
2.295495	0.672	0.386586	1.68E-01	5.94E-02
2.394654	0.696	0.418035	1.94E-01	7.47E-02
2.417959	0.72	0.444345	2.12E-01	8.36E-02
2.531036	0.744	0.471747	2.32E-01	9.37E-02
2.553441	0.792	0.536707	2.87E-01	1.27E-01
2.675837	0.816	0.570534	3.16E-01	1.46E-01
2.705573	0.84	0.610631	3.58E-01	1.78E-01
2.827882	0.864	0.648869	3.97E-01	2.05E-01
3.004799	0.912	0.74328	5.13E-01	3.09E-01
3.19517	0.92	0.761066	5.38E-01	3.33E-01
3.205215	0.944	0.819341	6.26E-01	4.31E-01
3.408748	0.968	0.885215	7.40E-01	5.71E-01
3.656557	0.992	0.966536	9.12E-01	8.35E-01
3.94444	1	1	1	1

NOTE: All diameters above are in mm.

Table 3-3 Results obtained from computer program for:

$d_1 = 7.972$, $d_2 = 10.164$, $d_3 = 14.772$, $d_4 = 20.614$, $d_5 = 25.448$

$N_1 = 0.15$	$N_2 = 0.3$	$N_3 = 0.2$	$N_4 = 0.25$	$N_5 = 0.1$
$L_1 = 0.0803$	$L_2 = 0.2047$	$L_3 = 0.1983$	$L_4 = 0.3459$	$L_5 = 0.1708$
$A_1 = 0.0374$	$L_2 = 0.1215$	$L_3 = 0.1710$	$L_4 = 0.4163$	$L_5 = 0.2538$
$V_1 = 0.0156$	$V_2 = 0.0646$	$V_3 = 0.1323$	$V_4 = 0.4493$	$V_5 = 0.3382$

Diameter of the pores (dc)	Probability Due to Number (P_{rn})	Probability Due to Length (P_{rl})	Probability Due to Area (P_{ra})	Probability Due to Volume (P_{rv})
1.23566	0.003375	0.000517	5.21E-05	3.79E-06
1.33094	0.023625	0.004473	5.61E-04	5.09E-05
1.443092	0.064125	0.014561	2.21E-03	2.46E-04
1.469858	0.077625	0.018394	2.93E-03	3.43E-04
1.57542	0.104625	0.026968	4.72E-03	6.13E-04
1.578567	0.1215	0.033655	6.47E-03	9.41E-04
1.603311	0.1755	0.053203	1.11E-02	1.74E-03
1.638988	0.18225	0.056504	1.22E-02	1.99E-03
1.728805	0.24975	0.090603	2.35E-02	4.70E-03
1.761223	0.30375	0.115527	3.11E-02	6.36E-03
1.798794	0.33075	0.132365	3.80E-02	8.41E-03
1.803303	0.34875	0.141835	4.13E-02	9.23E-03
1.913525	0.41625	0.18531	5.97E-02	1.49E-02
1.964144	0.46125	0.218348	7.57E-02	2.04E-02
1.994477	0.49725	0.242497	8.63E-02	2.38E-02
2.000081	0.52425	0.263965	9.76E-02	2.80E-02
2.055709	0.54225	0.280279	1.07E-01	3.22E-02
2.157553	0.660375	0.393341	1.79E-01	6.47E-02
2.185808	0.63225	0.364526	1.59E-01	5.53E-02
2.269556	0.682875	0.421799	2.02E-01	7.89E-02
2.28966	0.690875	0.429599	2.07E-01	8.13E-02
2.295495	0.726875	0.471199	2.39E-01	9.86E-02
2.394654	0.731375	0.478226	2.46E-01	1.04E-01
2.417959	0.787625	0.551703	3.09E-01	1.43E-01
2.531036	0.817625	0.592517	3.46E-01	1.67E-01
2.553441	0.862625	0.665083	4.23E-01	2.26E-01

2.675837	0.874625	0.685237	4.45E-01	2.43E-01
2.705573	0.883625	0.703154	4.69E-01	2.66E-01
2.827882	0.921125	0.774347	5.58E-01	3.46E-01
3.004799	0.951125	0.844657	6.66E-01	4.66E-01
3.19517	0.96675	0.886052	7.38E-01	5.57E-01
3.205215	0.97275	0.903412	7.71E-01	6.02E-01
3.408748	0.9915	0.964734	9.03E-01	8.07E-01
3.656557	0.999	0.995016	9.84E-01	9.61E-01
3.94444	1	1	1	1

NOTE: All diameters above are in mm.

Table 3-4 Results obtained from computer program for:

$d_1 = 7.972$, $d_2 = 10.164$, $d_3 = 14.772$, $d_4 = 20.614$, $d_5 = 25.448$

$N_1 = 0.4$	$N_2 = 0.2$	$N_3 = 0.15$	$N_4 = 0.2$	$N_5 = 0.05$
$L_1 = 0.2485$	$L_2 = 0.1584$	$L_3 = 0.1727$	$L_4 = 0.3213$	$L_5 = 0.0992$
$A_1 = 0.1296$	$A_2 = 0.1053$	$A_3 = 0.1668$	$A_4 = 0.4332$	$A_5 = 0.1651$
$V_1 = 0.0583$	$V_2 = 0.0605$	$V_3 = 0.1393$	$V_4 = 0.5046$	$V_5 = 0.2373$

Diameter of the pores (dc)	**Probability Due to Number (P_{rn})**	**Probability Due to Length (P_{rl})**	**Probability Due to Area (P_{ra})**	**Probability Due to Volume (P_{rv})**
1.23566	0.064	0.015344	0.002176	0.000199
1.33094	0.16	0.044688	0.007481	0.000817
1.443092	0.208	0.063395	0.011793	0.001458
1.469858	0.28	0.095381	0.020197	0.002881
1.57542	0.288	0.099356	0.021365	0.003102
1.578567	0.384	0.158871	0.043187	0.008259
1.603311	0.456	0.199652	0.056849	0.011209
1.638988	0.48	0.21802	0.065163	0.013634
1.728805	0.576	0.293899	0.100635	0.024321
1.761223	0.594	0.306897	0.106186	0.02585
1.798794	0.618	0.330316	0.119701	0.030876
1.803303	0.645	0.352542	0.130522	0.034272

1.913525	0.669	0.376728	0.144938	0.03981
1.964144	0.741	0.459437	0.201132	0.064416
1.994477	0.7545	0.473606	0.209927	0.067935
2.000081	0.7605	0.481071	0.215419	0.07054
2.055709	0.7785	0.506597	0.23683	0.082113
2.157553	0.8265	0.583543	0.309784	0.126693
2.185808	0.8625	0.636269	0.355457	0.152192
2.269556	0.8865	0.683765	0.411047	0.194127
2.28966	0.889875	0.688913	0.415692	0.196828
2.295495	0.898875	0.705185	0.433093	0.208821
2.394654	0.901875	0.712515	0.443683	0.218683
2.417959	0.925875	0.761566	0.502977	0.264878
2.531036	0.939375	0.790303	0.539155	0.294233
2.553441	0.951375	0.82058	0.584337	0.337688
2.675837	0.95475	0.829449	0.598121	0.351495
2.705573	0.95625	0.834121	0.606728	0.361714
2.827882	0.97425	0.887589	0.700662	0.468075
3.004799	0.98325	0.920592	0.77224	0.568128
3.19517	0.99125	0.953753	0.853539	0.696588
3.205215	0.992375	0.958846	0.867175	0.720118
3.408748	0.998375	0.989549	0.9601	0.901379
3.656557	0.999875	0.999025	0.995504	0.986634
3.94444	1	1	1	1

NOTE: All diameters above are in mm.

Table 3-5 Results obtained from computer program for:

$d_1 = 7.972$, $d_2 = 10.164$, $d_3 = 14.772$, $d_4 = 20.613$, $d_5 = 25.448$

$N_1 = 0.21$	$N_2 = 0.16$	$N_3 = 0.16$	$N_4 = 0.16$	$N_5 = 0.31$
$L_1 = 0.0993$	$L_2 = 0.0965$	$L_3 = 0.1403$	$L_4 = 0.1957$	$L_5 = 0.4682$
$A_1 = 0.0400$	$A_2 = 0.0496$	$A_3 = 0.1047$	$A_4 = 0.2038$	$A_5 = 0.6019$
$V_1 = 0.0146$	$V_2 = 0.0230$	$V_3 = 0.0706$	$V_4 = 0.1920$	$V_5 = 0.6998$

Diameter of the pores (dc)	Probability Due to Number (P_{rn})	Probability Due to Length (P_{rl})	Probability Due to Area (P_{ra})	Probability Due to Volume (P_{rv})
1.23566	0.009261	0.000981	6.41E-05	3.10E-06
1.33094	0.030429	0.003839	3.02E-04	1.78E-05
1.443092	0.046557	0.006614	5.97E-04	4.09E-05
1.469858	0.067725	0.010768	1.10E-03	8.59E-05
1.57542	0.071821	0.011666	1.22E-03	9.81E-05
1.578567	0.092989	0.017462	2.20E-03	2.20E-04
1.603311	0.125245	0.025531	3.45E-03	3.63E-04
1.638988	0.166258	0.039393	6.34E-03	8.08E-04
1.728805	0.198514	0.050653	8.76E-03	1.19E-03
1.761223	0.210802	0.054572	9.53E-03	1.31E-03
1.798794	0.273298	0.081503	1.67E-02	2.72E-03
1.803303	0.289426	0.087367	1.80E-02	2.93E-03
1.913525	0.301714	0.092835	1.95E-02	3.24E-03
1.964144	0.33397	0.1092	2.46E-02	4.42E-03
1.994477	0.346258	0.114896	2.63E-02	4.77E-03
2.000081	0.370066	0.127976	3.07E-02	5.88E-03
2.055709	0.432562	0.167118	4.58E-02	1.02E-02
2.185808	0.457138	0.183014	5.22E-02	1.21E-02
2.157553	0.473266	0.194432	5.72E-02	1.37E-02
2.269556	0.535762	0.249053	8.66E-02	2.54E-02
2.28966	0.539858	0.251812	8.78E-02	2.58E-02
2.295495	0.587474	0.289834	1.06E-01	3.26E-02
2.394654	0.648017	0.355157	1.50E-01	5.40E-02
2.417959	0.660305	0.366248	1.56E-01	5.66E-02
2.531036	0.672593	0.3778	1.63E-01	5.94E-02
2.553441	0.720209	0.430858	1.99E-01	7.80E-02

2.675837	0.744017	0.458488	2.19E-01	8.85E-02
2.705573	0.790145	0.521942	2.73E-01	1.22E-01
2.827882	0.802433	0.538062	2.86E-01	1.30E-01
3.004799	0.850049	0.615176	3.63E-01	1.87E-01
3.19517	0.854145	0.622675	3.72E-01	1.94E-01
3.205215	0.900273	0.714896	4.85E-01	2.98E-01
3.408748	0.924081	0.768702	5.60E-01	3.75E-01
3.656557	0.970209	0.897395	7.82E-01	6.57E-01
3.94444	1	1	1.00E+00	1.00E+00

NOTE: All diameters above are in mm.

Table 3-6 Results obtained from computer program for:

$d_1 = 7.972$, $d_2 = 10.164$, $d_3 = 14.772$, $d_4 = 20.614$, $d_5 = 25.448$

$N_1 = 0.14$	$N_2 = 0.7$	$N_3 = 0.11$	$N_4 = 0.03$	$N_5 = 0.02$
$L_1 =0.1016$	$L_2 = 0.6478$	$L_3 = 0.1479$	$L_4 = 0.0563$	$L_5 = 0.0463$
$A_1 =0.0680$	$A_2 = 0.5524$	$A_3 = 0.1833$	$A_4 = 0.0974$	$A_5 = 0.0989$
$V_1 = 0.0405$	$V_2 = 0.4193$	$V_3 = 0.2023$	$V_4 = 0.1499$	$V_5 = 0.1880$

Diameter of the pores (dc)	Probability Due to Number (P_{rn})	Probability Due to Length (P_{rl})	Probability Due to Area (P_{ra})	Probability Due to Volume (P_{rv})
1.23566	0.002744	0.001049	0.000314	6.63E-05
1.33094	0.043904	0.021116	0.007968	2.13E-03
1.443092	0.249704	0.149042	0.070179	2.35E-02
1.469858	0.256172	0.153625	0.072719	2.45E-02
1.57542	0.599172	0.425459	0.241261	9.82E-02
1.578567	0.600936	0.427203	0.24261	9.89E-02
1.603311	0.665616	0.485636	0.283909	1.20E-01
1.638988	0.666792	0.487072	0.28528	1.20E-01
1.728805	0.684432	0.50931	0.307214	1.36E-01
1.761223	0.846132	0.69556	0.475045	2.42E-01
1.798794	0.857892	0.713862	0.497329	2.62E-01
1.803303	0.862974	0.720535	0.504184	2.67E-01

1.913525	0.907074	0.791418	0.593318	3.46E-01
1.964144	0.909846	0.796497	0.600599	3.53E-01
1.994477	0.935256	0.839034	0.656307	4.04E-01
2.000081	0.964656	0.897371	0.746867	5.04E-01
2.055709	0.966504	0.901551	0.754264	5.13E-01
2.157553	0.966882	0.902518	0.756197	5.16E-01
2.185808	0.980742	0.934895	0.81537	5.92E-01
2.269556	0.981246	0.936486	0.819298	5.99E-01
2.28966	0.982577	0.939724	0.825462	6.07E-01
2.295495	0.991817	0.966371	0.885581	7.03E-01
2.394654	0.991985	0.967026	0.887577	7.07E-01
2.417959	0.993875	0.973187	0.90329	7.35E-01
2.531036	0.994964	0.976884	0.91311	7.54E-01
2.553441	0.997484	0.987026	0.94504	8.25E-01
2.675837	0.99821	0.990069	0.955017	8.48E-01
2.705573	0.99905	0.994242	0.971237	8.92E-01
2.827882	0.999347	0.995649	0.976453	9.06E-01
3.004799	0.999743	0.997965	0.987051	9.40E-01
3.19517	0.99977	0.998144	0.987974	9.43E-01
3.205215	0.999902	0.999097	0.993358	9.65E-01
3.408748	0.999956	0.999537	0.996172	9.77E-01
3.656557	0.999992	0.9999	0.999032	9.93E-01
3.94444	1	1	1	1.00E+00

NOTE: All diameters above are in mm.

Table 3-7 Results obtained from computer program for:

$d_1 = 7.972$, $d_2 = 10.164$, $d_3 = 14.772$, $d_4 = 20.614$, $d_5 = 25.448$

$N_1 = 0.23$	$N_2 = 0.3$	$N_3 = 0.3$	$N_4 = 0.08$	$N_5 = 0.09$
$L_1 = 0.1383$	$L_2 = 0.2301$	$L_3 = 0.3344$	$L_4 = 0.1244$	$L_5 = 0.1728$
$A_1 = 0.0719$	$A_2 = 0.1524$	$A_3 = 0.3219$	$A_4 = 0.1672$	$A_5 = 0.2866$
$V_1 = 0.0325$	$V_2 = 0.0879$	$V_3 = 0.2699$	$V_4 = 0.1956$	$V_5 = 0.4141$

Diameter of the pores (dc)	Probability Due to Number (P_{rn})	Probability Due to Length (P_{rl})	Probability Due to Area (P_{ra})	Probability Due to Volume (P_{rv})
1.23566	0.012167	0.002648	0.000371	3.44E-05
1.33094	0.059777	0.015857	0.002733	3.13E-04
1.443092	0.121877	0.037824	0.007742	1.07E-03
1.469858	0.169487	0.057022	0.012732	1.92E-03
1.57542	0.196487	0.069199	0.016272	2.60E-03
1.578567	0.209183	0.076343	0.018864	3.23E-03
1.603311	0.333383	0.140194	0.040024	7.86E-03
1.638988	0.347666	0.150116	0.044467	9.17E-03
1.728805	0.380786	0.173877	0.055455	1.25E-02
1.761223	0.461786	0.226969	0.077887	1.88E-02
1.798794	0.499046	0.259969	0.096727	2.59E-02
1.803303	0.561146	0.306369	0.119075	3.30E-02
1.913525	0.582746	0.326126	0.130724	3.75E-02
1.964144	0.615866	0.360659	0.153935	4.78E-02
1.994477	0.696866	0.437822	0.201318	6.71E-02
2.000081	0.721166	0.465261	0.22129	7.67E-02
2.055709	0.758426	0.513221	0.261085	9.85E-02
2.157553	0.762842	0.519646	0.267111	1.02E-01
2.185808	0.806042	0.577075	0.316323	1.30E-01
2.269556	0.815978	0.594922	0.336988	1.46E-01
2.28966	0.842978	0.632304	0.37035	1.66E-01
2.295495	0.891578	0.712062	0.454724	2.24E-01
2.394654	0.897167	0.724455	0.472439	2.41E-01
2.417959	0.902927	0.735141	0.485217	2.51E-01
2.531036	0.924527	0.776873	0.537191	2.94E-01
2.553441	0.937487	0.806553	0.581006	3.37E-01

2.675837	0.961787	0.864512	0.670116	4.27E-01
2.705573	0.969077	0.885122	0.707677	4.73E-01
2.827882	0.974837	0.900651	0.734667	5.03E-01
3.004799	0.987797	0.943787	0.827216	6.35E-01
3.19517	0.988309	0.945714	0.831888	6.42E-01
3.205215	0.995599	0.975667	0.911225	7.81E-01
3.408748	0.997327	0.983693	0.935255	8.28E-01
3.656557	0.999271	0.99484	0.976454	9.29E-01
3.94444	1	1	1	1.00E+00

NOTE: All diameters above are in mm.

Table 3-8 Results obtained from computer program for:

$d_1 = 7.972$, $d_2 = 10.164$, $d_3 = 14.772$, $d_4 = 20.614$, $d_5 = 25.448$

$N_1 = 0.08$	$N_2 = 0.4$	$N_3 = 0.24$	$N_4 = 0.16$	$N_5 = 0.12$
$L_1 = 0.0437$	$L_2 = 0.2785$	$L_3 = 0.2428$	$L_4 = 0.2259$	$L_5 = 0.2091$
$A_1 = 0.0208$	$A_2 = 0.1690$	$A_3 = 0.2142$	$A_4 = 0.2781$	$A_5 = 0.3179$
$V_1 = 0.0088$	$V_2 = 0.0910$	$V_3 = 0.1677$	$V_4 = 0.3038$	$V_5 = 0.4287$

Diameter of the pores (dc)	**Probability Due to Number (P_{rn})**	**Probability Due to Length (P_{rl})**	**Probability Due to Area (P_{ra})**	**Probability Due to Volume (P_{rv})**
1.23566	0.000512	8.33E-05	8.99E-06	6.78E-07
1.33094	0.008192	1.68E-03	2.28E-04	2.18E-05
1.443092	0.046592	1.18E-02	2.01E-03	2.40E-04
1.469858	0.0512	1.32E-02	2.29E-03	2.79E-04
1.57542	0.1152	3.48E-02	7.12E-03	1.03E-03
1.578567	0.118272	3.61E-02	7.48E-03	1.10E-03
1.603311	0.164352	5.38E-02	1.20E-02	1.91E-03
1.638988	0.166656	5.50E-02	1.24E-02	2.01E-03
1.728805	0.197376	7.15E-02	1.83E-02	3.47E-03
1.761223	0.312576	1.28E-01	3.66E-02	7.64E-03
1.798794	0.335616	1.43E-01	4.33E-02	9.69E-03
1.803303	0.34944	1.51E-01	4.62E-02	1.04E-02

1.913525	0.42624	2.04E-01	7.00E-02	1.80E-02
1.964144	0.444672	2.18E-01	7.75E-02	2.07E-02
1.994477	0.513792	2.67E-01	1.01E-01	2.84E-02
2.000081	0.571392	3.16E-01	1.28E-01	3.90E-02
2.055709	0.585216	3.29E-01	1.36E-01	4.28E-02
2.157553	0.59136	3.36E-01	1.41E-01	4.52E-02
2.185808	0.68352	4.27E-01	2.02E-01	7.31E-02
2.269556	0.692736	4.40E-01	2.13E-01	7.99E-02
2.28966	0.70656	4.54E-01	2.23E-01	8.46E-02
2.295495	0.77568	5.39E-01	2.92E-01	1.24E-01
2.394654	0.779136	5.45E-01	2.98E-01	1.29E-01
2.417959	0.809856	5.87E-01	3.37E-01	1.54E-01
2.531036	0.837504	6.27E-01	3.75E-01	1.80E-01
2.553441	0.883584	7.06E-01	4.65E-01	2.51E-01
2.675837	0.90432	7.43E-01	5.09E-01	2.87E-01
2.705573	0.9216	7.80E-01	5.60E-01	3.37E-01
2.827882	0.940032	8.17E-01	6.10E-01	3.84E-01
3.004799	0.96768	8.86E-01	7.23E-01	5.15E-01
3.19517	0.971776	8.97E-01	7.45E-01	5.43E-01
3.205215	0.982144	9.29E-01	8.10E-01	6.35E-01
3.408748	0.99136	9.61E-01	8.84E-01	7.54E-01
3.656557	0.998272	9.91E-01	9.68E-01	9.21E-01
3.94444	1	1.00E+00	1.00E+00	1.00E+00

NOTE: All diameters above are in mm.

Table 3-9 Results obtained from computer program for:

d_1 = 7.972, d_2 = 10.164, d_3 = 14.772, d_4 = 20.614, d_5 = 25.448

N_1 = 0.2	N_2 = 0.33	N_3 = 0.17	N_4 = 0.15	N_5 = 0.15
L_1 = 0.1110	L_2 = 0.2334	L_3 = 0.1748	L_4 = 0.2152	L_5 = 0.2656
A_1 = 0.0520	A_2 = 0.1393	A_3 = 0.1515	A_4 = 0.2604	A_5 = 0.3968
V_1 = 0.0212	V_2 = 0.0725	V_3 = 0.1146	V_4 = 0.2748	V_5 = 0.5169

Diameter of the pores (dc)	Probability Due to Number (P_{rn})	Probability Due to Length (P_{rl})	Probability Due to Area (P_{ra})	Probability Due to Volume (P_{rv})
1.23566	0.008	0.001366	0.00014	9.52E-06
1.33094	0.0476	0.009988	0.001267	1.07E-04
1.443092	0.11294	0.028126	0.004288	4.41E-04
1.469858	0.13334	0.034581	0.005514	5.95E-04
1.57542	0.169277	0.0473	0.008216	9.76E-04
1.578567	0.187277	0.055249	0.010322	1.35E-03
1.603311	0.254597	0.082409	0.016898	2.40E-03
1.638988	0.272597	0.092221	0.020108	3.10E-03
1.728805	0.331997	0.125664	0.031408	5.63E-03
1.761223	0.387536	0.154232	0.040227	7.44E-03
1.798794	0.446936	0.195516	0.057447	1.22E-02
1.803303	0.464276	0.205684	0.061025	1.30E-02
1.913525	0.513281	0.24086	0.076178	1.74E-02
1.964144	0.543881	0.265898	0.088473	2.14E-02
1.994477	0.572492	0.287287	0.098069	2.42E-02
2.000081	0.621497	0.330712	0.121163	3.24E-02
2.055709	0.652097	0.361622	0.139901	3.99E-02
2.157553	0.665597	0.377037	0.150464	4.47E-02
2.185808	0.716087	0.429709	0.183441	5.84E-02
2.269556	0.743087	0.467769	0.215638	7.64E-02
2.28966	0.748	0.473107	0.219119	7.80E-02
2.295495	0.79849	0.538131	0.269376	1.04E-01
2.394654	0.81199	0.561624	0.29391	1.21E-01
2.417959	0.834265	0.594052	0.322242	1.37E-01
2.531036	0.84727	0.61377	0.340184	1.48E-01
2.553441	0.89182	0.693835	0.426539	2.10E-01

2.675837	0.904825	0.718177	0.453883	2.30E-01
2.705573	0.9271	0.767597	0.519685	2.88E-01
2.827882	0.938575	0.791876	0.550514	3.14E-01
3.004799	0.961525	0.851821	0.644481	4.12E-01
3.19517	0.9649	0.861786	0.662138	4.33E-01
3.205215	0.976375	0.898787	0.73374	5.24E-01
3.408748	0.9865	0.935692	0.81447	6.42E-01
3.656557	0.996625	0.981252	0.937501	8.62E-01
3.94444	1	1	1	1.00E+00

NOTE: All diameters above are in mm.

