TO STUDY THE EFFECT OF WINDING PARAMETERS ON THE PERFORMANCE OF STRING WOUND FILTER CARTRIDGES PRODUCED ON WINDER WITH CHAIN TRAVERSE

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SUBMITTED BY

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CERTIFICATE

This is to certify that the thesis titled "To study the effect of winding parameters on the performance of string wound filter cartridges produced on winder with chain traverse" presented in this volume by Mrs. Pragnya Sanjiv Kanade for the award of degree of Doctor of Philosophy in Textile Engineering to the Maharaja Sayajirao University of Baroda has been carried out under my guidance and supervision.

She has put in research work for the requisite number of terms as required by the University. It is also certified that the work has not been submitted to any other University or Institute for any other degree.

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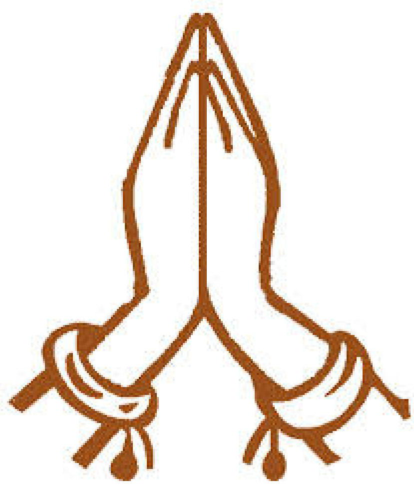
DEDICATED TO



MY FAMILY

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CHAPTER – I

INTRODUCTION

1.0 Introduction:

The world scenario today is such that there is tremendous depletion of natural resources. The renewable resources include water, flora and fauna. Water is the lifeline of our civilization. But due to industrialization and new developments, the level of pollution has increased by leaps and bounds. The polluted water is directly discarded into the water bodies due to which it no longer remain suitable to be used for drinking purpose by humans. Besides this, the ground water level is also decreasing and this has further added to the troubles. Due to global warming, with the passing years the amount of rise in temperature has increased. Thus the water evaporation rate has increased resulting in scarcity of water. Inadequate methods of collecting rain water and preventing soil erosion have made the problem all the more acute. People are now more inclined to use various water purification systems to ensure that the drinking water being consumed is safe. Thus filtration has become a key factor in removal of impurities from the water. Membrane filtration is very useful and makes use of a permeable membrane through which the concerned fluid is forced. This technology has been popularized in the present day water purification systems used for the household purposes. Depending upon the pore size of the membrane, particles which are larger than that are retained on its surface, while those smaller will pass through. Along with the membrane a candle cartridge filter is also commonly used. Various types of filter media are available but one of the cheapest and most popular disposable filters available consists of a textile material wrapped on a perforated cylindrical core. Though a direct connection is not there between textile field and filtration which can be considered to be a part of chemical engineering, the said application makes it necessary to take a look in to the filtration process whose main component is textile.

Lot of work has been reported on membrane filtration which may be used either for air or water filtration. But how the textile related variables can play a role in affecting the behavior of cartridge was highly intriguing. Thus to produce a cartridge, cross winding technique would prove to be more fruitful. The parallel wound packages don't offer enough resistance to flow of fluid, which implies that the particles dispersed through the medium will not be removed effectively. Hence it was but natural that either cartridge should be procured from the industry, wound with different winding parameters or develop a cartridge winder which was different and unique. It was decided to opt for the latter option. Cam traverse is the established method of reciprocating the yarn especially for Precision winding system. Random winding system, due its disadvantage of pattern formation is not suitable for filtration application. So there was a need to find some alternative means to reciprocate the yarn and hence instead of using cam to reciprocate yarn, some other means and that is chain was adopted. This chain was given reciprocating motion by means of servo motor. The rotation of package was through another servo and they were programmed to run synchronously. Thus due to development of this winder, cartridges with different winding variables could be produced.

To have an idea about the performance of the cartridges, water as the medium and polypropylene as the media was decided upon. To carry out testing of the cartridge a testing apparatus needed to be developed. The testing apparatus comprised of a tank which would supply slurry to cartridge housing via pump and flow meter. This system was developed on single pass which maintained constant flow rate throughout the test. The system was designed in such a manner that the slurry containing ISO A3 medium test dust was forced into the housing holding the cartridge. The media would resist the flow of slurry through it and this resistance would be reflected in terms of pressure drop across the media. Due to cross winding, the particles which enter inside the media do not get a straight and easy path through the media, thus arresting number of particles when they travel from outside to center. As a particle enters, the larger particles may not be able to enter at all and get arrested on the outside of the media itself.

The smaller ones follow a zigzag path through the channels created due to the cross-wound structure and while passing through the yarn, they may get arrested inside it, whereas the finer particles that do not get arrested come out in the filtrate. But as the surface of the cartridge gets clogged, the resistance offered increases, which shows further rise in resistance as the internal structure of the yarn also gets loaded with particles. But the disadvantage of this type of media is that the increase in pressure can cause the particles trapped inside the structure to be forced through it and come into the filtrate, more so for finer particles. The amount of particles coming in the filtrate would definitely be dependent on the winding pattern or other variables that may be selected during winding. To get an idea about the change in particle size distribution, the filtrate samples were collected and their particle size analysis was done. This particle density counted would be converted into frequency distribution by weight and frequency distribution by number. Thus this analysis would be helpful in coming to some concrete conclusion regarding the influence of winding parameters on filtration behavior of cartridges tested.

CHAPTER – II

REVIEW OF LITERATURE PERTAINING TO THE PRESENT WORK

2.0. Introduction:

Water filtration is gaining lot of importance day by day due to the serious environmental issues and water conditions. Gujarat is one such state where the domestic market for water filtration and its products has shown tremendous growth and potential. Out the total filtration market the disposable cartridge filters occupy 25% market share which is a clear indication of its popularity. A string wound cartridge is also known as the candle or the filter cartridge. It consists of a central perforated core around which the yarn is spirally wound. In order to produce this cartridge a specialty winder is used. Once the wound cartridge is produced, it would have to be tested for its performance making use of some standard test procedure if available or else it would have to be established. Hence a herculean task of finding standard test procedure for wound cartridges, with water as the medium was present ahead. After this another important task that needed to be addressed was the analysis of the test results.

Since the literature would have to be reviewed according to the above requirements, which is extremely wide spread. Hence this chapter is divided into three sections.

Section – I: Filtration related theory and work.

Section – II: Different testing methods currently used for filter cartridges.

Section – III: Cartridge winder and work related to its development.

SECTION – I

2.1 Introduction to filtration:

Filtration is removal of particles from fluid by passing it through a permeable media. The device used to achieve this is known as a filter. The industry[39] may follow any method/procedure of filtration & separation to remove unwanted particles or contaminants like centrifuge, continuous vacuum filter, filter press, cartridge filter (micro-filtration), dialysis, electro-dialysis, reverse osmosis, and ultra filtration/nano filtration. The figure 2.1 shows the micron (µm) range of the three different types of filtration techniques commonly adopted.

0.0001µm- 0.001µm 0.2µm 10µm*

$1A^0$ <-----------> $10A^0$ <-----------> $200A^0$ < -----------------> $100{,}000A^0$

Reverse Osmosis | Ultra Filtration | Micro filtration

Figure 2.1 shows particle size removal ranges of various types of filtration[39]

A human hair is of 75µm, the smallest pencil dot a human eye can see is 40 µm, and a yeast cell is 3 µm whereas a common bacterium is of 0.2 µm. Thus the fluid which needs to be filtered may contain contaminants of variable sizes, which may or not be visible, which may or may not be flexible and which may or may not be living things.

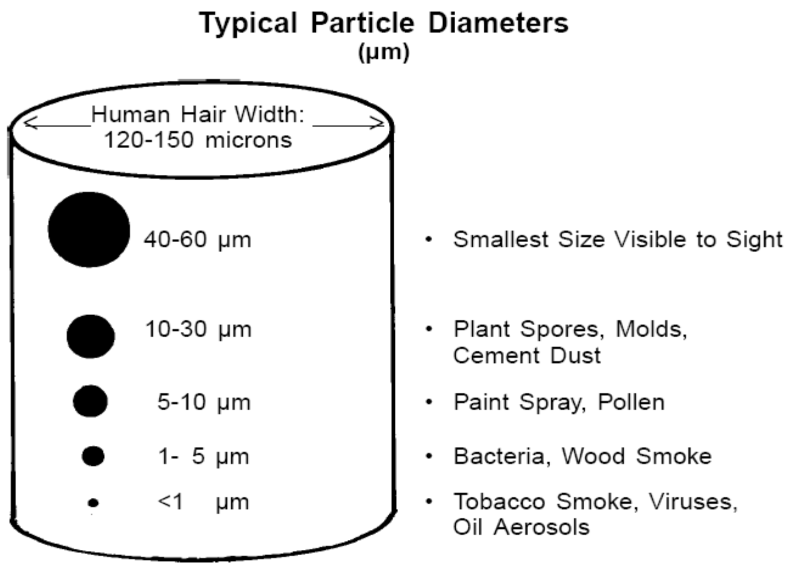

Fig 2.2 shows various known particles with their respective size[5]

2.2 Nature of contaminant and filtration characteristics:

The range of fluids used in chemical processing covers a vast spectrum from paint to food, to fine chemicals. Contaminants within these fluids fall into three categories:

1. Solids such as sand grit and pipe scale.
2. Gelatinous particles formed in the mixing process.
3. Fibers from hairs and packing materials.

Solids are relatively easy to remove from a fluid. Flexible contaminants including fibers aren't always easily removed because they sometimes can squeeze and make their way through the filter structure. The most difficult to remove are deformable gels. These have the ability to blind a filter by smearing over its surface. At high pressure drop, gels also can be extruded through the filter structure. They are best removed if filter media with gradual decreasing pore size is used. String wound cartridges are suitable to remove all of the three mentioned contaminants.

A single filter type may not be suitable for the removal of different types of contaminants and that too covering the wide range of particle sizes mentioned. Hence different types of filtration procedures and filters produced with different techniques are available to choose from as per requirement of the process.

2.3 Definitions[9]:

Before any further description is made related to filters, it would be better have a look at certain definitions/terms to understand the further sections clearly.

a. Porosity: The percent of open pore area per unit volume of filter media
b. Pore: Opening/Interstices in a medium, their size and distribution depending upon the type of medium.
c. Pore size: Diameter of pore in a filter media.
d. Pore size absolute rating: Particles equal or larger than the rated size will be retained with 100% efficiency.
e. Pore size nominal rating: A pore size at which particle of given size will be retained with efficiency below 100%. Typically between 90-98%/
f. Nominal rating: Nominal ratings take into account the particles captured within the filter media by the process of adsorption. Nominal filtration is typically described in percentage terms as between 80% and 90% efficiency. A good wound cartridge (the traditional depth filter) can remove 90% of the particles of a specified size approaching the matrix (same as e.).

g. Absolute rating: The absolute rating is an indication of the smallest particle that the filter will capture, and no particle of that diameter or larger should pass through the filter (same as d.).

h. Filtration threshold[20]: This corresponds to efficiency of 100%. There is no chance of finding a particle larger than this size in the filtrate.

i. Pressure drop: Difference in pressure between two points.

j. Differential pressure - Delta (Δ) P: The change in pressure or the pressure drop across a component or device located within the air/w/ater stream; the difference between static pressure measured at the inlet and outlet of a component device.

k. Down-stream: The filtrate/product stream side of the media/ fluid that have passed through the filter media.

l. Up-stream: Feed side of the filter. The fluid that has not yet entered the media.

m. Integrity test: Used to predict the functional performance of a filter. The valid use of this test requires that it be correlated to standardized bacterial or particle retention test. Examples: Bubble Point Test, Diffusion Test, Forward Flow Test, Pressure Hold Test.

n. Manometer: A U-shaped tube filled with a specific liquid. The difference in height between the liquid in each leg of the tube gives directly the difference in pressure on each leg of the tube. Used to monitor differential pressure.

o. Terminal pressure: Pressure drop across the unit at the time when the system is shut down or when the maximum allowable pressure drop is reached.

2.4 Mechanism of particle capture in various filters[39]:

Filtration can be classified on the basis of the particle size removal range or on the manner in which the particles get arrested during their course through the filter media. For example, if particle removal range is 0.2 µm to 150 µm, then the filtration technique can be put under the head of micro filtration. Similarly according to the way in which the particles get trapped during their passage, they can be put under the categories of surface, depth or adsorptive/surface active filters. For example if particles get trapped on the surface of the media then such a filter is called as a surface filter.

2.4.1 Surface filters:

Filter media where the pores are within the same plane are called screen or surface filters and act as sieves. Particles too large to pass through the pores are retained on the surface. As the contaminant cake builds up on the surface, the degree of filtration often grows finer. A surface filter medium is generally thin. The surface filter traps contaminants on the outside of the filter medium as shown in figure 2.3; to increase the performance, the medium is pleated to increase its surface area as shown in figure 2.4.

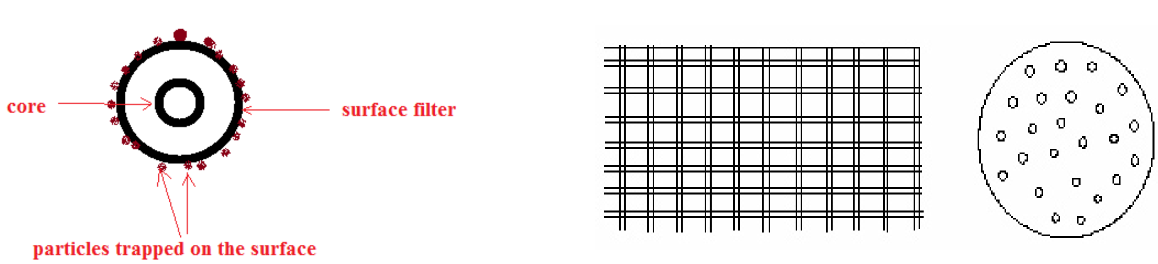

Fig. 2.3 Mechanism of particle capture in case of surface filter [39]

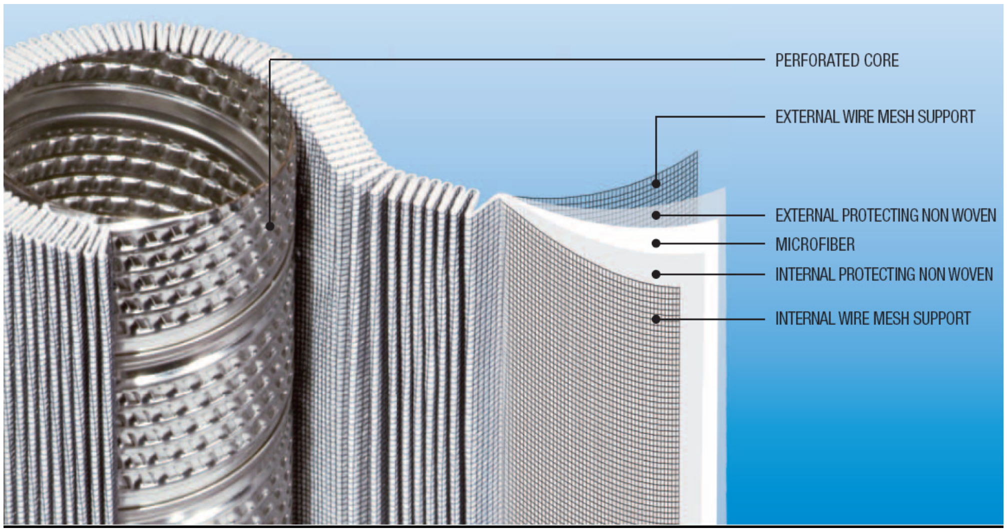

Fig. 2.4[40] shows photograph of a typical pleated filter

2.4.2. Depth filters:

The depth filter is the one, which traps contaminants within the medium. The surface filter is particularly good at removing solids. However, gelatinous and fibrous particles can, given certain conditions, such as high pressure differentials be forced through the pores, either by changing direction in the case of fibers, or changing shape in the case of a gel. The advantage of the depth filter is that it can remove all three types of contaminants effectively.

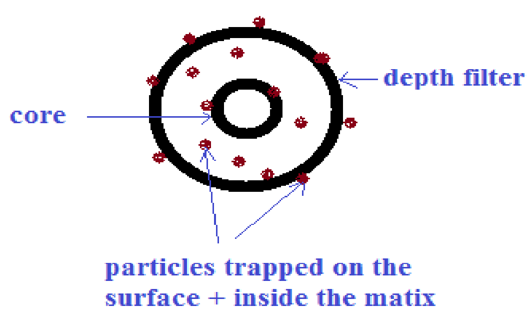

Figure 2.5 Mechanism of particle capture in case of depth filter

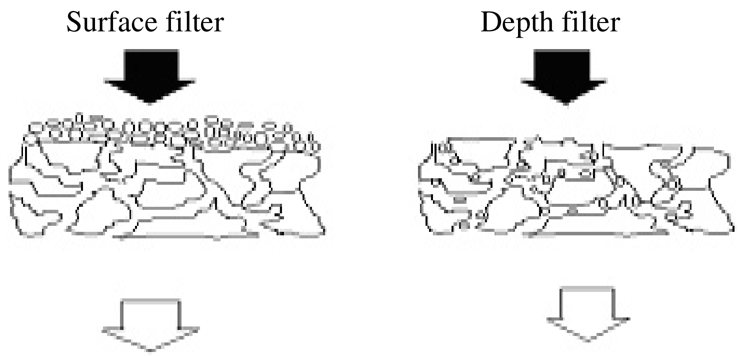

Figure 2.6[39] Percolation of particles in case of surface filter and depth filters

2.4.3 Adsorptive filters:

The adsorptive filter media are capable of retaining particles smaller than the rated filter pore size. This is possible in some systems because of surface charge modification of the filter media. The charge is most effective over short distances from the surface and falls off exponentially as distance increases. Accordingly such filters are used principally in the sub-micron filtration. Thus from the above classification it can be understood that the type of contaminant will also play an important role in deciding how the particles will get trapped i.e. whether on the surface or within the medium

2.5 Brief background of various types of cartridge/candle filters[19, 25]:

Out of the many options available the disposable filters, which include string wound cartridges, hold a substantial amount of share. Large variety of disposable filters are available like melt blown filters, cartridge filters, pleated filters, spun bonded filters etc. Each filter has its own merits and demerits and is suitable for a certain filtration range and application; some can be used as pre-filters while some have very good dirt holding capacity. The disposable filters can be produced using different techniques; this makes the mechanism of particle capture different in each of the case. The use of a specific filter size and type is dictated by the application for which it is chosen.

There are four basic types of filter cartridges/candles:

1 String Wound Filter Cartridges
2 Melt blown (Solid) Filter Cartridges
3 Pleated Filter Cartridges
4 Media Cartridges: Activated Carbon (GAC), DI resin, Calcite, Alumina, and more.

2.5.1 String Wound Filter Cartridges

The string wound cartridge was the original cartridge filter element. A string wound cartridge filter is effective in removing diverse sized particles. String wound filter cartridges are as shown in figure 2.7, are best suitable for carrying out micro filtration.

Figure 2.7 shows photograph of string wound filter[25]

They are capable of removing particles in the range of 0.2 to 100 microns. Because of the overlapping nature of the string windings, it has an effective surface area considerably larger than that of the melt blown filter and from the particle capture point of view, can be called as a depth filter. Cartridge filters[20] are also widely used in chemical, pharmaceutical, nuclear, health, microelectronics, biotechnology and water treatment industries. While string wound cartridges predate all the other filters with polypropylene fiber construction, a string wound is still a good general-purpose filter and in certain applications, the best choice. The choice of supply yarn to be wound on a perforated cylindrical core can be cotton, polyester, polypropylene or any other material for that matter, but in most of the cases it is polypropylene yarn due to its characteristics[7, 11 & 22] like greater volume of air, random fiber arrangement in the yarn structure, greater twist, round cross-section and most importantly its inert nature are advantageous from filtration point of view. These yarns can be produced on ring spinning system or on unconventional spinning systems. But yarns produced on the different spinning systems can exhibit lot of change in their properties especially compactness and hairiness. These two properties are very important as far as the filtration application is concerned. Like the melt blown filter cartridge, string wound cartridges are also inexpensive. It is the second most commonly used filter cartridge on the market and is used extensively in pre-filtration applications.

Typical applications include:

1. 1 to 50 micron filters used in upstream/downstream for general purpose applications.
2. 5-micron pre-filters are installed ahead of a reverse osmosis system to remove non-uniform sized particles.

2.5.2 Melt blown (Solid) Filter Cartridges

In comparison to string-wound cartridge, mention needs to be made of melt-blown cartridges. A melt blown filter cartridge, is as shown in figure 2.8, is a depth type filter that is good for the removal of relatively uniform sized particles throughout the body of the filter, not just on the surface. Grooves may be provided on their surface to increase its surface area.

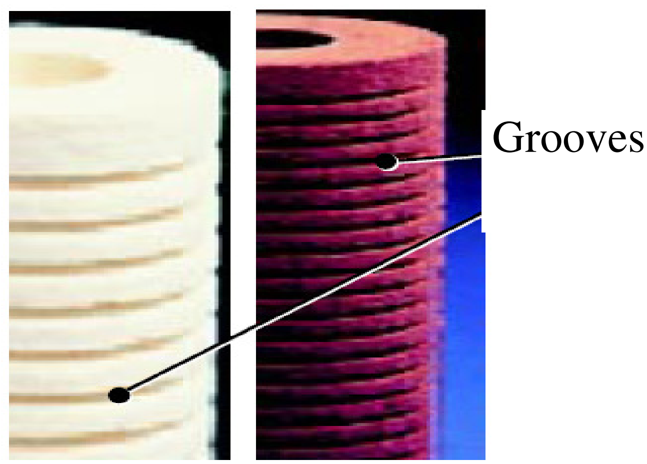

Figure 2.8 shows photograph of melt blown cartridge[25 &19]

They were developed several years ago as a lower cost substitute for string-wound cartridges. They are made using a one-step process in which high-velocity air blows molten polypropylene resin from an extruder die tip onto a take-up screen or a mandrel to form layers of self-bonding fiber web. The only real advantage melt-blown cartridges have over conventional string-wound filters is freedom from process chemicals. They are not suitable for many industrial applications, as they tend to collapse under even moderate pressure differential. A major shortcoming of the melt blown cartridge is its poor edge sealing that result in by-pass problems. The filter consists of layers of fibers, which can separate rather easily. It is one of the least expensive and most widely used filter cartridges on the market today and is used extensively for both commercial and domestic applications.

Typical applications include:

1. 1 to 50 micron filters used in general purpose applications, with the 5-micron cartridge being the most popular and can be installed upstream/downstream.
2. 5-micron pre-filters are installed ahead of a reverse osmosis system to remove particles that could clog up membranes and deteriorate performance.

2.5.3 Pleated Filter Cartridges

A pleated cartridge shown in figure 2.9, is a surface type filter cartridge that is effective in removing diverse sized particles in limited quantities. Pleated cartridges will remove particles of its micron rating with good resistance to being blinded by larger particles. Pleated filter cartridges are particularly effective on surface waters from streams/rivers.

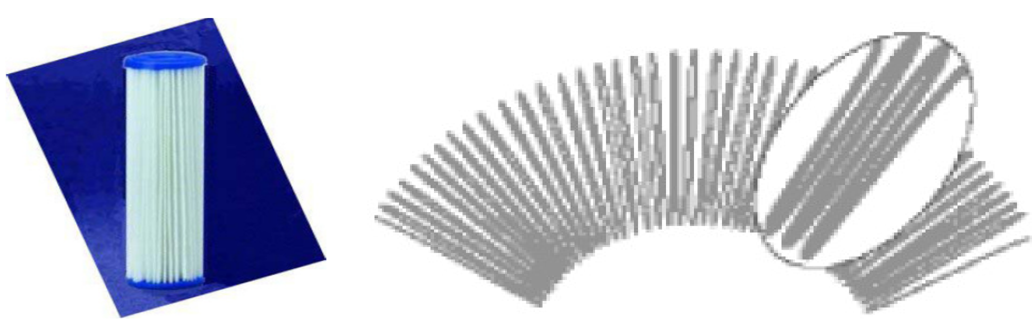

Figure 2.9 shows photograph of pleated filter[25 &19]

Pleated filter cartridges are constructed to provide a surface area far in excess of the diameter of the filter. The micron rating of a pleated filter is more precise than either the melt blown or string wound cartridges. Though pleated cartridges are more expensive than melt blown or string wound, they are the only choice for sub-micron filtration which lies in the range of 0.45 to 0.1 microns. Sub-micron pleated filter cartridges are used extensively as biological blocks in the production of high-purity and sterile water.

Typical applications include:

1. 5-micron general-purpose filters can be used before and after ion exchange resin columns.
2. 1 to 50 micron filter can be installed on the vent of a water storage tank to help prevent airborne particles from entering the tank during draw down in non-critical applications.
3. Sub-micron post-filters can be installed as final filters for particle/micro-organism sensitive or for critical applications.

2.5.4 Media Filter Cartridges

A Media Filter cartridge is not like the mechanical filters described above. A media cartridge as shown in figure 2.10 is actually a water treatment device that effects chemical changes in the water. The flow rate through a media cartridge is substantially lower than that of a similarly sized particle filter. Replacement of media cartridges is not dictated by pressure drop. Carbon media cartridge replacement should be scheduled for every three months or more often. De ionizer (DI) cartridges should be replaced according to water quality.

Figure 2.10 Photograph of media filter[25]

Typical applications include:

1 • Activated Carbon for the removal of chlorine, taste and odor.

2 • Mixed Bed DI resin for water purification.

3 • Calcite media for neutralization of acidic water.

4 • Many other media are available to handle a wide variety of water problems.

The water purification systems available in the market are comprised of the above variety due to which not only removal of particles takes place but also any odor that may be there gets removed.

SECTION – II

2.6 Test methods: (Integrity test methods for filters)[20, 35, 36 & 39]

Dr. Graham Rideal and et.al[8] have made comparison between 2D and 3D filters and according to them a substantial difference in performance of 3D filters can occur when tested in dry and wet states. Hence filters which are to be used in wet conditions should be tested with a liquid carrier. In case of dry filtration the effectiveness may not be directly related to the pore size but other mechanism of particle capture may then come into play. Attractive forces between particles and fibers increases hence particles which may get arrested in dry filtration may directly pass through when an aqueous medium is used. Filters require to be tested to assure they are integral and fulfill its purpose. Such filter tests are called integrity test and can be performed before or after the filtration process especially, in case of those filters that need to be sterilized. Integrity tests as the Diffusive Flow, Pressure Hold, Bubble Point or Water Intrusion Test are non-destructive tests and can be correlated to the destructive bacteria challenge test.

A cartridge may still be useful for its filtration application after testing it using a non-destructive type of test unlike to a destructive method of testing a filter.

2.6.1 Non-destructive methods[20, 33, 36 & 39]

2.6.1.1 Assessing weight of the cartridge:

Assessments of element weight and media thickness are used to ensure a consistent and even bed depth, particularly in the manufacture of spool-wound cartridges.

2.6.1.2 Measuring air permeability:

By measuring permeability of the filter medium to the passage of air provides an indication of the overall porosity of the element.

2.6.1.3 Bubble point test:

The most widely used non-destructive integrity test is the bubble point test. Bubble point is based on the fact that liquid is held in the pores of the filter by surface tension and capillary forces. The minimum pressure required to force liquid out of the pores is a measure of the pore diameter.

$$P = \frac{4k\cos\theta}{d}\sigma \quad , \qquad \text{Equ 2.5.1}$$

where, P = bubble point pressure, d = pore diameter, k = shape correction factor, θ = liquid- solid contact angle, σ = surface tension.

This test consists of forcing appropriate fluid through a membrane in a pressurized system (about 80% of the expected bubble point pressure which is stated in the manufacturer's literature). The pressure is gradually increased till a steady stream of bubbles is seen emerging from the membrane. Bubble point values lower than the specification could be due to lack of care taken during the test like high temperature, fluid with different surface tension than the recommended test fluid, incompletely wetted membrane etc. Since the minimum bubble radius corresponds to the maximum differential pressure before bubbles are released from the hole, the measurement of differential pressure can be used to establish a size for the hole.

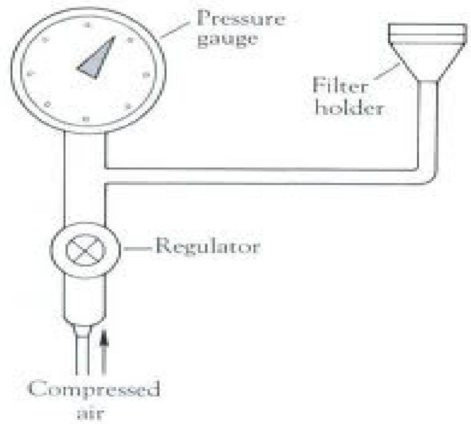

Figure 2.11[35] shows a typical bubble point test apparatus

2.6.1.4 Forward flow test

This test is a modification of the bubble point test, where the first stream of bubbles emerges from the largest pore. Increasing the pressure further produces bubbles from successively smaller pores. Eventually the point is reached where bubbles appear over the entire surface of the element. The corresponding pressure at which this occurs provides an indication of the mean effective pore size of the element. This mean effective pore size is far more useful than the nominal rating, and in case of elements, in which the pore size is varying, is far more realistic than an absolute rating, since it establishes the particle size above which the filter starts to become effective.

When[36] an air/gas pressure difference exists between the two sides of a wetted membrane filter, air/gas molecules dissolve/migrate continuously through the water-filled pores of a wetted membrane following Law of Diffusion. The liquid on the higher-pressure side diffuses through the liquid film in the pore system and escapes on the lower-pressure side. Air diffusion takes place and this diffusion is very slight across small filtration areas. In systems with larger areas, however, it is more pronounced and constitutes the basis of the forward-flow and pressure holding tests. In the forward flow test, also known as diffusion test, a definite test pressure below the bubble point pressure (approximately 80% of the minimum bubble point) is applied to a wetted membrane, in a manner analogous to the bubble point test. The gas diffusion flow rate for a filter is proportional to the differential pressure and the total surface area of the filter. The gas which diffuses through the membrane is measured to determine a filter's integrity. This is achieved by determining the pressure drop on the side of the filter medium on which pressure is applied. The flow of gas is very low in small area filters, but it is significant in large area filters.

$$DF = \frac{K(P1 - P2)A \times P}{L} \qquad \text{Equ 2.5.2}$$

where, K = Diffusivity/Solubility coefficient, P1and P2 = Pressure difference across the system, P = Membrane porosity, L = Effective path length, A = Membrane area,

DF = Diffusion Flow.

Maximum diffusion flow specifications have been determined for specific membranes/devices and are used to predict bacterial retention test results or on the results of the bacterial loading test. A filter producer can specify the maximum rate of gas diffusion for each filter membrane. The rate of air diffusion depends on the thickness of the wetting liquid in the filter and not on the pore size. Indirect confirmation of the pore size is obtained by the level of the applied test pressure. A direct correlation exists between air diffusion and particle or germ retention ratio.

2.6.1.5 Pressure Hold Testing

The Pressure Hold Test, also known as pressure decay or pressure drop test, is a variation of the diffusion test. In this test, a highly accurate gauge is used to monitor upstream pressure changes due to gas diffusion through the filter. Because there is no need to measure gas flow downstream of the filter, any risk to downstream sterility is eliminated. The pressure hold value is dependent on the diffusion flow and upstream volume. It can be calculated using the following equation:

$$\text{Pressure hold test formula} = \frac{D\ (T)(Pa)}{Vh} = \Delta P \qquad \text{Equ 2.5.3}$$

where, D = Diffusion rate (cc/min), T = Time (minutes), Pa = Atmosphere pressure (1 Atm. or 14.7 psi), Vh = Upstream volume of apparatus (cc), ΔP = Pressure Drop (bar or psi)

2.6.2 Destructive test methods:

The currently used methods rely on determining the initial efficiency without clogging the filtering surface or determining the efficiency as a function of the clogging level with or without recycling of these particles (multi-pass or single-pass testing). All destructive filter tests operate by forcing a known quantity of contaminant particles through the filter under a predefined set of test conditions. The nature of contaminant particles and the method used to measure its presence in the flow stream determines the type of testing.

__2.6.2.1 Glass bead test:__

A typical glass bead test set up is shown in figure 2.12. This test makes use of suspension of glass beads of different but known diameters, and are passed through the filter and the filtrate is passed through the analysis membrane, which is inspected under a microscope and thus the size of the largest bead that passes through the filter is determined. This measurement gives the absolute rating of the filter. So, the absolute rating of the filter can be defined as the largest hard spherical particle, which would just pass through the filter. But here even a stray bead would disturb the results, besides these glass beads are costly. To make the process cost effective means to recover the glass beads have to be applied or cheaper methods available like the bubble point test can be adopted. Instead of glass beads fluorescent and non-fluorescent latex spheres, silica dust etc. can also be used.

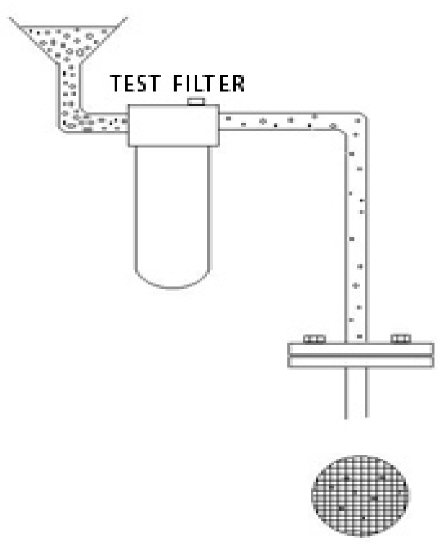

Figure 2.12[39] shows a typical glass bead test apparatus

Both the glass bead test and the bubble point test were historically reputed to provide an absolute rating for the filter media, but also implied that this was a cut-off point, in the sense that in service no particles below this size were removed, and all particles above this size were removed. Both methods were based on spherical particles, which occur rarely in real filtration applications. In an effort to address these difficulties, a further test was developed, and is also included in MIL-F-8815. This has been called the nominal rating especially applicable to the depth type of filters.

2.6.2.2 Single pass test:

This test system is designed to be representative of a typical filter circuit. Fresh contaminates are introduced in a slurry into the test reservoir, mixed with fluid and pumped through the test filter. Unlike the multi-pass test method where the filtrate is recirculated, here the filtrate is directly discharged as soon as it passes through the filter once and its set up is shown in figure 2.13.

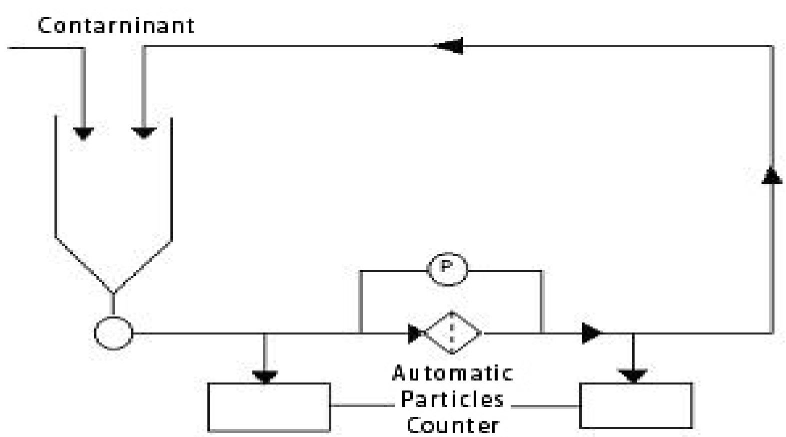

Figure 2.13[39] shows a typical apparatus showing single pass test method

ASTM [2 & 3] shows a simple procedure to find out the performance of a filter. There are two ways of carrying out the test; either it can be performed under constant flow-rate conditions or under constant pressure drop conditions. If the test is performed under the former conditions then a plot of pressure-drop against time can be generated at the end of the test, whereas if the latter method is adopted then a plot of flow-rate against time can be obtained. Quantities like filtration ratio and filtration efficiency based on the number of particles upstream and downstream have also been defined .

2.6.2.3 Multi-pass test method:

This test was originally developed[20] at Oklahoma State University, and a typical test system is shown in the figure 2.14. In the ISO 16889 multi-pass test circuit, MIL-H 5606 hydraulic fluid circulates through the test filter at a constant rate.

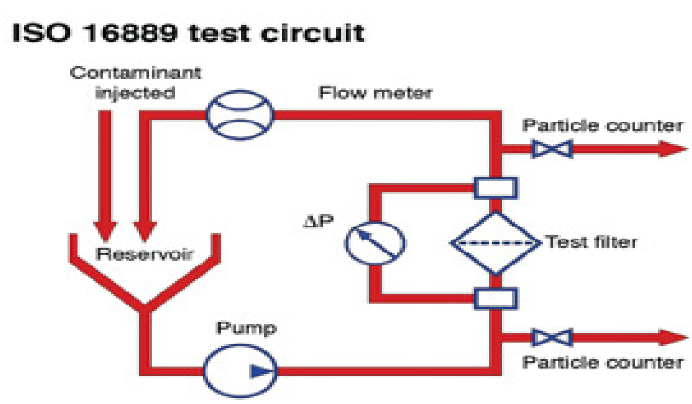

Figure 2.14[10] shows a typical multi-pass test method

Contaminated fluid is added at a constant rate, and the difference between particle counts before and after the filter gives a measure of its performance. The test fluid containing the appropriate contaminant suspension is circulated around the test system through the filter under test. The contaminant slurry is fed continuously into the system, in order to replace what has been removed from the fluid by the filter, thus maintaining a constant contaminant level.

Samples of test fluid are drawn simultaneously from the sampling ports located up and down stream of the test filter. These samples are analyzed in various ways, and the particle removal efficiency of the filter under test is calculated from the analyses. An adaptation of this test is the dynamic efficiency test. This test has been internationally accepted and specifically relates to hydraulic systems where test fluid is oil. The pollutant/contaminant mainly used is the silica dust[20] (ACFTD). The number of particles upstream and downstream are counted using particle size counter and the ones working on absorption principle have been found to be most reliable. The most common measure of filter performance is removal (capture) efficiency, which addresses how efficiently a filter removes particles from the fluid. Few consider filter characteristics known as retention efficiency, which measures how effectively that filter holds onto particles it has previously captured under stresses of a hydraulic system. A filter is not a black hole, and its performance must not be based only on how efficiently it captures particles. If not designed and applied correctly, a filter can be one of the most damaging sources of contamination in a system. The figure 2.15[10] shows a plot of flow rate versus pressure drop which is a normal way to express the results of a filter test. While the ISO 16889 standard has made great progress in providing a repeatable method where identical filters should produce similar results when measured on different test stands, ratings in the lab often do not translate into predictable performance on actual lube and hydraulic systems.

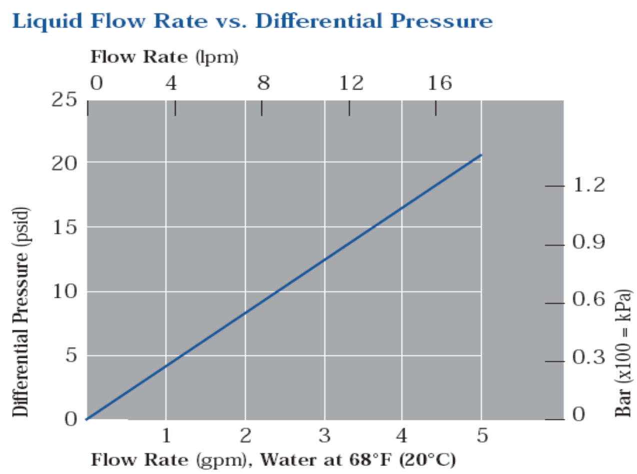

Figure 2.15[10] shows a typical test result

The challenge is selecting filters that will deliver fluid cleanliness below the critical contamination tolerance level to yield reliable operation and maximize component life. Filters must be tested in a dynamic environment to understand how they will perform when exposed to real-world conditions. The figure 2.16 shows a comparison between single pass and multi-pass test which is a clear indication of how change in the test method can change the rating of similar kind of filters.

Liquid Retention Ratings (μm) (by ASTM F-795 Test)

Single Pass	Multi-Pass
0.5	0.2
1	0.5
3	1
10	3
25	10

Figure 2.16[10] shows comparison between different test types

2.6.2.4 Dynamic efficiency test[10]:

This test method has now been recognized as the most widely used and a reliable test method especially, for hydraulic system where oil is used as fluid. This test can be performed as a single-pass/multi-pass test. Modifications in this test method enable it to work as a single-pass system and depending upon the application, either a single-pass or multi-pass test method may be adopted. Like fluid power industries may go for multi-pass system while process industries may go for single-pass operations[20]. The dynamic-filter efficiency (DFE) multi-pass test also uses upstream and downstream particle counters, a test filter, and contaminant injection upstream of the test filter, much like ISO 16889. But that is where the similarity ends. In contrast to ISO 16889, DFE introduces a range of duty cycles throughout the test, bridging the gap between the lab and real world. The DFE flow rate is not constant but, rather, hydro statically controlled so that full flow through the test filter can quickly change to simulate various hydraulic and lube duty cycles. Figure 2.17 makes a comparison between the two test methods. Flow across particle-counter sensors remains constant during all readings and no intermediate reservoirs collect fluid prior to measurements. This ensures that the fluid counted accurately represents real-time system contamination levels. Counts are made before, during, and after each flow change. The results are reported as filtration ratio (beta) efficiency and the actual number of particles per milliliter upstream and downstream of the filter.

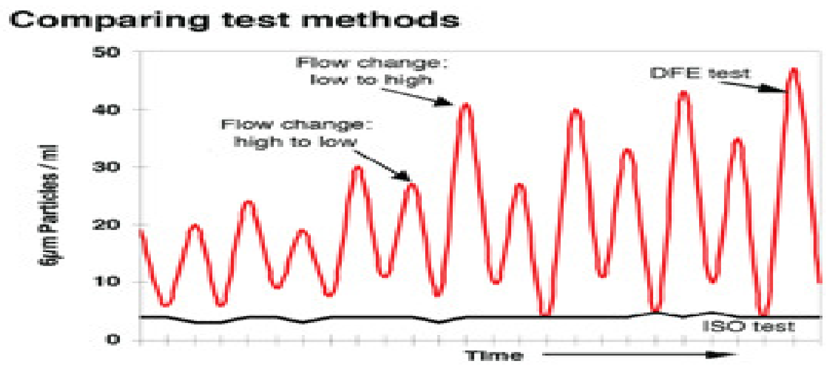

Figure 2.17[10] shows comparision between DFE and ISO test

DFE testing provides an inside look at the vital signs of a filter through a range of dynamic conditions to understand how well a filter will capture and retain contaminant in real time. DFE testing quantifies both capture and retention efficiency in real time, whereas ISO 16889 looks at normalized numbers over a time-weighted average. This method provides an inside look at the vital signs of a filter through a range of dynamic conditions and how well a filter will capture, retain contaminants in real time. There is no standardized test method available for finding out efficiency of cartridge filters[20] using water. C.J.Williams and Edyean[20] have listed the various types of tests in order to judge the performance of the cartridge filters and have also suggested modifications such that the test method gets improvised. The test methods discussed above are being used but they involve a very high degree of instrumentation and controls. They also have to make use of atleast two particle counters which are very costly. Hence instead of using these counters, results can be obtained using microscope. The errors associated with this technique can be minimized by taking necessary precautions, and the number of particles in the upstream and downstream can be found out.

2.7 Test dust[1]:

General Motors (GM) for many years manufactured Air Cleaner Fine Test Dust (ACFTD) or Arizona road dust which has been used in loading air as well as liquid filters and even for calibrating the particle counters, but now, they have discontinued producing it. Hence it became necessary to have an alternative; and so the National Fluid Power Association (NFPA) started a project in this context such that the dust would be as close to ACFTD in sizing and counting particles and the inherent shortcomings like greater quantity of particles smaller than 5 microns and difficulty in standardized calibration. Hence the new ISO Medium Test Dust (ISO MTD) is quite close to ACFTD and has similar kind of particle size distribution. ISO has given a standard method to calibrate the liquid automatic particle size counters which is ISO 11171 according to its new test dust developed. ISO 12103-1 defines four grades of test dust for evaluation of filters which have been tabulated in table 2.1[37].

A3 medium fine test dust was selected for the test purpose since cartridge filters are more popular as pre-filters and are not meant for removing very fine particles.

Table 2.1 – Particle size distribution of various standard test dusts

Sr.	ISO 12103-1	Micron size
1.	A1 ultra fine	0-10 microns
2.	A2 fine	0-80 microns
3.	A3 medium	0-80 microns (0-5 micron content< than A2)
4.	A4 coarse	0-180 microns

Out of the different filters listed, cartridge filters/string wound filters were selected because it involves winding of a string/roving of textile material on a cylindrical core, besides the fact that it is the most popular appliance for domestic water purification. According Dr. Ing Trommer.G[11], if the parameters related to winding like wind ratio, rotational speed of the driving elements or parameters related to the yarn used like its denier or the denier of the fibers from which it is spun or any other variable related to its production would be changed, then the performance of the filter would be affected. The commercially available filters have ratings on them, which are a function of fiber denier, yarn denier, wind ratio, speed (tension) and all them are textile related hence it becomes interesting to find out their influence on each other. Performance ratings are greatly dependent upon the test conditions and test method.

SECTION – III

2.8 Introduction:

In order to start the work related to development of the winding machine, survey of work that was already done was necessary. The first and foremost thing was that in order to use a wound cartridge, yarn would have to be wound, but not parallel to each other. In case of parallel wound packages as shown in figure 2.18 the contaminant particles would not have to face heavy resistance to travel through the media since easy channels would be available for their travel. But with cross-wound packages as shown in figure 2.19, where the yarns are laid crossing each other, the resistance offered would be substantial.

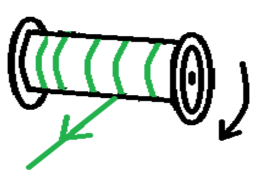

Figure 2.18 parallel wound package

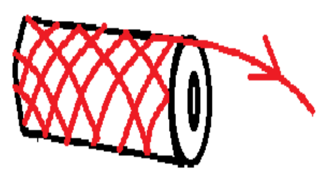

Figure 2.19 cross wound package

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Here it would be necessary to define certain terms which will be frequently used in the subsequent text.

2.8.1 Important winding related terms:

1. Traverse: The to and fro movement given to the yarn.(figure 2.20 & 2.21)
2. Wind /Wind ratio: The number coils laid on the package in a single traverse. (figure 2.20)

3. Traverse ratio: The number of coils laid on a package in a double traverse. (figure 2.21)
4. Patterning: When successive coils are laid exactly on top of previously laid coils.

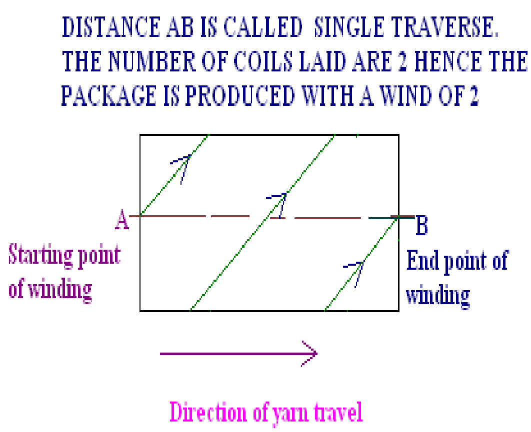

Figure 2.20 shows single traverse

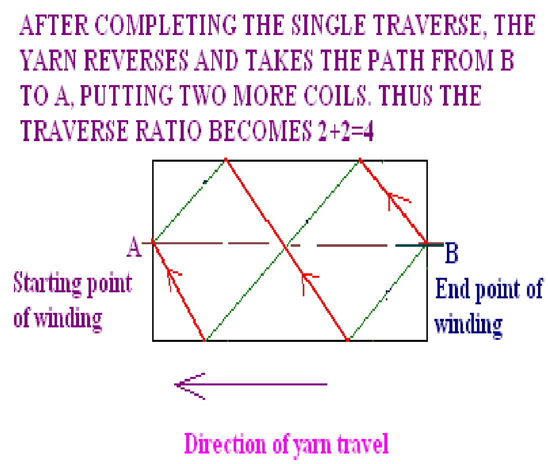

Figure 2.21 shows double traverse

2.8.2 Classification of winding systems:

As mentioned earlier, there can be parallel or cross wound packages. Parallel wound packages are not useful for the filtration application. The winding systems commercially available for producing cross wound packages are Random, Precision and Step precision.

2.8.3 Random winding:

This system is shown in figure 2.22 and makes use of a drum which may be grooved or plain. If a grooved drum is used, then the yarn is traversed due to the spirally cut grooves whereas with a plain drum, a separate traversing guide has to be used. The typical characteristics of this system provide constant surface, traverse and winding speed. The angle at which the coils are laid during the entire build up of the package also remains constant. Only one quantity changes or rather decreases and that is the wind/traverse ratio. This is a very serious disadvantage from the pattern formation point of view. Due to pattern formation there will be zones where coils will be laid exactly on top of previously laid coils causing density variations. Thus a package with non-uniform density will be formed. Just as this system is not suitable for dyeing application so is it not suitable for filtration application, since both the end-uses demand a package with uniform density. Although anti-patterning devices are provided on the Random winding systems, there are other options where the problem of pattern formation is totally eliminated and will be considered in the following sections.