Table 3-10 Results obtained from computer program for:

$d_1 = 7.972$, $d_2 = 10.164$, $d_3 = 14.772$, $d_4 = 20.614$, $d_5 = 25.448$

$N_1 = 0.47$	$N_2 = 0.24$	$N_3 = 0.14$	$N_4 = 0.07$	$N_5 = 0.08$
$L_1 = 0.3193$	$L_2 = 0.2079$	$L_3 = 0.1763$	$L_4 = 0.1230$	$L_5 = 0.1735$
$A_1 = 0.1791$	$A_2 = 0.1487$	$A_3 = 0.1832$	$A_4 = 0.1783$	$A_5 = 0.3107$
$V_1 = 0.0829$	$V_2 = 0.0877$	$V_3 = 0.1571$	$V_4 = 0.2134$	$V_5 = 0.4589$

Diameter of the pores (dc)	**Probability Due to Number (P_{rn})**	**Probability Due to Length (P_{rl})**	**Probability Due to Area (P_{ra})**	**Probability Due to Volume (P_{rv})**
1.23566	0.103823	0.032565	0.005746	0.000569
1.33094	0.262871	0.09617	0.020055	0.002377
1.443092	0.344087	0.137579	0.031932	0.00429
1.469858	0.436865	0.191503	0.049562	0.007527
1.57542	0.450689	0.200489	0.052848	0.008202
1.578567	0.497078	0.238114	0.070015	0.0126
1.603311	0.59183	0.308328	0.099283	0.019452
1.638988	0.644846	0.361411	0.129182	0.028909
1.728805	0.692222	0.410402	0.15768	0.038219
1.761223	0.716414	0.433258	0.169828	0.041845
1.798794	0.770558	0.502377	0.219463	0.061862
1.803303	0.798194	0.53214	0.237495	0.067997

1.913525	0.81029	0.548088	0.249323	0.072923
1.964144	0.837926	0.589622	0.284437	0.089595
1.994477	0.852038	0.608999	0.299404	0.096087
2.000081	0.865862	0.631499	0.320005	0.106679
2.055709	0.897446	0.690098	0.381163	0.142526
2.157553	0.904355	0.704588	0.398258	0.153852
2.185808	0.918467	0.731629	0.427405	0.171495
2.269556	0.934259	0.772515	0.486954	0.220201
2.28966	0.937003	0.777991	0.493102	0.224077
2.295495	0.953131	0.816142	0.543867	0.262013
2.394654	0.962155	0.844984	0.595726	0.314375
2.417959	0.965683	0.854418	0.609915	0.326362
2.531036	0.969799	0.865881	0.627872	0.34216
2.553441	0.977863	0.8925	0.677301	0.393705
2.675837	0.982567	0.908672	0.708577	0.427672
2.705573	0.987175	0.927449	0.751622	0.483087
2.827882	0.989233	0.935447	0.769106	0.504552
3.004799	0.993937	0.958015	0.830011	0.596858
3.19517	0.99428	0.959875	0.835685	0.60658
3.205215	0.996968	0.975795	0.888724	0.705815
3.408748	0.998144	0.983668	0.918375	0.768526
3.656557	0.999488	0.994776	0.970018	0.903361
3.94444	1	1	1	1

NOTE: All diameters above are in mm.

Table 3-11 Results obtained from computer program for:

$d_1 = 7.972$, $d_2 = 10.164$, $d_3 = 14.772$, $d_4 = 20.614$, $d_5 = 25.448$

$N_1 = 0.51$	$N_2 = 0.3$	$N_3 = 0.08$	$N_4 = 0.07$	$N_4 = 0.04$
$L_1 = 0.3779$	$L_2 = 0.2834$	$L_3 = 0.1100$	$L_4 = 0.1341$	$L_5 = 0.0946$
$A_1 = 0.2374$	$A_2 = 0.2270$	$A_3 = 0.1279$	$A_4 = 0.2179$	$A_5 = 0.1898$
$V_1 = 0.1228$	$V_2 = 0.1497$	$V_3 = 0.1226$	$V_4 = 0.2915$	$V_5 = 0.3134$

Diameter of the pores (dc)	**Probability Due to Number (P_{rn})**	**Probability Due to Length (P_{rl})**	**Probability Due to Area (P_{ra})**	**Probability Due to Volume (P_{rv})**
1.23566	0.132651	0.053984	0.013385	0.001853
1.33094	0.366741	0.175445	0.051781	0.00863
1.443092	0.504441	0.266539	0.088494	0.016893
1.469858	0.566865	0.313613	0.110122	0.022441
1.57542	0.593865	0.336386	0.121823	0.025799
1.578567	0.648486	0.393865	0.158675	0.038991
1.603311	0.721926	0.464474	0.200034	0.052519
1.638988	0.753138	0.505022	0.232127	0.066702
1.728805	0.817398	0.591238	0.302601	0.098869
1.761223	0.838998	0.617716	0.322375	0.107115
1.798794	0.875718	0.678536	0.383747	0.141696
1.803303	0.88551	0.692218	0.395396	0.147233
1.913525	0.90441	0.724549	0.429089	0.16684
1.964144	0.921546	0.757963	0.468785	0.193173
1.994477	0.927306	0.768225	0.479924	0.199924
2.000081	0.938106	0.791032	0.509266	0.221003
2.055709	0.947898	0.814603	0.543835	0.249313
2.157553	0.955395	0.835003	0.577655	0.28062
2.185808	0.965475	0.860064	0.615612	0.312722
2.269556	0.974043	0.888845	0.674517	0.380037
2.28966	0.974555	0.890171	0.676608	0.381879
2.295495	0.980315	0.907849	0.709663	0.416392
2.394654	0.982763	0.918001	0.735311	0.452576
2.417959	0.987173	0.933301	0.76765	0.490743
2.531036	0.988517	0.938157	0.77834	0.503883
2.553441	0.993557	0.959743	0.834664	0.585947

2.675837	0.994325	0.963168	0.843973	0.600074
2.705573	0.995765	0.970782	0.868498	0.644186
2.827882	0.996941	0.976712	0.886714	0.675431
3.004799	0.998285	0.985078	0.918439	0.742612
3.19517	0.998628	0.987491	0.928785	0.767377
3.205215	0.999012	0.990442	0.942599	0.803489
3.408748	0.9996	0.995549	0.969629	0.883361
3.656557	0.999936	0.999152	0.993167	0.969229
3.94444	1	1	1	1

NOTE: All diameters above are in mm.

Table 3-12 Results obtained from computer program for:

$d_1 = 7.972$, $d_2 = 10.164$, $d_3 = 14.772$, $d_4 = 20.614$, $d_5 = 25.448$

$N_1 = 0.4$	$N_2 = 0.25$	$N_3 = 0.11$	$N_4 = 0.11$	$N_5 = 0.13$
$L_1 = 0.2466$	$L_2 = 0.1965$	$L_3 = 0.1257$	$L_4 = 0.1754$	$L_5 = 0.2558$
$A_1 = 0.1233$	$A_2 = 0.1253$	$A_3 = 0.1164$	$A_4 = 0.2267$	$A_5 = 0.4083$
$V_1 = 0.0516$	$V_2 = 0.0669$	$V_3 = 0.0903$	$V_4 = 0.2454$	$V_5 = 0.5458$

Diameter of the pores (dc)	**Probability Due to Number (P_{rn})**	**Probability Due to Length (P_{rl})**	**Probability Due to Area (P_{ra})**	**Probability Due to Volume (P_{rv})**
1.23566	0.064	0.014998	0.001874	0.000138
1.33094	0.184	0.050852	0.007586	0.000673
1.443092	0.259	0.079422	0.01339	0.001365
1.469858	0.3118	0.10235	0.018699	0.002087
1.57542	0.327425	0.109938	0.020665	0.002386
1.578567	0.380225	0.141934	0.031004	0.004348
1.603311	0.446225	0.178474	0.041791	0.006219
1.638988	0.508625	0.225153	0.060413	0.010582
1.728805	0.574625	0.276144	0.08142	0.015666
1.761223	0.59525	0.290703	0.0869	0.016877
1.798794	0.67325	0.365096	0.124737	0.02818
1.803303	0.68777	0.376779	0.12975	0.029444
1.913525	0.708395	0.397095	0.140421	0.032736

1.964144	0.737435	0.429703	0.159946	0.039603
1.994477	0.74651	0.439013	0.165039	0.041239
2.000081	0.770885	0.468653	0.184259	0.04856
2.055709	0.805205	0.516226	0.219424	0.063827
2.157553	0.819725	0.538978	0.238435	0.073157
2.185808	0.837875	0.564961	0.258271	0.082052
2.269556	0.872195	0.631348	0.32675	0.123542
2.28966	0.873526	0.633333	0.328328	0.124278
2.295495	0.894976	0.671242	0.364054	0.144055
2.394654	0.915256	0.71967	0.425723	0.190179
2.417959	0.924331	0.737799	0.445037	0.202265
2.531036	0.928324	0.746107	0.454254	0.208272
2.553441	0.949774	0.799008	0.523826	0.262014
2.675837	0.954493	0.811129	0.540428	0.27537
2.705573	0.967168	0.849719	0.603081	0.335116
2.827882	0.971161	0.861312	0.621031	0.35144
3.004799	0.980599	0.895142	0.685691	0.424032
3.19517	0.98193	0.900534	0.697343	0.438819
3.205215	0.987507	0.925212	0.755572	0.519521
3.408748	0.992226	0.948816	0.81853	0.618155
3.656557	0.997803	0.983253	0.931923	0.837462
3.94444	1	1	1	1

NOTE: All diameters above are in mm.

Table 3-13 Results obtained from computer program for:

d_1 = 7.972, d_2 = 10.164, d_3 = 14.772, d_4 = 20.614, d_5 = 25.448

N_1 = 0.54	N_2 = 0.31	N_3 = 0.08	N_4 = 0.04	N_5 = 0.03
L_1 = 0.4210	L_2 = 0.3081	L_3 = 0.1156	L_4 = 0.0806	L_5 = 0.0747
A_1 = 0.2854	A_2 = 0.2664	A_3 = 0.1452	A_4 = 0.1414	A_5 = 0.1616
V_1 = 0.1608	V_2 = 0.1913	V_3 = 0.1515	V_4 = 0.2059	V_5 = 0.2905

Diameter of the pores (dc)	Probability Due to Number (P_{rn})	Probability Due to Length (P_{rl})	Probability Due to Area (P_{ra})	Probability Due to Volume (P_{rv})
1.23566	0.157464	0.074616	0.023259	0.004155
1.33094	0.428652	0.238455	0.088373	0.018986
1.443092	0.584334	0.358373	0.149135	0.036632
1.469858	0.654318	0.419823	0.184629	0.048382
1.57542	0.684109	0.44908	0.203529	0.05538
1.578567	0.719101	0.491956	0.238089	0.071345
1.603311	0.799453	0.581909	0.304332	0.099303
1.638988	0.825697	0.621607	0.343833	0.12183
1.728805	0.865873	0.684371	0.408333	0.159819
1.761223	0.888937	0.717291	0.439242	0.176452
1.798794	0.919069	0.775402	0.512965	0.230055
1.803303	0.929437	0.792271	0.531019	0.24113
1.913525	0.940969	0.81524	0.561114	0.263729
1.964144	0.951337	0.838781	0.596273	0.293825
1.994477	0.957289	0.851127	0.613121	0.307002
2.000081	0.965938	0.872394	0.64752	0.338889
2.055709	0.973714	0.89419	0.687706	0.381356
2.157553	0.976306	0.902402	0.704823	0.401802
2.185808	0.982258	0.919632	0.737632	0.43761
2.269556	0.986146	0.934839	0.776761	0.495311
2.28966	0.986658	0.936383	0.779822	0.49879
2.295495	0.991122	0.952335	0.817323	0.549315
2.394654	0.99258	0.959376	0.839685	0.590024
2.417959	0.994068	0.965386	0.855658	0.614351
2.531036	0.994836	0.968618	0.864601	0.628535
2.553441	0.997068	0.979748	0.901115	0.697185

2.675837	0.997644	0.98274	0.911336	0.717199
2.705573	0.998481	0.987893	0.932203	0.765633
2.827882	0.998865	0.990147	0.94091	0.784905
3.004799	0.999441	0.994322	0.960814	0.839292
3.19517	0.999505	0.994846	0.96364	0.848021
3.205215	0.999721	0.996779	0.975015	0.886392
3.408748	0.999865	0.998235	0.984705	0.923341
3.656557	0.999973	0.999584	0.99578	0.975478
3.94444	1	1	1	1

NOTE: All diameters above are in mm.

Note that All the below figures are for :

$d_1 = 7.972$ mm , $d_2 = 10.164$, $d_3 = 14.772$, $d_4 = 20.614$, $d_5 = 25.448$

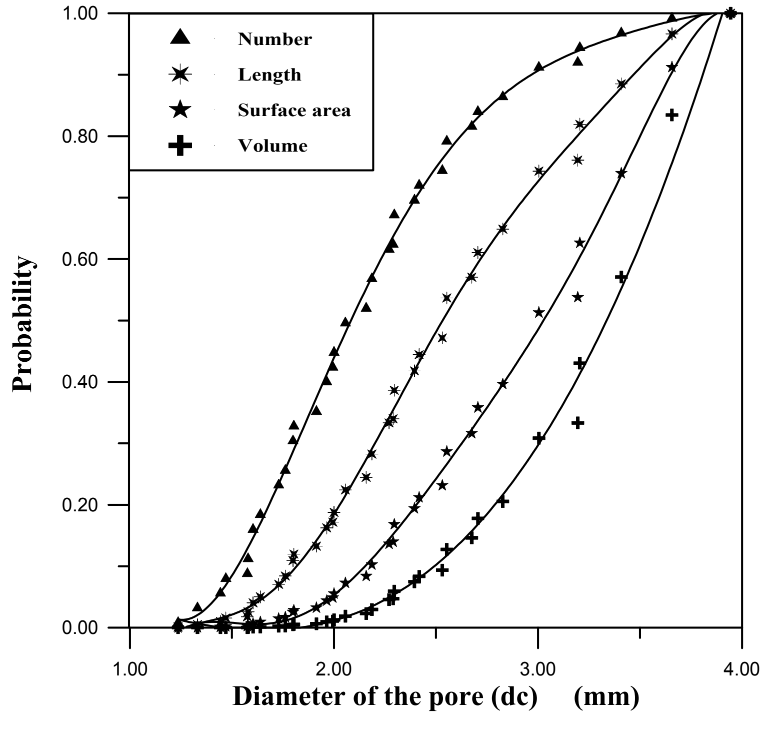

Figure 3-1 The pore size distribution due to number, length, area and volume for $N_1 = 0.2$, $N_2 = 0.2$, $N_3 = 0.2$, $N_4 = 0.2$, $N_5 = 0.2$

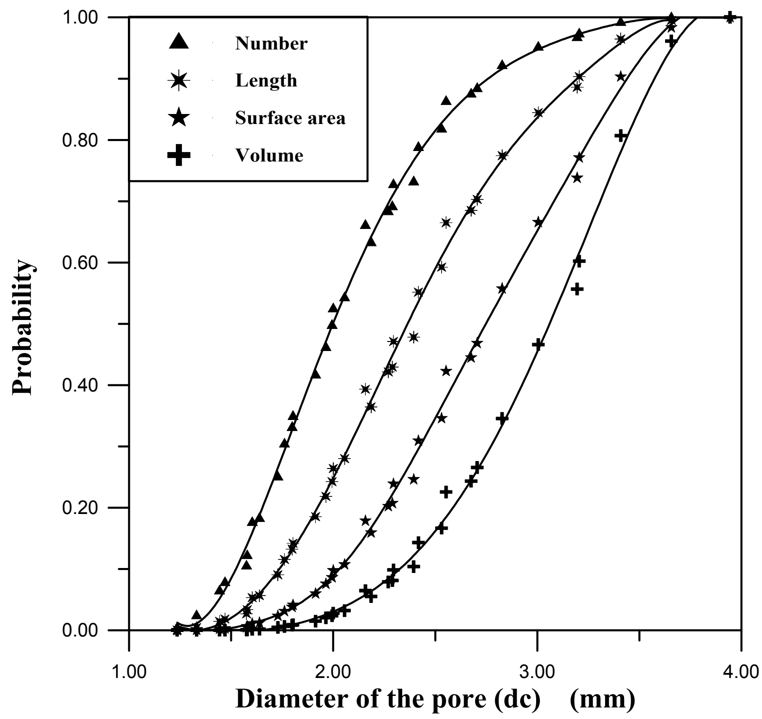

Figure 3-2 The pore size distribution due to number, length, area and volume for $N_1 = 0.15$, $N_2 = 0.3$, $N_3 = 0.2$, $N_4 = 0.25$, $N_5 = 0.1$

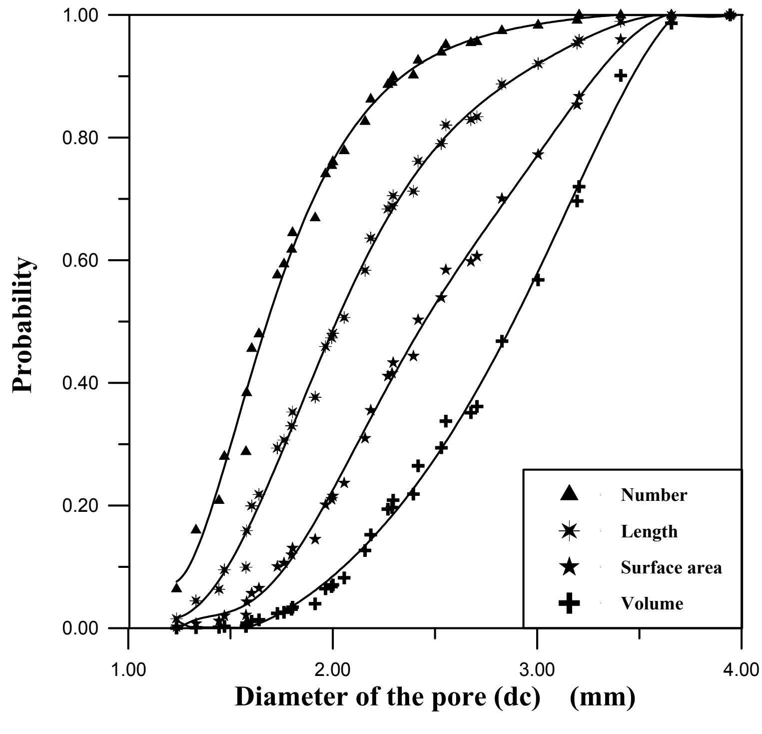

Figure 3-3 The pore size distribution due to number, length, area and volume for $N_1 = 0.4$, $N_2 = 0.2$, $N_3 = 0.15$, $N_4 = 0.2$, $N_5 = 0.05$

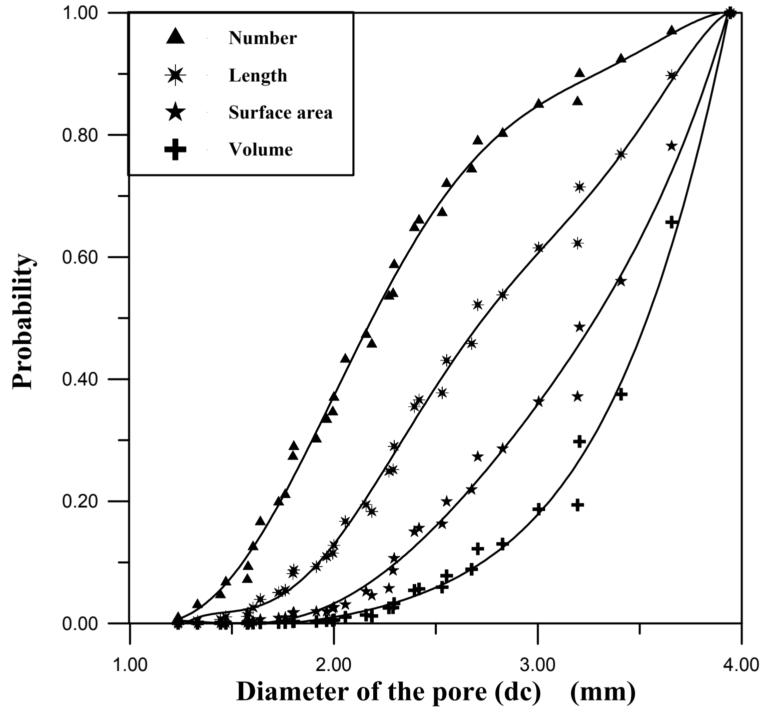

Figure 3-4 The pore size distribution due to number, length, area and volume for N_1= 0.21, N_2 = 0.16, N_3 = 0.16, N_4 = 0.16, N_5 = 0.31

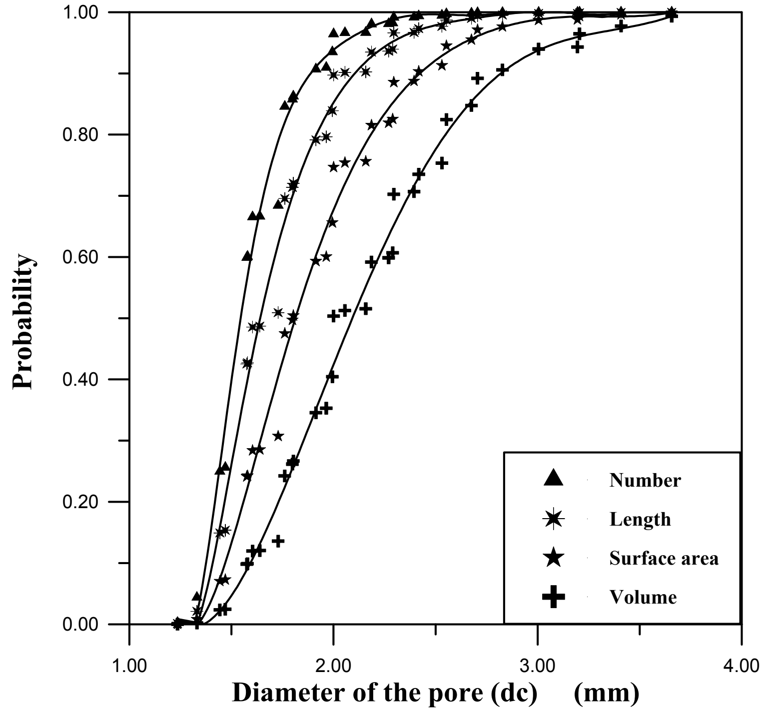

Figure 3-5 The pore size distribution due to number, length, area and volume for N_1= 0.14, N_2 = 0.7, N_3 = 0.11, N_4 = 0.03, N_5 = 0.02

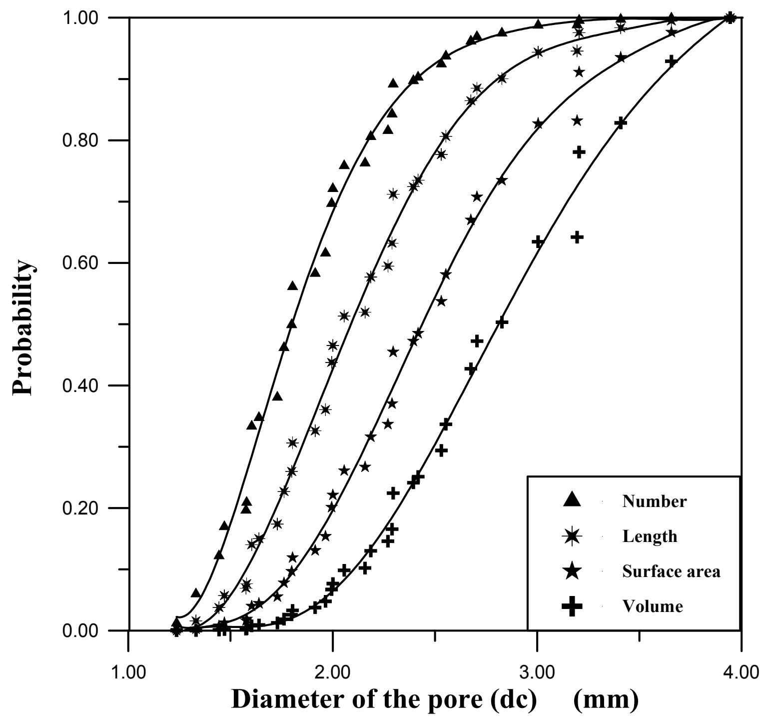

Figure 3-6 The pore size distribution due to number, length, area and volume for $N_1 = 0.23$, $N_2 = 0.3$, $N_3 = 0.3$, $N_4 = 0.08$, $N_5 = 0.09$