2.8.4 Precision winding[4]:

A winding system that does not make use of drum of any sort but the package is directly driven while yarn is traversed using some other means can be termed as a precision winding system and one such arrangement is as shown in the figure 2.23.

Figure 2.22[32] shows random winding system

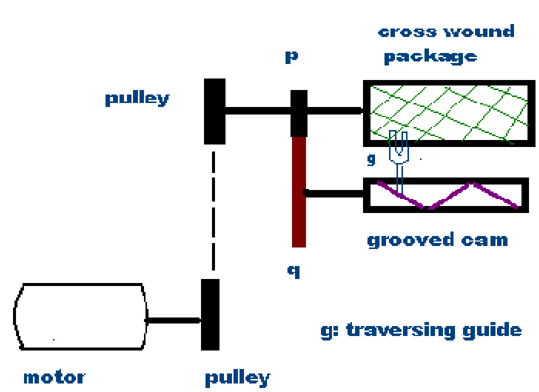

Figure 2.23 shows precision winding system

It also shows that the package is mounted on a spindle and is driven directly from the motor, while the yarn is traversed with the help of traversing guide mounted inside the grooves of the grooved cam.

The typical characteristics of a precision winding system are discussed in detail and are as follows since the system is more suitable for purpose of filtration:

The surface speed (S.S) of the package would be a function of its speed and its diameter at that instant.

$$\text{Surface speed} = \pi \times d \times n \quad \text{Equ. 2.7.1}$$

where d = instantaneous package diameter and n = rotations/min (rpm) of the package .

This value would not remain a constant since the package diameter is continuously increasing. This would means that the yarn demanded would progressively go on increasing resulting in an increase in the yarn tension. Therefore when a constant spindle speed system is devised, then a slightly different tensioning arrangement should be used. As the package diameter increases the tension should go on decreasing automatically. But if a constant spindle speed system is not used then the rotations per minute of the spindle should be reduced in proportion to the increase in the package diameter. The traverse speed (T.S) is the function of the traverse length, and the rotational speed of the grooved cam.

$$\text{Traverse speed} = 2 \times L \times n \times (p/q) \quad \text{----------------------- Equ. 2.7.2}$$

Where L = traverse length, n = rotations/min (rpm) of the package and (p/q) = gear ratio between cam shaft and package shaft

The winding speed is square root of the sum of the surface speed and the traverse speed.

$$\text{Winding speed} = \sqrt{(S.S)^2 + (T.S)^2} \quad \ldots\ldots\ldots\ldots\ldots \text{Equ. 2.7.3}$$

But the winding speed would not be a constant since the surface speed is not constant. The coil angle (θ) is a function of traverse speed and the surface speed.

$\tan\theta = (T.S) / (S.S)$ ……………………. Equ. 2.7.4

It would decrease progressively. This feature limits the maximum package diameter.

The traverse ratio (TR) would be the number of rotations made by the package in a double traverse. If it is assumed that the grooved cam makes one rotation in a double traverse, then the package would make q/p rotations in a double traverse inthat case.

$T.R = q/p$ ……………………. Equ. 2.7.5

This is a constant since it is the gear ratio. If the traverse ratio is set as a whole number, then the coil will come to the same starting point after completing its pattern, thus the advantage of precision winding will be lost. To prevent patterning, the traverse ratio should be so selected that it is not a whole number and after every pattern repeat the coils should get displaced precisely. The pattern repeat will depend upon the traverse ratio selected (nominal/TRn/N.T.R) and can written as fraction with no common factor between the numerator and the denominator. The number of diamonds formed length wise will be the numerator divided by two and circumferential diamonds formed will be equal to the denominator, with reference to the fraction mentioned earlier. For example if the traverse ratio is 24 (24/1) i.e. 24 coils should be laid in a double traverse, length wise diamonds formed in this case would be 12 and circumferentially one diamond will be formed. This traverse ratio is a whole number and will result in severe pattern formation. But if traverse ratio is 12½, that make the traverse ratio as 25/2 when written in fraction form. In this case the pattern will repeat after every double traverse and length wise diamonds will be 12.5 while two diamonds will be formed circumferentially. Similarly if the traverse ratio is 8⅓, then the traverse ratio becomes 25/3 in fraction form, where, the pattern will repeat after every three double traverse and so on with traverse ratios having 4, 5, 6 etc. in the denominator. It should be noted that the traverse ratios considered in the above examples, are in the form of improper fraction and do not have any common factor between them other than one. In each of the above mentioned case the amount of displacement/scatter will be different. Thus traverse ratio is the mirror which shows the characteristics of a given cartridge/package. If a nominal traverse ratio of 24 is needed then to avoid pattern formation the gear ratio q/p should not be [(48×20)/(20×20)] but such a gear combination will have to be worked such that instead of a whole number, it should be a fraction very close to 24. For example consider a cartridge which on visual examination shows approximately 4.5 diamonds length wise and 2 diamonds circumferentially. This means that the nominal traverse ratio should be 9/2 (4½). If the coils appear to be touching each other, it suggests close wind i.e. gain is less. The actual traverse ratio will be only slightly greater or only slightly less than the nominal traverse ratio.

Gain is the precise displacement of the yarn at the end of each pattern repeat. This can be achieved mechanically either by making use of gears or timing pulley and timing belt. When gears are used the precise displacement obtained can be called as gear gain and when belt it is known as the belt gain. If gain value is less, then close wind can be obtained but if it is more, then, an open package will result. Hence it now becomes important to find out which quantities determine the gain.

Two quantities are defined namely linear gain (L.G) and revolution gain (R.G). Linear gain is written in the following way:

$L.G = \text{yarn diameter} \div (\sin\theta)$ -------------------------- Equ. 2.7.6

But R.G is a better known quantity which is written as follows,

$R.G = L.G \div \text{circumference of the package}$ ----------------------- Equ. 2.7.7

Substitution of the values of L.G in the above equation, we get

$R.G = \text{yarn diameter} \div \pi \times d \times \sin\theta$ ---------------------- Equ. 2.7.8

where R.G stands for revolution gain/pattern repeat.

A.T.R = N.T.R – gain ------------------- Equ. 2.7.9

where A.T.R stands for actual traverse ratio and N.T.R stands for nominal traverse ratio[13].

Thus actual traverse ratio (A.T.R) is derived from N.T.R such that pattern formation can be avoided. Since here the traverse ratio does not change, the wind ratio if selected to be very close to the nominal traverse ratio can ensure that pattern formation does not occur and gain ensure precise displacement of coil after every pattern repeat and coils are laid touching each other. The only disadvantage is that the coil angle goes on reducing thus imposing a limit to the maximum package diameter that can be produced with the selected/desired coil angle.

2.8.5 Step precision winding[15]:

Concept of stepped precision winding system has been briefly explained in this section. The two methods of producing cross-wound system explained earlier, have their own limitations. Though the random winding system has the advantage of maintaining constant coil angle but can produce a patterned package, hence any random winding machine has to by default have an anti-patterning device and the disadvantages of patterned package are well known. While the precision winding system operates with a constant wind ratio, which is so selected that it does not form a patterned package but has disadvantage of decreasing coil angle with increasing package diameter. This implies that the maximum package diameter would be restricted otherwise the package would approach parallel winding. Therefore where ever large packages are required (greater yarn content), the use of precision winding system is limited. Hence the third system was needed which had the advantage of a random winding system as well as precision winding system. This was called as the step precision winding (SPW), which not only produces packages with constant coil angle but also do not produce patterned package. Thus it is a combination of the advantageous features of both the earlier systems. As it can be seen from the figure 2.24, the package is mounted on the spindle which gets drive from the motor via the motor pulley, machine pulley and the belt. A grooved cam is also seen which gets drive from the various gear combinations mounted between the cam and package shaft. At a time only one pair of gears A1 and B1 or A2 and B2 or A3 and B3 or A4 and B4 will be engaged.

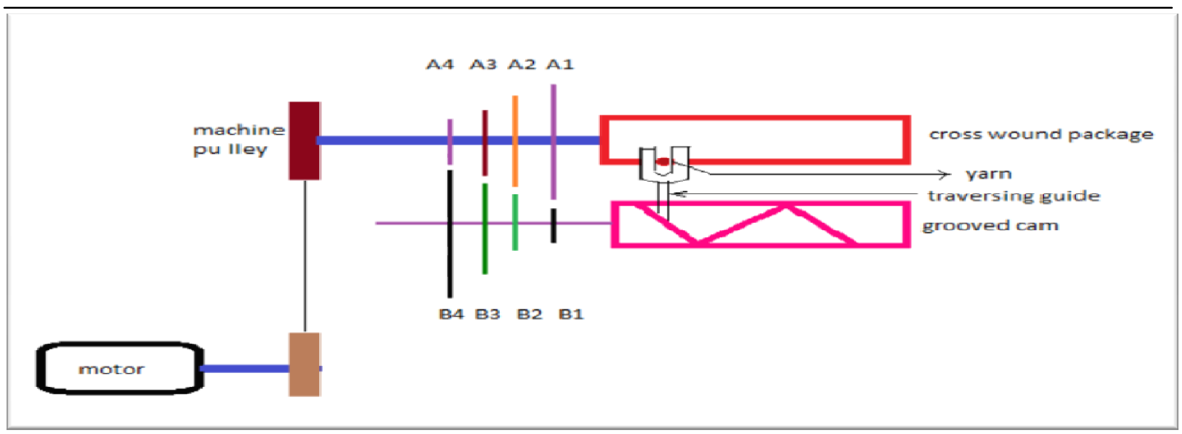

Figure 2.24 shows step precision winding system

It also can be understood that the change of gear pair will result in the change in the driver to driven ratio which ultimately will change the number of coils being laid. This arrangement will thus help in changing the traverse ratio such that coil angle remains the same. So B1/A1 or B2/A2 or B3/A3 or B4/A4 is same as p/q shown in equ. 2.7.5 of the earlier section. These are selected as per requirement to achieve desired coil angle, which is maintained constant over a certain diameter range.

Supposing the targeted coil angle is X°, then as the winding proceeds the coil angle will start reducing say it becomes X_1° ($X_1^{\circ} < X^{\circ}$). At this time say the gear combination in use was A1 and B1. But a constant coil angle is desirable. Hence when the coil angle drops to X_1°, to achieve same coil angle, X°, the gear combination A2 and B2 is engaged at the same time pattern formation is also avoided. Similarly as the package diameter further increases the coil angle will drop to say X_2° ($X_2^{\circ} < X^{\circ}$). So in that case the gear combination A3 and B3 is engaged and so on. Thus roughly the same coil angle is maintained. This system due to its cost and complexity, it is not as popular as the random winding or the precision winding system explained earlier. Most of the cartridge winders available in the market either use scroll cams or grooved drums or propeller blades for traversing the yarn.

The basic understanding of the three different principles played a key role in the decision to choose the precision winding system for the filter winder which was to be developed. In order to design a machine to achieve this, there were plenty of winding machines available even in the local market, but the desire to do something different, has been an inspiration to take the difficult path. The traversing mechanism was identified as the one wherein something novel could be implemented.

2.9 Methods to traverse yarn:

From winding machine point of view, two things become very important one is the rotational motion to the package and other is the traverse given to the yarn. Normally for traversing, cam is a very popular option used in both the Random winding system as well as Precision winding system as shown in figure 2.25. The other way of traversing yarn is shown in figure 2.26, which is by means of the propeller blades. But instead of using the cam it was decided to opt for something different that is to say that the above mentioned commercially available arrangements have the limitation of having to reverse at the end of its traverse. Due to this, the traverse mechanism has to accelerate, come to stop at the extreme and then again reaccelerate in the opposite direction.

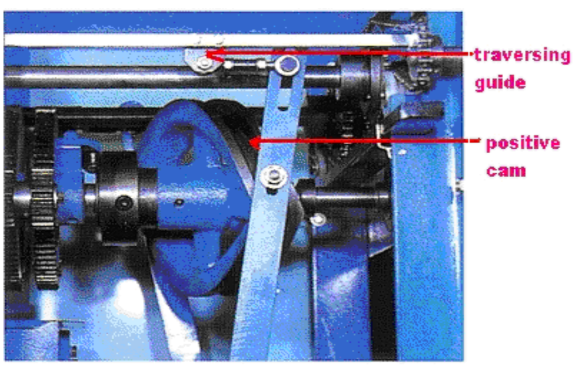

Figure 2.25 shows cam traverse[24]

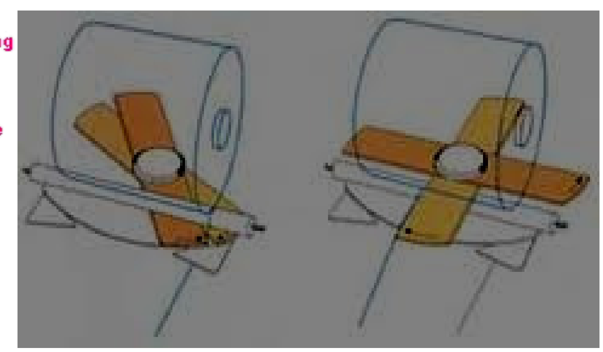

Figure 2.26[38] shows bladed/propeller traverse

To overcome this difficulty and the desire to achieve something different has led to this development. It was thought of developing a system such that there is no reversal of the yarn guide at its extreme. The rotation of the package and the reciprocating movement to the yarn guide can be imparted using present day devices.

Table 2.2 shows commercial winding machines with different means to traverse the yarn, whereas table 2.3 shows commercial cartridge winders, except one all of them are locally made using cam to traverse while only one makes use of chain to traverse but it is not Indian make. The cartridges are available in different sizes like 10”, 20”, and 30” and so on up to 70”.

Table 2.2 Commercially popular winders using different traversing arrangements

Sr. No	Method to rotate Package	Method to traverse	Manufacturer	
			International	Indian
1.	Surface contact	Grooved drum/ plain drum with separate traversing arrangement like cam or propeller blade	Autoconer, Murata, Savio, SSM	Lohia, Drum manufactures like J.H. drums, Windwell etc.
2.	Spindle drive	Cam	Scharer, Schweiter	

Table 2.3 Cartridge winder manufacturers (National and International)

Sr no	Manufacturer	Traverse type
1.	Dietze Shell	Chain traverse
2.	M/s Avon international	Cam traverse
3.	M/s Aishwarya marketing	Cam traverse
4.	M/s Prakash engineering	Cam traverse

2.10 Important features of commercial cartridge winders:

The figure 2.27 shows a commercial cartridge winder show twin winding positions.

2.10.1 Creel:

This will hold the supply package (cross-wound), which normally is friction spun polypropylene yarn.

Figure 2.27 commercial cartridge winder[29]

2.10.2 Yarn guides and tensioning arrangement:

The guides will then take the yarn into the correct passage and into the tensioning assembly. Here it is possible to use either a disc tensioning device or gate tensioning device or even both depending upon the level of tension to be generated.

2.10.3 Take-up unit:

From the tensioning device the yarn is directed via yarn guides into the traversing guide, which gets too and fro movement. The required pattern is achieved due to the relative speed ratio between the package and the traverse guide. In order to obtain a compact package normally the precision winders make use of press roll. The package is kept pressed against it either by spring tension or by hydraulic or pneumatic means.

2.10.4 Drive:

If the arrangements like the one shown in figure 2.23, then one motor will be enough for the said purpose since both the package as well as the cam gets rotational motion. Due to the groove cut inside the cam, the yarn guide reciprocates. The winding pattern can be changed with the help of gears p and q shown in the same figure. Thus a large number of gear combinations have to be kept ready so that they can be changed as per the requirement. At present the various motors used on commercial winding machines along with their features have been given in brief. With increasing use of electronics some other devices have become regular feature of winding machine and hence they also have been briefly explained in the following sections.

2.11 Electric motors[41]:

The direct current (DC) motor is one of the first machines devised to convert electrical energy to mechanical power working on fundamental concepts of electromagnetism according to which if a conductor, or wire, carrying current is placed in a magnetic field, a force will act upon it. In the present day context servo motors find their use for precise applications. Along with servo motor its drive, PLC and other electronic devices also need to be incorporated in the circuitry.

2.11.1 Servo:

The servomotor is paired with some type of encoder to provide position/speed feedback. A servomechanism may or may not use a servomotor. It is a programmable motor, and acts according to the command given to it, the most common being the position control. It is a system of devices for controlling some item (load). The item (load) can be controlled /regulated either by its position, direction or speed.

For example, if the motor is commanded to rotate at 1000 rpm, but it is actually rotating at 900 rpm, the feedback signal informs the controller that actual rpm is 900. The controller compares the command signal (desired speed) with the feedback signal (actual speed), and notes an error, which is rectified by increasing the voltage in this case till the desired signal equals the feedback signal.

Not many innovations/inventions are there to show variety of mechanically controlled traversing arrangements. However it is possible to go beyond the conventional methods available and develop a new system which has advantages. In order to use the cartridge for filter application instead of parallel wound package, a cross-wound package would be more suited. Also in order to produce a cross wound package, well established systems like random winding, precision winding and the step precision winding are available. Though these systems are commercially very popular, they have their advantages and disadvantages and with reference to the filtration application the package has to be cross-wound. With the mechanical systems, changes in the traverse length or the winding pattern are not that easy which can be considered as a limiting factor. Therefore this idea has become an inspiration to develop some other means to traverse the yarn for producing precision wound filter cartridges or a flexi-system. And further adopting a test procedure to find out the performance in terms of its efficiency and using this as a basis for making comparison between cartridges wound with different winding parameters.

2.12 Aim of Present Study:

- To produce a model filter winder using chain as a means to reciprocate the yarn.
- To develop an electronic system such that it can produce cross wound packages with yarn lay similar to commercially available winders.
- To produce cartridges/ filters with different wind patterns and check whether they are in accordance to the theoretical calculations.
- To develop a testing facility/ rig in order to test the cartridges produced on the filter winder.
- To develop/adopt a standard procedure to carry out testing of the cartridges.
- To study and compare the results obtained for various combinations of the winding and filtration parameters.
- To analyze the test results and come to a proper conclusion regarding the micron range, efficiency and the dirt holding capacity of the candle produced.

CHAPTER – III

EXPERIMENTAL WORK

3.0 Introduction:

Though filter cartridges are very popular in the filter industry not much has been done to relate the winding parameters with the performance of the cartridge when in field. Most of the commercial random winders employ grooved drum to produce a cross wound package, while the precision winding machines most commonly make use of positive cams and a set of gears to get the required package with desired wind ratio. Since it was decided to develop some alternative method to traverse the yarn (without cam); therefore a reciprocating chain was selected for traversing the yarn, (due to its positive nature). Although in the initial stages of work, instead of having a reciprocating motion for the chain, it was thought of giving it unidirectional motion, such that, when the yarn reaches the end of its traverse, it pushed out of one guide and inserted into another guide moving in the opposite direction, achieving traverse reversal. Thus using mechanical means to transfer the yarn also reverse the direction of yarn travel.

Why chain? This thought comes very naturally to the mind. As mentioned, chain was chosen in the initial stages as at that point there was no surety about success of the work started; besides compared to any other positive means like timer pulley and belt, chain is relatively cheaper. Similar results would have been obtained had timer belt and pulley been used. As it was found latter on that the cartridges produced on the newly developed winder (chain traverse) and the commercial winders (cam traverse) gave similar results. Thus the point is proved that irrespective of the method used to traverse the yarn, comparable results are obtained in either of the case. Of course one would not expect ditto results due to difference in other aspects but the similarity in their filtration behavior is obvious. The system was basically mechanical in action including the initiation of transfer, transfer of yarn from giver to the taker guide or the changes in pattern/length. But most importantly the system did not ensure that the transfer success was cent percent. Now electronic systems are becoming more popular and textile field is no exception to this. Thus the desire to develop some electronic system which can make the changes in coil angle/wind ratio, traverse length, yarn diameter, gain etc easy, without the need to change cam/gears or any external device to help the yarn reverse at the end of the traverse, has materialized in the development of the said cartridge winder.

In order to carry out testing of the cartridges, a test rig following single pass test system has been developed and the analysis of filtrate collected is done using microscope.

3.1 Methodology:

The entire work can be divided into different phases, like

I) **Phase I-** Development of the prototype cartridge winder with electronic controls working on precision winding principle.

II) **Phase II-** Evaluating the working of new cartridge winder and checking whether theory matches with the practical. This could be confirmed by taking trials on the newly developed winding machines in order to produce cartridges with different winding parameters like wind ratio, coil angles, speed, tension, gain and package diameter.

III) **Phase III -** Developing a testing rig for testing of the string wound filter cartridges produced on the newly fabricated cartridge winder.

IV) Phase IV – Taking trials of cartridges wound under different winding parameters on the prototype (following single pass test method) testing rig so that a relation can be established between winding parameters and its performance.

V) Phase V – Analysis of the filtrate samples collected during the test trials and finding out the performance of the cartridge in terms of its nominal rating, pressure differential, efficiency etc.

VI) Phase VI – Comparisons of the performance of the cartridges produced on the fabricated winder and those produced on the commercial filter winder.

PHASE – I

3.2 Development of prototype cartridge winder with electronic controls working on precision winding system:

Working principle of precision winding system has already been shown in the earlier chapter in section 2.7.4 and in the following sections the details of the newly developed cartridge winder with electronic controls will be shown. As the name indicates, aim was to develop a filter winder with electronic controls and for this purpose the motion of the driving elements (motors) should be fully controllable. The package has to get rotational motion while the yarn guide has to reciprocate meaning to say that both the motions required are different. Two servo motors have been used one for rotating the package and the other for reciprocating the traversing element. The details of which have been described in the latter part of this chapter. Just like the commercial filter winders shown in the section 2.9 of the previous chapter, the yarn was passed through various elements of the winding machine and the schematic diagram of passage is shown in figure 3.1.

3.3 Details of newly designed filter winder:

3.3.1 Creel section:

The creel was designed to hold the cross-wound package of polypropylene roving so that the axis of the package was aligned with the guide shown in figure 3.1. This was done so that the balloon that would formed during unwinding would be uniform and unnecessary tension variations could be avoided.

3.3.2 Tensioning section:

The next important element of winding machine is the tensioning device. For this purpose, multiplicative type of tensioner was selected.

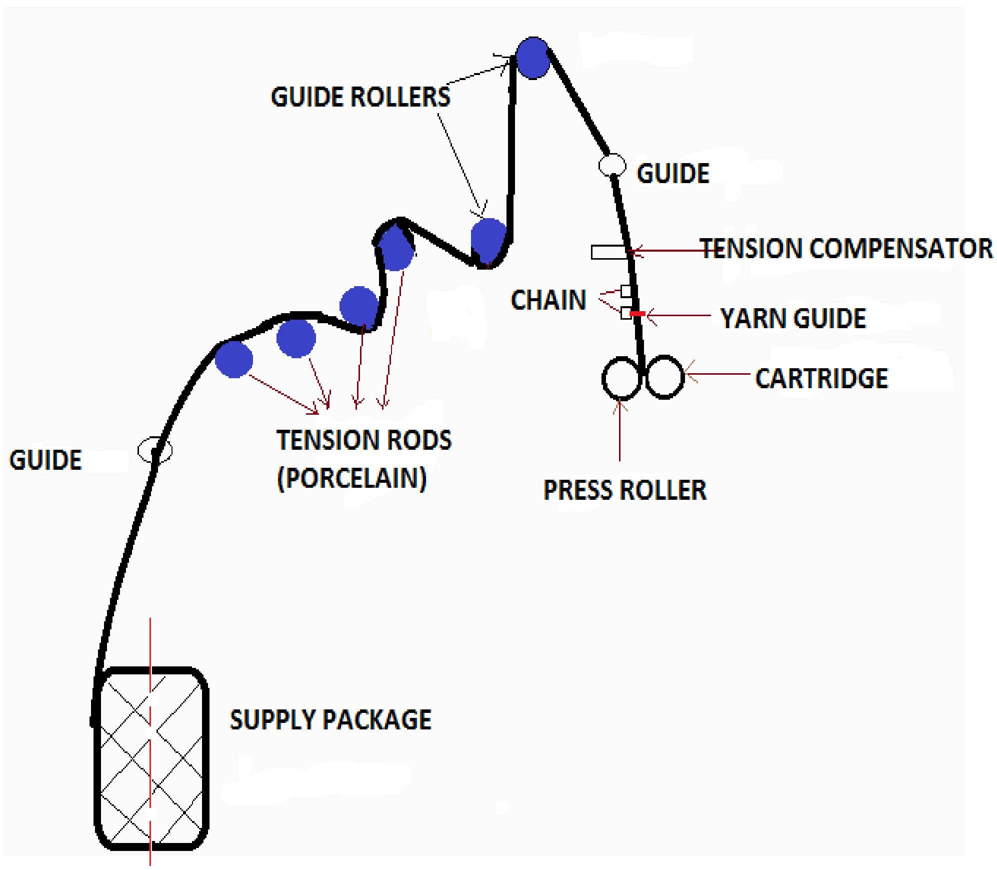

Figure 3.1 shows passage of yarn on newly developed winder

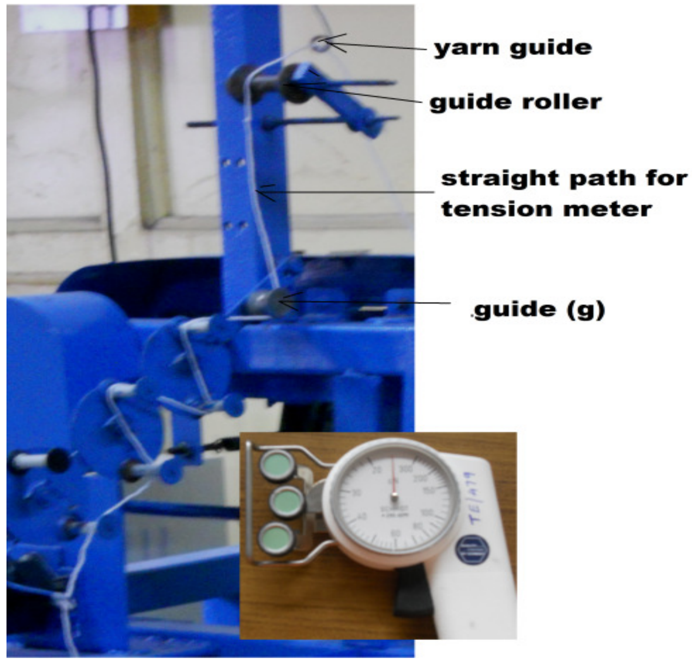

Figure 3.2 and Figure 3.3 photograph of supply package and path of yarn through tensioning assembly and in (inset) tension meter

Changing the number of guides coming in the path, would change the tension level. From there onwards the path of yarn is as shown in the next figure. The straight path from the guide (g) after the tensioner ensures correct placing of the tension meter during tension measurements and is shown in figure 3.3. In the inset Schmidt make tension meter version ZD2 02.3E is shown.