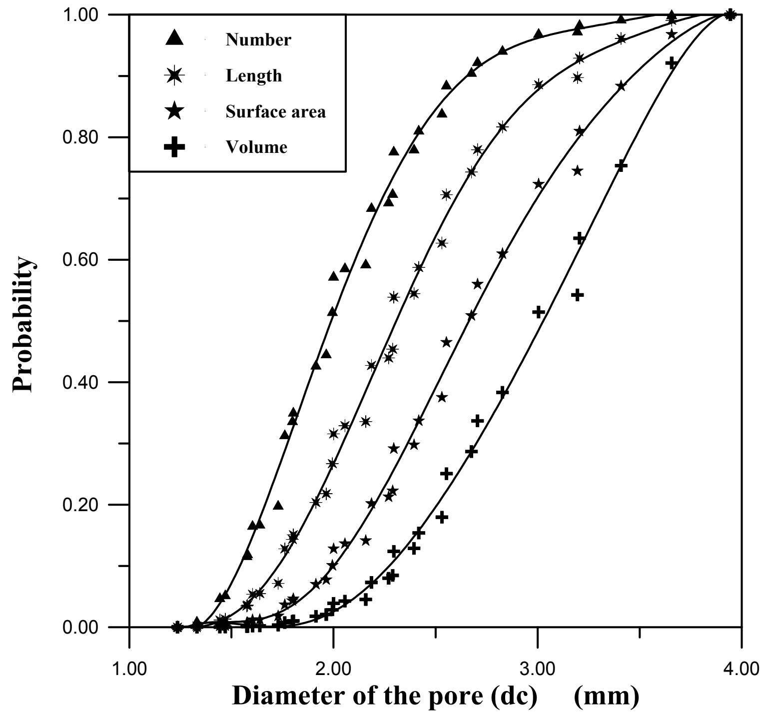

Figure 3-7 The pore size distribution due to number, length, area and volume for $N_1 = 0.08$, $N_2 = 0.4$, $N_3 = 0.24$, $N_4 = 0.16$, $N_5 = 0.12$

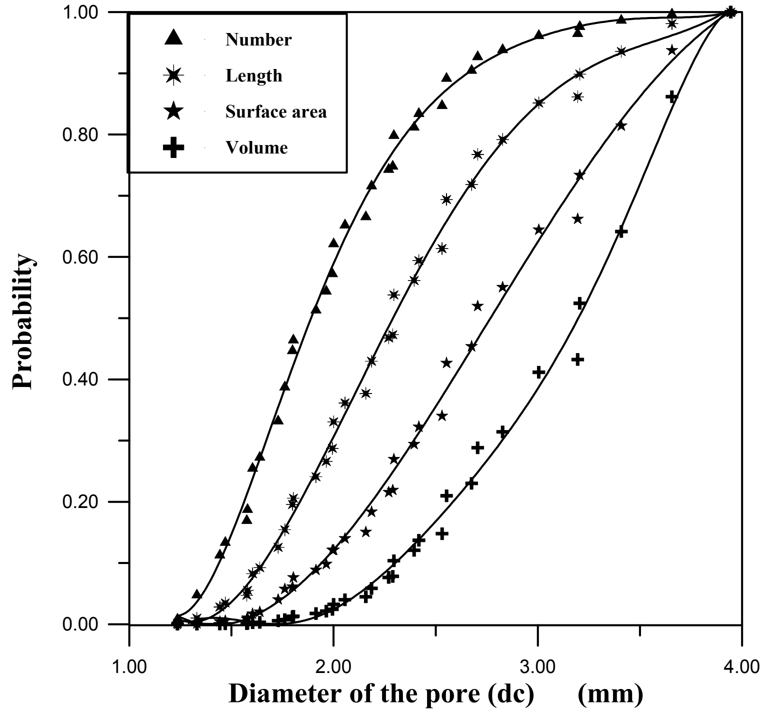

Figure 3-8 The pore size distribution due to number, length, area and volume for $N_1 = 0.2$, $N_2 = 0.33$, $N_3 = 0.17$, $N_4 = 0.15$, $N_5 = 0.15$

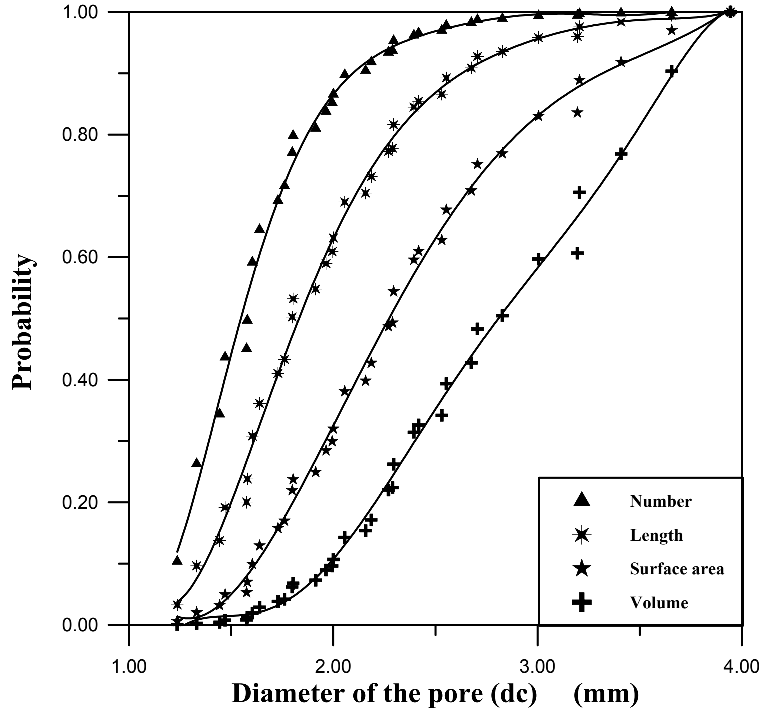

Figure 3-9 The pore size distribution due to number, length, area and volume for $N_1 = 0.47$, $N_2 = 0.24$, $N_3 = 0.14$, $N_4 = 0.07$, $N_5 = 0.08$

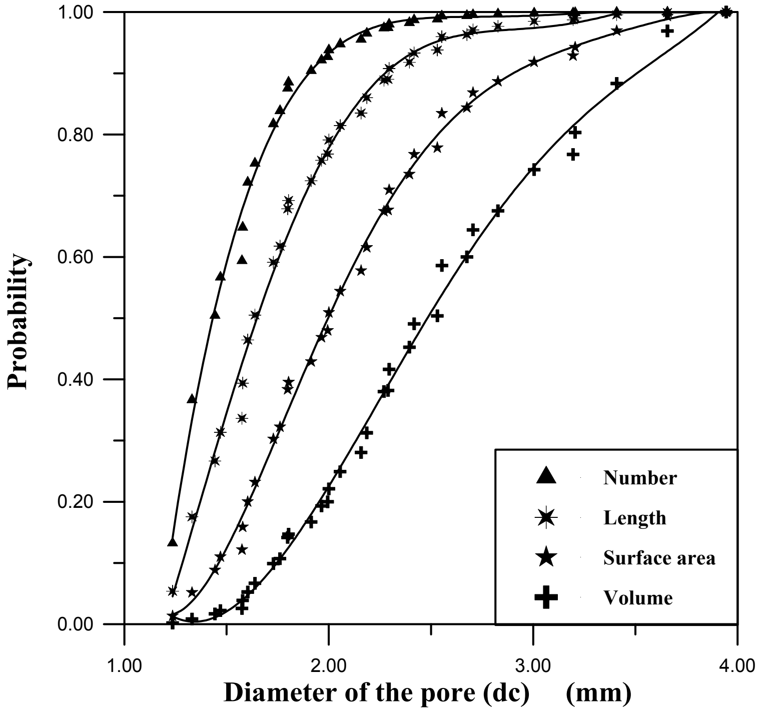

Figure 3-10 The pore size distribution due to number, length, area and volume for $N_1 = 0.51$, $N_2 = 0.3$, $N_3 = 0.08$, $N_4 = 0.07$, $N_5 = 0.04$

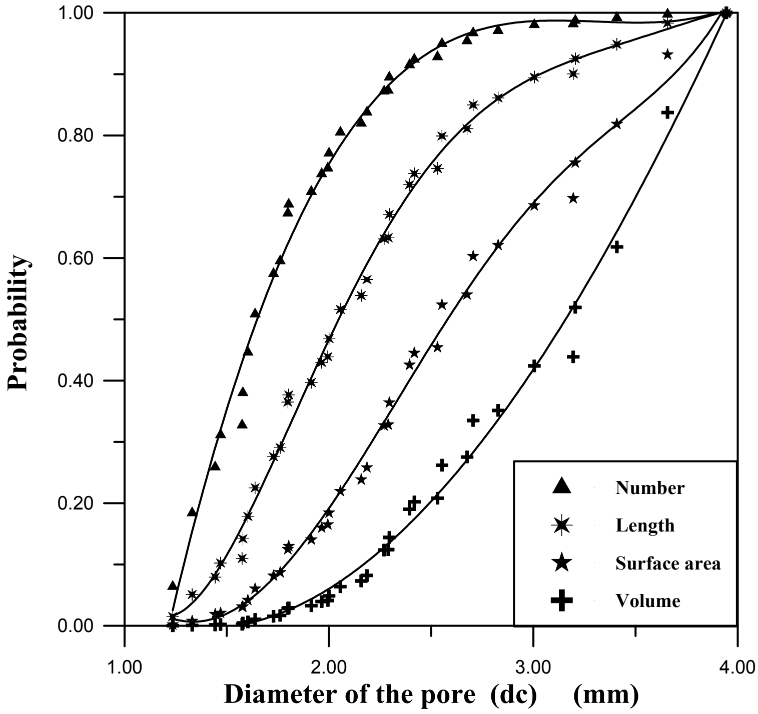

Figure 3-11 The pore size distribution due to number, length, area and volume for $N_1 = 0.4$, $N_2 = 0.25$, $N_3 = 0.11$, $N_4 = 0.11$, $N_5 = 0.13$

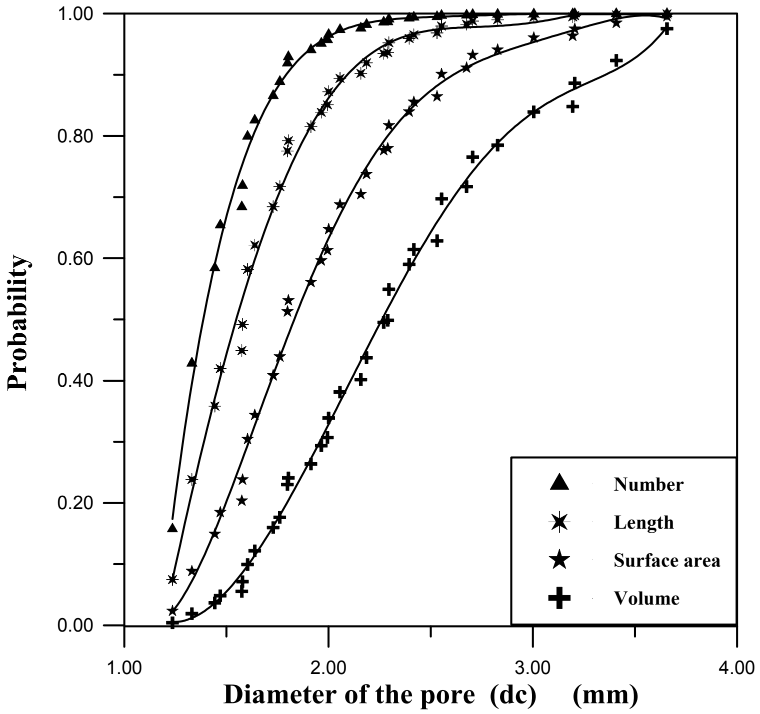

Figure 3-12 The pore size distribution due to number, length, area and volume for $N_1= 0.54$, $N_2 = 0.31$, $N_3 = 0.08$, $N_4 = 0.04$, $N_5 = 0.03$

Now to calculate the mean diameter (dc_m) due to number; length, surface area and volume equation (5) must be applied, so the results of the main diameter were (dc_m) also computed by computer program in appendix [B].

Table 3-14 Values of mean pore diameter for:

$d_1 = 7.972$, $d_2 = 10.164$, $d_3 = 14.772$, $d_4 = 20.614$, $d_5 = 25.448$

$N_1 = 0.2$, $N_2 = 0.2$, $N_3 = 0.2$, $N_4 = 0.2$, $N_5 = 0.2$

Mean pore diameter due to number	2.2059
Mean pore diameter due to length	2.6364
Mean pore diameter due to area	3.0251
Mean pore diameter due to volume	3.3072

Table 3-15 Values of mean pore diameter for:

$d_1 = 7.972$, $d_2 = 10.164$, $d_3 = 14.772$, $d_4 = 20.614$, $d_5 = 25.448$

$N_1 = 0.15$, $N_2 = 0.3$, $N_3 = 0.2$, $N_4 = 0.25$, $N_5 = 0.1$

Mean pore diameter due to number	2.1135
Mean pore diameter due to length	2.4595
Mean pore diameter due to area	2.7984
Mean pore diameter due to volume	3.0733

Table 3-16 Values of mean pore diameter for:

$d_1 = 7.972$, $d_2 = 10.164$, $d_3 = 14.772$, $d_4 = 20.614$, $d_5 = 25.448$

$N_1 = 0.4$, $N_2 = 0.2$, $N_3 = 0.15$, $N_4 = 0.2$, $N_5 = 0.05$

Mean pore diameter due to number	1.7954
Mean pore diameter due to length	2.1451
Mean pore diameter due to area	2.5435
Mean pore diameter due to volume	2.8882

Table 3-17 Values of mean pore diameter for:

$d_1 = 7.972$, $d_2 = 10.164$, $d_3 = 14.772$, $d_4 = 20.614$, $d_5 = 25.448$

$N_1 = 0.21$, $N_2 = 0.16$, $N_3 = 0.16$, $N_4 = 0.16$, $N_5 = 0.31$

Mean pore diameter due to number	2.3302
Mean pore diameter due to length	2.8333
Mean pore diameter due to area	3.2382
Mean pore diameter due to volume	3.4973

Table 3-18 Values of mean pore diameter for:

$d_1 = 7.972$, $d_2 = 10.164$, $d_3 = 14.772$, $d_4 = 20.614$, $d_5 = 25.448$

$N_1 = 0.14$, $N_2 = 0.7$, $N_3 = 0.11$, $N_4 = 0.03$, $N_5 = 0.02$

Mean pore diameter due to number	1.6399
Mean pore diameter due to length	1.7475
Mean pore diameter due to area	1.9234
Mean pore diameter due to volume	2.1941

Table 3-19 Values of mean pore diameter for:

$d_1 = 7.972$, $d_2 = 10.164$, $d_3 = 14.772$, $d_4 = 20.614$, $d_5 = 25.448$

$N_1 = 0.23$, $N_2 = 0.3$, $N_3 = 0.3$, $N_4 = 0.08$, $N_5 = 0.09$

Mean pore diameter due to number	1.8911
Mean pore diameter due to length	2.1810
Mean pore diameter due to area	2.5293
Mean pore diameter due to volume	2.8798

Table 3-20 Values of mean pore diameter for:

$d_1 = 7.972$, $d_2 = 10.164$, $d_3 = 14.772$, $d_4 = 20.614$, $d_5 = 25.448$

$N_1 = 0.08$, N2 = 0.4, $N_3 = 0.24$, $N_4 = 0.16$, $N_5 = 0.12$

Mean pore diameter due to number	2.0868
Mean pore diameter due to length	2.3987
Mean pore diameter due to area	2.7427
Mean pore diameter due to volume	3.0551

Table 3-21 Values of mean pore diameter for:

$d_1 = 7.972$, $d_2 = 10.164$, $d_3 = 14.772$, $d_4 = 20.614$, $d_5 = 25.448$

$N_1 = 0.2$, $N_2 = 0.33$, $N_3 = 0.17$, $N_4 = 0.15$, $N_5 = 0.15$

Mean pore diameter due to number	2.0095
Mean pore diameter due to length	2.4011
Mean pore diameter due to area	2.8234
Mean pore diameter due to volume	3.1745

Table 3-22 Values of mean pore diameter for:

$d_1 = 7.972$, $d_2 = 10.164$, $d_3 = 14.772$, $d_4 = 20.614$, $d_5 = 25.448$

$N_1 = 0.47$, $N_2 = 0.24$, $N_3 = 0.14$, $N_4 = 0.07$, $N_5 = 0.08$

Mean pore diameter due to number	1.6491
Mean pore diameter due to length	1.9579
Mean pore diameter due to area	2.4037
Mean pore diameter due to volume	2.8761

Table 3-23 Values of mean pore diameter for:
$d_1 = 7.972$, $d_2 = 10.164$, $d_3 = 14.772$, $d_4 = 20.614$, $d_5 = 25.448$
$N_1 = 0.51$, $N_2 = 0.3$, $N_3 = 0.08$, $N_4 = 0.07$, $N_5 = 0.04$

Mean pore diameter due to number	1.5435
Mean pore diameter due to length	1.7663
Mean pore diameter due to area	2.1321
Mean pore diameter due to volume	2.5933

Table 3-24 Values of mean pore diameter for:
$d_1 = 7.972$, $d_2 = 10.164$, $d_3 = 14.772$, $d_4 = 20.614$, $d_5 = 25.448$
$N_1 = 0.4$, $N_2 = 0.25$, $N_3 = 0.11$, $N_4 = 0.11$, $N_5 = 0.15$

Mean pore diameter due to number	1.7819
Mean pore diameter due to length	2.1901
Mean pore diameter due to area	2.6974
Mean pore diameter due to volume	3.1390

Table 3-25 Values of mean pore diameter for:

$d_1 = 7.972$, $d_2 = 10.164$, $d_3 = 14.772$, $d_4 = 20.614$, $d_5 = 25.448$

$N_1 = 0.54$, $N_2 = 0.31$, $N_3 = 0.08$, $N_4 = 0.04$, $N_5 = 0.03$

Mean pore diameter due to number	1.4897
Mean pore diameter due to length	1.6586
Mean pore diameter due to area	1.9561
Mean pore diameter due to volume	2.3881

CHAPTER FOUR
Experimental work and Results

4.1 Experimental apparatus, and Material

The main system, by which the experimental work is done, consists of the following parts: -

1. Glass cylinder (Fig.4.1) with height of 36.5 cm, diameter of 13 cm, and this cylinder is opened from the top and bottom.

2. A sieve is used to retain the spheres that the packed bed consist of, and has square pores with diameter of 1.1 * 1.1 cm. it is connected to the cylinder by a resin material mixed with black cascade maker. The parts are shown in figure 4.1.

3. Blower of velocity (13000 r/min) to introduce air after putting the sizes of spheres and the impurities.

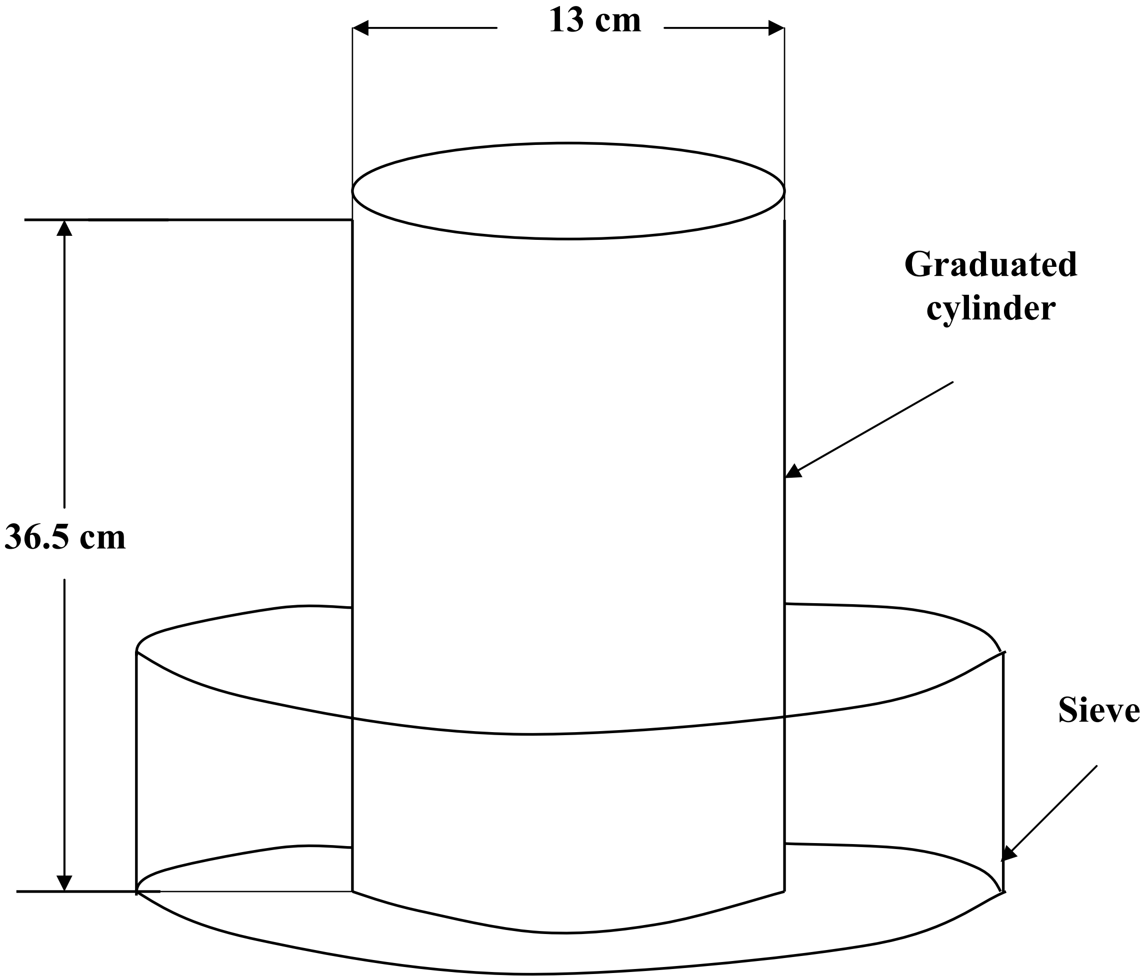

Figure 4-1 main system of experiments work

In experimental work used other necessary parts and these parts are: -

1. A digital balance (for accuracy of 0.1) was used to weight the mass of the input and output impurities.
2. Glass spheres with different sizes used to make a packed bed **(d_1= 7.972, d_2= 10.164, d_3= 14.772, d_4= 20.614 and d_5= 25.448 mm).**
3. A small sizes of spheres was used to represented the impurities, and these impurities are listed with their weight in table 4.1: -

Table 4-1 Diameters, weight and number of impurities

Sample of impurities	Diameter of impurities (mm)	Weight (gm)	Density (gm/cm^3)	No. of spheres
A	1.2-3.3 (glass spheres)	100	2.456	635
B	4.2 (Lead alloy)	80	12.814	161
C	6.0 (lead alloy)	24.7	9.927	22

4. Vernier with an accuracy of about 0.02 mm.

4.2 Procedure of Experimental work

To make the Packed bed, spheres of five diameters (7.972, 10.164, 14.772, 20.614, 25.448 mm) were used by taking a suitable quantity of each sphere size and choosing a certain number percent.

In each experiment, the following steps were taken: -

1. The number percent of the five sizes of spheres was chosen to make the packed bed.

2. The number of the layer was chosen, and at the beginning make four layers were chosen.

3. A certain number of each size that had the same number percent which was chosen in step 1 are taken to make the first layer, and then put these inside the cylinder.

4. The other layers are made and put inside the cylinder to make the total number of chosen layers in step 2..

5. After that, our configuration was completed and the system is ready for starting the experiment. A certain weight is taken of each sample of impurities, starting with sample “A” by entering the sample from the top of cylinder.

6. Using the blower of (13000 r/min) to enter air from the top of cylinder for (3 min) until the system reaches the steady state (her the steady state reaches when all the spheres stop move).

7. taking the output of impurities (from the bottom of cylinder) and weight it by the digital balance.