3.3.3 Take-up section:

The figure 3.5 shows the tension compensator which is specially designed to take care of the variations in tension due to the different path lengths shown in figure 3.4.

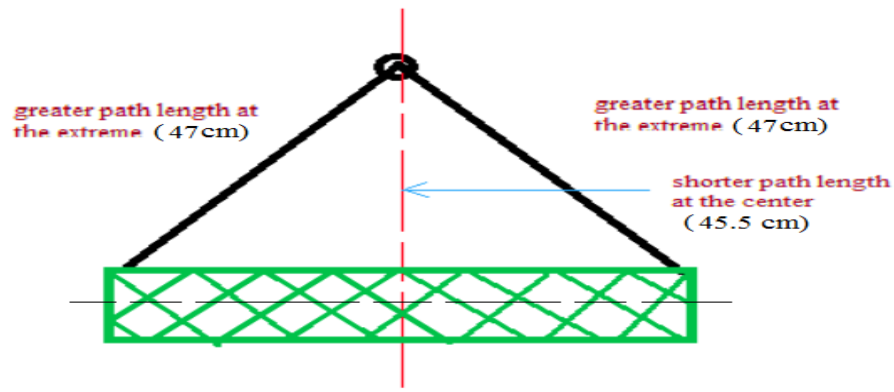

Figure 3.4 shows geometry of thread line during winding

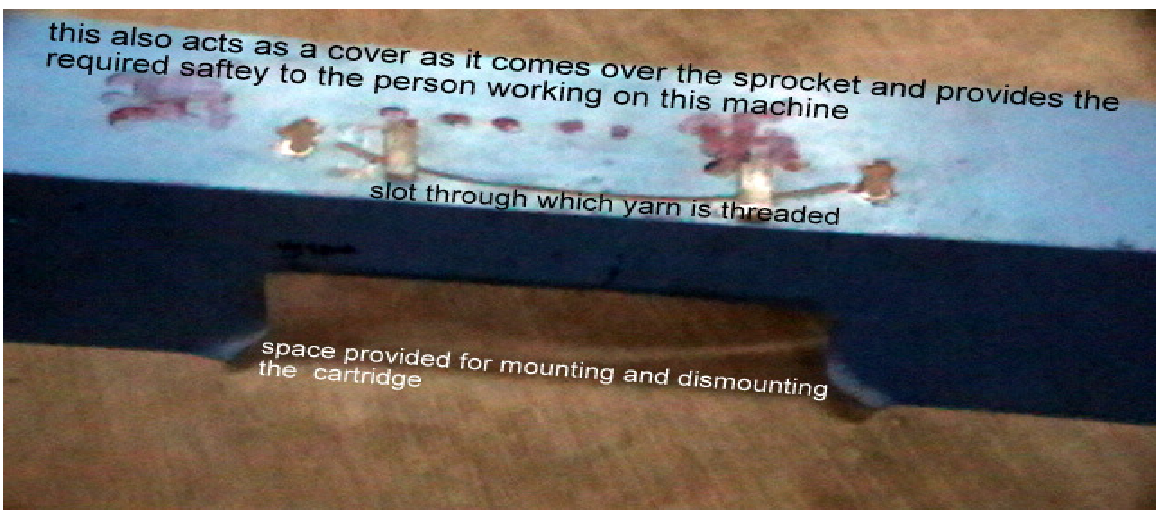

Figure 3.5 shows photograph of compensator

From the yarn guide shown in figure 3.3, the yarn comes straight to the yarn guide on the chain passed over the tension compensator. The yarn is then delivered between the nip of the press roller and the core tube mounted on the spindle. The figure 3.6 shows the front view of the novel cartridge winder. In this figure the tension compensator has been removed to have a clear picture of the arrangement.

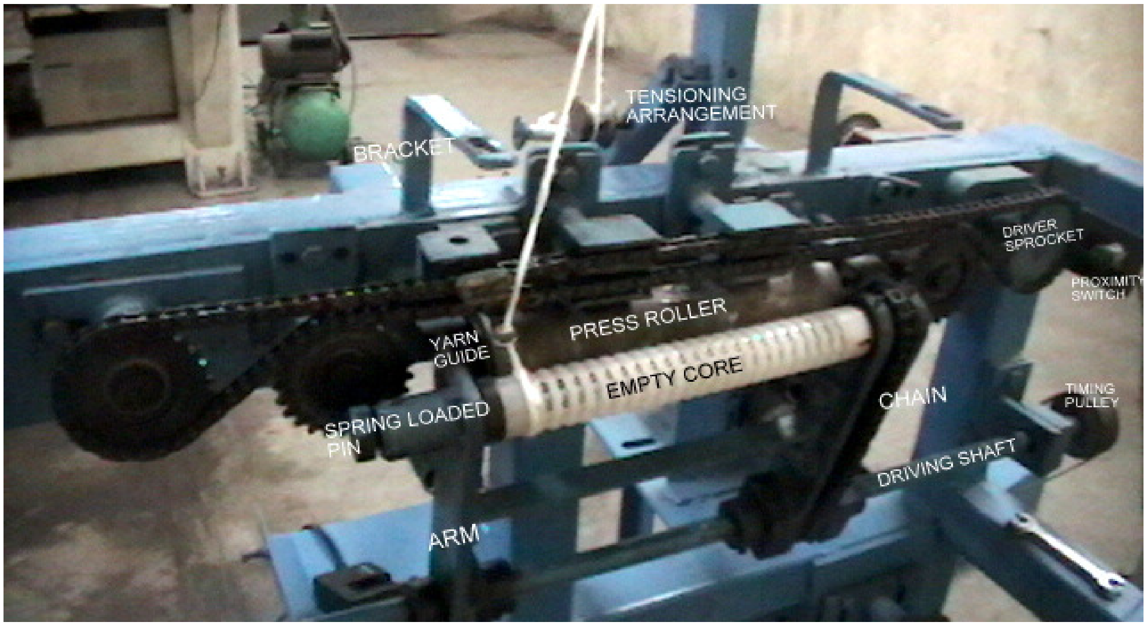

Figure 3.6 shows front view of newly designed filter winder

The yarn guide mounted on the chain, the driver sprocket and the carrier sprockets are clearly visible in the above photograph. The cartridge gets drive from the package servo via a pair of timing pulleys and timing belt in 1:1 ratio. Below the driver sprocket, the cover that is visible shows the shaft on which the drive from the package servo is transmitted. From here the drive is transferred to the pin on which the cartridge is mounted via pair of sprockets having equal teeth and driven by a chain.

Similarly the cartridge mounted between the two adapters is clearly seen, out of which the one on the left hand side has been labeled as spring loaded pin. This enables easy removal/mounting of the full/empty bobbins respectively. The driver sprocket gets drive from the traverse servo motor through a pair of timing pulleys driven by timing belt in 1:1 ratio. The cover on pulley can be seen exactly behind the driver sprocket.

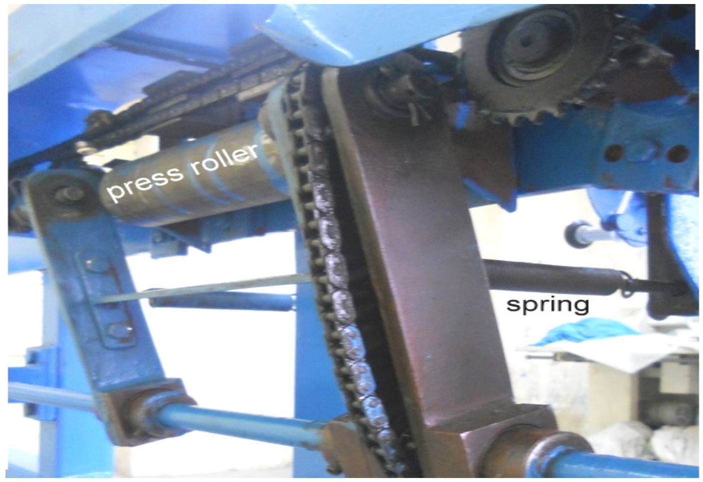

Figure 3.7 shows photograph of two arms along with spring which presses the cartridge against press roller

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The contact pressure between the package and the press roller was maintained with the help of spring tension. This will be pressed against the press roller due to the spring which is fixed on both the RHS and LHS arms and is clearly visible in figure 3.7 which shows the two arms that hold the core tube and its pressing arrangement.

3.4 Drive developed:

Two separate driving arrangements would be required due to different directional requirements. The rotational motion transmission required for the package/cartridge is shown in figure 3.8.

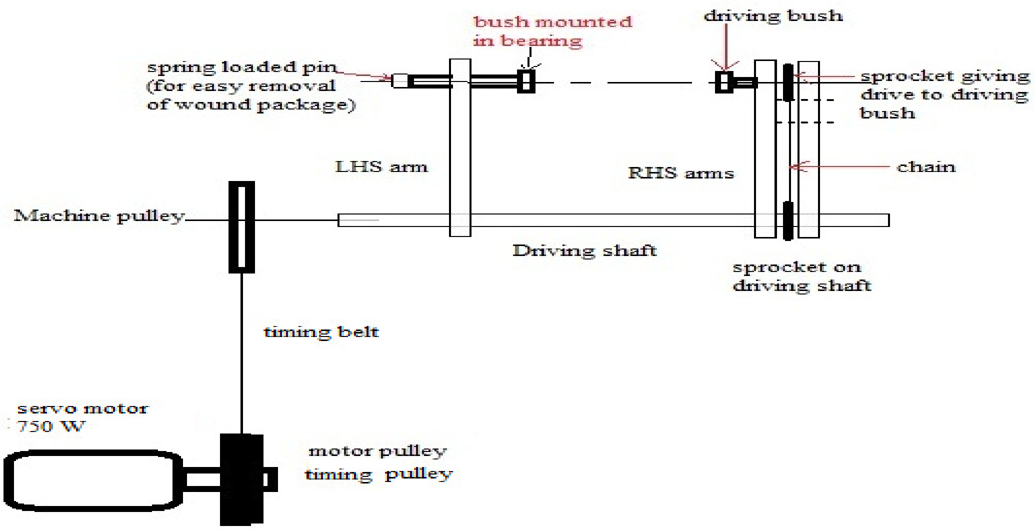

Figure 3.8 shows driving arrangement on newly developed winder

The chain was reciprocated using the second servo and was stabilized by passing it between two 'E' shaped brackets. This would ensure that the chain does not sag unnecessarily and remains steady during its traverse so that yarn which is carried inside it does not get disturbed. The driving arrangement for the chain is as shown in figure 3.9; it shows two views for better understanding. The discussion in section 3.2 and 3.3 dealt with the final set-up that has been developed but several intermediate steps have not been discussed which were taken in this course to reach this stage. In the following sections all the steps have been explained in detail.

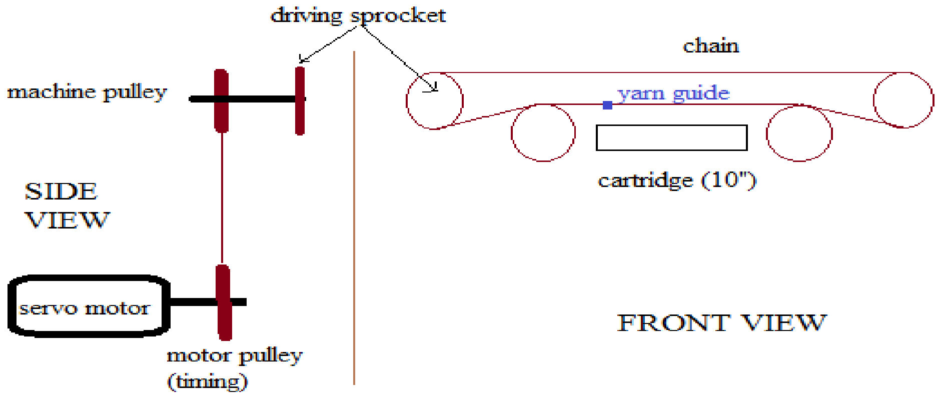

Figure 3.9 shows front view and side view drive on newly developed winder

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3.5 Design and development of mechanical system:

Initially the work was started on a winder basically meant for long traverse (30”). It made use of chain and with the help of a guide mounted on it, it reciprocated the yarn. The intention of developing such a machine was to find replacement to the existing traversing arrangement. The speed of a winding machine is restricted by the ability of the traversing element to reverse. So if it would be possible to eliminate the reciprocating action then the most important limitation could be overcome. For this purpose it was decided to use an endless chain such that it got unidirectional motion and is as shown in the figure 3.10 (b), whereas figure 3.10 (a) is a hypothetical arrangement, which also can be adopted easily due to its simplicity. The two yarn guides shown at the right extreme are one above the other and this position would result in the yarn getting transferred from either the top to the bottom guide or bottom to top guide.

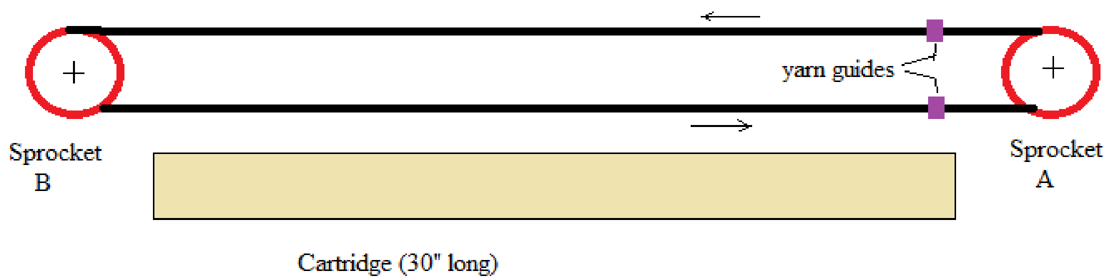


Figure 3.10 (a) shows a hypothetical mechanical system

If it is considered that transfer takes place from bottom to top yarn guide then the time taken by the bottom yarn guide to reach the top transfer position would be very less that is equal to time taken to travel around the curvature of sprocket A. But during this time the top yarn guide would not have covered the entire distance of 30” length.

This means that two guides would not be enough hence it was now needed to choose and decide the chain type, its pitch, length and the number of guides. The arrangement shown in figure 3.10 (b) was adopted for trials.

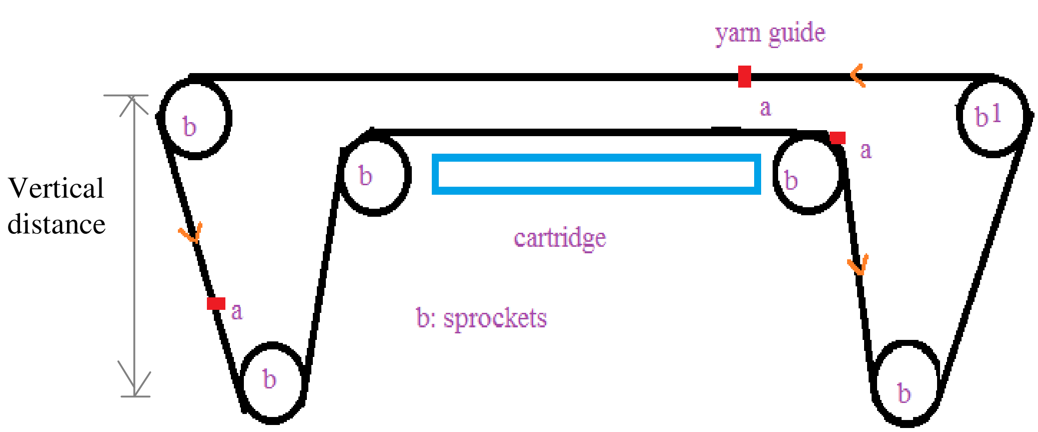


Figure 3.10 (b) shows fabrication of mechanical system which was developed initially

The most commonly available chain for general applications was having a pitch of 3/8”. The length of the cartridge was 30” and that would require 80 links in the chain and this calculation has been done excluding the curvature around the sprockets and the vertical distances between the sprockets 'b' shown in figure 3.10 (b). But the disadvantage of not providing vertical distance between the sprocket shown in figure 3.10 (a) have been mentioned earlier. Thus in order to achieve correct transfer position, the chain would have to make use of more than 80 links and three guides would then serve the purpose. Any guide number greater than three would also be possible but it was decided to stick to the minimum number to minimize errors due to differences in their profiles. The physical measurement showed a length requirement of approximately 182” and this would need 486 links in the chain. The system was established using a total of three yarn guides. In order to accommodate them at equal intervals, each guide had to be mounted after an interval of 162 links. The yarn guide shown in the top line of the chain, is at the starting of the traverse and carries the yarn from the right hand side of the traverse to the left hand side. On reaching its extreme position, a mechanical arrangement was provided which enabled the yarn to come out of the giver guide and enter into the taker guide. Therefore in the transfer zone out of the three guides, two would be exactly on the top of one another whereas the third guide would be somewhere in between depending upon where the transfer took place. The arrangements shown in figures 3.11 and 3.12 were adopted for mechanical ejection of the yarn.

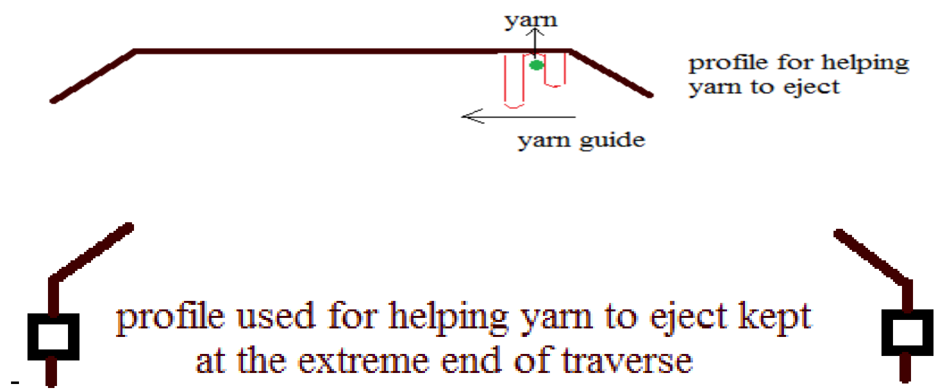


Figure 3.11 (top) a straight rod bent at extremes and Figure 3.12 (below) two profiles kept at extreme meant for ejecting the yarn at end of traverse

The driving arrangement is shown in the figure 3.13, the label b1 in figure 3.10 (b) is the driving sprocket shown in figure 3.13.

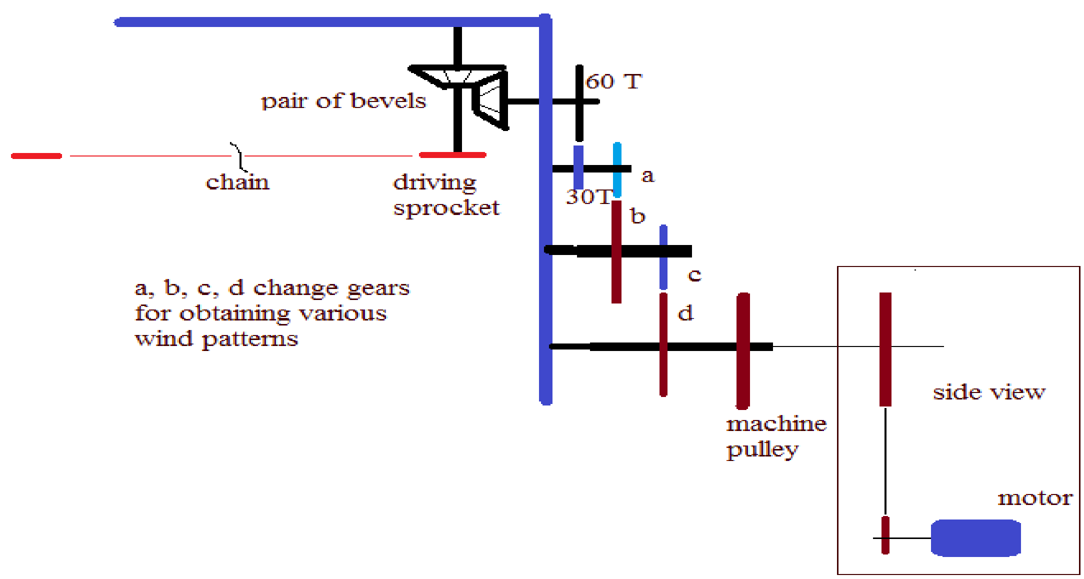


Figure 3.13 combined view of driving arrangement

The calculation of traverse ratio for the mechanical system will be discussed shortly. In chapter 2, section 2.7.4 the principle along with the useful formulas has already been discussed. Taking equations 2.7.1, 2.7.2 and substituting these values into equation 2.7.4 established in chapter 2, these can be further developed as follows:

$\tan\theta = \left[2 \times L \times n \times \left(\frac{p}{q}\right)\right] \div \pi \times d \times n$, on reducing the equation becomes

$\tan\theta = 2\times L \div \pi \times d \times T.R$ ---------------------------------- Equ. (3.5.1)

For finding out the value of traverse ratio or the coil angle, the above equation is equally suitable, only thing is that the traverse ratio meant here is the nominal traverse ratio. The nominal traverse ratio can also be expressed in a generalized form i.e. in form of an improper fraction like x/y, and as explained in chapter 2, where x and y do not have any common factor other than one.

$\theta = \tan^{-1}[(2 \times L \div \pi \times d \times TRn])$ Equ. (3.5.2)

OR

$TR_n\ (x/y) = (2 \times L \div \pi \times d \times \tan\theta)$ ------------------------ Equ. (3.5.3)

$L.G = \text{yarn diameter} \div \sin\theta$ ------------------------ Equ. (2.7.6)

Writing the equation 2.7.6 after substituting the value of θ from Equ. 3.5.2

$L.G = \text{yarn diameter} \div \sin[\tan^{-1}(2 \times L \div \pi \times d \times T.Rn)]$ Equ. (3.5.4)

$R.G = L.G \div \pi \times d \times \sin\theta$ ------------------------ Equ. (3.5.5)

$R.G = \text{yarn diameter} \div \{\sin[\tan^{-1}(2 \times L \div \pi \times d \times T.Rn)] \times \pi \times d\}$ Equ. (3.5.6)

Actual traverse ratio (A.T.R) can be found out from Equ. 2.7.9

$$A.T.R = (2 \times L \div \pi \times d \times \tan\theta) - R.G \qquad \text{Equ. (3.5.7)}$$

The first term in the above equation is nothing but the nominal traverse ratio(x/y).