8. All the above steps, must be repeated for other size of impurities (B+C).

9. All the above steps must be repeated for five and six layers.

4.3 Results of the Experiments

The results of the experiments are given below in detail: -

Experiment 1

- Number of spheres of group 1 in each layer = 10
- Number of spheres of group 2 in each layer = 10
- Number of spheres of group 3 in each layer = 10
- Number of spheres of group 4 in each layer = 10
- Number of spheres of group 5 in each layer = 10

$N_1 = 0.2$, $N_2 = 0.2$, $N_3 = 0.2$, $N_4 = 0.2$, $N_5 = 0.2$

Table 4-2 Results of Exp. 1

No. of layers		**4**	**5**	**6**
Size of Impurities (mm)	**Weight of spheres Input (gm)**	**Weight of spheres Output (gm)**	**Weight of spheres Output (gm)**	**Weight of spheres Output (gm)**
1.2 – 3.3	100	95.1	90.5	82.4
4.2	80	32.5	20.3	9.6
6.0	24.7	14.3	10.4	6.5
Height of the bed (cm)		10	12	14

No. of layers	4	5	6
Size of impurities (mm)	Percent output (wt. %)	Percent output (wt.%)	Percent output (wt.%)
1.2 – 3.3	95.1	90.5	82.4
4.2	40.6	25.38	12
6.0	57.89	42.11	26.32

Experiment 2

- Number of spheres of group 1 in each layer = 8
- Number of spheres of group 2 in each layer = 15
- Number of spheres of group 3 in each layer = 10
- Number of spheres of group 4 in each layer = 13
- Number of spheres of group 5 in each layer = 5

$N_1 = 0.15$, $N_2 = 0.3$, $N_3 = 0.2$, $N_4 = 0.25$, $N_5 = 0.1$

Table 4-3 Results of Exp. 2

No. of layers		4	5	6
Size of Impurities (mm)	Weight of spheres Input (gm)	Weight of spheres Output (gm)	Weight of spheres Output (gm)	Weight of spheres Output (gm)
1.2 – 3.3	100	76.9	73.2	59.0
4.2	80	28.4	13.3	5.0
6.0	24.7	11.3	8.5	5.2
Height of the bed (cm)		7	9	13

No. of layers	4	5	6
Size of impurities (mm)	Percent output (wt. %)	Percent output (wt. %)	Percent output (wt. %)
1.2 – 3.3	76.9	73.2	59
4.2	35.5	13.3	6.25
6.0	45.75	8.5	5.2

Experiment 3

- Number of spheres of group 1 in each layer = 30
- Number of spheres of group 3 in each layer = 15
- Number of spheres of group 3 in each layer = 11
- Number of spheres of group 4 in each layer = 15
- Number of spheres of group 5 in each layer = 4

$N_1 = 0.4, N_2 = 0.2, N_3 = 0.15, N_4 = 0.2, N_5 = 0.05$

Table 4-4 Result of Exp. 3

No. of layers		**4**	**5**	**6**
Size of Impurities (mm)	**Weight of spheres Input (gm)**	**Weight of spheres Output (gm)**	**Weight of spheres Output (gm)**	**Weight of spheres Output (gm)**
1.2 – 3.3	100	73.8	43.5	50.5
4.2	80	25.0	14.5	6.0
6.0	24.7	10.1	8.8	4.7
Height of the bed (cm)		6	9	11

No. of layers	**4**	**5**	**6**
Size of impurities (mm)	**Percent output (wt. %)**	**Percent output (wt. %)**	**Percent output (wt. %)**
1.2 – 3.3	37.8	43.5	50.5
4.2	31.25	18.13	7.5
6.0	40.89	35.63	19.03

Experiment 4

- Number of spheres of group 1 in each layer = 7
- Number of spheres of group 2 in each layer = 5
- Number of spheres of group 3 in each layer = 5
- Number of spheres of group 4 in each layer = 5
- Number of spheres of group 5 in each layer = 10

$N_1 = 0.21$, $N_2 = 0.16$, $N_3 = 0.16$, $N_4 = 0.16$, $N_5 = 0.31$

Table 4-5 Results of Exp. 4

No. of layers		**4**	**5**	**6**
Size of Impurities (mm)	**Weight of spheres Input (gm)**	**Weight of spheres Output (gm)**	**Weight of spheres Output (gm)**	**Weight of spheres Output (gm)**
1.2 – 3.3	100	97.3	93.1	88.1
4.2	80	54.9	37.3	27.7
6.0	24.7	18.5	15.3	10.5
Height of the bed (cm)		7	10	12

No. of layers	**4**	**5**	**6**
Size of impurities (mm)	**Percent output (wt. %)**	**Percent output (wt. %)**	**Percent output (wt. %)**
1.2 – 3.3	97.3	93.1	88.1
4.2	68.63	37.3	34.63
6.0	74.91	15.3	42.51

Experiment 5

- Number of spheres of group 1 in each layer = 12
- Number of spheres of group 2 in each layer = 60
- Number of spheres of group 3 in each layer = 10
- Number of spheres of group 4 in each layer = 3
- Number of spheres of group 5 in each layer = 2

$N_1 = 0.14$, $N_2 = 0.7$, $N_3 = 0.11$, $N_4 = 0.03$, $N_5 = 0.02$

Table 4-6 Result of Exp. 5

No. of layers		**4**	**5**	**6**
Size of Impurities (mm)	**Weight of spheres Input (gm)**	**Weight of spheres Output (gm)**	**Weight of spheres Output (gm)**	**Weight of spheres Output (gm)**
1.2 – 3.3	100	71.5	48.7	40.0
4.2	80	45.2	10.7	3.8
6.0	24.7	5.7	3.8	2.1
Height of the bed (cm)		4	6	7

No. of layers	**4**	**5**	**6**
Size of impurities (mm)	**Percent output (wt. %)**	**Percent output (wt.%)**	**Percent output (wt. %)**
1.2 – 3.3	71.5	48.7	40
4.2	56.5	13.38	4.75
6.0	23.08	15.38	8.50

Experiment 6

- Number of spheres of group 1 in each layer = 15
- Number of spheres of group 2 in each layer = 20
- Number of spheres of group 3 in each layer = 20
- Number of spheres of group 4 in each layer = 5
- Number of spheres of group 5 in each layer = 6

$N_1 = 0.23$, $N_2 = 0.3$, $N_3 = 0.3$, $N_4 = 0.08$, $N_5 = 0.09$

Table 4-7 Results of Exp. 6

No. of layers		**4**	**5**	**6**
Size of impurities (mm)	**Weight of spheres input (gm)**	**Weight of spheres output (gm)**	**Weight of spheres output (gm)**	**Weight of spheres output (gm)**
1.2 – 3.3	100	81.5	78.7	75.3
4.2	80	44.4	11.2	2.5
6.0	24.7	8.8	6.3	3.5
Height of the bed (cm)		5.5	7.5	9

No. of layers	**4**	**5**	**6**
Size of impurities (mm)	**Percent output (wt. %)**	**Percent output (wt. %)**	**Percent output (wt. %)**
1.2 – 3.3	81.5	78.7	75.3
4.2	55.5	14	3.13
6.0	35.63	25.51	14.17

Experiment 7

- Number of spheres of group 1 in each layer = 5
- Number of spheres of group 2 in each layer = 25
- Number of spheres of group 3 in each layer = 15
- Number of spheres of group 4 in each layer = 10
- Number of spheres of group 5 in each layer = 8

$N_1 = 0.08, N_2 = 0.4, N_3 = 0.24, N_4 = 0.16, N_5 = 0.12$

Table 4-8 Results of Exp. 7

No. of layers		**4**	**5**	**6**
Size of Impurities (mm)	**Weight of spheres Input (gm)**	**Weight of spheres Output (gm)**	**Weight of spheres Output (gm)**	**Weight of spheres Output (gm)**
1.2 – 3.3	100	80.0	75.3	65.8
4.2	80	28.4	14.7	4.7
6.0	24.7	15.8	11.1	8.1
Height of the bed (cm)		9	11	13

No. of layers	**4**	**5**	**6**
Size of impurities (mm)	**Percent output (wt. %)**	**Percent output (wt. %)**	**Percent output (wt. %)**
1.2 – 3.3	80	75.3	65.8
4.2	35.5	18.38	5.88
6.0	63.97	44.94	32.79

Experiment 8

- Number of spheres of group 1 in each layer = 12
- Number of spheres of group 2 in each layer = 20
- Number of spheres of group 3 in each layer = 10
- Number of spheres of group 4 in each layer = 9
- Number of spheres of group 5 in each layer = 9

$N_1 = 0.2$, $N_2 = 0.33$, $N_3 = 0.17$, $N_4 = 0.15$, $N_5 = 0.15$

Table 4-9 Results of Exp. 8

No. of layers		4	5	6
Size of Impurities (mm)	**Weight of spheres Input (gm)**	**Weight of spheres Output (gm)**	**Weight of spheres Output (gm)**	**Weight of spheres Output (gm)**
1.2 – 3.3	100	75.9	71.8	60.7
4.2	80	30.6	22.4	7.1
6.0	24.7	16.3	12.1	4.3
Height of the bed (cm)		10	11	12

No. of layers	4	5	6
Size of impurities (mm)	**Percent output (wt. %)**	**Percent output (wt. %)**	**Percent output (wt. %)**
1.2 – 3.3	75.9	71.8	60.7
4.2	38.3	28	8.88
6.0	65.99	48.99	17.41

Experiment 9

- Number of spheres of group 1 in each layer = 40
- Number of spheres of group 2 in each layer = 20
- Number of spheres of group 3 in each layer = 12
- Number of spheres of group 4 in each layer = 6
- Number of spheres of group 5 in each layer = 7

$N_1 = 0.47$, $N_2 = 0.24$, $N_3 = 0.14$, $N_4 = 0.07$, $N_5 = 0.08$

Table 4-10 Results of Exp. 9

No. of layers		**4**	**5**	**6**
Size of Impurities (mm)	**Weight of spheres Input (gm)**	**Weight of spheres Output (gm)**	**Weight of spheres Output (gm)**	**Weight of spheres Output (gm)**
1.2 – 3.3	100	66.7	57.4	50.9
4.2	80	29.0	17.5	4.9
6.0	24.7	7.8	4.5	2.1
Height of the bed (cm)		7	8	9

No. of layers	**4**	**5**	**6**
Size of impurities (mm)	**Percent output (wt. %)**	**Percent output (wt. %)**	**Percent output (wt. %)**
1.2 – 3.3	66.7	57.4	50.9
4.2	36.3	21.88	6.13
6.0	31.58	18.22	8.50

Experiment 10

- Number of spheres of group 1 in each layer = 60
- Number of spheres of group 2 in each layer = 35
- Number of spheres of group 3 in each layer = 10
- Number of spheres of group 4 in each layer = 8
- Number of spheres of group 5 in each layer = 5

$N_1 = 0.51$, $N_2 = 0.3$, $N_3 = 0.08$, $N_4 = 0.07$, $N_5 = 0.04$

Table 4-11 Results of Exp. 10

No. of layers		**4**	**5**	**6**
Size of Impurities (mm)	**Weight of spheres Input (gm)**	**Weight of spheres Output (gm)**	**Weight of spheres Output (gm)**	**Weight of spheres Output (gm)**
1.2 – 3.3	100	53.5	43.6	24.7
4.2	80	11.9	4.2	1.2
6.0	24.7	3.1	2.2	1.0
Height of the bed (cm)		6.5	9	10

No. of layers	**4**	**5**	**6**
Size of impurities (mm)	**Percent output (wt. %)**	**Percent output (wt. %)**	**Percent output (wt.%)**
1.2 – 3.3	53.5	43.6	24.7
4.2	14.88	5.3	1.5
6.0	12.55	8.91	4.05

Experiment 11

- Number of spheres of group 1 in each layer = 30
- Number of spheres of group 2 in each layer = 20
- Number of spheres of group 3 in each layer = 8
- Number of spheres of group 4 in each layer = 8
- Number of spheres of group 5 in each layer = 10

$N_1 = 0.4$, $N_2 = 0.25$, $N_3 = 0.11$, $N_4 = 0.11$, $N_5 = 0.13$

Table 4-12 Results of Exp. 11

No. of layers		4	5	6
Size of Impurities (mm)	**Weight of spheres Input (gm)**	**Weight of spheres Output (gm)**	**Weight of spheres Output (gm)**	**Weight of spheres Output (gm)**
1.2 – 3.3	100	78.2	52.3	46.9
4.2	80	18.5	7.6	5.9
6.0	24.7	4.1	2.5	1.9
Height of the bed (cm)		7	10	13

No. of layers	4	5	6
Size of impurities (mm)	**Percent output (wt. %)**	**Percent output (wt. %)**	**Percent output (wt. %)**
1.2 – 3.3	78.2	52.3	46.9
4.2	23.13	9.5	7.38
6.0	16.61	10.12	7.69

Experiment 12

- Number of spheres of group 1 in each layer = 70
- Number of spheres of group 2 in each layer = 40
- Number of spheres of group 3 in each layer = 10
- Number of spheres of group 4 in each layer = 5
- Number of spheres of group 5 in each layer = 4

$N_1 = 0.54$, $N_2 = 0.31$, $N_3 = 0.08$, $N_4 = 0.04$, $N_5 = 0.03$

Table 4-13 Results of Exp. 12

No. of layers		4	5	6
Size of Impurities (mm)	**Weight of spheres Input (gm)**	**Weight of spheres Output (gm)**	**Weight of spheres Output (gm)**	**Weight of spheres Output (gm)**
1.2 – 3.3	100	40	30.7	21.9
4.2	80	5.7	2.3	0.8
6.0	24.7	1.3	0.6	0
Height of the bed (cm)		5.5	7	8

No. of layers	4	5	6
Size of impurities (mm)	**Percent output (wt. %)**	**Percent output (wt. %)**	**Percent output (wt. %)**
1.2 – 3.3	40	30.7	21.9
4.2	7.125	2.875	1
6.0	5.263	2.429	0

CHAPTER FIVE

DISCUSSION OF THEORETICAL AND EXPERIMENTAL RESULTS

5.1 Introduction

In chapter three, the details are given for finding the pore size in the packed bed and probabilities of those pore sizes and also the mean pore diame-ters for each type pf distribution (due to number, length, area and volume) are calculated and the results are listed in table 3.2-1 to 3.2-24, after that the experimental work is given in chapter four which contains the experiments for several packed beds with a different number percent for each type of this packed bed and those experiments were repeated with three size of impurities that were added in each experiment and the same experiments and size of impurities were repeated for four , five and six layers and the result were given in table 4.3-1 to 4.3-2 .

Now, this chapter will explain and discuss those results (theoretical and experimental), also a suitable relation between the number of layer and percent output of impurities, must be found relation between the size of impurities and percent output of impurities, also in order to relate the theoretical and experimental results to each other in a way to study the properties of packing, A suitable relation between the mean pore diameter due to (number, length, area and volume) and percent output of impurities must be found .

Eventually, we notice that the constant parameters in this chapter are the diameters (d_1 = 7.972 mm, d_2 = 10.164 mm, d_3 = 14.772 mm, d_4 = 20.614 mm, d_5 = 25.448 mm).

5.2 Relationship between the Number of layers and percent output of impurities

The experimental work in chapter four was repeated to four, five and six layers and in each layer three different sizes of impurities were used and these sizes are:

- Glass spheres of 1.2 – 3.3 mm mixtures.
- Alloy of lead spheres of 4.2 mm.
- Alloy of lead spheres of 6.0 mm.

The curves of this relation are shown in figures 5.1 to 5.12, the values of percent output (wt. %) of impurities are taken from table 4.2-1 to 4.2-12.

The figures 5.1 to 5.12 show the proportionality between the number of layer and the percent output of impurities. It is obvious from the curve of 1.2 – 3.3 mm that when this kind of impurities are passed from the packed bed in case of four layers, a large weight of output of impurities that leave the packed bed appeared, and this weight decreased in the case of five layers and a noticeable decrease was seen in case of the six layers, hence it is obvious from figures that when increasing the number of layers a decrease in the weight of output of impurities (leaving the packed bed) occurs, so the percent output of impurities will be decreased; but incase of 6 mm impurities it is obvious the percent output of impurities increased not like other cases and this make us sure that the exist of bigger pores than the theoretical maximum pores, but the effect of these pores is reduce and disappear when we increasing of the number of layers, and the number of available pores for passing the first particle, which has volume with 6 mm and that will be more than the available particles for the smaller particles and that leading to increase the probability of configuration the bridge between the little particles and that will prohibit the little particles from passing through a good pores for passing particles as a speed not a pile. Also it is obvious that the curve of fine mixture of impurities (1.2 – 3.3 mm) has higher values of percent output of impurities.

Note that all the below figures are for diameters: -

$d_1 = 7.972$, $d_2 = 10.164$, $d_3 = 14.772$, $d_4 = 20.614$, $d_5 = 25.448$ mm

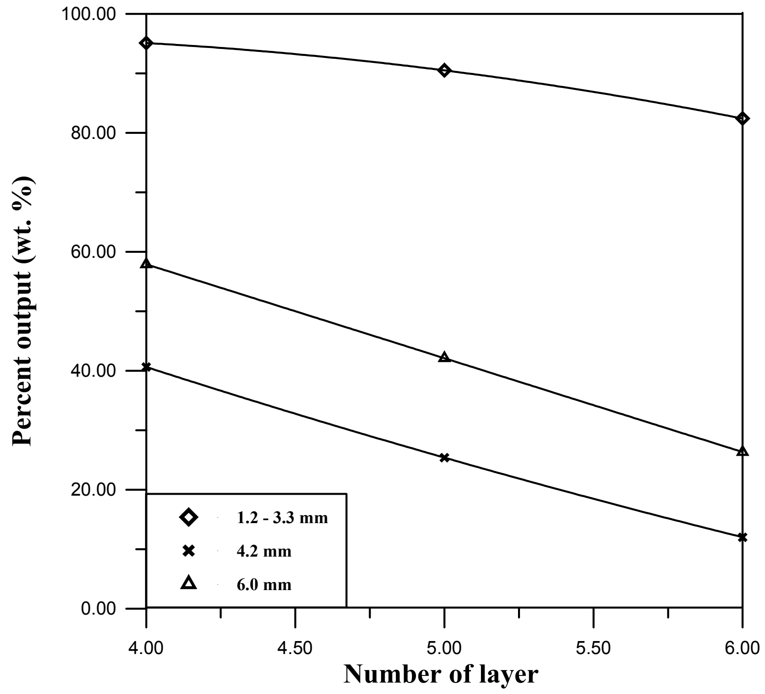

Figure 5-1 Number of layers vs. percent output of impurities for: $N_1 = 0.2$, $N_2 = 0.2$, $N_3 = 0.2$, $N_4 = 0.2$, $N_5 = 0.2$

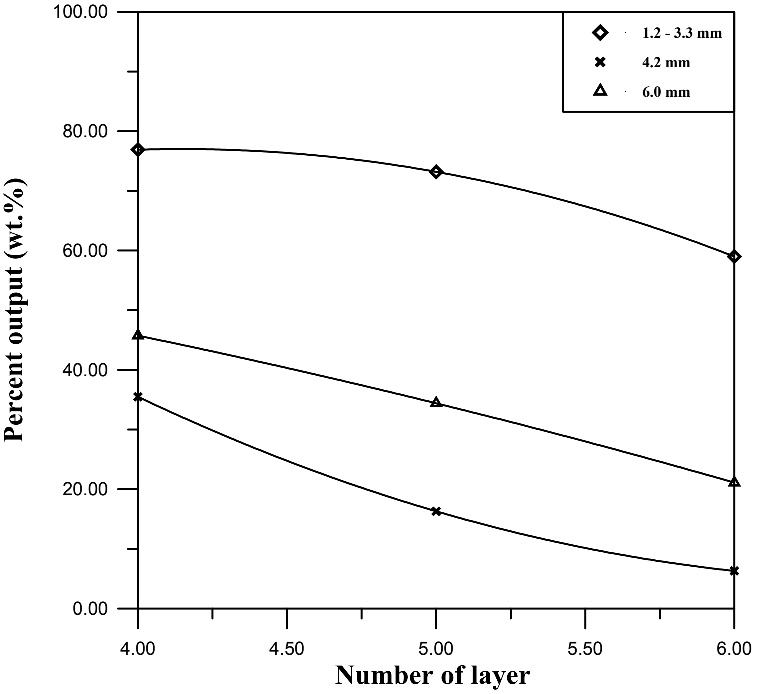

Figure 5-2 Number of layers vs. percent output of impurities for: $N_1 = 0.15$, $N_2 = 0.3$, $N_3 = 0.2$, $N_4 = 0.25$, $N_5 = 0.1$

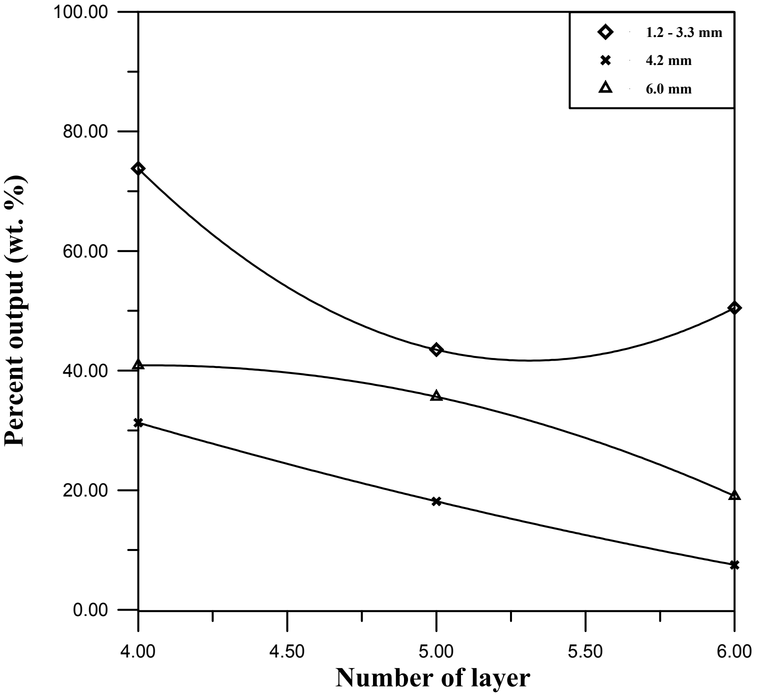

Figure 5-3 Number of layers vs. percent output of impurities for: $N_1= 0.4$, $N_2 = 0.2$, $N_3 = 0.15$, $N_4 = 0.2$, $N_5= 0.05$

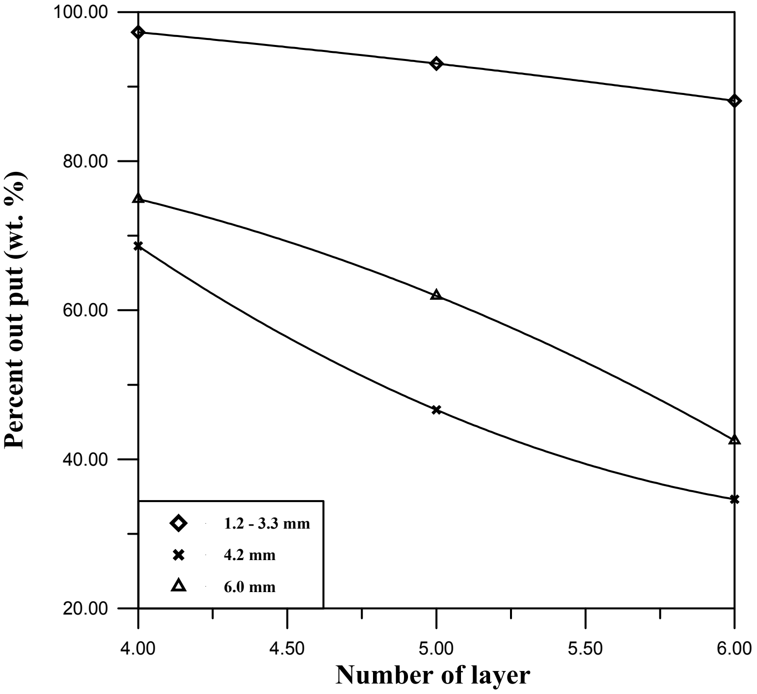

Figure 5-4 Number of layers vs. percent output of impurities for: $N_1 = 0.21$, $N_2 = 0.16$, $N_3 = 0.16$, $N_4 = 0.16$, $N_5 = 0.31$

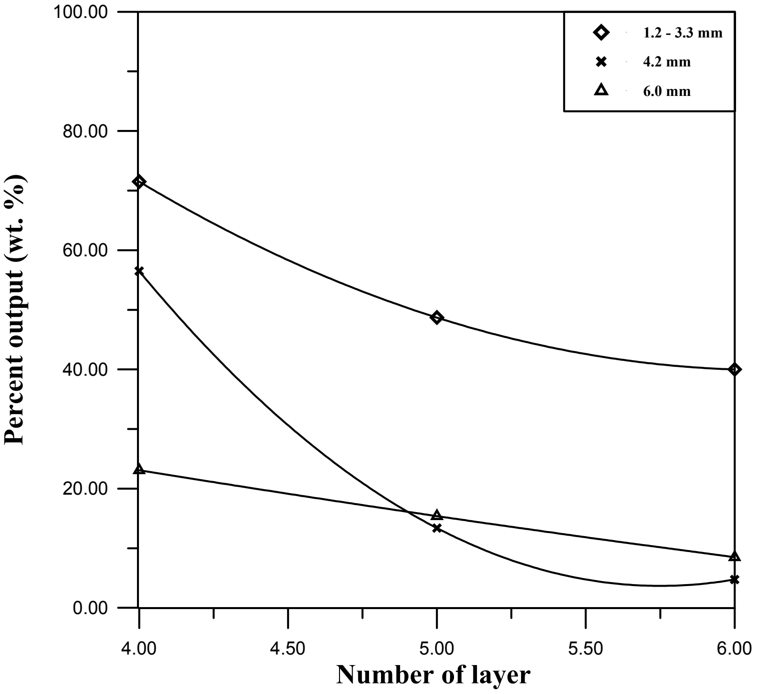

Figure 5-5 Number of layers vs. percent output of impurities for: $N_1 = 0.14$, $N_2 = 0.7$, $N_3 = 0.11$, $N_4 = 0.03$, $N_5 = 0.02$