Therefore the equation 3.5.7 can be rewritten as

$$A.T.R = \frac{x}{y} - R.G \qquad \text{Equ. (3.5.8)}$$

$$A.T.R = \left(\frac{x}{y}\right) - \frac{\text{yarn diameter}}{\{\sin[\tan^{-1}(2 \times L \div \pi \times d \times T.Rn)] \times \pi \times d\}} \qquad \text{Equ. (3.5.9)}$$

OR

$$A.T.R = \frac{x - \text{yarn diameter}}{\{\sin[\tan^{-1}(2 \times L \div \pi \times d \times T.Rn)] \times \pi \times d\}} \times \frac{1}{y} \qquad \text{Equ. (3.5.10)}$$

Consider that a package with targeted coil angle of 25° is to be produced, then using Equ. 3.5.1, the value of N.T.R comes out to be 34.67698. On rounding off suppose, its value for example is taken as 34. Now with N.T.R of 34, a cartridge with a targeted coil angle of 25˚51' will be produced. Linear gain (L.G) will be 6.984975 and A.T.R will be 33. 925887. These values have been calculated taking yarn diameter as 3 mm. In order to achieve these particulars on the cartridge, the gear train put should be such that its driver to driven ratio is as per the A.T.R required. In equ. 3.5.9, the value of x will be 34 and value of y will be 1. They do not have any other common factor other than one. This cartridge will show 17 diamonds lengthwise (x/2) and one circumferential diamond. The winding pattern, whether it would produce a single circumferential diamond or two diamonds or three etc would depend upon the nominal traverse ratio selected as explained in chapter 2, section 2.7.4. Here also in order to obtain the required winding pattern, four gears had to be changed. If the gear ratio came out to be prime number then, it became difficult to get these gears and had to be specially manufactured. And in some cases they could not be manufactured at all.

The yarn guide profile at extreme used in the system could not ensure that every time the yarn got successfully transferred into the taker guide with large stock of gears for producing various patterns. It was also observed that in producing a 30” cartridge the yarn required would be more compared to a 10” cartridge (three times more) and performance of a cartridge would be proportionate to the cartridge length for the same winding pattern. Besides this, with the increase in length (30”), proper support to the chain became all the more difficult. It was finally decided to adapt the system for winding 10” cartridge. Two separate drives have been provided, one for the package and other for the traversing element.

3.6 Developing mechanical system for short traverse:

The arrangement in figure 3.14 shows an endless chain used to traverse the yarn and three (shaped/profiled guides) mounted at regular intervals performed the function of giver and taker guides and thus laid yarn on the bobbin. The driver sprocket (D1) drives the chain whereas the other sprockets are carrier sprockets. The guide on the top chain moves towards the left and hence the yarn travels towards the left in the figure, and vice versa. Since the chain does not reverse when the guide reaches the extreme end of its traverse, problems due to guide reversal are avoided. This arrangement can work with a single motor also as the package and the chain would be getting unidirectional motion.

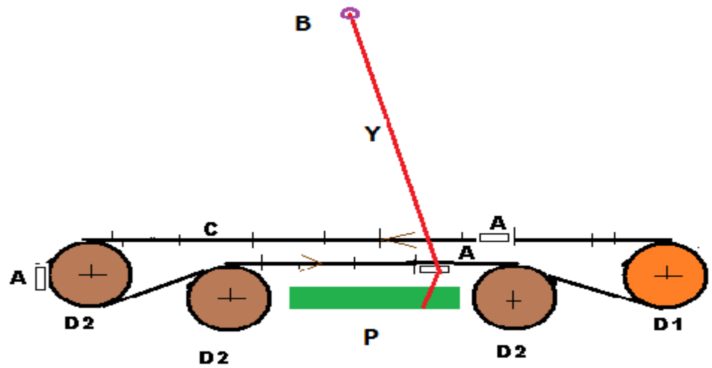


Fig 3.14 shows mechanical system for short traverse

But since appropriate arrangement as shown in figure 3.13 was not provided at the time of fabrication, so there was no possibility of having a common drive and hence two motors had to be used. An A.C motor was used for the package and a D.C motor was used for the traversing element. In figure 3.14 the three profiled guide(s) placed at equal intervals from each other and are shown labeled as ‘A’. So the entire traverse can be divided into three main divisions namely, the two extremes and the central portion. The two extreme zones can be called as the transfer zone whereas the central can be called as the traverse zone. The transfer zones have been very critical and the profiles have been designed as per the geometry in that region. The arrangement is such that when the top chain enters the transfer zone (top left side), another yarn guide mounted on the bottom chain also enters the transfer zone. In this zone the yarn should get transferred from the top yarn guide to the bottom one and the point at which this occurs has been referred to as the transfer point. After the transfer, the yarn would be in the guide on the bottom chain moving towards the right, thus causing reversal of the yarn.

This system does not contain any reciprocating element, which is an added advantage. Now with the basic set-up ready, the next important challenge was to design a yarn guide which would give a smooth yarn transfer when the yarn reached the transfer zone. This system had its own problems, transfer failure being the major one.

3.6.1. Problems faced while using D.C motor:

When fabrication of the machine was started, the drive to the package and the traversing element was separated though the chain was getting unidirectional motion. A D.C motor that was used for giving motion to the traversing element for the above application had very high rpm. The motor along with its drive was mounted on the machine such that it gave rotational motion to the sprocket (A) required to run at slow rpm. But running at slow speed gave problem of jerks. Hence a controller was incorporated in the setup. Even with the use of controller, the control over the rpm was in the range of ± 2 rpm. This means that the traverse speed was varying. But worst than this was the problem of transfer failure and pattern disturbance. Several factors could be responsible for this, like, errors while making the guides, varying speeds of the rotating and traversing devices. The guides were made from acrylic sheets. The shape of the first guide was drawn with help of marker pen and was cut accordingly. The other two were produced in the similar manner. The final profile was achieved by grinding the profile on a grinder. So there was always this possibility of the guides differing in shape as the entire process of preparing the guides was manual. Hence in order to ensure that transfer took place, the positions of the guides were simulated using CAD software. This along with the difficulties faced have been mentioned in the next section 3.6.2.

As mentioned earlier an A.C motor was used to give rotational motion to the package. In the initial trials, motor without any controls was used. So in the above system there seemed to be no communication between the two drives namely the traverse and the rotation. Both of them worked as if independent of each other which should not be the case.

So obviously problems like, when the guides reached their extreme position, either the yarn used to be released earlier or it used to remain inside the giver guide were observed and the net result of this was stretching of the yarn. This also caused changes in the lay of the yarn on the package. A major drawback of the said arrangement was that the ratio of rotation between the package and the traverse could not be maintained. This would result in the failure of the principle on which the machine ought to be working. An arrangement in which, speed variation, if at all, occurred then both the drives would simultaneously get affected. Any increase/decrease in say the traverse speed, then the rotational speed would also get changed by same proportion. This would require continuous monitoring of the individual speed and in case of variation, corrective action should also be taken. So it was decided to tackle problems one by one. The first was to improve the guides by improving its design so that transfer success could be increased.

3.6.2 Profiled yarn guide development:

On the commercial winding machines, in order to traverse the yarn, only one guide is used since it is of reciprocating type. So it is normally a piece which has a hole at center lined with ceramic, through which the yarn passes. This shape would not be suitable for the above application since the yarn has to be moved out of the giver guide and moved into the taker guide. The following considerations would have to be made before the exact profile of the guide can be designed:

a. The yarn guide would have to be open from its front side.
b. The guide would have to be anchored to the reciprocating element (chain).
c. At the transfer point the yarn needed to be removed from top guide and made to sit in the bottom guide or vice versa. So it was imperative to device a mechanism whereby the yarn could be gradually ejected from one of the guides and smoothly transferred to the other one.

There were two options, either to make use of a profiled guide which would do two fold function that is firstly to carry the yarn to and fro and secondly its profile would facilitate yarn ejection from the giver guide at the same time help the receiver guide to receive the yarn, and can be called self acting. The second option would be to make use of a yarn guide and a separate tapered profile. The tapered profile would be helpful to bring the yarn gradually out of the giver guide and transfer it to the taker guide. While finalizing the guide designs various shapes were thought of. Some of which have been shown in figure 3.15. It was understood that various such profiles could be helpful to achieve the task of traverse and transfer but only with a scientific approach. Engineering software Pro-Engineer was used for this purpose, wherein the successive positions of the giver and the taker guides were placed and with its reference the profile of guide was developed such that the yarn would come out easily and would transfer from the giver to the taker guide.

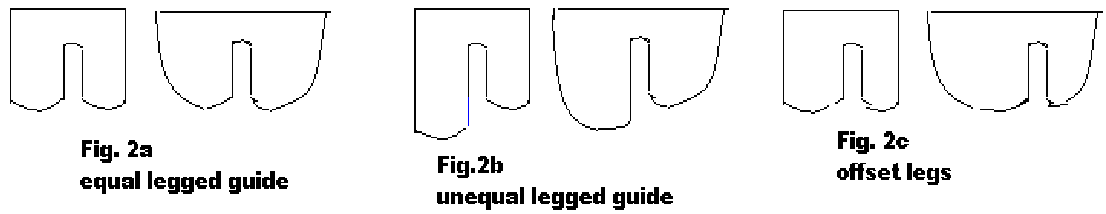


Figure 3.15 shows profile of various guides

It was understood that along with profiled guides stationery profile would also have to be used would facilitate in pushing the yarn out of the 'U' shape of the giver guide and once the yarn was out, another profile would ensure that the yarn is not uncontrolled and is pushed inside the taker guide. Thus guaranteeing transfer success. The entire work of simulation has been reported in the paper[13] titled "CAD software based design of yarn guide profile". The work describes the stage wise development of the profiled guides as well as the stationery profiles. The findings of the work are summarized and reported as follows:

With the profiled guide and stationery profile arrangement though the transfer success rate increased, the yarn came under lot of tension. In the transfer zone the yarn came under the influence of both the stationery profiles exerting pressure in the opposite directions. As mentioned earlier also the chain was getting unidirectional motion so unlike the cam whose profile is designed to accelerate and decelerate the yarn guides at its extreme, the chain moves at constant speed. The yarn from the giver guide was expected to get transferred into the taker guide at full speed making things all the more difficult. This problem could not be visualized at the time of simulating, since the work has been done considering the yarn to be a taut wire, which it is not. Therefore during the dynamics of the yarn transfer at the transfer zone, it came under lot of tension which could lead to changes in yarn profile, surface damage (increase in hairiness due to abrasion) along with stretch. At the same time getting the exact profile was difficult since the pieces were hand- made from acrylic. Hence it was concluded that though the simulation work had been useful in increasing the transfer success but it still did not give 100% success. Thus the transfer success, precise lay of yarn on the package and the correct pattern would be function of ratio of rotation of traversing element to the package revolution and accurate profile of the guides. The above work focused only on the betterment of the guide profiles but the accuracy of rotation of the winding elements was neglected.

Hence serious thought had to be given to improve the drive. Besides whenever the yarn failed to get transferred from the giver to the taker guide, the machine would have to be stopped and reversed, thereafter judging the correct position of yarn, the machine would be restarted. This system, if used as it is, would not be suitable for commercial machines. Finally it was decided that this mechanical transfer arrangement would be very difficult to achieve since the kind of precision it demanded in producing the accurate shape of the guides was very high and the driving elements used in the present set-up would not be able to maintain constant ratio of rotation between the package and the guiding element. So it was decided to revert back to the most successful method and that is of reciprocating the yarn guide in order to achieve traverse of yarn. Now there would be no need to use three guides and that too profiled ones. Similarly the stationery profiles could also be removed. The system proposed in figure 3.14, would work with one motor because both the package and the chain got unidirectional motion. But here, the chain, on reaching its extreme would have to reverse its direction whereas the package would continue to rotate in one direction only. Thus with the new change, two motors were inevitable though the earlier trials were also taken using two motors as explained in section 3.6.1.

It was required to develop a drive such that the two drives would be synchronized to obtain the desired pattern. The motor and its characteristics would now have to be considered in greater details to achieve the said objective as have been discussed in Chapter 2, section 2.10.

3.6.3 One servo and one A.C motor:

Since the D.C motor and its drive could not give a constant rpm due to which traverse speed fluctuated, so instead of it a servo was tried. This was made to run in the master and slave mode, where the package was considered as the master and the traverse was considered as slave. It simply would follow the package speed so that the ratio of rotation of package with respect to the traverse would be maintained constant and is shown in figure 3.9. While designing a package of requirement, an idea about the nominal traverse ratio (TRn) can be had for a given value of coil angle from equ. 3.5.1 and by substituting the actual values it can mathematically be obtained and will be explained shortly with the help of an example. With the set-up ready, the calculation had to be perfected to get a package with desired output. To understand this, a small example has been quoted over here. The calculations that were explained in section 3.5 were with reference to the system which made use of a common driving arrangement, which now had to be changed so that they could be applied here. The package diameter (bare bobbin diameter), the traverse length and the desired coil angle on the package had to be fixed so that the values could be used in the equations.

Let's say a package with coil angle of 15° is to be designed, let the traverse length be 239mm and the bare bobbin/package diameter be 33.6mm on substituting these values in Equ. 3.5.1 we get,

$$\tan\theta = \frac{2 \times L}{\pi \times d \times TRn}$$

$$\tan 15^\circ = \frac{2 \times 239}{\pi \times 33.6 \times TRn}$$

OR

$$TRn = \frac{2 \times 239}{\pi \times 33.6 \times \tan 15^\circ} \approx 17$$

This would mean that 17 (x/y =17/1) coils will be laid in a double traverse or 8.5 coils each will be laid in the single traverse. To get precise displacement after every double traverse the gain has been calculated considering yarn diameter of 3 mm. Using equation 3.5.6 to calculate, the value of revolution gain obtained is rounded off to 0.11. The value of actual traverse ratio comes out to be 16.89 (using equ. 3.5.9). In the above mentioned case, pattern repeat would be after every double traverse and would result in one diamond being formed circumferentially. The challenge was to apply this knowledge to the existing system, so that as per the calculations based on the precision winding principle a suitable program could be developed.

The pulses of A.C motor which was rotating the package were given to the encoder, which gave them to the servo motor used to give to and fro motion to the traversing element. The servo was made to follow the A.C motor (follower mode). In order to synchronize the two drives, the input of the package was needed. Based on this input the PLC calculated the speed at which the servo had to be run. With the servo, the rpm could be reduced in integer values. For example if rpm of 12.4 was to be set, then it would have to be either 12 rpm or 13 rpm. To overcome this problem a gear box was used in the ratio of approximately 1:40 and is shown in figure 3.16.

This solved the above problem to a great extent. When trials were taken, it was found that the input values did not match with the practical results observed on the package (in terms of the number of coils laid). When a package with wind of 7 was given as input to the program, it gave a package with either higher or lower number of coils. Therefore redefinition of certain parameters was needed. And it was understood that A.C or D.C motors will not be suitable for the said application since precision in both i.e. the position control and speed consistency was needed; hence two servo motors have been used. Lot of brain storming gave positive results.

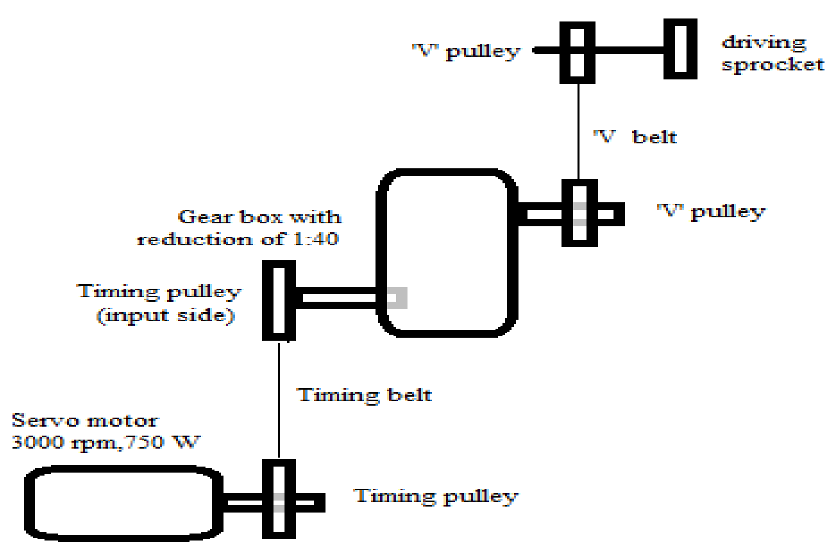


Figure 3.16 driving arrangement with gear box

It was thought of using a stepper motor for the said application but the stepper motors are delicate and would not have been able to provide the required torque. Besides in case of overload they start slipping and so the error may go unnoticed whereas a servo motor is immediately able to track these errors, which are shown in form of display on the drive. So the only option left was to use a servo motor.

3.6.4 Logic development:

So now the main aim was to get constant speed for the package as well as for the traverse using servo motors. One of the servos would give to and fro motion to the yarn guide mounted on the chain whereas the other would rotate the package. From the servo, the drive was transferred to the concerned part through timer belt and pullies. Now the next most important thing was to synchronize the two drives. Since the machine was to be developed on Precision winding principle so the ratio of rotation between the package and the traverse guide had to be maintained constant throughout the built-up. In the example shown earlier that if a package with coil angle of 15° is to be designed then, the N.T.R in that case would be 17, the gain would be 0.11 and the A.T.R would be 16.890. This means that the number of coils laid in a single traverse would be half of A.T.R, which would come out to be 8.445. Servo 1 which rotates the package will have to make 8.445 revolutions in a single traverse thus covering a fixed length of 239mm, whereas the servo 2 would make one revolution to move traverse guide from one end of the traverse to the other end. Thus the ratio of rotation between the two (servo 2: servo 1) would work out as 1: 8.445 and this has been used as one of the inputs in the control panel with the name, gear ratio, which is nothing but the wind ratio. In one revolution of the traverse servo (servo 2), the distance traveled is 239 mm and at the same time the package makes 8.445 revolutions. The (servo 1) rpm initially was kept at 225, so automatically the (servo 2) rpm would come out to be @ 27. As far as the drive was concerned it became all the more simplified. With reference to figure 3.16, the gear box used in the traverse was removed and drive was transmitted straight from the driver timing pulley to the driven pulley mounted on the same shaft as the driver sprocket.

In the program, rpm of package earlier had been restricted to 225 but later on the program was further modified and now the package can be rotated at higher rpm of 800. The PLC calculated the package rpm and the traverse rpm as per the internal formulas fed. The figure 3.17 shows the flow of signals for the developed control panel. The homing switch is given so that the starting position of the guide remains same rather; it reverses after counting the length input given on the control panel. This is achieved with the help of proximity switch shown in figure 3.6. The photograph of the control panel developed is shown in figures 3.18 and 3.19. This work has been reported and accepted for publication[14].

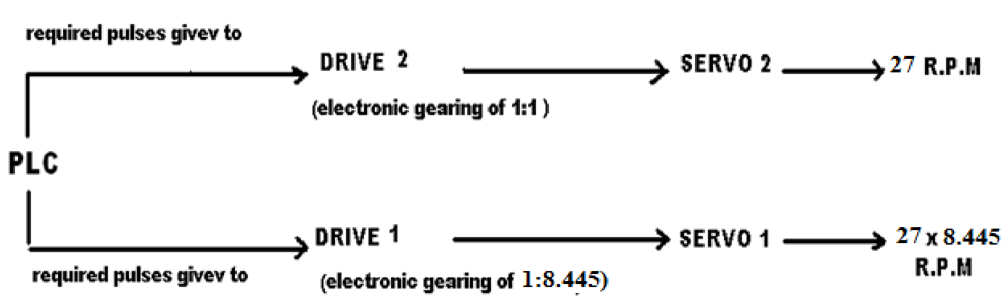


Fig. 3.17 shows flow chart for the newly developed drive

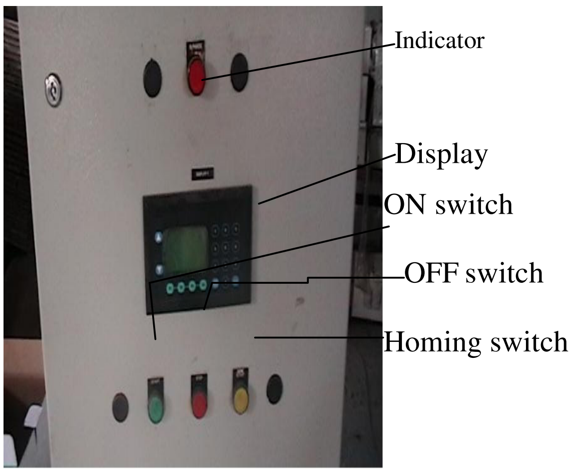


Figure 3.18 control panel & display

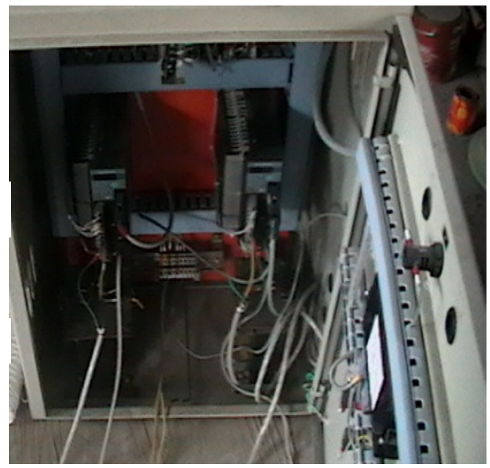


Figure 3.19 wiring of control panel

PHASE – II

3.7 Evaluating the working of newly developed cartridge winder and taking trials.

The machine fabrication part was complete with two separate servos along with their driving arrangements ready. Evaluation of performance of the wound cartridge had to be undertaken so as to confirm whether for a given input, the winder was able to produce the required winding pattern. But before starting the machine few things needed to be confirmed, mainly check had to be made whether the two drives were synchronized correctly or not.

3.8 Development of drive:

3.8.1. Requirements:

The package needed to rotate continuously at a fixed rpm - unidirectional. This rpm should be such that it can be changed as and when needed. The rotational motion to package was given by servo 1. The other servo, i.e. servo 2 (traverse servo) was used to give to and fro motion to the traversing element. This servo has a forward and reverse application. With both the motions being different (one rotational and other to and fro) it was not possible to use the follower mode method which then would have made it very easy to achieve the required results. The servo 2, in its forward stroke, would cause the guide to cover a fixed length after which, the guide would to move in the opposite direction to again travel by the same fixed length. The servo counts the number of pulses for a given traverse length and once that is achieved will cause the chain to move in the opposite direction. Due to the nature of this application, the servo

2 not only has an acceleration and deceleration parameter in its cycle but also has a stop time parameter. Any device which reciprocates cannot, or rather it is not advisable to allow instant reversal. Hence such a system at the starting of its stroke in one direction accelerates, and reaches its maximum value, after which it begins to decelerate towards the end of the same stroke and will come to a stop for infinitely small amount of time before accelerating in the reverse direction. This will keep on repeating but of course in the running condition it is difficult to identify this. The servo takes 5 milli-seconds to accelerate and 5 milli-seconds to decelerate when its rpm is less than 600. Thus during the forward stroke of servo 2, the package has to make a fixed number of rotations so that desired pattern can be achieved. Thus the total time for package to complete its required number of revolution would have to be inclusive of the acceleration, deceleration and stop time.

This means that if servo 2, takes some time (X sec) to travel forward by preset distance (with acceleration, deceleration and stop) and then travel in the reverse direction by the same preset distance again (with acceleration, deceleration and stop), then (X sec + X sec) would complete one cycle of traverse (double traverse). The most important point in this regard is that on completion of one traverse cycle, the package has also completed the preset revolutions but its angular position should be precisely displaced so that it does not coincide with the same starting point of the coil laid in the previous double traverse. This will take care of the pattern formation issue. Also one thing needs to be made clear here that the pattern repeat will depend upon the nominal traverse ratio selected. Here it is important to mention that the servos were individually tested. The servo 1 was table tested with the necessary drive to find out whether it made the required number of revolutions. The servo was given a count; initial marks were made on the servo shaft and a fixed reference on the frame as shown in figure 3.20. After completing the count the position of the marks was observed. Similarly the servo 2 was also table tested. It was made to rotate once in the forward direction and once in the reverse direction thus completing one traverse cycle with similar marking arrangement. For checking both the servos simultaneously, they were mounted on the machine. In the program developed earlier (section 3.6.1), the acceleration and deceleration time was not considered and hence the required pattern could not be achieved but in the latter one the necessary changes in the program were made which resulted in the attainment of correct pattern.

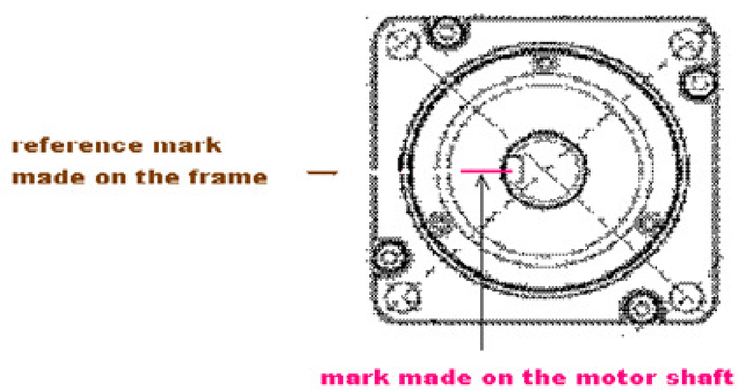


Figure 3.20 shows reference marking made on motor shaft and frame

The drive to the package and the traversing element was given via timing pullies and belts to ensure minimum loss of drive as mentioned earlier also. The program used for the above application was external position control. The display on the control panel has four screens and it is possible to toggle between them. The first screen shows a display of the traverse length, total number of strokes along with a counter for showing the actual strokes made. The next screen shows a display of several other data which needs to be input like rotational speed of package, gear ratio which is nothing be the wind ratio, yarn diameter and coil angle. The next screen enables corrections to be made to the traverse length and the last screen enables this program to work as step precision or can be helpful in producing graded filters. For all trials the contact pressure was maintained constant. equ. 3.5.1 to equ. 3.5.10, have been suitably used in the program developed which enables internal calculations of revolution gain. The rotational speed of the cartridge is reduced with the build-up to maintain tension within an acceptable range. The speed of servo is reduced with the increase in package diameter and is possible due to internal program fed. This rate of increment has been decided after taking trials. The plan of action to produce different cartridges with different winding parameters is described in the following section.

3.9 Pilot trials:

As mentioned at the beginning of this chapter, pilot trials were taken in Phase – II the entire experimental work is described in Sets II – III. In the Phase – VI trials of cartridges of similar specifications as the fabricated winder produced on commercial winder were taken.

Set – I:

Identifying various variables/parameters related to the winding process or to the raw material so that their influence can be studied. The raw material variables identified were the yarn count, fiber fineness and fiber length whereas the winding variables identified were coil angle, tension, the maximum diameter of the package, the take-up speed of the package, the number of diamonds formed circumferentially and gain.

Set – II:

The trials that were to be taken on the winding machine would deal with producing cartridges produced by varying each of the above mentioned winding or raw material parameters one at a time. Besides these, other related information that can be gathered is weight of yarn, density of the cartridge and even hardness of the cartridge can be found out. Changes in hardness of the cartridge can be due to tension, speed or the contact pressure. For each of the trial the contact pressure has been maintained the same. One variable would be varied at a time. This would thus help in judging the performance in a more realistic manner.

Set – III:

Comparisons of the performance of the cartridges produced on the fabricated winder and those produced on the commercial filter winder has been undertaken in this set. Cartridges similar to the ones produced on the newly fabricated winder would be produced on filter winders using cam to traverse the yarn. Wound cartridges were produced in KBS filters factory in G.I.D.C at Makarpura in Vadodara. The cartridges were manufactured as per our requirement of coil angle/traverse ratio, gain and tension due to the cooperation of the owner. The detailed discussion of which has been done in Chapter V.

SET – I

3.9.1 Raw material:

Various types of materials can be used to produce a filter cartridge. But for filtration application, roving made of polypropylene is best suited. The raw material selected was DREF – II spun polypropylene yarn due to its advantages[2] like greater volume of air, random fiber arrangement in the yarn structure, greater twist, round cross-section and economic production [7, 27, 35] and are bulky i.e. the ratio of volume of voids to fiber is more. The hairiness of yarn becomes an added advantage for filtration application. Inertness is the property of polypropylene due to which it is least affected by the medium in which it is placed.

3.9.2 Operating principle[23]:

This process of DREF spinning belongs to open end group because the fiber strand (draw frame sliver) must be opened completely to obtain individual fibers and then reassembled to a new strand (yarn). The formation of new strand is carried out by using suction to bring the individual fibers into engagement with the rotating open end of the yarn, e.g., by perforated drums. Binding-in of fibers and imparting strength, are affected by continual rotation of the yarn in the converging region of two drums. The fineness and the number of wraps depend upon the machine parameters set. The series of operations to be performed to convert the sliver into yarn are opening of the fiber strand, collecting the fibers into a new strand, imparting strength by twisting, withdrawing the resultant yarn and winding the yarn on to cross-wound package. The figure 3.21 shows principle of a typical DREF – II spinning machine.

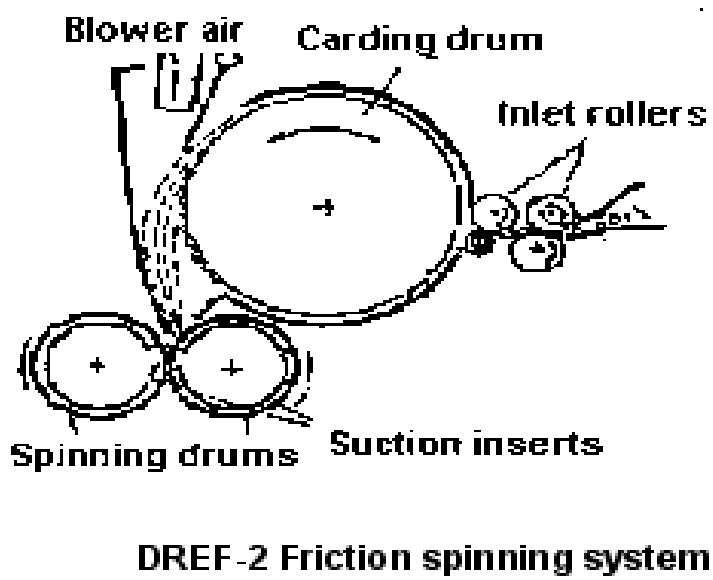


Figure 3.21 DREF – II spinning principle[31]

Normally multiple slivers are fed to the drafting arrangement, as they improve the evenness and are passed to the main opening roller similar to carding cylinder as it has saw tooth wire points in the direction indicated. The drafting arrangement creates a light drawing whereas the saw tooth roller opens the strand to individual fibers. The fibers separated are then lifted off the roller by a blower and forms a cloud in the channel provided. The suction stream shown on either side of the drums draws the fibers into a convergent stream between the drums. The drums are rotating hence the yarn also rotates in the convergent region. If a seed yarn is inserted in this region, the newly arriving fibers will contact the rotating yarn and are thereby caught and get twisted in. Now on withdrawing, continuous production of the yarn will be possible.

The table 3.1 shows the properties of the friction spun yarn used for preparing the cartridges.

Table 3.1: Properties of the DREF – ii spun yarn

Sample No.	Yarn Fineness Tex (Ne)	Strength (g.p.t)	Strain %	U%
1.	995.418 (0.6)	9.36	31.1	5.83
2.	1134.322 (0.521)	6.468	37.11	6.09
3.	1334.148 (0.443)	8.757	41.45	6.66

Fiber fineness=2.5 denier

The raw material has been selected as per the availability and not by choice. For the confirmation trials the coarsest count was selected i.e. using sample no. 3 shown in table 3.1. The testing of the properties listed was done in lab.

For testing the yarn fineness, cutting and weighing method was used. The samples were cut to a length of one meter and were accurately weighted on balance with ±0.01 accuracy, whereas the tensile tests were performed on Llyod make tensile tester working on CRE principle shown in figure 3.22. Five such tests have been performed and their average has been considered. The evenness measurement has been done on PREMIER *i* Q2 DX V 1.0.22 shown in figure 3.23

Figure 3.22 Llyod tensile strength tester

Figure 3.23 Premier evenness tester

SET – II

3.10 Winding machine trials:

The winding variables identified in the Set – I namely traverse ratio (coil angle), tension, gain, maximum package diameter, circumferential diamonds, speed and the feed material count would now be varied one by one to produce cartridges. The table 3.2 shows the group wise division of the experimental work. As per the coding used in the table 3.2, if it is written as A1T1G2D2S1C1/1, it would mean that the package was designed to produce desired coil angle of 15° with one circumferential diamond, medium gain and diameter with the coarsest count wound at minimum rotational speed selected for the trials.

Table 3.2 Group wise division of experimental work

Winding variables													
G-I		G-II		G - III		G-IV		G- V		G- VI		G- VII	
SC	CA/ TR	SC	AT	SC	Y.D	SC	PD	SC	PS	SC	CD	SC	YC
A1	15°	T1	145	G1	2.5	D1	60	S1	225	/1	1	C1	0.4
A2	25°	T2	252	G2	2.8	D2	65	S2	425	/2	2	C2	0.6
A3	35°	T3	360	G3	3.1	D3	70	S3	625	/4	4	C3	0.8

G Group; SC sample code; CA coil angle; TR Traverse ratio; Y.D yarn diameter (mm); PD package diameter (mm); PS package speed (rpm); CD circumferential diamonds; YC Yarn count (Ne)

Group – I: In this set all packages were wound under identical conditions of average winding tension (145 gm), package rpm (225), maximum package diameter (65 mm), gain and circumferential diamonds (1) except the coil angle as shown in table 3.2. Cartridges with three different coil angles were produced namely 15°, 25° and 35° and the photographs of these cartridges produced have been shown in figures 3.24, 3.25 and 3.26. In Group – II cartridges were produced at three different tension levels namely

T1=145 gm, T2=252 gm and T3=360 gm, while in Group – III cartridges were produced at three different values of gain/yarn diameter namely d1=2.5 mm, d2=2.8 mm and d3=3.1 mm, in Group – IV cartridges were produced at three different full package diameter of 60 mm, 65 mm and 70 mm, whereas in Group – V rotational speed of the packages was varied as S1=225 rpm, S2=425 rpm and S3=625 rpm, while in Group – VI cartridges with different circumferential diamonds namely /1, /2 and /4 were produced whereas in Group – VII the cartridges with change in fineness of the feed material namely C1=0.4's Ne, C2=0.6's Ne and C3=0.8's Ne were prepared. Other than the group related parameters rest of the variables were maintained constant. The table 3.3 and table 3.4 show the feed values to the control panel for Group – III and Group VI and table 3.4 for Group – I.

Table 3.3 shows data related to gain and circumferential diamonds

Package variable		Revolution Gain for different spacing and diamonds					
		Spacing between neighboring yarns			Circumferential diamonds*		
		G1(2.5mm)	G2(2.8mm)	G3 (3.1mm)	1	2	4
Coil	15°	0.0915	0.103	0.1135	0.0915	0.04575	0.02288
angle	25°	0.05742	0.0643	0.0695	0.05742	0.02871	0.01436
	35°	0.0436	0.0488	0.0541	0.0436	0.0218	0.0109

*the calculation of circumferential diamonds is for coil angle of 15° only.

Table 3.4 shows details of winding parameters fed to control panel

Sr. No.	Coil angle	Yarn diameter	Revolution gain	N.C.D	Wind
1.	15°	2.8	0.103	1	8.448
2.	25°	2.8	0.0643	1	4.968
3.	35°	2.8	0.0488	1	3.476

N.C.D =No. circumferential diamond

Fig. 3.24 shows a cartridge produced on newly developed winder (15° /ATR=16.896)

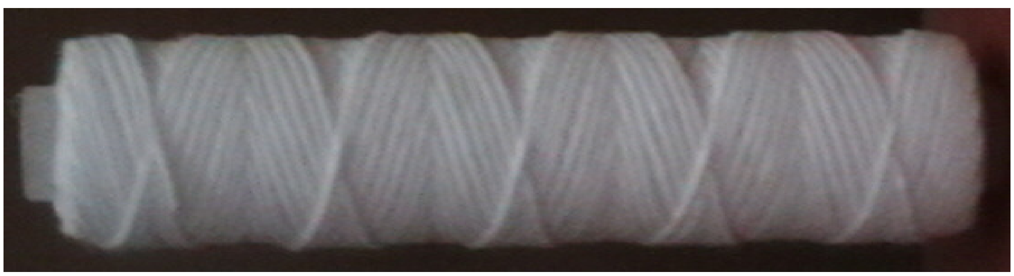


Fig. 3.25 shows a cartridge produced on fabricated winder (25°/ATR=9.936)

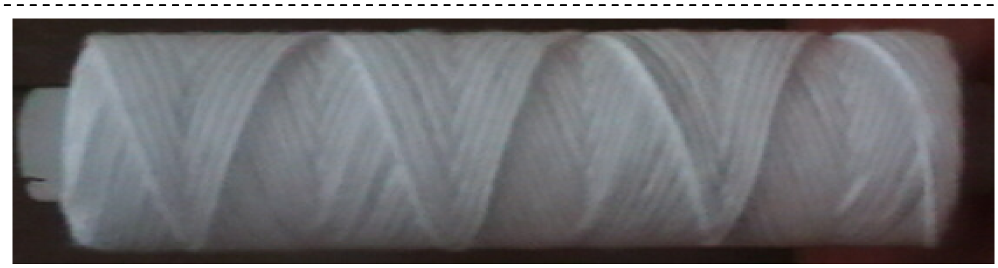


Fig. 3.26 shows a cartridge produced on fabricated winder (35° /ATR=6.952)

3.10.1 Method:

Before winding yarn for a given group, the empty cartridges were accurately weighed on digital balance with ± 0.01gm accuracy. The full bobbins were weighed on ordinary balance with an accuracy of ± 5 gm accuracy. The rpm of the winding machine was one of the input parameters which needed to be fed to the control panel. Besides rpm the other parameters which were fed to the control panel were the traverse length, the total number of strokes, the wind ratio, the coil angle, the empty bobbin diameter and the yarn diameter.

Tachometer confirmation of the cartridge rpm was not need since a servo is used and it makes exactly the same number of revolution as it is commanded to do. During winding, the tension was measured using a Schmidt make tension meter version ZD2 02.3E shown while their hardness was tested using durometer, version HP 05.01.E.

SET – III

3.11 Comparisons of the performance of the cartridges produced on the newly developed winder and those produced on the commercial filter winder

As mentioned earlier also this work was done in an industry specializing in producing filters of various types. They had filter winding machines in various traverse lengths and were making use of cam in order to traverse the yarn. Thus it would only be justified in using such type of machine to produce cartridges matching the winding parameters set on the newly fabricated machine so that comparison between the different traversing arrangements could be done along with the confirmation that performance of the cartridges produced with different systems matched or not. This will be discussed separately in 4.2 section of chapter 4.

PHASE - III

3.12 Developing a testing rig for testing of the string wound filter cartridges produced on the newly fabricated cartridge winder

3.12.1 Requirements of testing apparatus:

1) A column/cylinder to hold the cartridge made up of perforated central core around which yarn is wound spirally would have to be provided.

2) Because single-pass system was decided upon, in which the filtrate has to be drained after passing it once through the media, hence water was selected as a medium. Proper sealing and pressure ports would have to be provided suitably so that respective pressures could be noted. The details of the cylinder are as shown in figure 3.27

3) A pumping arrangement and a control device which would ensure that the water was pumped at a constant flow would be needed.

4) Supply/feed tank would be required so that uninterrupted supply of water during the entire test would be ensured.

5) After preparing the test slurry, if it is left as it is then the particles would tend to settle causing the concentration to vary during the test. Hence suitable arrangements to prevent the test dust from settling during test trial.

6) Last but not the least a standard test dust would be required so that the analysis of the particles coming downstream can be done by the using ocular microscope. ISO 12103-1 defines four grades of test dust for evaluation of filters which have been tabulated in table 2.1 in Chapter - II, section 2.6. A3 medium fine test dust was selected for the test purpose

since cartridge filters are more popular as pre-filters and are not meant for removing very fine particles[2].

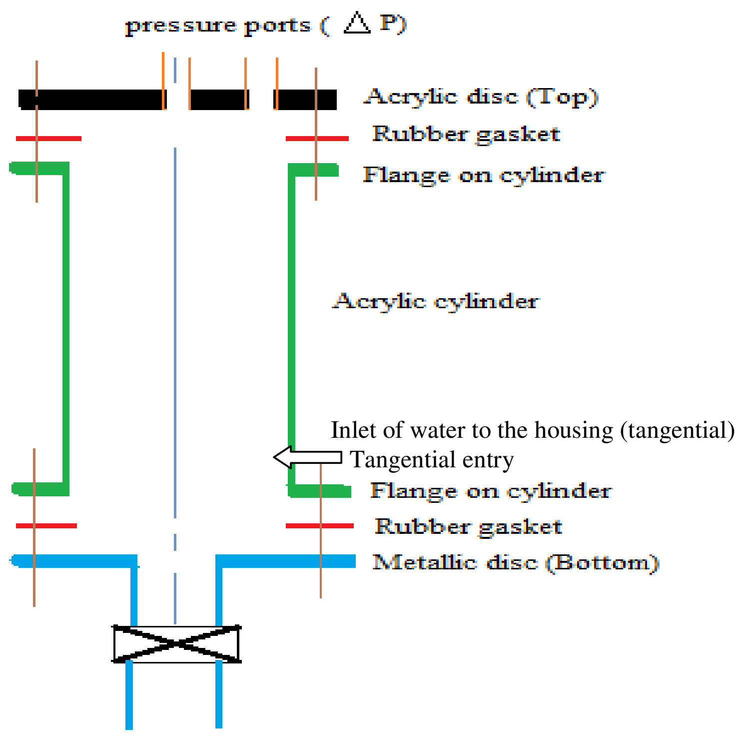


Figure 3.27 shows schematic diagram of construction of housing

3.12.2 Experimental setup:

As mentioned in the earlier Chapter – II, in order to find out the efficiency of the cartridge, a destructive test needs to be performed for which, it was necessary to develop a testing rig. As it is already known that there can be two laboratory methods to test the cartridge for its performance namely the single pass test and the multi-pass test or its modified test methods. In the single pass test, the fluid after passing once through the filter is drained at its outlet thus maintaining the concentration of the inlet fluid constant. Whereas in case of multi-pass test, the fluid is re-circulated and again passed through the filter, thus a small quantity of fluid is sufficient to conduct this test. These tests procedures simulate real parameters on a laboratory scale. At present there is no standard for liquid filter testing except multi-pass test to ISO 4572, which is for hydraulic filters. To select a proper filter system for the requirements of a given application, knowledge of filter efficiency and dirt holding capacity is required. The filter manufacturer needs to rate the filter and provide other data, which are based either on a single pass test method or a multi-pass test. In Gujarat no such laboratory could be located which does this test. BTRA and IIT Delhi were contacted for finding out whether such facility exists at their end but, no response was obtained. Hence in absence of any convenient and reliable testing facility, it was decided to develop the test rig. The justifications for selection of single-pass test system and water as a medium have already been discussed in the earlier chapter.

The apparatus has been developed taking the ASTM F 795 88[2, 3] standard as reference and measurements have been taken under constant flow-rate conditions. Most of the researchers [6, 25, 26, 27 and 28] have in their work tested the filters at flow rates in the range of 9.5-16 L/min and also have performed the test till the pressure drop reached the value recommended by the manufacturer. But here since the filters were manufactured on the novel winding machine for the first time hence their rating and the pressure drop were not known. Besides, the aim here was to relate the yarn and winding parameter of cartridges produced on fabricated winder with their performance tested under same test conditions.

Lot of trials and effort resulted in the development of the final test rig used for testing and is as shown in figure 3.28. The device labeled as 'a' in this figure are the control valves with the help of which flow-rate can be controlled. In the figure the by-pass arrangement has been shown, which forms a very important part of the system and is helpful in adjusting the challenge/flow rate.

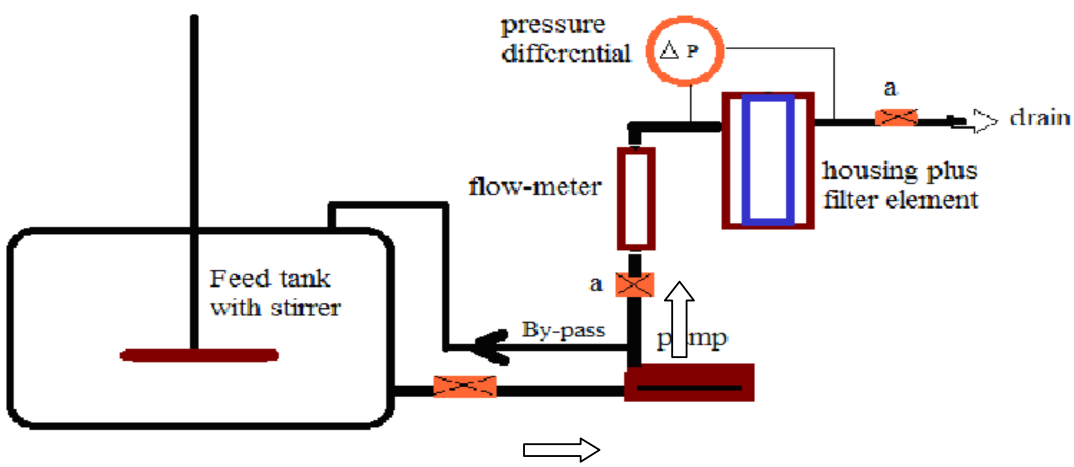


Figure 3.28 shows testing apparatus on single pass test (constant flow rate)

3.12.3 Stages of development of the testing apparatus:

Here also lot of changes had to be made in order to reach the final arrangement shown in figure 3.28. The initial stages dealt with the fabrication of the testing apparatus. As mentioned earlier each and every requirement will have to be fulfilled one by one. For the present purpose it was decided to input water from the side of the cylinder tangentially as shown in figure 3.27, so that the water is not directly forced upon the cartridge or else the coils on the package could get disturbed. The water containing impurities will be forced to enter inside the cartridge. Due to the perforations on the tube, spacing available between the adjacent yarns on the cartridge and due to spaces within the yarn, the water will get collected at the center. Thus the flow would be from outside to inside, which means that an outlet would be needed at the center of the column to remove the filtered water. Along with this the pressure and the flow rate needed to be known. For this purpose, two manometers one in upstream and other in the downstream and a flow meter would be needed. So the sequence in which the required devices would have to be arranged in the testing apparatus is as follows:

Firstly a pump to force the water, connected to a slurry tank after which a flow meter to measure the flow and then to the housing with ports to measure the pressure and exit.

3.12.4 Fabrication:

Literature recommends the use of a transparent housing[6, 21] so that the cartridge can be observed during test trial also. Hence the initial design given to the fabricator is as shown in figure 3.29, had a housing that was made from acrylic. The part labeled tank was of stainless steel as provided by the fabricator whereas the pump was of tulu make of 0.5 H.P. The flow meter was of local make and the acrylic cylinder with an inner diameter of 80 mm was given tangentially entry point so that the water spirals and reaches the top. The construction of the cylinder provided by the fabricator as per design supplied is already shown in figure 3.27. Top and bottom discs were prepared. A flange was fixed on the top and bottom edges of the cylinder using chloroform. Now the top and bottom discs prepared were clamped to the flanges on the cylinder thus sealing the housing. ‘C’ clamps were used to fix the top flange on the top disc. Care had to be taken that the water does not leak between the cartridge and the bushes provided inside the housing. This was checked by fixing a test PVC pipe of 10” (without perforations) inside the housing and running the pump, at the outlet no water was collected and this was the indication of zero leakage between the test PVC pipe and the bushes.

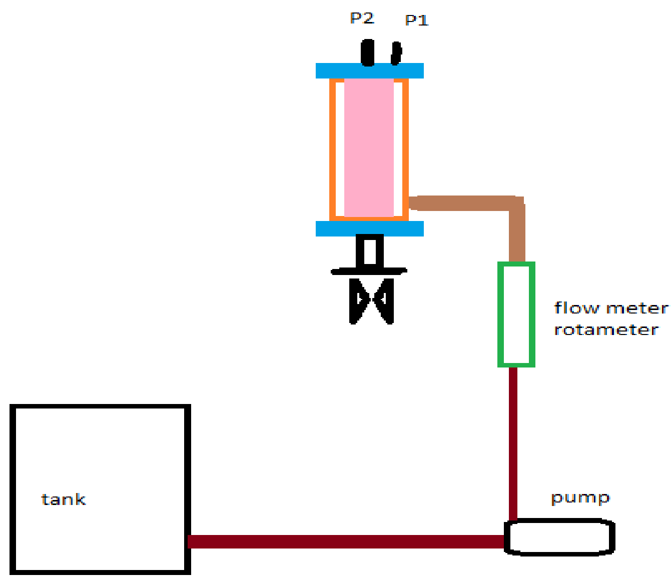


Figure 3.29 shows design of testing apparatus given to fabricator

3.12.5 Problems faced and their solutions:

1) The housing had to be fixed such that no leakage resulted. The ‘C’ clamps were not enough and so bolting was done on the outer perifery of the flange and the discs.

2) The capacity of the steel tank provided was very less hence it was replaced by sintex tank. It was also thought that only one tank would not be enough as continuous supply of water had to be ensured. Two tanks were procured out which one had a capacity of 100 liters and other one was of 500 liters.

3) Rubber tubes were mounted over the port for pressure measurement and the manometer. As the test started the water sometimes leaked out of that. So PU fitting was done wherever needed.

4) While testing the cartridge, it was observed that the float on the flow meter continuously kept fluctuating. To avoid this, a valve was introduced just before the entry of water to the flow meter. Another important observation was that the pressure at which water entered inside the cylinder was so high that on connecting it to the manometer, the mercury rose inside the capillary to the extent of overflow. Hence in the present set up by-pass has been added. Even carbon tetrachloride instead of mercury was tried but the identification became difficult. At the same time the joint of the manometer tube came off due to the use of CCl_4. With this arrangement when the pressure gauge was used at the inlet, still the pressure exceeded the maximum limit on the gauge of 1 Kg/cm^2.