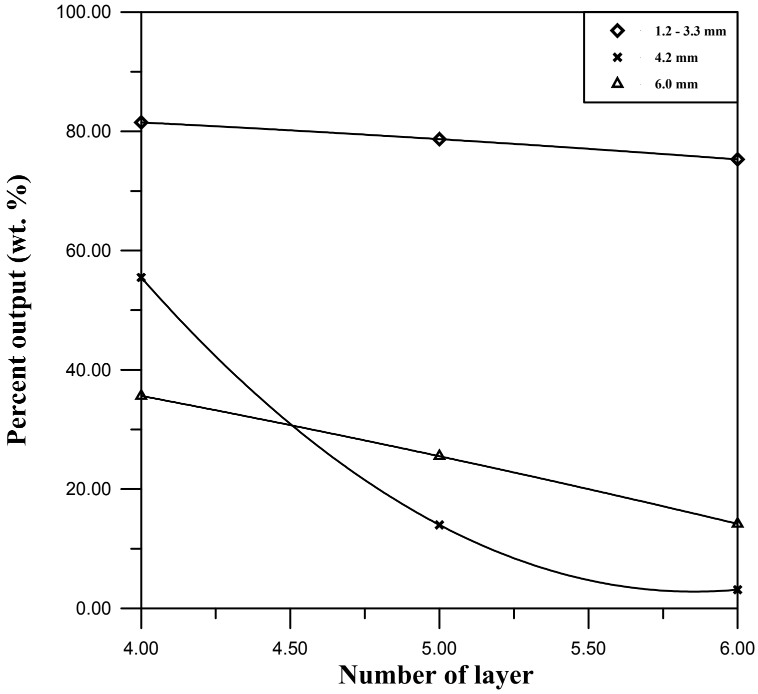

Figure 5-6 Number of layers vs. percent output of impurities for: $N_1 = 0.23$, $N_2 = 0.3$, $N_3 = 0.3$, $N_4 = 0.08$, $N_5 = 0.09$

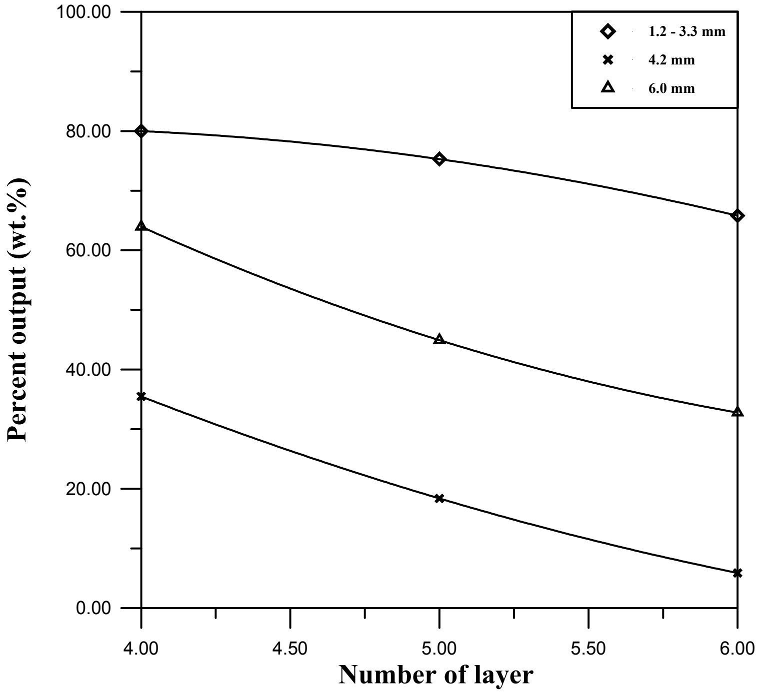

Figure 5-7 Number of layers vs. percent output of impurities for: $N_1 = 0.08$, $N_2 = 0.4$, $N_3 = 0.24$, $N_4 = 0.16$, $N_5 = 0.12$

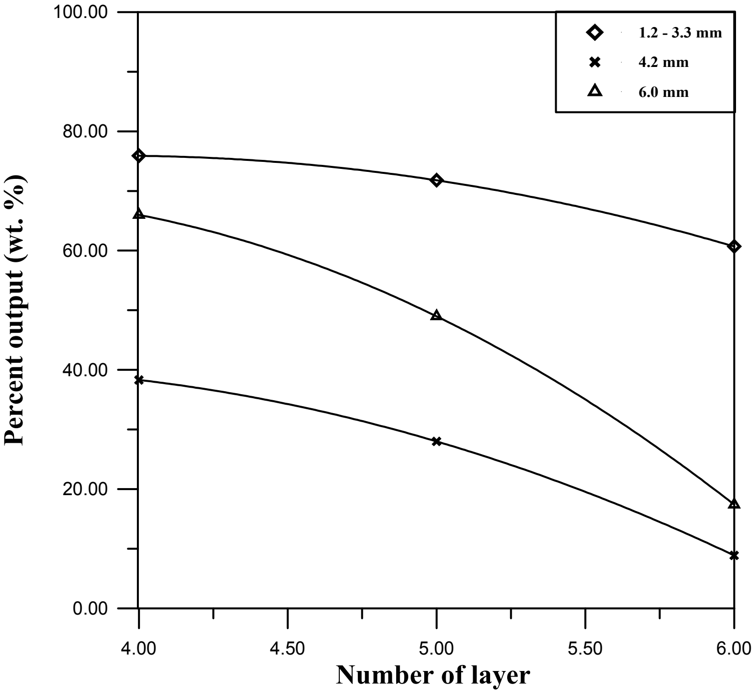

Figure 5-8 Number of layers vs. percent output of impurities for: $N_1 = 0.2, N_2 = 0.33, N_3 = 0.17, N_4 = 0.15, N_5 = 0.15$

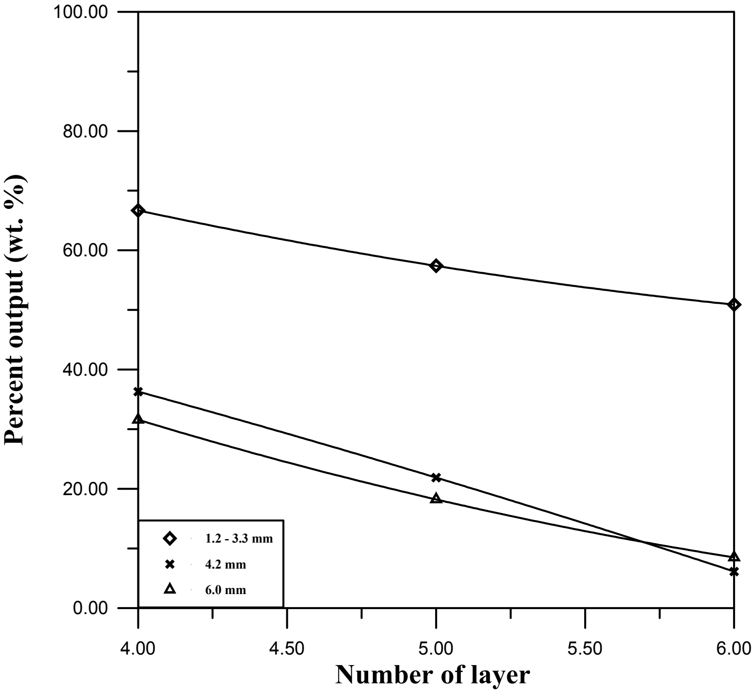

Figure 5-9 Number of layers vs. percent output of impurities for: $N_1 = 0.47, N_2 = 0.24, N_3 = 0.14, N_4 = 0.07, N_5 = 0.08$

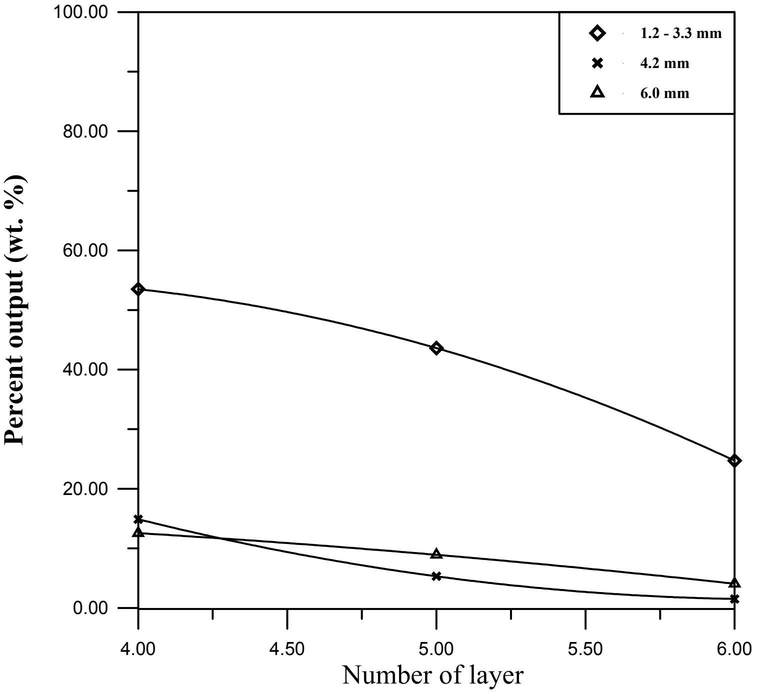

Figure 5-10 Number of layers vs. percent output of impurities for: $N_1 = 0.51$, $N_2 = 0.3$, $N_3 = 0.08$, $N_4 = 0.07$, $N_5 = 0.04$

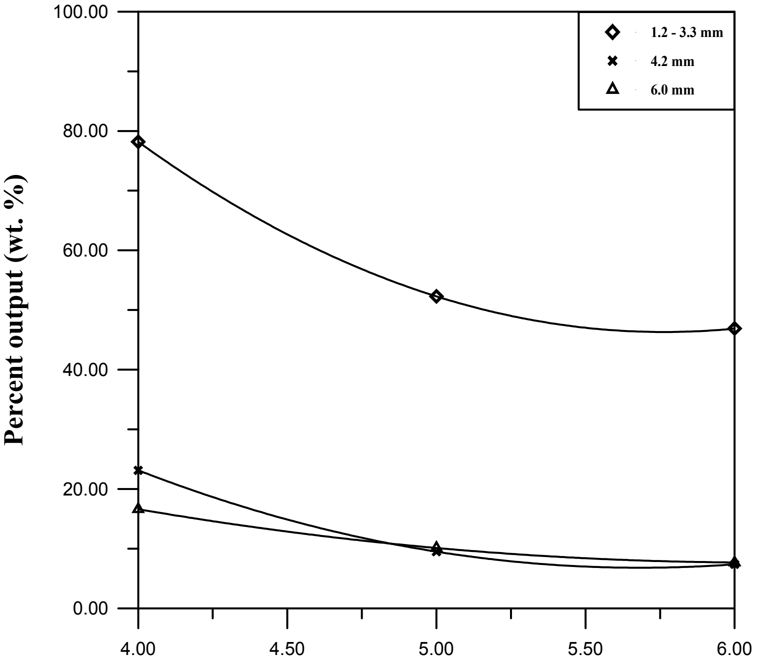

Figure 5-11 Number of layers vs. percent output of impurities for: $N_1 = 0.4$, $N_2 = 0.25$, $N_3 = 0.11$, $N_4 = 0.11$, $N_5 = 0.13$

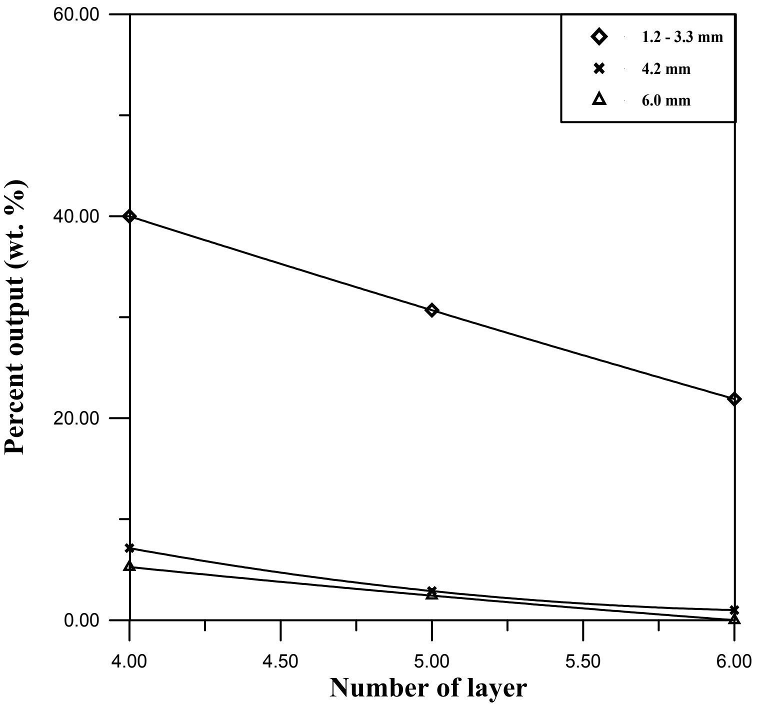

Figure 5-12 Number of layers vs. percent output of impurities for: $N_1 = 0.54$, $N_2 = 0.31$, $N_3 = 0.08$, $N_4 = 0.4$, $N_5 = 0.03$

5.3 Relationship between the size of impurities and percent output of impurities

From the previous, it is known that the same kinds of sizes of impurities were used in the experiments in case of four, five and six layer. The curves of this relation are shown in figures 5.13 to 5.24, and these curves show the relation between the size of impurities and the percent output of impurities. It is obvious from the figures that when impurities of large size are passed in the packed bed lead to decrease in the weight of output of impurities (leaving the packed bed) has occurred, so this will lead to decrease in the percent output of impurities and this decrease is noticeable in the case of

6.0 mm while the percent output of impurities will increase with the decrease in the size of impurities and this increase is noticeable in the case of 1.2 – 3.3 mm; but incase of 6 mm impurities it is obvious the percent output of impurities increased not like other cases and this make us sure that the exist of bigger pores than the theoretical maximum pores, but the effect of these pores is reduce and disappear when we increasing of the number of layers, and the number of available pores for passing the first particle, which has volume with 6 mm and that will be more than the available particles for the smaller particles and that leading to increase the probability of configuration the bridge between the little particles and that will prohibit the little particles from passing through a good pores for passing particles as a speed not a pile.

Note that all the below figures are for diameters: -

d_1 = 7.972 , d_2 = 10.164 , d_3 = 14.772 , d_4 = 20.614 , d_5 = 25.448 mm.

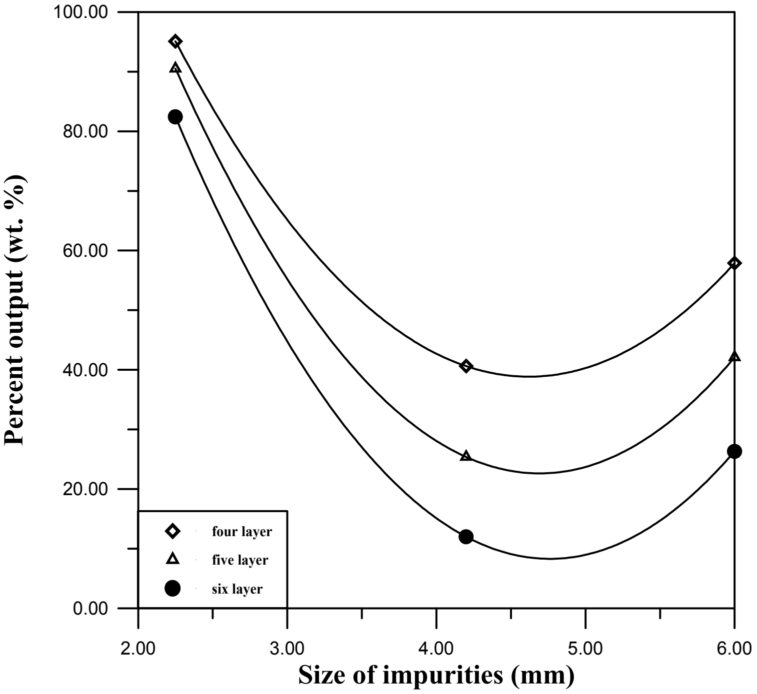

Figure 5-13 Size of impurities vs. percent output of impurities for: $N_1 = 0.2, N_2 = 0.2, N_3 = 0.2, N_4 = 0.2, N_5 = 0.2$

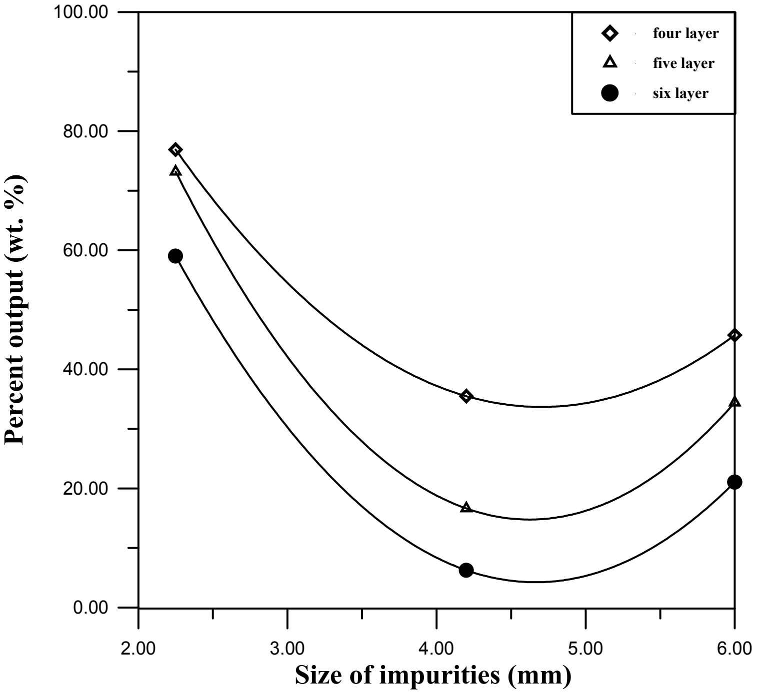

Figure 5-14 Size of impurities vs. percent output of impurities for:
$N_1 = 0.15$, $N_2 = 0.3$, $N_3 = 0.2$, $N_4 = 0.25$, $N_5 = 0.1$

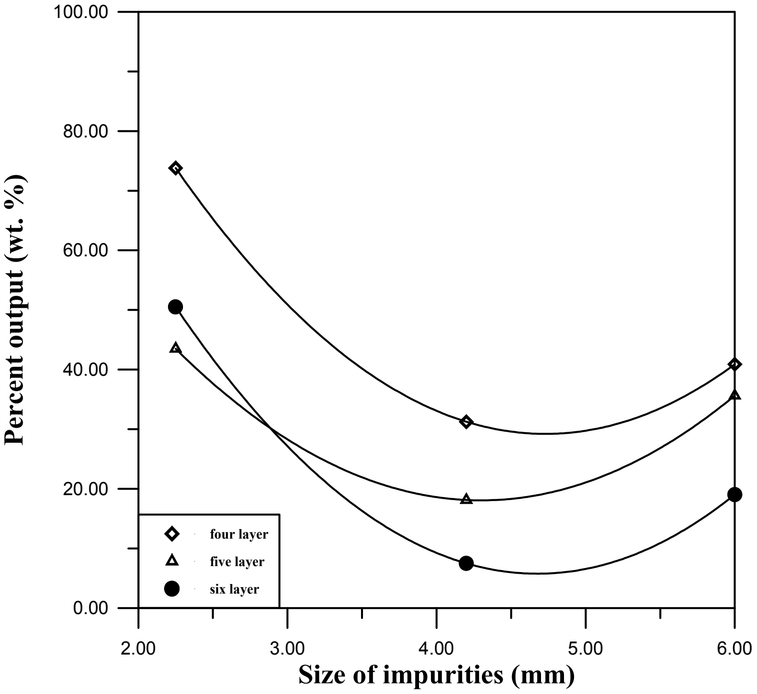

Figure 5-15 Size of impurities vs. percent output of impurities for:
$N_1= 0.4$, $N_2 = 0.2$, $N_3 = 0.15$, $N_4 = 0.2$, $N_5= 0.05$

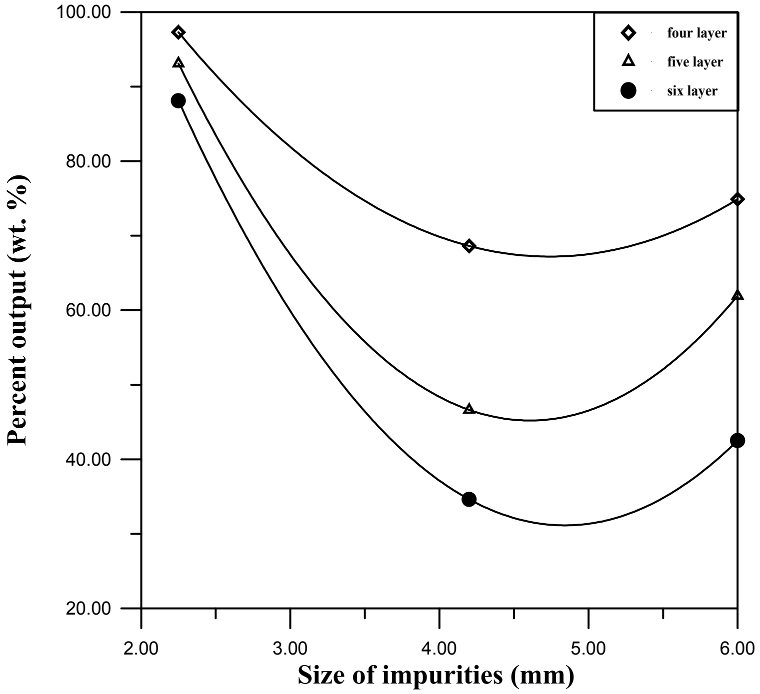

Figure 5-16 Size of impurities vs. percent output of impurities for: $N_1 = 0.21, N_2 = 0.16, N_3 = 0.16, N_4 = 0.16, N_5 = 0.31$

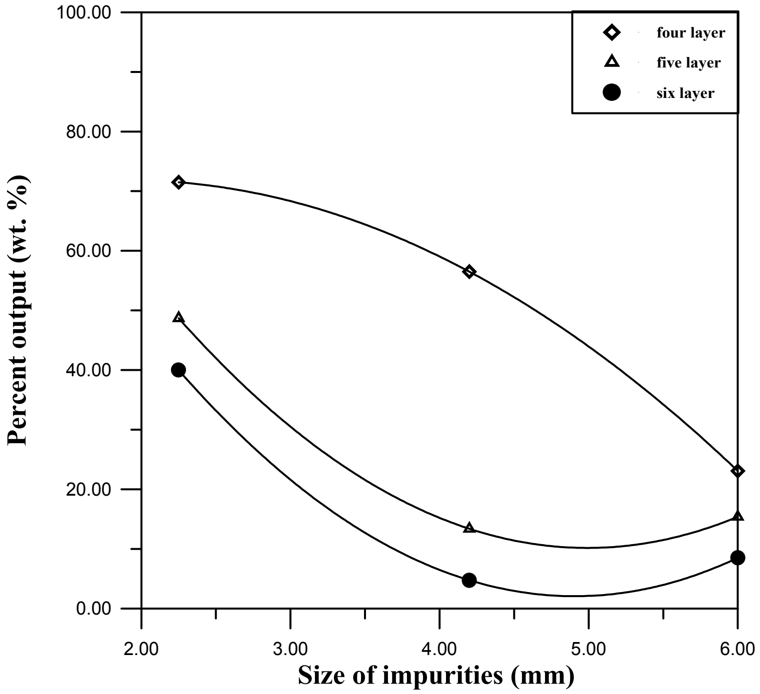

Figure 5-17 Size of impurities vs. percent output of impurities for: $N_1 = 0.14, N_2 = 0.7, N_3 = 0.11, N_4 = 0.03, N_5 = 0.02$

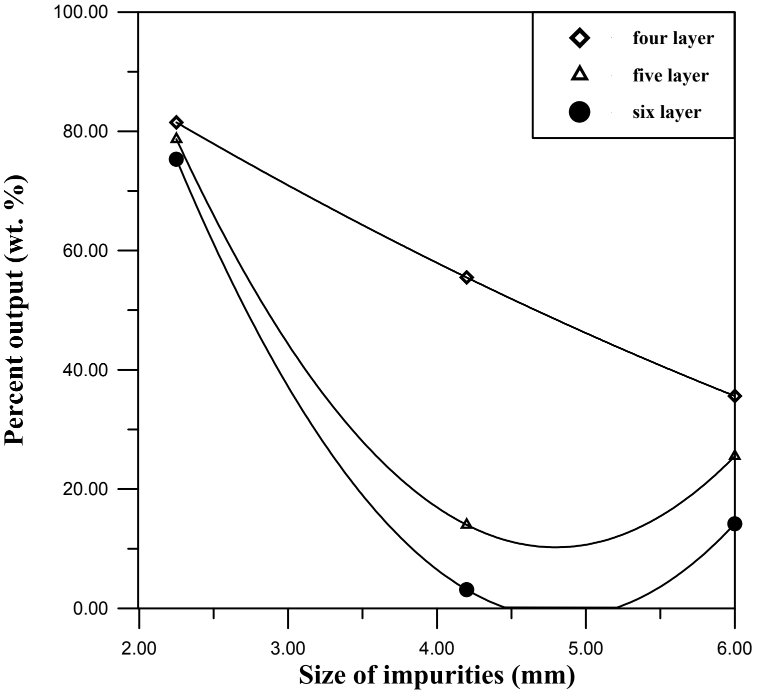

Figure 5-18 Size of impurities vs. percent output of impurities for:
$N_1 = 0.23$, $N_2 = 0.3$, $N_3 = 0.3$, $N_4 = 0.08$, $N_5 = 0.09$

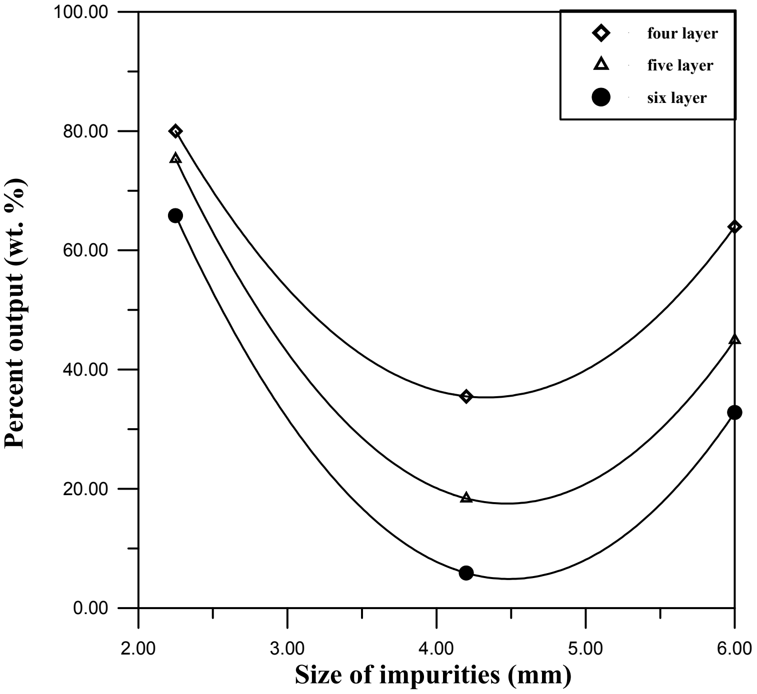

Figure 5-19 Size of impurities vs. percent output of impurities for:
$N_1 = 0.08$, $N_2 = 0.4$, $N_3 = 0.24$, $N_4 = 0.16$, $N_5 = 0.12$

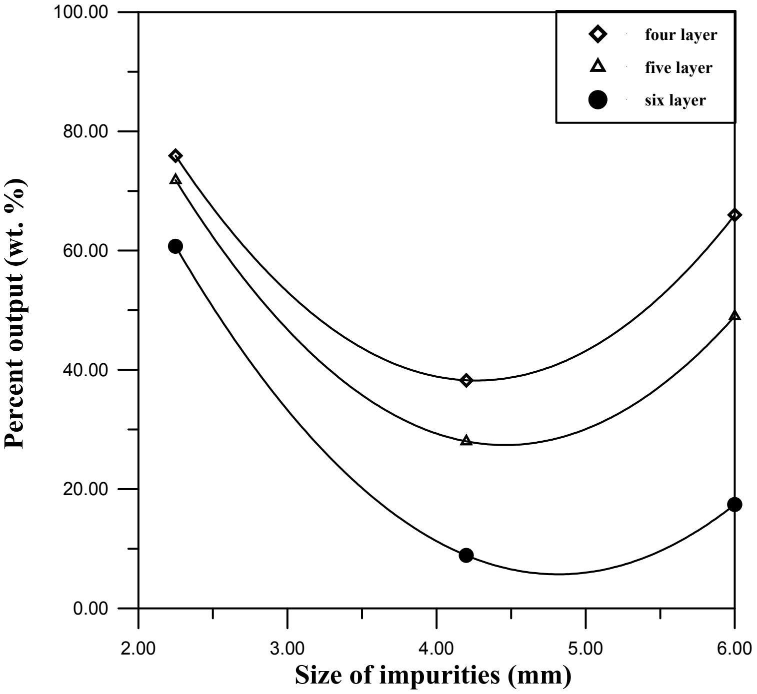

Figure 5-20 Size of impurities vs. percent output of impurities for: $N_1 = 0.2, N_2 = 0.33, N_3 = 0.17, N_4 = 0.15, N_5 = 0.15$

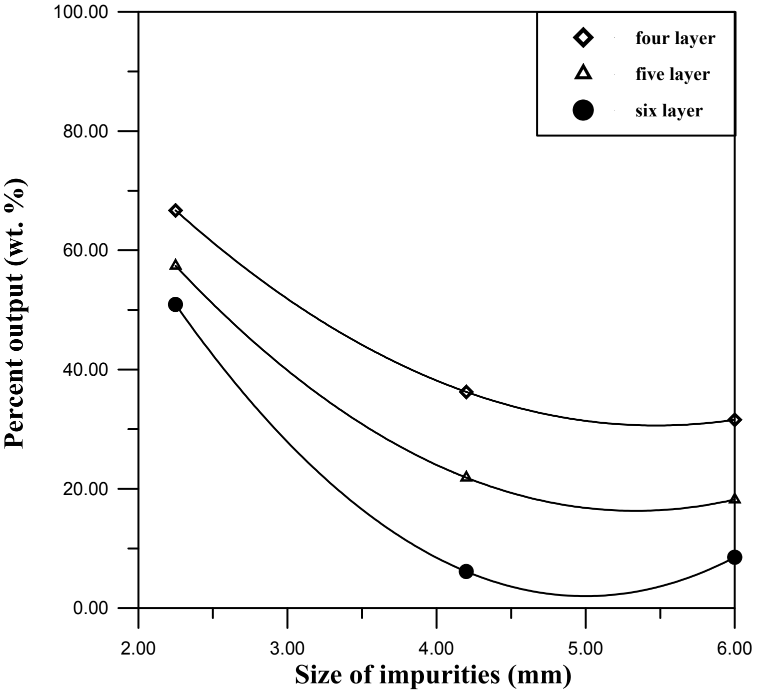

Figure 5-21 Size of impurities vs. percent output of impurities for: $N_1 = 0.47, N_2 = 0.24, N_3 = 0.14, N_4 = 0.07, N_5 = 0.08$

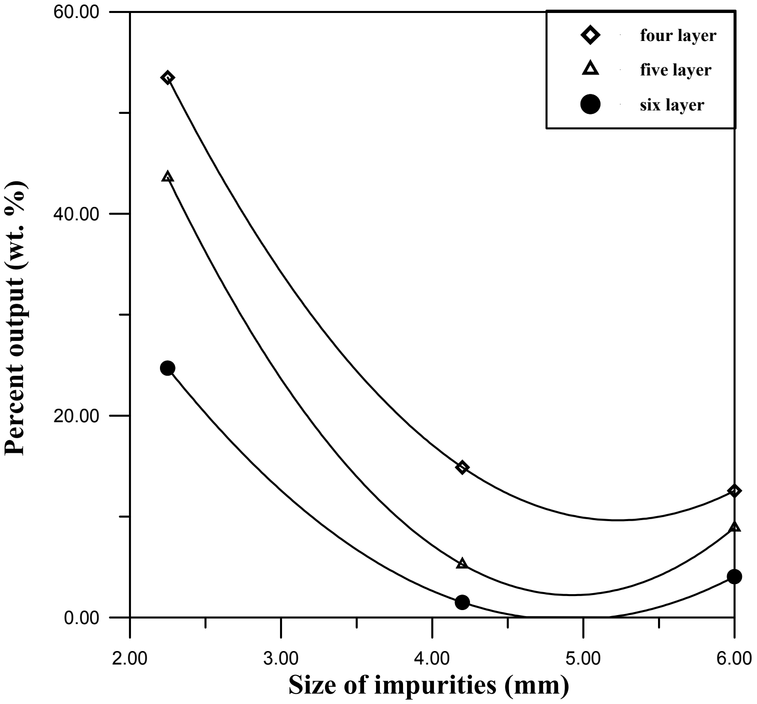

Figure 5-22 Size of impurities vs. percent output of impurities for: $N_1 = 0.51$, $N_2 = 0.3$, $N_3 = 0.08$, $N_4 = 0.07$, $N_5 = 0.04$

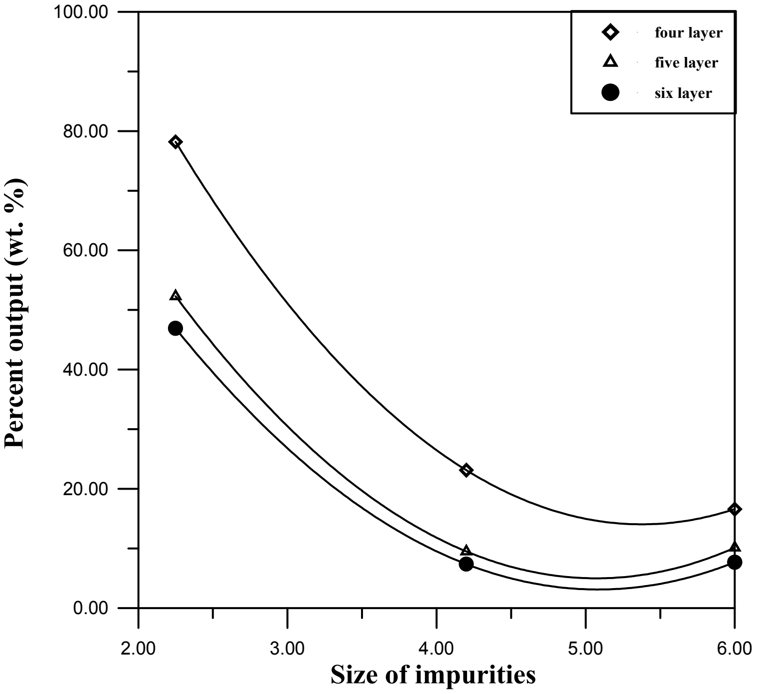

Figure 5-23 Size of impurities vs. percent output of impurities for: $N_1 = 0.4$, $N_2 = 0.25$, $N_3 = 0.11$, $N_4 = 0.11$, $N_5 = 0.13$

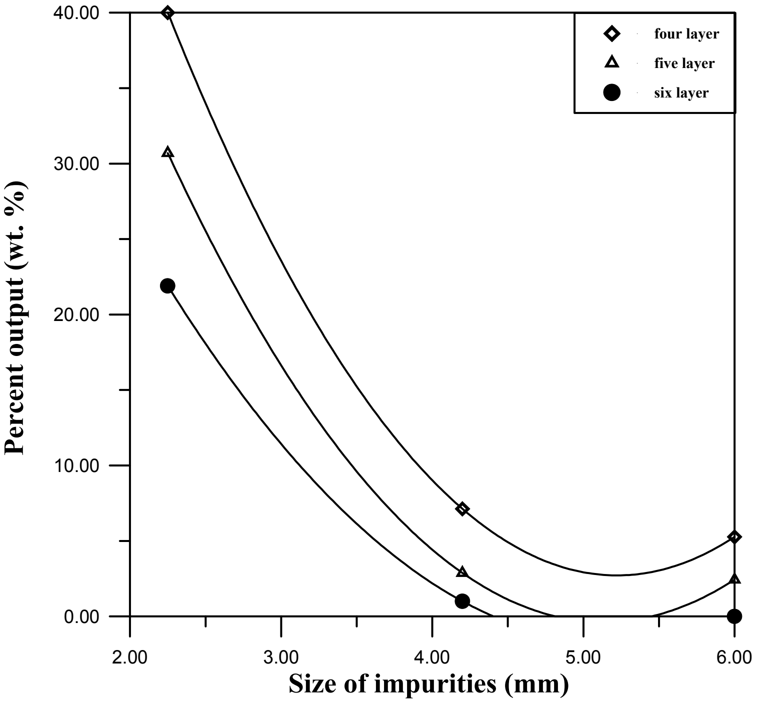

Figure 5-24 Size of impurities vs. percent output of impurities for: $N_1 = 0.54$, $N_2 = 0.31$, $N_3 = 0.08$, $N_4 = 0.04$, $N_5 = 0.03$

5.4 Relationship between Mean pore diameter and percent output of impurities

In this section the mean pore diameter (due to number, length, surface area and volume) will be related with the weight percent output of impurities for each packed bed made from five sizes of spheres.

Table 5.4-1,2,3 list the points of figures 5.25 to 5.27 and these figures show the proportionality between the mean pore diameter due to number ($d_{cm}n$) and the percent output of impurities for four, five and six layer respectively and the comparison between each curve for three type of impurities done in this section in each figure.

From the above figures, it is obvious that when the number of the large spheres (Group 3,4 and 5) increase, there will be an increase in the percent output of impurities, and this leads to the increase in the mean pore diameter, so to reduce the mean pore diameter we must increase the number of small and medium spheres (Group 1 and 2) and this is very intelligible in the case of four layers. Also the mean pore diameter due to (number, length, area, and volume), decrease with increase the number of layers

For the mean pore diameter due to length ($d_{cm}l$) the relation between the mean pore diameter due to length and relates with the same percent output of impurities that are obtained from the experimental work, and the difference between the case of length percent and number percent is in the shape of the curve, as shown in figures 5.28 to 5.30 and the points of these curves are listed in table 5.4-4,5,6.

The same relations were made for mean pore diameter due to surface area ($d_{cm}a$) and volume ($d_{cm}v$) and tables 5.4-7,8,9, 5.4- 10,11,12 list the results of these relations, and figures 5.31 to 5.36 shows the curves of these relations.

Note that all the below tables and figures are for diameters: -
$d_1 = 7.972$, $d_2 = 10.164$, $d_3 = 14.772$, $d_4 = 20.614$, $d_5 = 25.448$

Table 5-1 Values of percent output of impurities for four layers in the bed for each mean pore diameter due to number

d_{cm} n (mm)	N_1	N_2	N_3	N_4	N_5	Percent output of impurities (wt. %)		
						1.2 – 3.3 (mm)	4.2 (mm)	6.0 (mm)
1.4897	0.54	0.31	0.08	0.04	0.03	40	7.13	5.26
1.5435	0.51	0.3	0.08	0.07	0.04	53.5	14.88	18.55
1.6399	0.14	0.7	0.11	0.03	0.02	71.5	56.5	23.08
1.6491	0.47	0.24	0.14	0.07	0.08	66.7	36.25	31.58
1.7819	0.4	0.25	0.11	0.11	0.15	78.2	23.13	16.61
1.7954	0.4	0.2	0.15	0.2	0.05	73.8	31.25	40.89
1.8911	0.23	0.3	0.3	0.08	0.09	81.5	55.5	35.63
2.0095	0.2	0.33	0.17	0.15	0.15	75.9	38.25	65.99
2.0868	0.08	0.4	0.24	0.16	0.12	80	35.5	63.97
2.1135	0.15	0.3	0.2	0.25	0.1	76.9	35.5	45.75
2.2059	0.2	0.2	0.2	0.2	0.2	95.1	40.63	57.89
2.3302	0.21	0.16	0.16	0.16	0.31	97.3	68.63	74.91

Table 5-2 Values of percent output of impurities for five layers in the bed for each mean pore diameter due to number

d_{cm} n	N_1	N_2	N_3	N_4	N_5	Percent output of impurities (mm)		
						1.2 – 3.3 (mm)	4.2 (mm)	6.0 (mm)
1.4897	0.54	0.31	0.08	0.04	0.03	30.7	2.88	2.43
1.5435	0.51	0.3	0.08	0.07	0.04	43.6	5.25	8.91
1.6399	0.14	0.7	0.11	0.03	0.02	48.7	13.38	15.38
1.6491	0.47	0.24	0.14	0.07	0.08	57.4	21.88	18.22
1.7819	0.4	0.25	0.11	0.11	0.15	52.3	9.5	10.12
1.7954	0.4	0.2	0.15	0.2	0.05	43.5	18.13	35.63
1.8911	0.23	0.3	0.3	0.08	0.09	78.7	14	25.51

2.0095	0.2	0.33	0.17	0.15	0.15	71.8	28	48.99
2.0868	0.08	0.4	0.24	0.16	0.1275.3	75.3	18.38	44.94
2.1135	0.15	0.3	0.2	0.25	0.1	73.2	16.63	34.41
2.2059	0.2	0.2	0.2	0.2	0.2	90.5	25.38	42.11
2.3302	0.21	0.16	0.16	0.16	0.31	93.1	46.63	61.94

Table 5-3 Values of percent output of impurities for six layers in the bed for each mean pore diameter due to number

d_{cm} n	N_1	N_2	N_3	N_4	N_5	Percent output of impurities (mm)		
						1.2 – 3.3 (mm)	4.2 (mm)	6.0 (mm)
1.4897	0.54	0.31	0.08	0.04	0.03	21.9	1	0
1.5435	0.51	0.3	0.08	0.07	0.04	24.7	1.5	4.05
1.6399	0.14	0.7	0.11	0.03	0.02	40	4.75	8.50
1.6491	0.47	0.24	0.14	0.07	0.08	50.9	6.13	8.50
1.7819	0.4	0.25	0.11	0.11	0.15	46.9	7.38	7.69
1.7954	0.4	0.2	0.15	0.2	0.05	50.5	7.5	19.03
1.8911	0.23	0.3	0.3	0.08	0.09	75.3	3.13	14.17
2.0095	0.2	0.33	0.17	0.15	0.15	60.7	8.88	17.41
2.0868	0.08	0.4	0.24	0.16	0.12	65.8	5.88	32.79
2.1135	0.15	0.3	0.2	0.25	0.1	59	6.25	21.05
2.2059	0.2	0.2	0.2	0.2	0.2	82.4	12	26.32
2.3302	0.21	0.16	0.16	0.16	0.31	88.1	34.63	42.51

Table 5-4 Values of percent output of impurities for four layers in the bed for each mean pore diameter due to length

d_{cm} l (mm)	N_1	N_2	N_3	N_4	N_5	Percent output of impurities (wt. %)		
						1.2 – 3.3 (mm)	4.2 (mm)	6.0 (mm)
1.6586	0.54	0.31	0.08	0.04	0.03	40	7.13	5.26
1.7475	0.14	0.7	0.11	0.03	0.02	71.5	56.5	23.08
1.7663	0.51	0.3	0.08	0.07	0.04	53.5	14.88	18.55
1.9579	0.47	0.24	0.14	0.07	0.08	66.7	36.25	31.58
2.1451	0.4	0.2	0.15	0.2	0.05	73.8	31.25	40.89
2.1810	0.23	0.3	0.3	0.08	0.09	81.5	55.5	35.63
2.1901	0.4	0.25	0.11	0.11	0.15	78.2	23.13	16.61
2.3987	0.08	0.4	0.24	0.16	0.12	80	35.5	63.97
2.4011	0.2	0.33	0.17	0.15	0.15	75.9	38.25	65.99
2.4595	0.15	0.3	0.2	0.25	0.1	76.9	35.5	45.75
2.6364	0.2	0.2	0.2	0.2	0.2	95.1	40.63	57.89
2.8333	0.21	0.16	0.16	0.16	0.31	97.3	68.63	74.91

Table 5-5 Values of percent output of impurities for five layers in the bed for each mean pore diameter due to length

d_{cm} l	N_1	N_2	N_3	N_4	N_5	Percent output of impurities (mm)		
						1.2 – 3.3 (mm)	4.2 (mm)	6.0 (mm)
1.6586	0.54	0.31	0.08	0.04	0.03	30.7	2.88	2.43
1.7475	0.14	0.7	0.11	0.03	0.02	48.7	13.38	15.38
1.7663	0.51	0.3	0.08	0.07	0.04	43.6	5.25	8.91
1.9579	0.47	0.24	0.14	0.07	0.08	57.4	21.88	18.22
2.1451	0.4	0.2	0.15	0.2	0.05	43.5	18.13	35.63
2.1810	0.23	0.3	0.3	0.08	0.09	78.7	14	25.51
2.1901	0.4	0.25	0.11	0.11	0.15	52.3	9.5	10.12

2.3987	0.08	0.4	0.24	0.16	0.1275.3	75.3	18.38	44.94
2.4011	0.2	0.33	0.17	0.15	0.15	71.8	28	48.99
2.4595	0.15	0.3	0.2	0.25	0.1	73.2	16.63	34.41
2.6364	0.2	0.2	0.2	0.2	0.2	90.5	25.38	42.11
2.8333	0.21	0.16	0.16	0.16	0.31	93.1	46.63	61.94

Table 5-6 Values of percent output of impurities for six layers in the bed for each mean pore diameter due to length

d_{cm} l	N_1	N_2	N_3	N_4	N_5	Percent output of impurities (mm)		
						1.2 – 3.3 (mm)	4.2 (mm)	6.0 (mm)
1.6586	0.54	0.31	0.08	0.04	0.03	21.9	1	0
1.7475	0.14	0.7	0.11	0.03	0.02	40	4.75	8.50
1.7663	0.51	0.3	0.08	0.07	0.04	24.7	1.5	4.05
1.9579	0.47	0.24	0.14	0.07	0.08	50.9	6.13	8.50
2.1451	0.4	0.2	0.15	0.2	0.05	50.5	7.5	19.03
2.1810	0.23	0.3	0.3	0.08	0.09	75.3	3.13	14.17
2.1901	0.4	0.25	0.11	0.11	0.15	46.9	7.38	7.69
2.3987	0.08	0.4	0.24	0.16	0.1275.3	65.8	5.88	32.79
2.4011	0.2	0.33	0.17	0.15	0.15	60.7	8.88	17.41
2.4595	0.15	0.3	0.2	0.25	0.1	59	6.25	21.05
2.6364	0.2	0.2	0.2	0.2	0.2	82.4	12	26.32
2.8333	0.21	0.16	0.16	0.16	0.31	88.1	34.63	42.51

Table 5-7 Values of percent output of impurities for four layers in the bed for each mean pore diameter due to surface area

d_{cm} a (mm)	N_1	N_2	N_3	N_4	N_5	Percent output of impurities (wt. %)		
						1.2 – 3.3 (mm)	4.2 (mm)	6.0 (mm)
1.9234	0.14	0.7	0.11	0.03	0.02	71.5	56.5	23.08
1.9561	0.54	0.31	0.08	0.04	0.03	40	7.13	5.26
2.1321	0.51	0.3	0.08	0.07	0.04	53.5	14.88	18.55
2.4037	0.47	0.24	0.14	0.07	0.08	66.7	36.25	31.58
2.5293	0.23	0.3	0.3	0.08	0.09	81.5	55.5	35.63
2.5435	0.4	0.2	0.15	0.2	0.05	73.8	31.25	40.89
2.6974	0.4	0.25	0.11	0.11	0.15	78.2	23.13	16.61
2.7427	0.08	0.4	0.24	0.16	0.12	80	35.5	63.97
2.7984	0.15	0.3	0.2	0.25	0.1	76.9	35.5	45.75
2.8234	0.2	0.33	0.17	0.15	0.15	75.9	38.25	65.99
3.0251	0.2	0.2	0.2	0.2	0.2	95.1	40.63	57.89
3.2382	0.21	0.16	0.16	0.16	0.31	97.3	68.63	74.91

Table 5-8 Values of percent output of impurities for five layers in the bed for each mean pore diameter due to surface area

d_{cm} a	N_1	N_2	N_3	N_4	N_5	Percent output of impurities (mm)		
						1.2 – 3.3 (mm)	4.2 (mm)	6.0 (mm)
1.9234	0.14	0.7	0.11	0.03	0.02	48.7	13.38	15.38
1.9561	0.54	0.31	0.08	0.04	0.03	30.7	2.88	2.43
2.1321	0.51	0.3	0.08	0.07	0.04	43.6	5.25	8.91
2.4037	0.47	0.24	0.14	0.07	0.08	57.4	21.88	18.22
2.5293	0.23	0.3	0.3	0.08	0.09	78.7	14	25.51
2.5435	0.4	0.2	0.15	0.2	0.05	43.5	18.13	35.63
2.6974	0.4	0.25	0.11	0.11	0.15	52.3	9.5	10.12