5) Another observation was that the outlet valve below and the cylinder was opened during trial (figure 3.29), this did not allow the water to rise to sufficient extent inside the central column therefore when the tube was connected to the manometer, bubble used to enter and the readings could not be obtained. Hence it was decided to connect the pressure gauge at the outlet to get pressure. Herein the entry point of the housing was reversed, that is to say in the earlier figure 3.27 it was at the bottom, which was now changed to the top as shown in figure 3.30. The outlet was to be kept closed, so that water column could be developed. And in order to reduce the pressure at the inlet, a bypass arrangement was given. These final modifications made it possible to obtain the pressure and flow rate values.

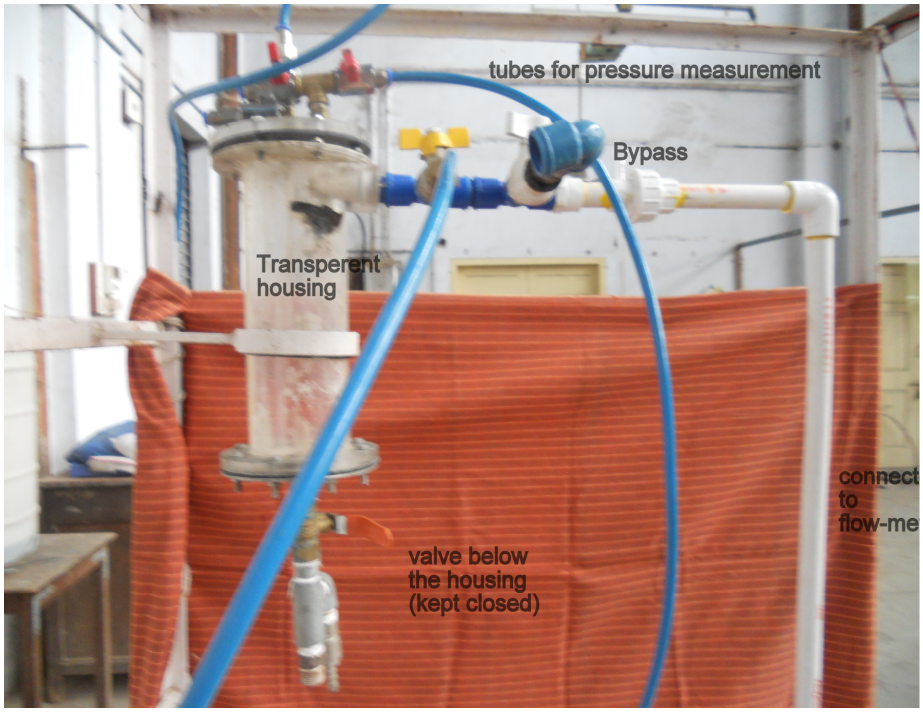


Figure 3.30 photograph of test rig with transparent housing and fittings

The pipe fittings used made the arrangement heavy and so there were leakages at the point where the entry point was fixed to the cylinder. To fix this chloroform, M-seal were tried but finally silicone helped in solving the problem and to make it light weight, these pipes were replaced by plastic fittings. It was understood that fixing acrylic would be troublesome and hence the housing was replaced by the readymade one's available and the pressure measurement was made inline. Attempt to use pressure gauge of local make was done but unfortunately the working was not satisfactory hence in the present system manometers have been used to find inlet and outlet pressures.

6) So a new manometer of one meter on one side and one and half meter on the other side was purchased. However the problem of rise in mercury level persisted. So the

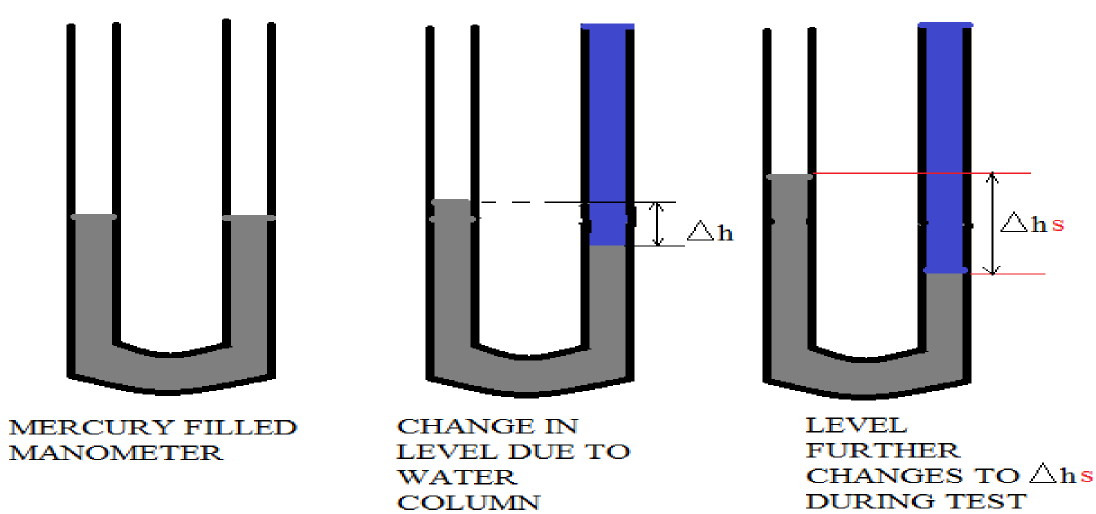
finally it was decided to take trial at lower flow rate of 400 LPH although literature recommends the use of 600 LPH. But since a comparison between cartridges with different winding variables is to be done hence any flow rate would suit equally well.

3.12.6 'U' tube manometer and its working: figure 3.31

Every time before starting the test, the Δh, that is, the mercury difference due to water column was noted and this was considered as starting position and calculations have been done using the following formula.

Pressure = $\rho \times g(\Delta h s - \Delta h)$ Equ 3.12.6.1,

where ρ is density of mercury in m3, g is the gravitational acceleration in kg/sec^2 and the level difference values are taken in meters. This was useful in calculating the pressure differential in psi (pounds/ sq. in) and Kg/cm^2.



(a) (b) (c)

Figure 3.31 "U" tube manometer

3.12.7 Details of stirring arrangement:

The stirring arrangement would not allow the test dust to settle. Since two tanks have been used, so stirring arrangement has been provided for both of them, so that, when water is being consumed from the active tank (connected to the pump), then the mixing (other) tank holding known volume of water could be filled. To which known weight of dust could be added and kept in ready condition for use thus getting a slurry with pre-decided concentration every time. The motor used was a 3 phase motor having 940 rpm. The drive is transmitted from the motor pulley via a 'V' belt to a shaft on which two pulleys are mounted. Here a self aligning bearing has been used to take care of any non-alignment. This shaft was longer and was extended further inside the tank to work as a stirrer. The other pulley transmits the drive to pulley on the second stirrer shaft.

This shaft was relatively shorter since the 500 liters tank was rectangular, but the stirrer blades had to be longer. Thus for both the tanks, two different sets of stirrer blades were made. On the stirrer shaft, collars were fixed, on to which the blades were attached at varying angles so that proper churning was achieved The plumbing arrangement was done in such a manner that it facilitated the above working explained. The water supply was taken from the over head tank and line was drawn from there till the location of the testing apparatus. After this the supply was divided into two for the two separate tanks. While deciding the rpm at which the stirrer should be rotated, it was thought that it should be enough to avoid settlement of the dust. The pulley ratios were so adjusted to achieve an rpm of approximately 40. The drive was kept common so that when one tank is being utilized, the other tank could be used to prepare the slurry and ensure that dust did not settle when it would be discharged into the active tank.

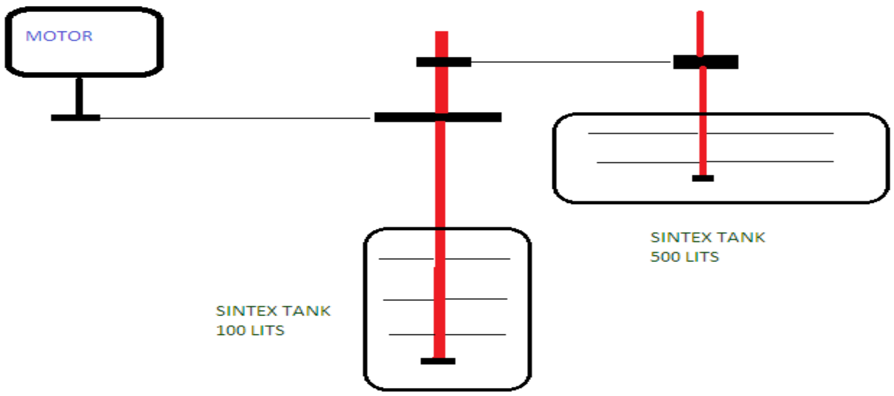


Figure 3.32 shows diagram of stirring arrangement fabricated earlier

The active tank is the one which is connected to the pump while the other one is the mixing tank. The driving arrangement for the stirrer is as shown in figure 3.32 and details of the dimensions of various driving elements is shown in figure 3.33.

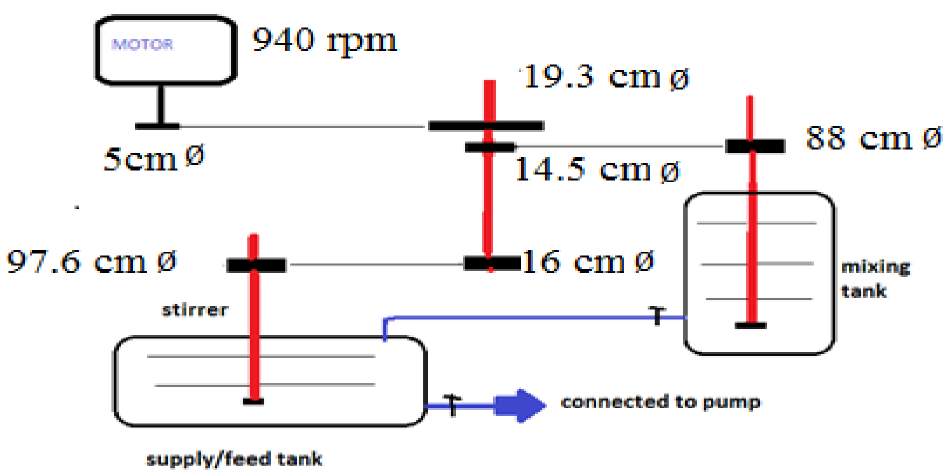


Figure 3.33 shows stirring arrangement

The figure 3.34 shows photograph of the testing apparatus developed. The important features of this apparatus have been labeled. They include the mixing tank, where slurry of required concentration is prepared and is fed to the supply tank. The pump, pumps the slurry up to the housing via a flow-meter which shows the flow rate and required/constant flow rate is achieved with the help of by-pass valve. The inlet and outlet of the housing are connected to the manometers to obtain pressure drop across the media. The filtrate is drained and ports are provided to collect the samples from downstream as well as from upstream of the housing.

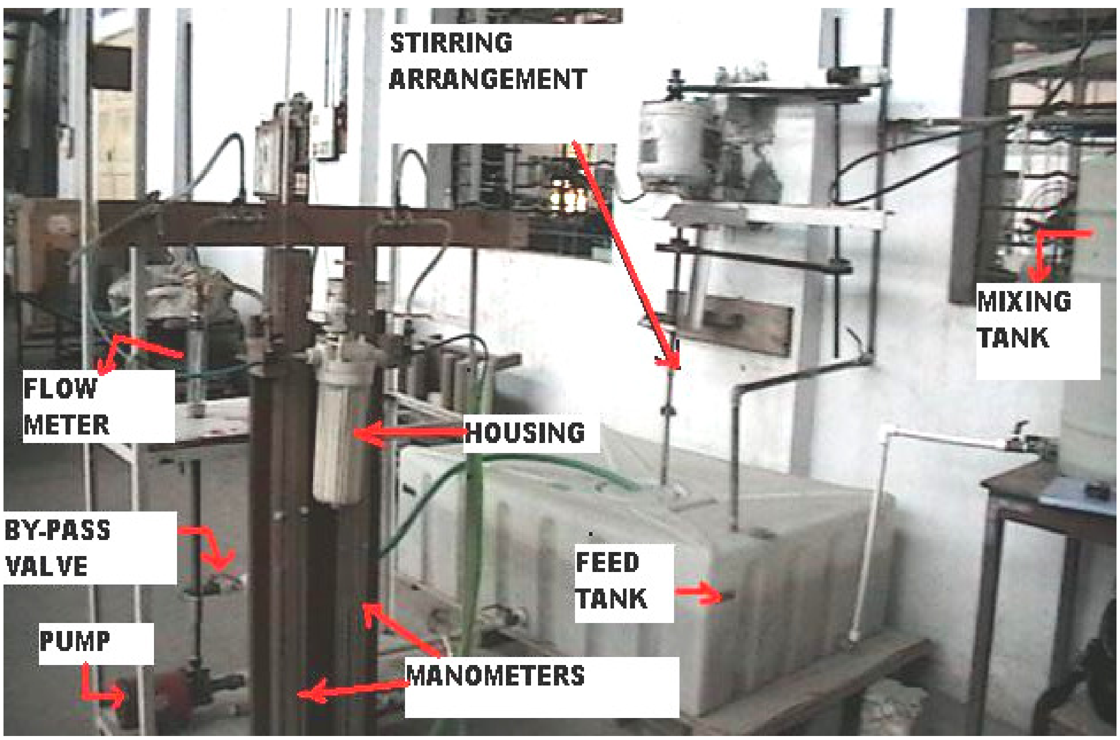


Figure 3.34 shows photograph of the testing apparatus along with accessories

3.13 Test dust:

Till it now it has been mentioned that the dust would be added to the over head tank water. Initially suggestions were that ordinary mud should be sieved and used. Samples of white fly ash (below 75μ), black cotton soil (up to 75 μ), bhadarpur sand (up to 212 μ), pozzonalic ash and even glass beads were considered for this purpose. The problem with this would be that if the distribution of the particle size in terms of its micron value is not known, then the performance rating of the wound cartridge would be difficult to be established. Even spherical glass beads could be used but they are costly and some method would have to be devised to recover them. But literature shows that standard test dust developed by SAE were used, but are meant for road vehicles. So for the present study ISO A3 medium test dust is utilized. It contains particles in the range of <1 microns up to 80 microns. This dust also has a definite distribution of the various micron size particles by volume.

PHASE – IV

3.14 Taking trials on the testing apparatus of cartridges produce on newly fabricated winder:

As per the pre-decided winding parameters, the cartridges produced would be tested on the test rig. While taking the test trials the variables identified for testing conditions include flow-rate, concentration, and type of test dust. During this trial the change in pressure would be observed and the pressure drop would be calculated. It was decided to perform the test for two hours. For all the trials the concentration (0.1 gm/L) and the flow-rate (400 LPH) was decided to be kept the same so that the results could be compared and the effect of winding parameters would then be clear. The total volume of the water passed through the filter, the bare bobbin weight, full bobbin weight (dry & clean), and dust loaded bobbin weight (dry & dusty) would also be recorded. Their difference would give the weight of dust present on the cartridge after the specified test time which would give an estimate of the dirt holding capacity. While conducting the trials, samples would be drawn from the ports provided and analyses of these samples would be done by finding out the particle size and converting the number to mass/lit and number/lit and finally obtaining the % frequency of various particle sizes present in the filtrate. Plots of change in % frequency of particles in the filtrate with time would help in understanding the filtration characteristics of each of the winding variable selected. Increase in the frequency of the particles in the filtrate is an indication either of higher pressure drop or the inability of the cartridge to trap particles of those sizes effectively. The retention efficiency or efficiency can easily be calculated from the number of particles/lit of given sizes in the feed and the filtrate, and based on these findings the nominal rating has been worked out, thus judgment of performance can be obtained.

PHASE – V:

3.15 Analysis of the filtrate samples collected during the test trials and finding out the performance of the cartridge.

3.15.1 Introduction to Particle size analysis:

Particle size influences many properties of particulate[16] materials and is a valuable indicator of quality and performance. The size and shape of powders influences flow and compaction properties. Measurements in the laboratory are often made to support unit operations taking place in process environment.

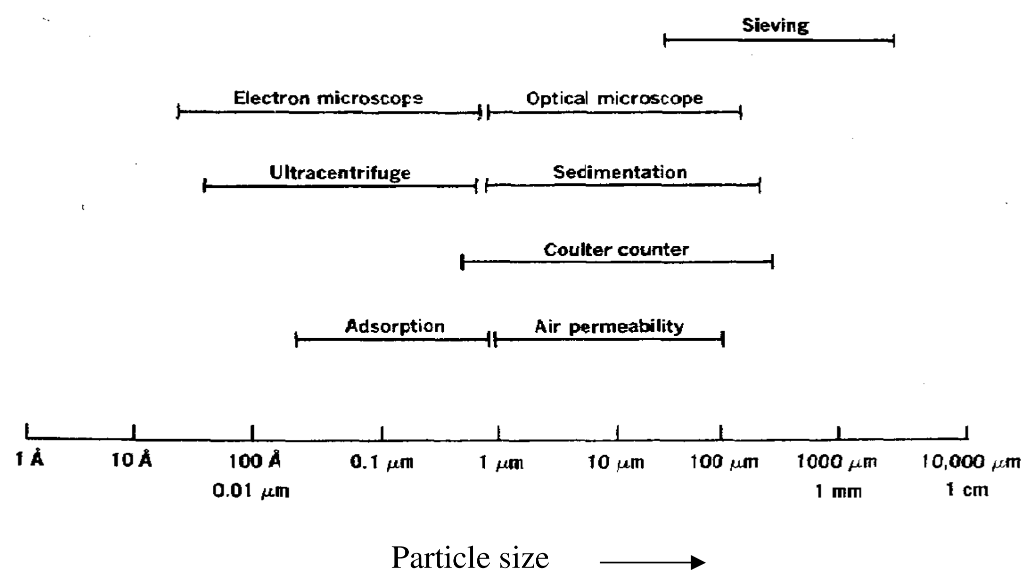


Figure 3.35 Range of particle size measurement applicable for different techniques[16]

Particle size measurement may be required in case of emulsification, homogenization or in case of separation steps such as screening, filtering or during operations like granulation/crystallization or in case of industry/application for specific reasons like paint. For example in the paint and pigment industries particle size influences appearance properties including gloss and tinctorial strength, particle size of cocoa powder used in chocolate affects color and flavor. The size and shape of the glass beads used in highway paint impacts reflectivity. A spherical particle can be described using a single number because every dimension is identical. Non-spherical particles can be described using multiple length and width measures. These descriptions provide greater accuracy, but also greater complexity. Hence it is very convenient to assume spherical particle shape. The reported value is typically an equivalent spherical diameter. Shape factors cause disagreements when particles are measured with different particle size analyzers. The only techniques that can describe particle size using multiple values are microscopy or automated image analysis. The samples have been collected at regular intervals. The filtrate was collected in new sample bottles of 100 ml capacity. The filtrate bottles then where checked for both the particle size and turbidity. In order to find out the particle size ocular microscope was used and since its working is well known hence it has not been discussed in this text.

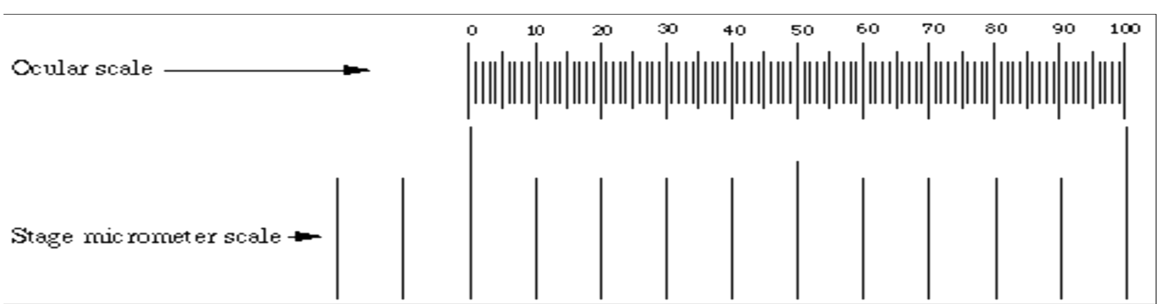


Figure 3.36 shows scales on ocular and stage micrometer[26]

3.15.2 Method:

A clean slide is taken and drop of filtrate was put on it. After putting the cover slip, the slide was mounted on the microscope[26 & 28]. After adjusting the focus, at 10X magnification, when the particles come into focus, they appear brownish. The particle's largest diameter was considered for measurement, and in order to get un-biased measurement out of the standard method of 'Z', measurement along the circumference, etc., 'Z' method was adopted. Particle count in each case has been fixed as 300 particles /sample so that errors related to manual measurement can be minimized. Here though it needs to be mentioned that it would have been possible to make use of particle size analyzer either META sizer or ZETA sizer and it was tried to find out particle size by this method also. But in order to obtain correct results the filtrate should have some definite concentration level of particles. Since the concentration of slurry was kept at 0.1g/l, the number of particles in the filtrate was so less that the threshold limit was not reached, hence although the instrument showed results but they cannot be considered to be reliable. Hence the manual method of counting the number of particles in each size range was adopted[16]. Here the results have been represented in two different ways, one based on the % frequency of particles of various sizes observed in the filtrate that is these particles could not be retained by the filter and other would be by finding the ratio of retained particles to particles in the inlet and expressing it as percentage, known as filtration/retention efficiency.

CHAPTER – IV

RESULTS

AND

DISCUSSION

4.0 Introduction:

As mentioned in the introduction itself that the water filtration industry is becoming very popular due to the environmental issues. When one goes to the market it becomes obvious that there a vast gap between the consumer and the manufacturer. It seems as if there is no relation between the manufacturing process and performance of a cartridge in field at least as far as the local market is concerned. An imported cartridge is many times used as a reference by the local manufacturers who by imitating its weight and winding pattern try to produce a similar cartridge. This project has been under taken with the intention of bridging the gap between the customer and manufacturer. Finding out definite relation between various winding parameters and relating it to the performance of the cartridge has also been attempted. Besides a testing facility using standard procedure would be available for testing of wound cartridges.

4.1 Brief background:

This chapter deals with detailed discussion of Phase – IV mentioned in Chapter 3, wherein mention of the group wise work is also there. The testing of the cartridge involved two parts namely the test trial conducted on the concerned cartridge and the particle size analysis. The cartridge was mounted inside the housing, its inlet pressure and outlet pressure were noted for duration of two hours whereas the flow rate was maintained constant. The pressure readings were recorded at an interval of fifteen minutes. The pressure drop developed is purely a function of the test conditions (flow rate, concentration and winding parameters) and whether proper sealing is achieved or not. For the pressure measurement the most reliable technique, that is mercury manometers have been used. The flow rate selected for the entire testing work undertaken was 400 LPH (6.7 L/min) and all the filters have been tested using a slurry having concentration of 0.1 gm/L. Thus after the test the normalized pressure drop was calculated instead of finding the terminal pressure. The water samples for the particle size analysis were collected at three different time intervals namely initial (15 min), intermediate (45 min) and final (120 min).

4.1.1 GROUP – I

The coding used in the entire chapter is as explained and tabulated in table 3.2 of chapter 3 and has been put here again for ready reference. As mentioned in chapter 3, in this set all packages were wound under identical conditions of average winding tension (145 gm), package rpm (225), maximum package diameter (65 mm), gain (using yarn diameter as 2.8 mm) and circumferential diamonds (1) except the coil angle as shown in table 3.2, table 3.3 and table 3.4

Table 3.2 Group wise division of experimental work

Winding variables													
G-I		G-II		G - III		G-IV		G- V		G- VI		G- VII	
SC	CA/ TR	SC	AT	SC	Y.D	SC	PD	SC	PS	SC	CD	SC	YC
A1	15°	T1	145	G1	2.5	D1	60	S1	225	/1	1	C1	0.4
A2	25°	T2	252	G2	2.8	D2	65	S2	425	/2	2	C2	0.6
A3	35°	T3	360	G3	3.1	D3	70	S3	625	/4	4	C3	0.8

G Group; SC sample code; CA coil angle; TR Traverse ratio; Y.D yarn diameter (mm); PD package diameter (mm); PS package speed (rpm); CD circumferential diamonds; YC Yarn count (Ne)

Cartridges with three different coil angles were produced for the trials taken in Group – I namely 15° (ATR=16.894), 25° (ATR=9.936) and 35° (ATR=6.952). The table 4.1 shows the change in pressure with time. As mentioned earlier also, the cartridges were tested under identical conditions of concentration of feed slurry (0.1 gm/L), a flow rate of 400 LPH for two hours and pressure is reported in terms of pounds/inch^2 (psi).