2.7427	0.08	0.4	0.24	0.16	0.1275.3	75.3	18.38	44.94
2.7984	0.15	0.3	0.2	0.25	0.1	73.2	16.63	34.41
2.8234	0.2	0.33	0.17	0.15	0.15	71.8	28	48.99
3.0251	0.2	0.2	0.2	0.2	0.2	90.5	25.38	42.11
3.2382	0.21	0.16	0.16	0.16	0.31	93.1	46.63	61.94

Table 5-9 Values of percent output of impurities for six layers in the bed for each mean pore diameter due to surface area

d_{cm} a	N_1	N_2	N_3	N_4	N_5	Percent output of impurities (mm)		
						1.2 – 3.3 (mm)	4.2 (mm)	6.0 (mm)
1.9234	0.14	0.7	0.11	0.03	0.02	40	4.75	8.50
1.9561	0.54	0.31	0.08	0.04	0.03	21.9	1	0
2.1321	0.51	0.3	0.08	0.07	0.04	24.7	1.5	4.05
2.4037	0.47	0.24	0.14	0.07	0.08	50.9	6.13	8.50
2.5293	0.23	0.3	0.3	0.08	0.09	75.3	3.13	14.17
2.5435	0.4	0.2	0.15	0.2	0.05	50.5	7.5	19.03
2.6974	0.4	0.25	0.11	0.11	0.15	46.9	7.38	7.69
2.7427	0.08	0.4	0.24	0.16	0.1275.3	65.8	5.88	32.79
2.7984	0.15	0.3	0.2	0.25	0.1	59	6.25	21.05
2.8234	0.2	0.33	0.17	0.15	0.15	60.7	8.88	17.41
3.0251	0.2	0.2	0.2	0.2	0.2	82.4	12	26.32
3.2382	0.21	0.16	0.16	0.16	0.31	88.1	34.63	42.51

Table 5-10 Values of percent output of impurities for four layers in the bed for each mean pore diameter due to volume

d_{cm} v (mm)	N_1	N_2	N_3	N_4	N_5	Percent output of impurities (wt. %)		
						1.2 – 3.3 (mm)	4.2 (mm)	6.0 (mm)
2.1941	0.14	0.7	0.11	0.03	0.02	71.5	56.5	23.08
2.3881	0.54	0.31	0.08	0.04	0.03	40	7.13	5.26
2.5933	0.51	0.3	0.08	0.07	0.04	53.5	14.88	18.55
2.8761	0.47	0.24	0.14	0.07	0.08	66.7	36.25	31.58
2.8798	0.23	0.3	0.3	0.08	0.09	81.5	55.5	35.63
2.8882	0.4	0.2	0.15	0.2	0.05	73.8	31.25	40.89
3.0551	0.08	0.4	0.24	0.16	0.12	80	35.5	63.97
3.0733	0.15	0.3	0.2	0.25	0.1	76.9	35.5	45.75
3.1390	0.4	0.25	0.11	0.11	0.15	78.2	23.13	16.61
3.1745	0.2	0.33	0.17	0.15	0.15	75.9	38.25	65.99
3.3072	0.2	0.2	0.2	0.2	0.2	95.1	40.63	57.89
3.4973	0.21	0.16	0.16	0.16	0.31	97.3	68.63	74.91

Table 5-11 Values of percent output of impurities for five layers in the bed for each mean pore diameter due to volume

d_{cm} v	N_1	N_2	N_3	N_4	N_5	Percent output of impurities (mm)		
						1.2 – 3.3 (mm)	4.2 (mm)	6.0 (mm)
2.1941	0.14	0.7	0.11	0.03	0.02	48.7	13.38	15.38
2.3881	0.54	0.31	0.08	0.04	0.03	30.7	2.88	2.43
2.5933	0.51	0.3	0.08	0.07	0.04	43.6	5.25	8.91
2.8761	0.47	0.24	0.14	0.07	0.08	57.4	21.88	18.22
2.8798	0.23	0.3	0.3	0.08	0.09	78.7	14	25.51
2.8882	0.4	0.2	0.15	0.2	0.05	43.5	18.13	35.63
3.0551	0.08	0.4	0.24	0.16	0.1275.3	75.3	18.38	44.94

3.0733	0.15	0.3	0.2	0.25	0.1	73.2	16.63	34.41
3.1390	0.4	0.25	0.11	0.11	0.15	52.3	9.5	10.12
3.1745	0.2	0.33	0.17	0.15	0.15	71.8	28	48.99
3.3072	0.2	0.2	0.2	0.2	0.2	90.5	25.38	42.11
3.4973	0.21	0.16	0.16	0.16	0.31	93.1	46.63	61.94

Table 5-12 Values of percent output of impurities for six layers in the bed for each mean pore diameter due to volume

d_{cm} v	N_1	N_2	N_3	N_4	N_5	Percent output of impurities (mm)		
						1.2 – 3.3 (mm)	4.2 (mm)	6.0 (mm)
2.1941	0.14	0.7	0.11	0.03	0.02	40	4.75	8.50
2.3881	0.54	0.31	0.08	0.04	0.03	21.9	1	0
2.5933	0.51	0.3	0.08	0.07	0.04	24.7	1.5	4.05
2.8761	0.47	0.24	0.14	0.07	0.08	50.9	6.13	8.50
2.8798	0.23	0.3	0.3	0.08	0.09	75.3	3.13	14.17
2.8882	0.4	0.2	0.15	0.2	0.05	50.5	7.5	19.03
3.0551	0.08	0.4	0.24	0.16	0.1275.3	65.8	5.88	32.79
3.0733	0.15	0.3	0.2	0.25	0.1	59	6.25	21.05
3.1390	0.4	0.25	0.11	0.11	0.15	46.9	7.38	7.69
3.1745	0.2	0.33	0.17	0.15	0.15	60.7	8.88	17.41
3.3072	0.2	0.2	0.2	0.2	0.2	82.4	12	26.32
3.4973	0.21	0.16	0.16	0.16	0.31	88.1	34.63	42.51

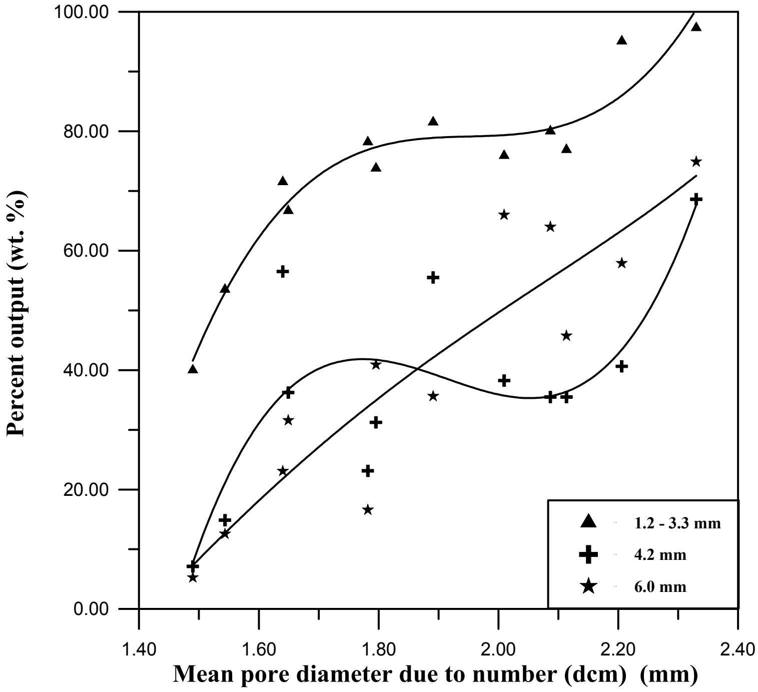

Figure 5-25 Mean pore diameter due to number vs. percent output of impurities for four layers

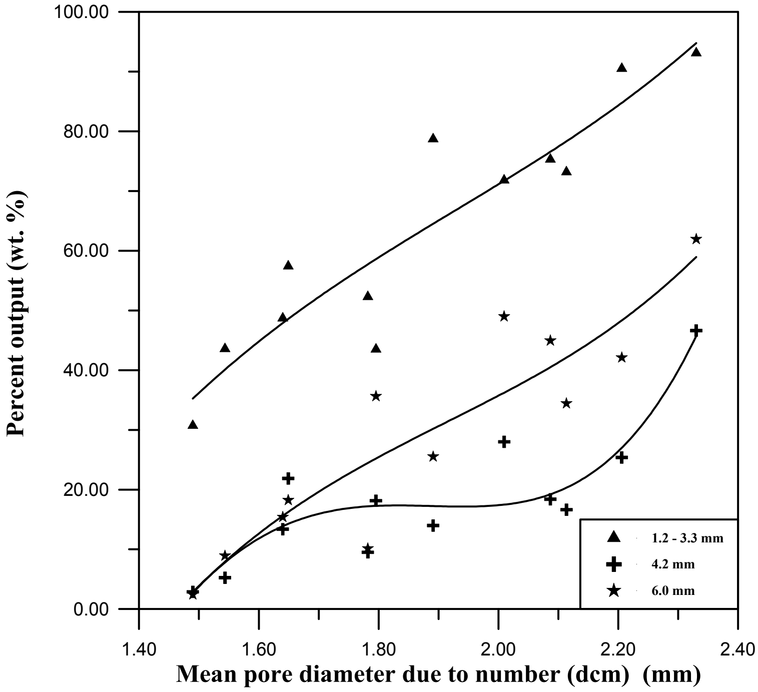

Figure 5-26 Mean pore diameter due to number vs. percent output of impurities for five layers

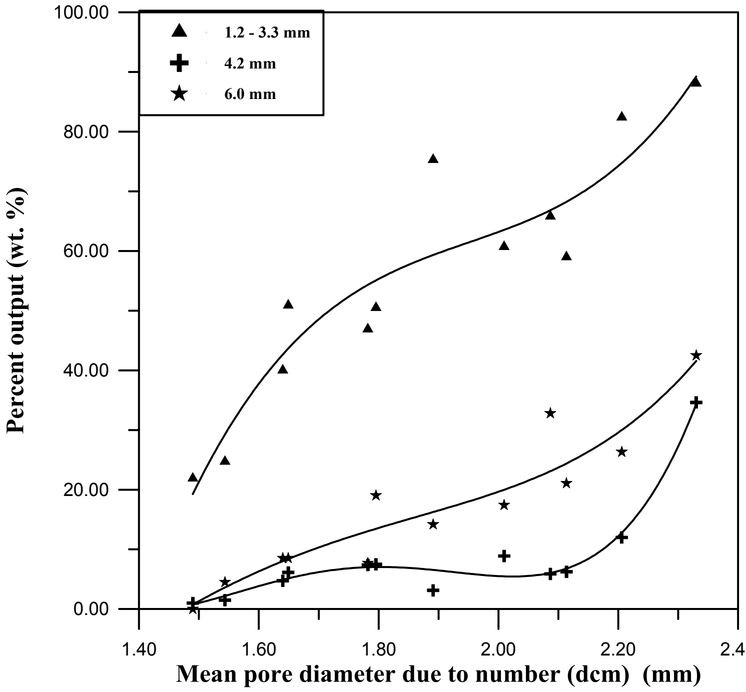

Figure 5-27 Mean pore diameter due to number vs. percent output of impurities for six layers

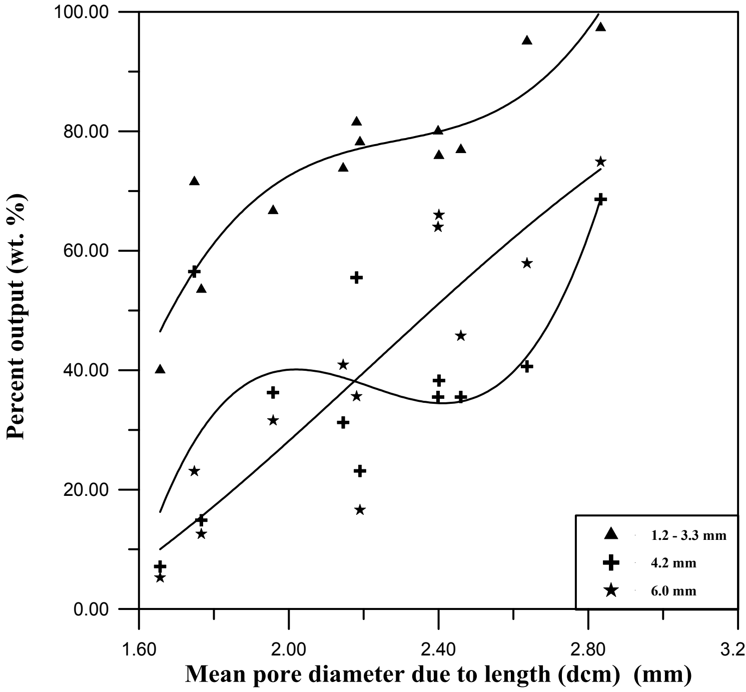

Figure 5-28 Mean pore diameter due to length vs. percent output of impurities for four layers

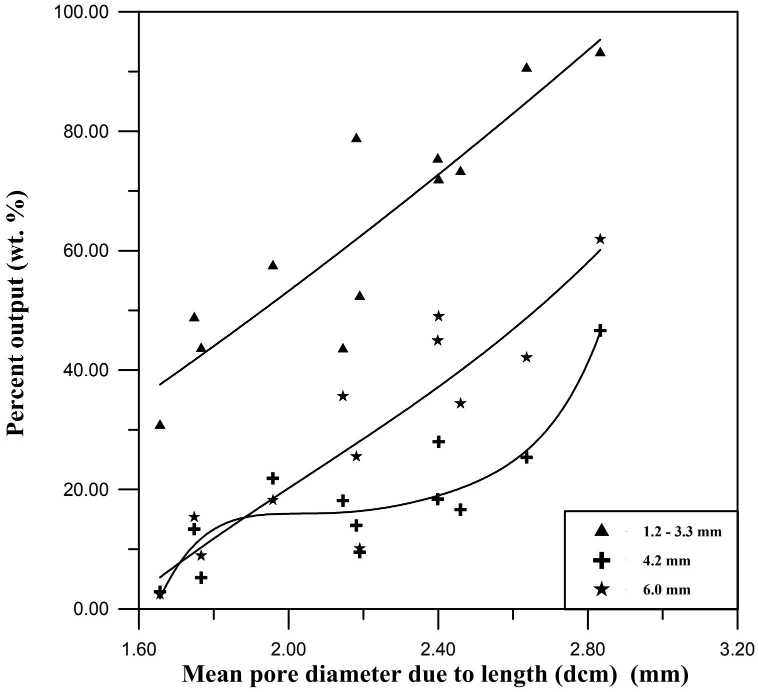

Figure 5-29 Mean pore diameter due to length vs. percent output of impurities for five layers

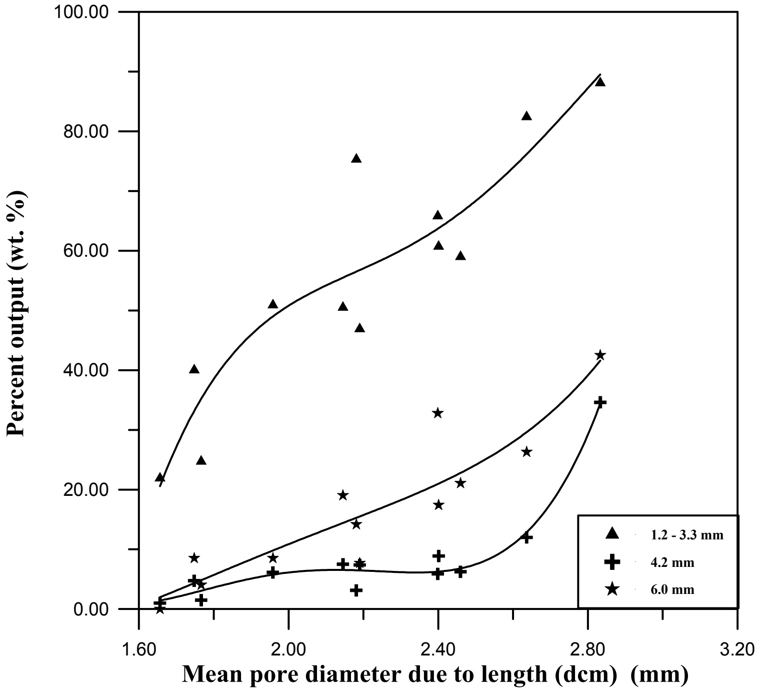

Figure 5-30 Mean pore diameter due to length vs. percent output of impurities for six layers

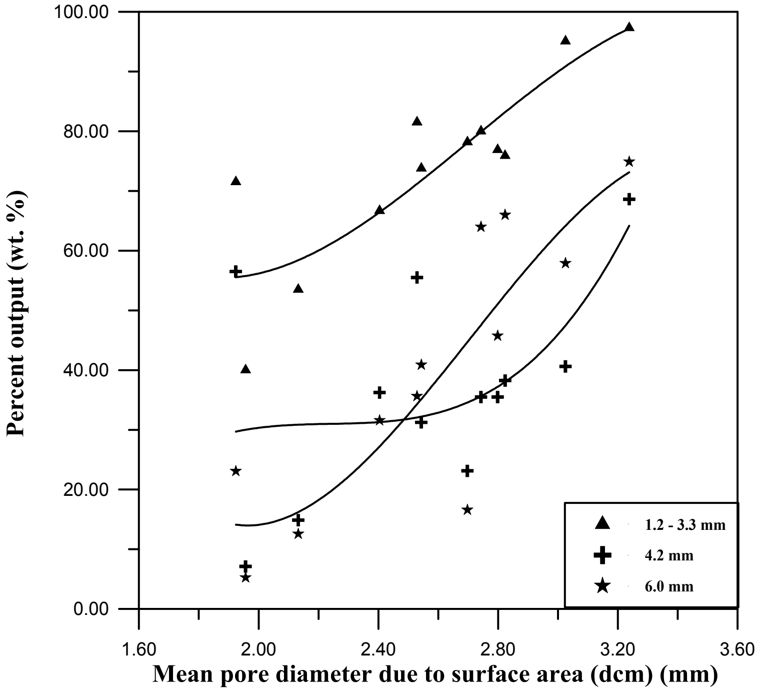

Figure 5-31 Mean pore diameter due to surface area vs. percent output of impurities for four layers

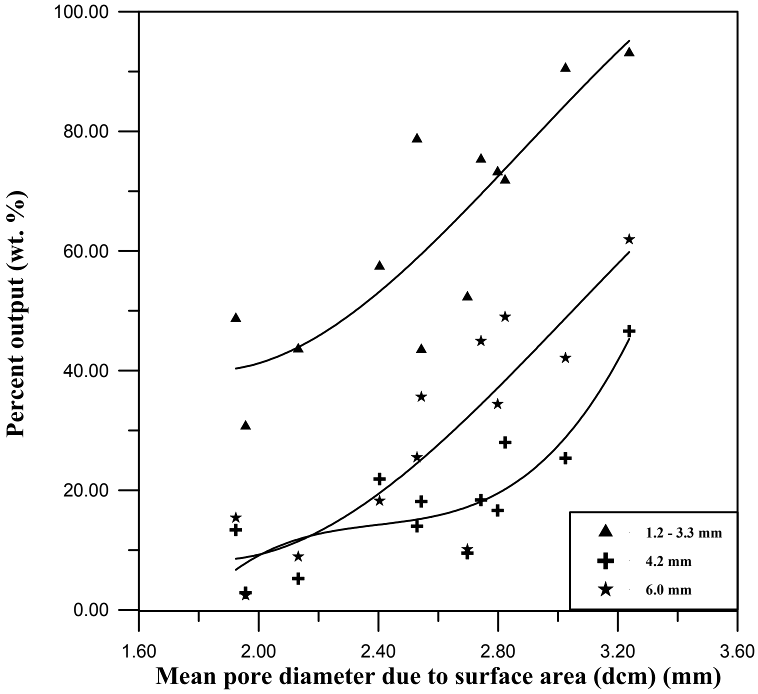

Figure 5-32 Mean pore diameter due to surface area vs. percent output of impurities for five layers

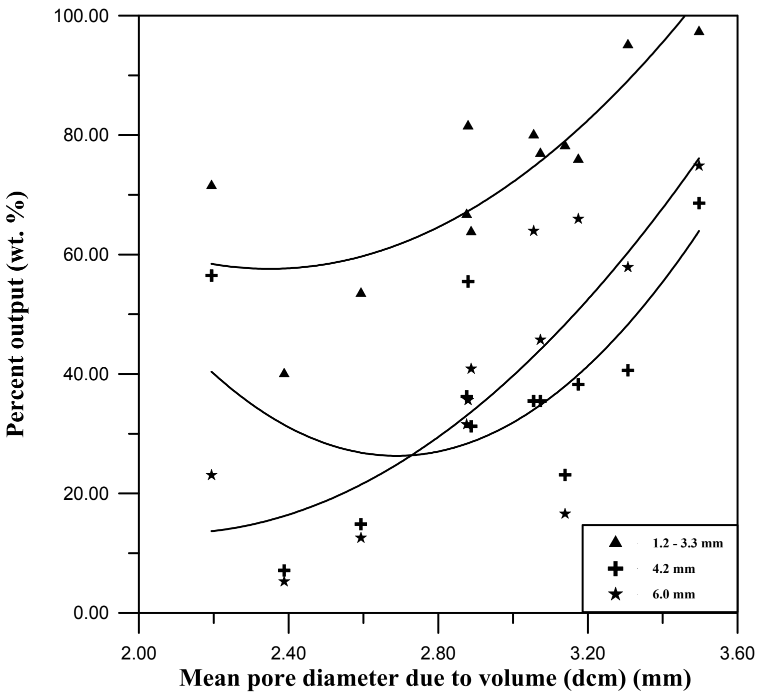

Figure 5-33 Mean pore diameter due to surface area vs. percent output of impurities for six layers

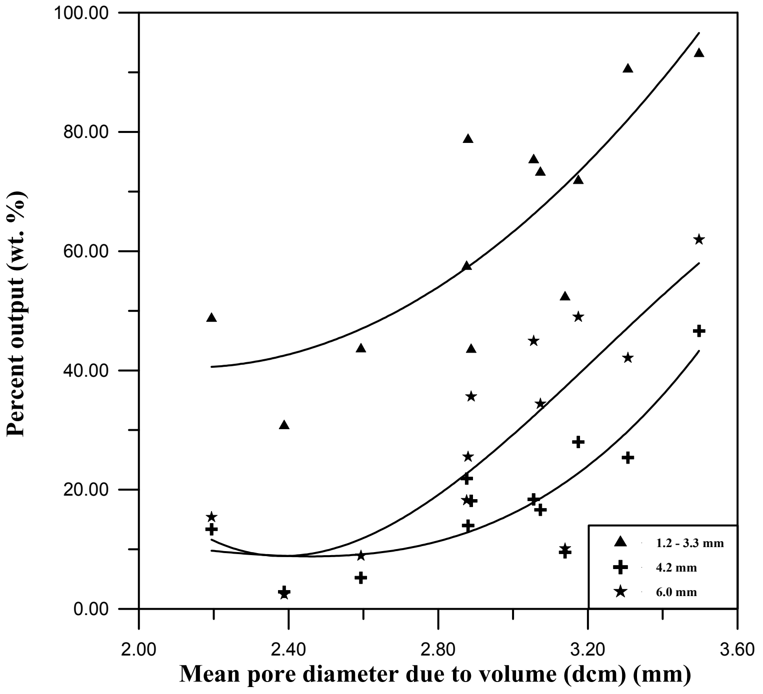

Figure 5-34 Mean pore diameter due to volume vs. percent output of impurities for four layers

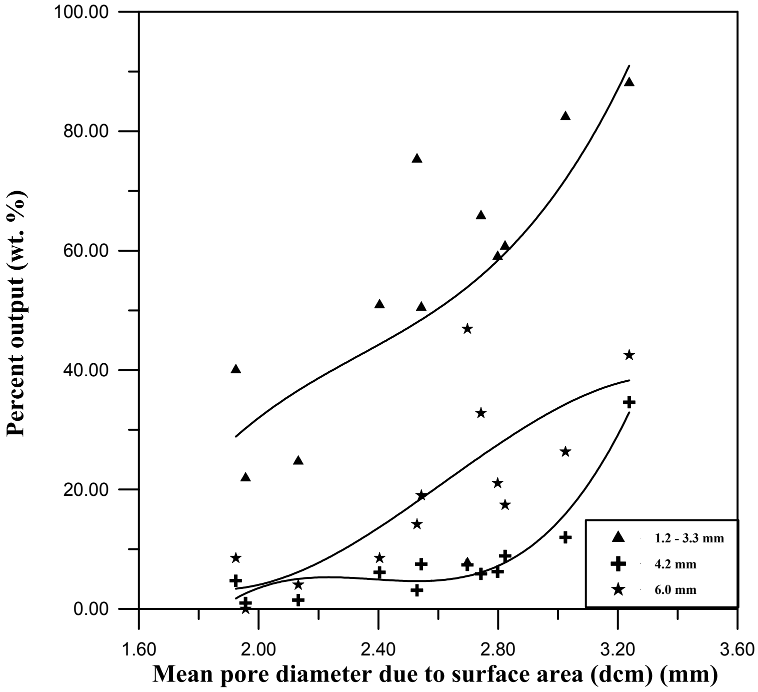

Figure 5-35 Mean pore diameter due to volume vs. percent output of impurities for five layers

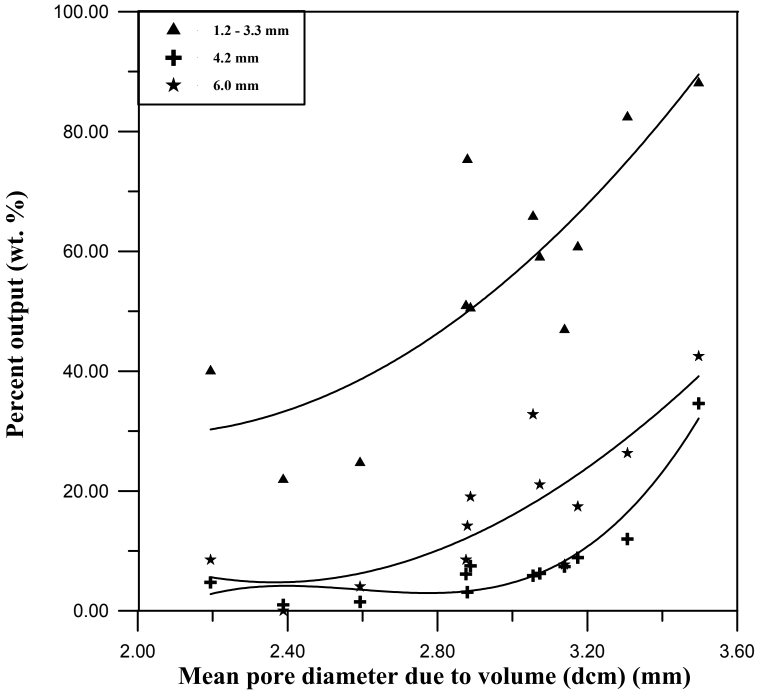

Figure 5-36 Mean pore diameter due to volume vs. percent output of impurities for six layers

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATION

6.1 Conclusions

1- From the theoretical part of this research, it was concluded that the probability of finding pore size in any packed bed is different for each kind of distribution, (due to number, length, area, and volume).

2. The percent output of impurities, which are passed through the packed bed decreases with the increasing the number of layers; and also decrease with the increase in the size of impurities; but incase of 6 mm impurities it is obvious the percent output of impurities increased not like other cases and this make us sure that the exist of bigger pores than the theoretical maximum pores, but the effect of these pores is reduce and disappear when we increasing of the number of layers, and the number of available pores for passing the first particle, which has volume with 6 mm and that will be more than the available particles for the smaller particles and that leading to increase the probability of configuration the bridge between the little particles and that will prohibit the little particles from passing through a good pores for passing particles as a speed not a pile.

3. Increasing the number of large spheres in the packed bed leads to an increase in the percent output of impurities and this in turn leads to an increase the mean pore diameter (due to number, length, surface area and volume), and an increase in the number of small or medium spheres leads to a reduction in the output of impurities and that in turn leads to a reduction in the mean pore diameter (due to number, length, surface area and volume).

6.2 Recommendation

1. Finding an equation, which is able to give a relation between the probability and the pore diameter and helps to make the work easier and thus obtained better results.

2. Further experiments should be made for more kinds of impurities (which are passed through the packed bed) and this helps in the study of the properties of the packed bed.

3. Further experiments should be made for another kind of packed bed, which consists of more diameters of spheres.

4. Further experiments should be made for more number of layers like seven, eight layers.

5. Simplifying eq. (1) in chapter two (the equation of three different diameters) and making it easier by reducing the number of variables to obtain more accuracy and to reduce the time used to calculate the pore diameter.

6. Using water instead of air passing through the cylinder to get more accurate results.

7. Choosing the distribution for the types of spheres which are used in the packing bed to increase accuracy and this is achieved by using equations or graphics, and this kind of distribution helps in knowing best kind of impurities that may be used to pass through the packed bed.

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APPENDIX [A]

SAPMLE OF CALCULATIONS

A-For pore size calculation

d_1= 7.972, d_2= 10.164, d_3= 14.772, d_4= 20.614, d_5 = 25.448

Example $N_1 = 0.15$, $N_2 = 0.3$, N3 = 0.2, $N_4 = 0.25$, $N_5 = 0.1$

For the case of three different sizes of spheres: -

Example if we take d_1, d2, d3 (dk= 7.9972, d_m= 10.164, d_g= 14.772)

$$dc_{III} = \frac{K_4 - (K_4^2 - 4k_5)^{1/2}}{2} * dg \qquad \ldots\ldots (2\text{-}1)$$

Where:

$$K_1 = \left[\frac{(am+1)}{(am-1)}\right]^2$$

$$am = \frac{dm}{dg} \quad (=1) \quad \Longrightarrow \quad am = 0.6881$$

$\therefore\ K_1 = 29.2839$

$$K_2 = \frac{4am}{(am+1)}$$

K_2 = **1.6304**

$$K_3 = (ak^2 + akK_2)^{1/2} - ak$$

$$ak = \frac{dk}{dg} \quad (\leq 1) \quad \Longrightarrow \quad ak = 0.5397$$

$\therefore\ K_3 = 0.5425$

$\mathbf{K_4 = (K_2 + 2K_3)K_1}$

$K_4 = 215.9293$

$\mathbf{K_5 = K_3^2 K_1}$

$K_5 = 8.6189$

$\mathbf{dc_{III}} = 0.5897$ mm

For the case of two large diameters and one small diameter: -

Example if we take d_1, d_2, d_2 (d_1= 7.972, d_2 = 10.164, d_3= 10.164)

$$\mathbf{dc_{II} = \frac{[(2ak + ak^2)^{1/2} - ak]^2}{2+2[(2ak+ak^2) - ak]} * dg} \qquad \mathbf{\ldots\ldots\ (2\text{-}2.a)}$$

dc_{II} = = 1.2436 mm

For the case of two small diameters and one large diameter: -

Example if we take d_1, d_1, d_2 (d_1= 7.972, d_2 = 7.972, d_3= 10.164)

$$\mathbf{dc_{II} = \frac{[(2/ak + ak^{-2})^{1/2} - ak^{-1}]^2}{2+\ 2+2[(2/ak + ak^{-2})^{1/2} - ak^{-1}]} * dk} \qquad \mathbf{\ldots\ldots\ (2\text{-}2.b)}$$

dc_{II} = 1.4680 mm

For the case of three equal diameters: -

Example if we take d_1, d1, d1 (d_1= 7.972, d_2 =7.972, d_3 = 7.972)

$$\mathbf{dc_I = 0.155 * dg} \qquad \mathbf{\ldots\ldots\ (2\text{-}3)}$$

dc_I = 1.2357 mm

B- For probability calculation

d_1= 7.972, d_2= 10.164, d_3= 14.772, d_4= 20.614, d_5 = 25.448

N_1 = 0.15, N_2 = 0.3, N_3 = 0.2, N4 = 0.25,N_5= 0.1

i- Calculate the probability due to length: -

$L = (d_1*N_1) + (d_2 * N_2) + (d_3 * N_3) + (d_4 * N_4) + (d_5 * N_5)$

L= 14.8977

For d_1 = 7.972, d_2= 10.164, d_3 = 14.772

Lk = (dk* Nk) / L

Lk = 0.0803

Lm = (dm* Nm) / L

Lm = 0.2047

Lg = (dg * Ng) / L

Lg = 0.1983

Where N: number percent.

$$P_i = \frac{3!}{n_g!\, n_m!\, n_k!} Pr_{(dg)}^{ng}\, Pr_{(dm)}^{nm}\, Pr_{(dk)}^{nk} \qquad \ldots\ldots (2\text{-}4)$$

Where **$rg + r_m + r_k = 3$**

P_i = 0.0195

ii- Calculate the probability due to area: -

$A = (d_1^2 * N_1) + (d_2^2 * N_2) + (d_3^2 * N_3) + (d_4^2 * N_4) + (d_5^2 * N_5)$

A = 255.1617

$Ak = (dk^2 * Nk) / A$

Ak = .0374

$Am = (dm^2 * Nm) / A$

Am = 0.1215

Ag = (dg^2 * Ng) / A

Ag = 0.1710

According to eq.4 P_i = 0.0047

iii- Calculate the probability due to volume

V = (d_1^3 * N_1) + (d_2^3 * N_2) + (d_3^3 * N_3) + (d_4^3 * N_4) + (d_5^3 * N_5)

V = 4873.6124

Vk = (dk^3 * Nk) / V

Vk = 0.0156

Vm = (dm^3 * Nm) / V

Vm = 0.0646

Vg = (dg^3 * Ng) / V

Vg = 0.1323

P_i = 0.0007

C-Calculation of the mean pore diameter

$$\mathbf{dc_m} = \sum_{i=1}^{n} \mathbf{P_i\ dc_i} \qquad \text{......} \ \mathbf{(2\text{-}5)}$$

To determine the mean pore diameter due to length

$$\mathbf{d_{cm}n} = \sum_{i=1}^{n} \mathbf{P_r n\ \ dc_i} \ \Longrightarrow \ d_{cm}n = 2.1135 \text{ mm.}$$

To calculate the mean pore diameter due to length

$$\mathbf{d_{cm}l =}\ = \sum_{i=1}^{n} \mathbf{P_r l\ \ dc_i} \ \Longrightarrow \ d_{cm}l = 2.4595 \text{ mm.}$$

To calculate the mean pore diameter due to surface area

$$\mathbf{d_{cm}a =}\ = \sum_{i=1}^{n} \mathbf{P_r a\ \ dc_i} \ \Longrightarrow \ d_{cm}a = 2.7984 \text{ mm.}$$

To calculate the mean pore diameter due to volume

$$\mathbf{d_{cm}v =}\ = \sum_{i=1}^{n} \mathbf{P_r v\ \ dc_i} \ \Longrightarrow \ d_{cm}v = 3.0733 \text{ mm.}$$

APPENDIX [B]

COMPUTER PROGRAM

Program number one

```
REM **********************************************************
REM ****** PROGRAM USED TO CALCULATE THE PORE *******
REM *** SIZE OF FIVE VALUES OF PARTICALE DIAMETER  ******
REM **********************************************************
CLS
DIM X (3): DIM Y (35): DIM N (5)
Z = J
FOR I = 1 TO 5
INPUT “THE VALUES OF PARTICLES THAT USE “; N (I)
NEXT
FOR I = 1 TO 4
FOR J = 1 TO 5 – I
IF N (J) < N (J+1) THEN 10
T = N (J): N (J) = N (J+1): N (J+1) = T
10  NEXT: NEXT
D1 = N (1): D2 = N (2): D3 = N (3): D4 = N (4): D5 = N (5)
20  PRINT “ INPUT THE DIAMETER VALUES “
FOR I  = 1 TO 3
INPUT X (I)
NEXT
FOR I = 1 TO 2
FOR J = 1 TO 3 – I
IF X (J) < X (J+1) THEN 30
T = X (J): X (J) = X (J +1): X (J+1) = T
30  NEXT: NEXT
FOR I = 1 TO 3
PRINT “ DIAMETERS ARRANGEMENT = “; X (I)
NEXT
DK = X (1): DM = X (2): DG = X (3)
IF X (1) = X (2) AND X (2) = X (3) THEN 40
40  IF X (1) = X (3) THEN 100
GOTO 80
50  IF DK = DM AND DK < DG THEN 60
```

```
AK = DG / DK: GOTO110
GOTO 120
70  AM = DM / DG
PRINT “ AM = “; AM
IF AM = 1 THEN 150
AK = DK / DG
PRINT “ AK=”; AK
IF AK > 1 THEN 150
K1 = ((AM+1)/ (AM-1))^2
K2 = 4*AM / (AM+1)
K3 = (AK ^2 + AK *K2)^.5 – AK
K4 = (K2 +2*K3)*K1
K5 = K3^2*K1
GOTO 130
80  E = 0
FOR I = 1 TO 2
IF X (I) < X (I+1) THEN 90
E = E + 1
90  NEXT
IF E = 2 THEN 100
IF E = 1 THEN 50
IF E = 0 THEN 70
PRINT “ THERE IS NO CHOICE LIKE THAT “
GOTO 180
100   PRINT “ EQUAL DIAMETER, SO THE RESULT IS “
DC1 = .155 * DG:Y (Z) = DC1:PRINT“dc1 (“; X (1); X (2); X (3);”)=”; DC1
PRINT “DC1=”; DC1
GOTO 160
110   IF DK = DM AND DK < DG THEN DG = DK
120   I =  ((2* AK + AK ^2)^.5 – AK) ^2
J = 2 + 2 * ((2 *AK + AK ^2)^ .5  - AK)
DC2 = (I/J)* DG: Y(Z) = DC2 : PRINT “dc2 (“;X (1);X (2);X (3);”) =”;DC3
PRINT “TWO EQUAL & ONE DIFFERENT, SO THE RESULT IS “
PRINT “DC2 =”; DC2
GOTO 160
130  L = K4 – (K4 ^2 – 4 * K5)^.5
DC3 = (L/2) * DG : Y(Z) = DC3 : PRINT “dc3(“;X(1);X(2);X (3); “)=”;DC3
PRINT “ DIFFERENT DIAMETERS, SO THE RESULT IS “
PRINT “ DC3 = “; DC3
140  GOTO 160
150  PRINT “ IMAGINARY NUMBER WE CANNOT CONTINUE “
```

```
GOTO 180
160  PRINT “ IF YOU WANT TO CONTINUE PRESS 0 “
INPUT W
IF W <> 0 THEN 180
Z = Z + 1
IF Z<> 36 THEN 20
FOR I = 1 TO 34
FOR J = 1 TO 35 – I
IF Y (J) < Y (J+1) THEN 170
T = Y (J): Y (J)= Y (J+1): Y (J+1) = T
170  NEXT: NEXT
FOR I = 1 TO 35
PRINT “ y (“;I;”) = ”; Y (I)
NEXT
180  INPUT “ ENTER 0 TO PRINT THE RESULT “; S
IF S = 0 THEN 190
GOTO 200
190  FOR I = 1 TO 35
PRINT “y (“;I;”) = “; Y (I)
NEXT
200  FOR I = 1 TO 5
PRINT “ d (“; I ;”) = “; N (I)
NEXT
END
```

Program number two

```
REM ****CALCULATING THE PROBABILITY OF PACKING*****
REM *****BED FOR FIVE DIAMETERS BY USING THEIR ******
REM  ***************** NUMBER PERCENT ****************
REM ****** R: TYPE OF DISTRIBUTION ********
REM * RK: TYPE OF DISTRIBUTION FOR SMALL PARTICALE *
REM* RM: TYPE OF DISTRIBUTION FOR MEDIUM PARTICALE*
REM* RG: TYPE OF DISTRIBUTION FOR LARGE PARTICALE *
CLS
DIM K (35)
Z = J
PRINT " INPUT THE FIVE DIAMETERS "
FOR I = 1 TO 5
PRINT " DIAMETER (";I;") = ";
INPUT N (I)
NEXT
FOR I = 1 TO 4
FOR J = 1 TO 5 – I
IF N (J) < N (J+1) THEN 10
T = N (J): N (J) = N (J+1): N (J+1) = T
10  NEXT: NEXT
D1 = N (1): D2 = N (2): D3 = N (3): D4 = N (4): D5 = N (5)
PRINT " ENTER THE NUMBER PERCENT OF EACH DIAMETER "
FOR I = 1 TO 5
PRINT " NUMBER PERCENT (";I;")="
INPUT G (I)
NEXT
OPEN "D:\ HUDA. TXT" FOR OUTPUT AS # 1
FOR I = 1 TO 35
15   PRINT " INPUT DIAMETER VALUE "
FOR I = 1 TO 3
INPUT X (I)
NEXT
PRINT " ENTER NUMBER PERCENT FOR EACH CHOICE
DIAMETER "
FOR I = 1 TO 3
INPUT E (I)
NEXT
REM **** CALCULATING THE VALUES OF RK, RM, RG ****
INPUT " THREE DIAMETERS "; D1, D2, D3
```

```
IF D1 <> D2 AND D1 <> D3 AND D2 <> D3 THEN RK = 1: RM = 1:
RG = 1: GOTO 50
IF D1 = D2 AND D2 = D3 THEN RG = 3: RM = 0: RK = 0: GOTO 50
IF D1 > D2 AND D1 > D3 AND D2 = D3 THEN GOTO 20
IF D2 > D3 AND D2 > D1 AND D1 = D3 THEN GOTO 20
IF D3 > D1 AND D3 > D2 AND D1 = D2 THEN GOTO 20
IF D1 < D2 AND D1 < D3 AND D2 = D3 THEN GOTO 30
IF D2 < D3 AND D2 < D1 AND D1 = D3 THEN GOTO 30
IF D3 < D1 AND D3 < D2 AND D1 = D2 THEN GOTO 30
20  RK = 2: RM = 0: RG = 1: GOTO 50
30  RK = 1: RM = 0: RG = 2: GOTO 50
50  PRINT “ RG = “; RG: PRINT “ RM = “; RM: PRINT “ RK = “; RK
REM *** CALCULATING THE FACTORIAL OF RG, RM, RK ***
B (1) = RM: B (2) = RK: B (3) = RG
FOR I = 1 TO 3
FACT = 1
IF B (I) = 0 THEN 60
FOR J = 1 TO B (I)
FACT = FACT * J
NEXT
60  F (I) = FACT
NEXT
PRINT “ FACT = “; FACT
REM ************ PROBABILITY CALCULATION **********
PRINT #1,
PRINT TAB (1); “ Prn”; TAB (20); “ Prl”; TAB (40); “ Pra”;
TAB (60); “ Prv”
PRINT TAB (1); “_____”; TAB (20); “_____”; TAB (40); “_____”;
TAB (60); “_____”
Prn = 6 *((E (1) ^RK) *(E (2)^RM) * (E (3) ^RG)) / (F (1) * F (2) * F
(3))
K (J) = Prn
S = S + K (J)
L = (N (1) * G (1))  + (N (2) * G (2)) + (N (3) * G (3)) +
      (N (4) * G (4)) + (N (5) * G (5))
Lk = (D1 * E (1))/ L
Lm = (D2 * E (2)) / L
Lg = (D3 * E (3)) / L
Prl = 6 * ((Lk ^ Rk) * (Lm ^ RM)* (Lg ^ RG))/ (F(1)* F(2) * F(3))
K (J) = Prl
W = W + K (J)
A = (G (1) * (N (1) ^2)) + (G (2) * (N (2) ^ 2)) + (G (3) * (N (3) ^2)) +
     (G (4) * (N (4) ^2))  + (G (5) * (N (5) ^2))
```

```
Ak = (E (1) * (D1 ^2)) / A
Am = (E (2) * (D2 ^2))/A
Ag = (E (3) * (D3 ^2))/A
Pra = 6 * ((Ak ^ RK) * (Am ^ RM) * (Ag ^ RG))/ (F (1) * F (2) * F(3))
K (J) = Pra
H = H + K (J)
V = (G (1) * (N (1) ^ 3)) + (G (2) * (N (2) ^ 3)) + (G (3) * (N (3) ^3)) +
     (G (4) * (N(4) ^ 3)) + (G (5) * (N (5) ^ 3))
Vk = (E (1) * (D1^ 3)) /V
Vm = (E (2) * (D2^ 3))/V
Vg = (E (3) * (D3 ^ 3))/V
Prv = 6 * ((Vk ^ RK) * (Vm ^ RM) * (Vg ^ RG))/ (F (1) * F (2) * F (3))
K (J) = Prv
U = U + Prv
PRINT TAB (1); Prn; TAB (20); Prl; TAB (40); Pra; TAB (60); Prv
PRINT TAB (1); “S”; TAB (20); “W”; TAB (40); “H”; TAB (60); “U”
PRINT TAB (1); “_____”; TAB (20); “_____”; TAB (40);”_____”;
          TAB (60); “_____”
PRINT TAB (1); S; TAB (20); W; TAB (40); H; TAB (60); U
INPUT Z
IF Z<> 36 THEN 15
FOR I = 1 TO 35
FOR J = 1 TO 35 – I
IF K (J) < K (J+1) THEN 100
T = K (J): K (J) = K (J+1): K (J+1) = T
100 NEXT: NEXT
```

Program number three

```
REM ****** Calculating the mean pore diameter due to Number *******
REM *********** Length, Surface area, and Volume ****************
REM ********* dcn : the mean pore diameter due to number **********
REM ********* dcl : the mean pore diameter due to length ***********
REM ********* dca : the mean pore diameter due to surface area  *****
REM ********* dcv : the mean pore diameter due to volume *********
REM ********* dcmn : the mean pore diameter due to number ********
REM ********* dcml : the mean pore diameter due to length **********
REM ********* dcma : the mean pore diameter due to surface area *****
REM ********* dcmv : the mean pore diameter due to volume *********
CLS
FOR I = 1 to 35
Input " The diameter of the pores" ; dc
Input " The Probability due to number" ; Prn
Input " The Probability due to length" ; Prl
Input " The Probability due to surface area" ; Pra
Input " The Probability due to volume" ; Prv
dcn = dc * Prn : Print " dcn="; dcn
dcl = dc * Prl : Print " dcl="; dcl
dca = dc * Pra : Print " dca="; dca
dcv = dc * Prv : Print " dcv="; dcv
dcmn = dcmn + dcn : Print " dcmn =" ; dcmn
dcml = dcml + dcl : Print " dcml =" ; dcml
dcma = dcma + dca : Print " dcma =" ; dcma
dcmv = dcmv + dcv : Print " dcmv =" ; dcmv
NEXT
END
```

الخلاصة

إن هدف هذا البحث هو دراسة الحشوة باستخدام الطرق النظرية والتجريبية. خمسة أنواع من الكرات الزجاجية استخدمت لتمثل الحشوة و هذهِ الأقطار هي (قطر النوع الأول من الكرات =٧¸٩٧٢ ، قطر النوع الثاني من الكرات = ١٠ ¸ ١٦٤ ، قطر النوع الثالث من الكرات = ١٤ ¸ ٧٧٢ ، قطر النوع الرابع من الكرات =٢٠ ¸ ٦١٤ ، قطر النوع الخامس من الكرات = ٢٥ ¸ ٤٤٨ ملم).

الطرق النظرية التي أعطت من قِبل لباحث (latif) تشمل حساب قطر المسام، معدل قطر المسام بالاعتماد على (العدد، الطول، المساحة، و الحجم) . تم إيجاد النتائج باستخدام برنامج الحاسوب و هذهِ النتائج توضح إن احتمالية حجم المسام في أي حشوة مختلف لكل التوزيعات (العدد، الطول، المساحة، و الحجم).

الجهاز التجريبي المكون، يشمل الأسطوانة الزجاجية التي وضعت فيها خمسة أنواع من الكرات و منخل و شوائب مرت خلال الحشوة.

النتائج التجريبية توضح إن النسبة المئوية للخارج من الشوائب تقل بزيادة عدد الطبقات وكذلك تقل بزيادة حجم الشوائب لكل عدد من الكرات.

النتائج التجريبية رُبطت مع النتائج النظرية لإيجاد علاقة بين معدل قطر المسام و النسبة المئوية الخارجة من الشوائب لكل حشوة، زيادة حجم الكرات تؤدي الى زيادة معدل قطر المسام.

شكر و تقدير

أودُ أن أعبر عن خالص شكري وتقديري وَ امتناني العميق للمشرف الدكتور محمد نصيف لطيف لما قدمه لي من توجيهات قيمة ونصائح سديدة طوال فترة إنجاز البحث.

أودُ أيضاً أن أشكر جميع أساتذة و موظفي قسم الهندسة الكيماوية في جامعة النهرين لإبدائهم المساعدة اللازمة أثناء هذا العمل .

ولا أنسى أن أتقدم بالشكر و الامتنان إلى من لازمني طوال فترة البحث وخلال أصعب الظروف إلى أعز من في الوجود إلى أبي و أمي و جميع أفراد عائلتي فلهم جزيل الشكر و التقدير.

م. هدى ضياء عبد القادر

الحشوة المكونة من أحجام مختلفة من الكرات الزجاجية

رسالة
مقدمة الى كلية الهندسة في جامعة النهرين كجزء من متطلبات نيل درجة ماجستير
علوم في الهندسة الكيمياوية

من قبل

هدى ضياء عبد القادر الخز رجي

(بكالوريوس في الهندسة الكيمياوية ٢٠٠٢)

صفر ١٤٢٦
نيسان ٢٠٠٥