Table 4.1 shows change in pressure for coil angle of 15° (A1) with time

Time	Inlet pr.	Outlet pr.	Pressure drop	
min.	(psi)	(psi)	(psi)	kg/sq.cm
0	6.887	3.560	3.327	0.251
15	6.829	3.366	3.463	0.261
30	7.274	3.502	3.772	0.284
45	8.144	3.424	4.720	0.355
60	8.880	3.579	5.301	0.399
75	9.015	3.560	5.455	0.411
90	10.505	3.772	6.732	0.507
105	11.356	3.443	7.912	0.596
120	14.528	3.850	10.679	0.804

The figure 4.1 is a plot of pressure versus time and the values which have been plotted are the inlet pressure, outlet pressure and the pressure drop for A1T1G2D2S1C1/1 written in short as A1. The figure 4.1 shows that the outlet pressure remained almost constant, whereas, the inlet and the pressure drop showed a similar kind of trend. These characteristics have been observed for all the experiments that were conducted especially outlet pressure, irrespective of the winding variables tested. The pressure drop when the test was termintaed was 10.679 psi. Approximately after 100 min the inlet pressure shows a very rapid increase and this can be an indication of the cartridge getting loaded with, further increase in pressure it would result in discharge of particles in the filtrate.

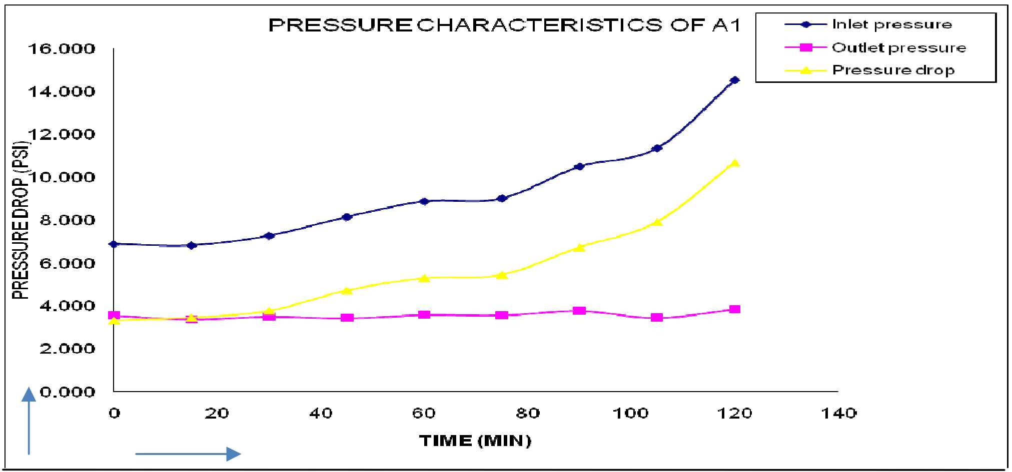


Figure 4.1 shows pressure characteristics of cartridge with desired coil angle (A1)/no. of coils 15°/16.89

The figure 4.2 shows filtration behavior of A1 (A1T1G2D2S1C1/1) cartridge (15°/ traverse ratio=16.89) based on the particle count of the filtrate collected at various time intervals.

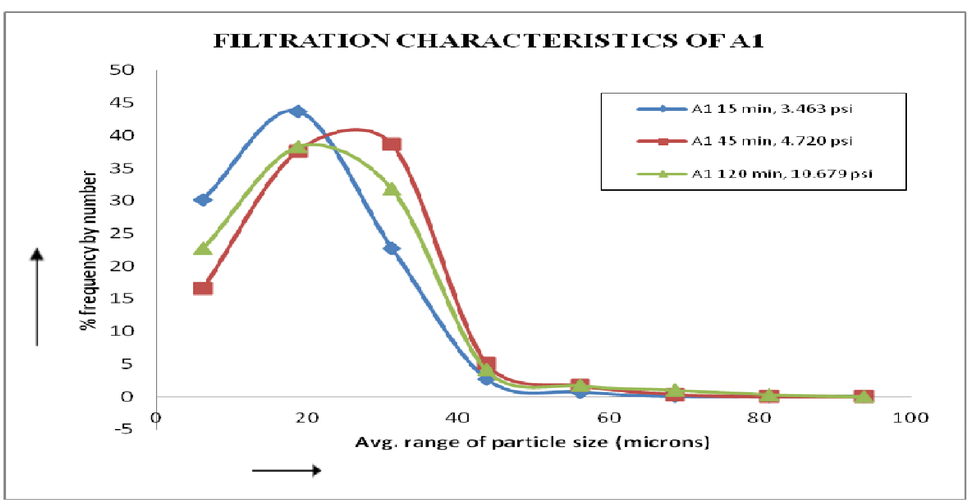


Figure 4.2 shows change in frequency of particles at different time intervals for cartridge with coil angle (A1)/no. of coils 15°/16.89

The values plotted in figure 4.3 have been tabulated in table 4.2, which also shows a combined data for the other two traverse ratios. The calculations taken up for making the plots have been shown in the Appendix – I. The microscopic examination gives the number of particles, and was converted into the weight and number frequency distribution, which yeilded more fruitful results. Obviously the cartridge shows improvement in the filtration behavior with time and figure 4.2 shows that the % frequency of particles present in the filtrate is less for the samples collected after 120 min unlike for the samples collected after 15 min and 45 min respectively. The table 4.2 and figure 4.3 is related to pressure characteristics, while figure 4.4 and figure 4.5 show the filtration characteristics of the cartridges produced with the other two coil angles/ traverse ratios respectively.

Table 4.2 shows change in pressure readings for A2 and A3

					PRESSURE DROP			
Time	INLET*		OUTLET*		psi		Kg/cm^2	
min.	A2	A3	A2	A3	A2	A3	A2	A3
0	4.217	5.784	2.283	3.560	1.935	2.225	0.156	0.136
15	7.351	5.978	4.024	3.173	3.327	2.805	0.197	0.234
30	7.429	7.487	4.063	3.734	3.366	3.753	0.264	0.237
45	7.757	7.854	4.004	4.159	3.753	3.695	0.260	0.264
60	8.357	8.280	4.004	3.888	4.353	4.391	0.309	0.306
75	8.609	8.667	3.888	3.811	4.720	4.856	0.341	0.332
90	9.015	10.176	3.946	4.237	5.068	5.939	0.418	0.356
105	9.750	10.601	4.024	3.908	5.726	6.693	0.471	0.403
120	12.632	12.226	4.004	3.850	8.628	8.377	0.589	0.607

- psi value.

In pressure characteristics A2 and A3 are very close. The N.T.R for A1 is 17, 10 for A2 and 7 for A3.

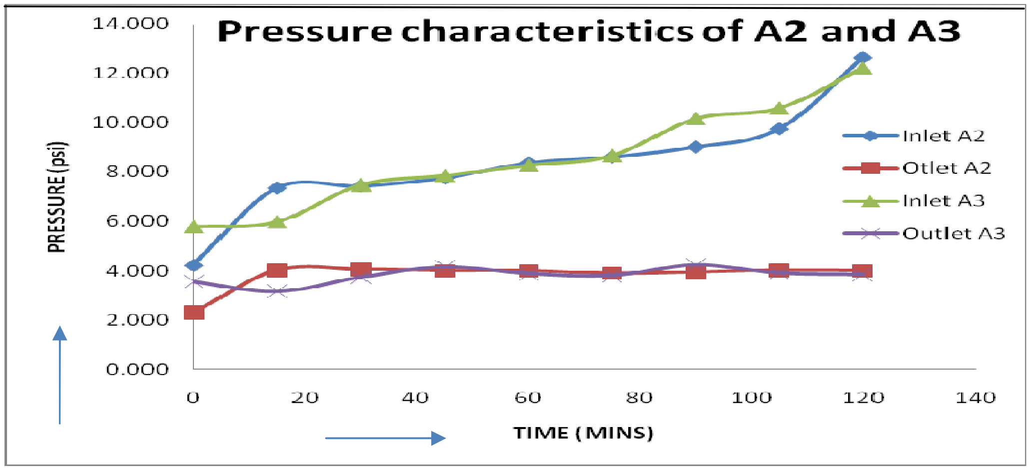


Figure 4.3 shows pressure characteristics of cartridge with desired coil angle/no. of coils 25° (A2) & 35° (A3) /9.936 & 6.952

When the winding is started the targeted coil angles in each of the three cases were 15°, 25° and 35° respectively, but by the time the cartridge is built to a diameter of 65 mm, there is considerable reduction in the coil angle (7°51') in case of desired coil angle of 15°. Similarly for desired coil angles of 25° and 35° the coil angle at 65 mm will be approximately 8°45' and 18° 49' respectively. Thus the number of coils on A3 is least and its coil angle is the maximum amongst the cartridges of this set. Since pressure drop of A3 is minimum, it will allow the particles trapped to remain so, whereas for A1 though the coils are more but the cartridge as a whole offers greater resistance to the path of the slurry, thereby increasing the pressure drop. Thus the number of times the bypass valve needs to be adusted to maintain constant flow rate is more. It should be noted that every time this is done there is a change in the fluid dynamics inside the housing due to which the cartridge tends to discharge trapped particles in the filtrate, reducing the filtration/trapping/retention efficiency. Figure 4.6 shows the pressure characteristics of cartridges with different traverse ratios. As seen the cartridge with higher number of coils (A1) develops the highest pressure drop after two hours, though the other two cartridges show a marginal difference in their pressure drop, the cartridge with the minimum number of coils has the least pressure drop.

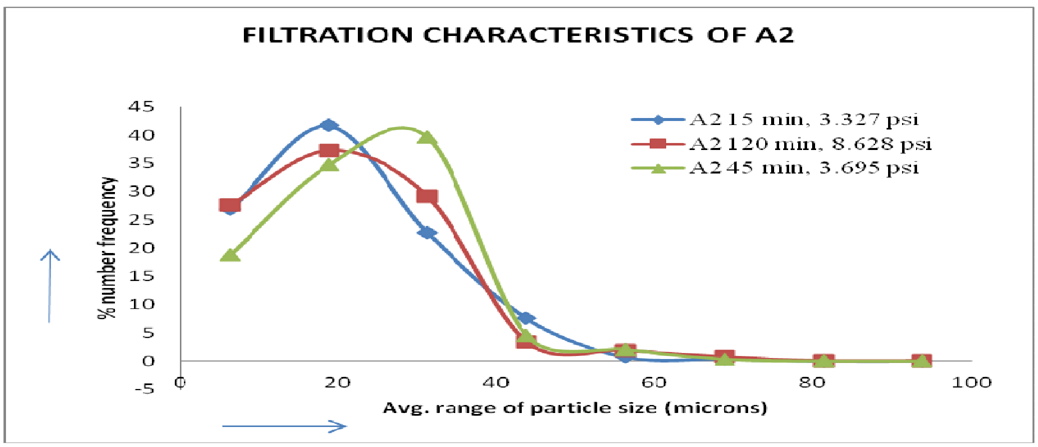


Figure 4.4 shows change in frequency of particles at different test time intervals for cartridge with desired coil angle/no. of coils of 25° /9.936

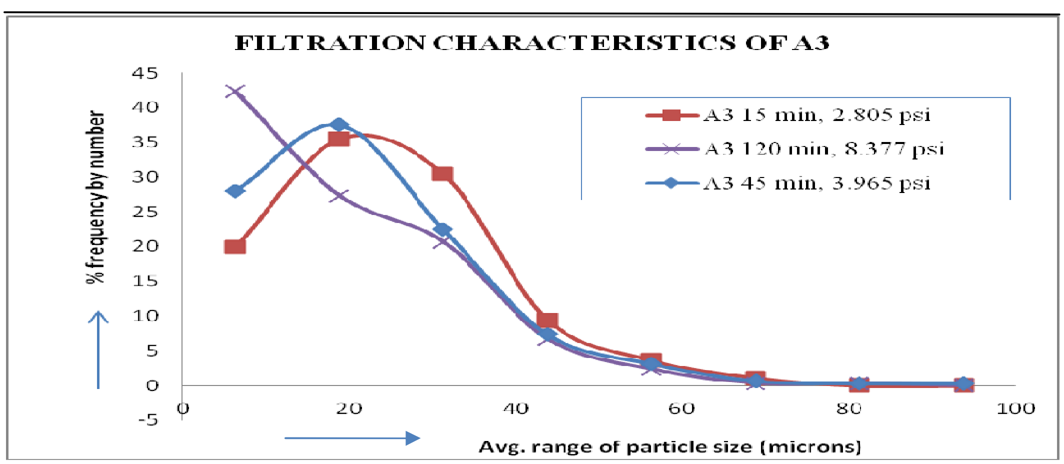


Figure 4.5 shows change in frequency of particles at different test time intervals for cartridge with desired coil angle/no. of coils of 35°/6.952

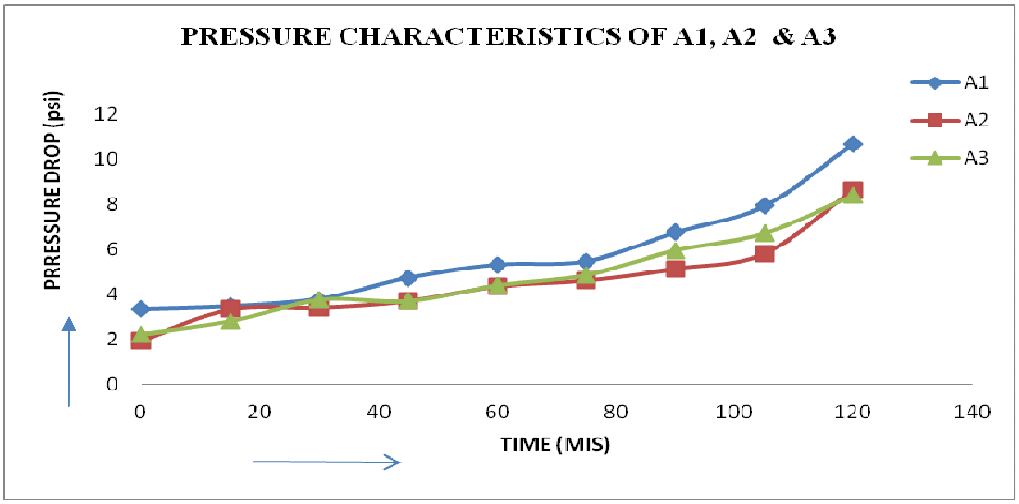


Figure 4.6 combined pressure characteristics of the three different numbers of coils/coil angles

The figure 4.7 and figure 4.8 show the comparative filtration characteristics of all the three cartridges considered in this group. The filtration behavior has close relation with its pressure characteristics. They clearly indicate that the A3 cartridge shows lesser % frequency of particles by number collected in the filtrate over two hours for similar distribution of particles in the inlet. Though A3 shows a greater % frequency in the smaller sized particles towards the end of test, which means it is no longer able to trap smaller particles that efficiently due to its porous nature. But A1 & A2 are still able to do so, due to more number of coils present on each of them. A3 was effective in trapping the smaller sized particles in the initial part of the test but with time the pressure across the cartridge goes on increasing and its efficiency for trapping those particles reduces. Thus with more number of coils the limit of releasing smaller sized particles into the filtrate with increasing pressure will be reached later.

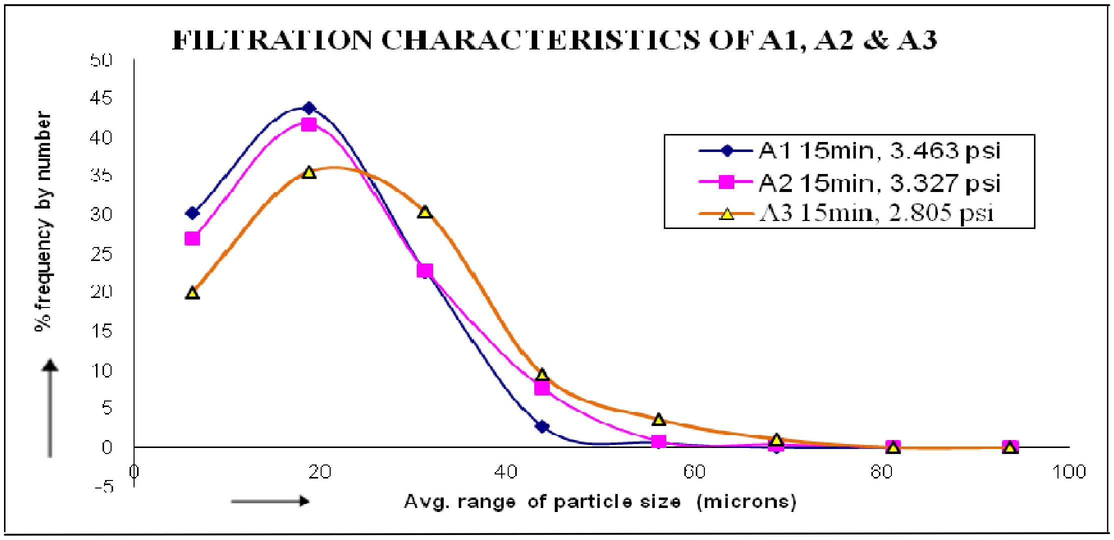


Figure 4.7 shows combined filtration characteristics of the three different number of coils/coil angles after 15 min of test time

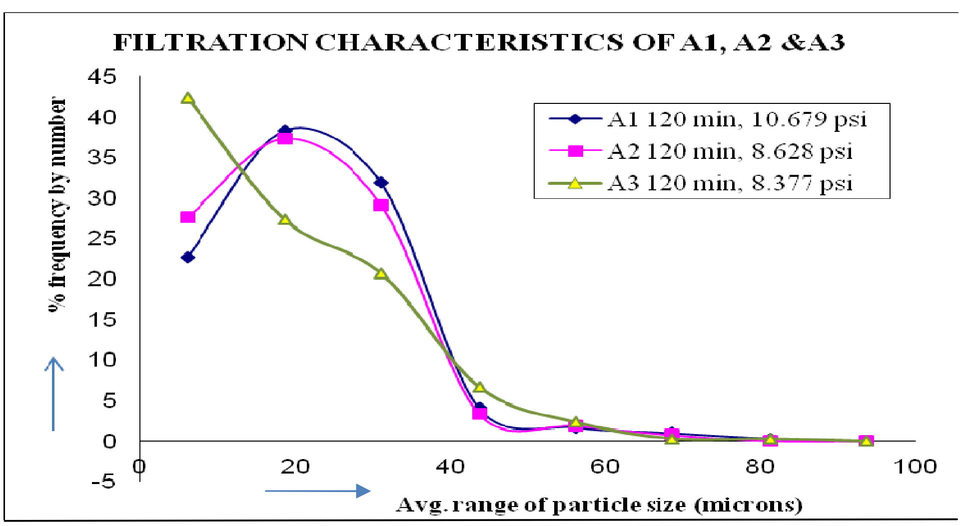


Figure 4.8 shows combined filtration characteristics of the three different number of coils/coil angles after 120 min of test time

Table 4.3 shows the combined data for the three different traverse ratios in terms of the frequency of different particle sizes emerging downstream with respect to time.

Table 4.3 shows data related to Group – I in terms of % frequency by number in filtrate

PERCENTAGE FREQUENCY BY NUMBER/R										
Particle size(microns)		A1T1G2D2S1C1/1			A2T1G2D2S1C1/1			A3T1G2D2S1C1/1		
Range	Avg. dia	15 min	45 min	120 min	15 min	45 min	120 min	15 min	45 min	120 min
≤100&≥87.5	93.75	0	0	0	0	0	0	0	0.351	0
≤87.5&≥75	81.25	0	0	0.339	0	0	0	0	0.351	0.333
≤75&≥62.5	68.75	0	0.339	1.017	0.379	0.347	0.746	1.087	0.702	0.333
≤62.5&≥50	56.25	0.678	1.695	1.695	0.758	2.083	1.866	3.623	3.158	2.333
≤50&≥37.5	43.75	2.712	5.085	4.068	7.576	4.514	3.358	9.420	7.368	6.667
≤37.5&≥25	31.25	22.712	38.644	31.864	22.727	39.583	29.104	30.435	22.456	20.667
≤25&≥12.5	18.75	43.729	37.627	38.305	41.667	34.722	37.313	35.507	37.544	27.333
≤12.5&≥0	6.25	30.169	16.610	22.712	26.894	18.750	27.612	19.928	28.070	42.333

Simlar kind of tables as table 4.3 for the other groups are shown in the Appendix – I as Tables – II, III, IV, V , VI and VII. The cartridge with the highest number of coils shows a comparitively poorer filtration behavior that is to say that, more number of particles tend to get discaharged into the filtrate with time due to the higher pressure drop developed across the cartridge. But at the same the number of particles trapped inside the filter matrix is larger than the cartridge with lesser number of coils due to greater yarn content and area. The efficiency of a cartridge is judged in the following manner.

$$\text{Retention Efficiency} = \frac{\text{Number of particles in feed} - \text{Number of particles in filtrate}}{\text{Number of particles in the feed}} \times 100$$

Thus the table 4.3 can be further modified and the retention efficiency (RE) can be calculated, the results of which have been tabulated in table 4.4.

The table 4.4 shows efficiency for Group –I where cartridges have been produced with three different traverse ratios.

Table 4.4 shows the Retention Efficiency (RE) by number for Group – I

Avg. dia	NUMBER RETENTION EFFICIENCY%								
	A1			A2			A3		
µm	15 min	45 min	120 min	15 min	45 min	120 min	15 min	45 min	120 min
93.75	100	100	100	100	100	100	100	73.72	100
81.25	100	100	80.76	100	100	100	100	86.86	83.07
68.75	100	93.26	80.76	74.07	80.73	82.23	61.10	73.72	83.07
56.25	94.28	91.58	91.99	82.71	61.46	60.19	62.95	66.21	66.14
43.75	88.06	86.81	89.96	35.17	68.69	73.13	60.33	67.54	60.16
31.25	65.67	65.60	73.01	57.38	39.81	48.96	73.75	79.74	74.70
18.75	59.37	79.41	80.06	40.58	59.85	50.24	75.79	73.22	73.55
6.25	61.33	87.46	83.69	64.25	79.79	65.68	81.47	72.70	44.15

In order to calculate the rating, the assessement has been considered after 120 minutes and have been rated at 80% that is after the specified time, the cartridge is able to remove atleast 80% of particles of that particular size. For A1 almost all sizes are removed at 80%, hence A1 can be rated as a cartridge with the lowest micron size identified using microscope, that is a nominal rating of 7 µm, while A2 and A3 as having rating of 69 µm. The 45 min readings lies closer to the the 120 min results. Hence from the next group onwards the intermediate level may/may not be considered for discussion.

This may be misleading though, since the test has not been carried out till the terminal pressure but it should be noted that for this particular work, rating has been reported after two hour test time since the basic object was of making a comparision between differently wound cartridges. The figures 4.9 and 4.10 are the plots of efficiency versus pressure drop for A1 and A3 respectively. Figure 4.9 shows the plot of efficiency versus pressure drop for A1 and figure 4.10 shows the same plot for A3 for four different particles sizes having average diameters of 68.75 µm, 56.25 µm, 18.75 µm and 6.25 µm. For the graph shown in figure 4.9, very large particles namely 93.75 µm and

81.25 µm have not been ploted since they show 100% efficiency. For particles having size of 68.75 µm there is a slight drop in their number towards the end of the test, while for the particle sizes of 56.25 µm, 43.75 µm and 31.25 µm size the plot is almost a straight line due to which the latter two have not been shown in the graph. For the smaller particles having average diameters of 18.75 µm and 6.25 µm, they shows an improvement in the efficiency with time.

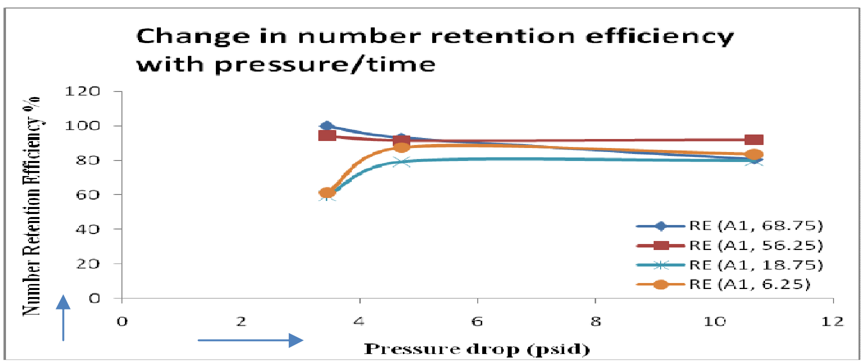


Figure 4.9 shows change in retention efficiency of A1 with pressure

The trapping power of A1 for smaller particles is good but larger particles that is greater than 56.25 µm show a slight drop which may be due to the discharge of particles trapped inside the filter matrix as pressure increases.

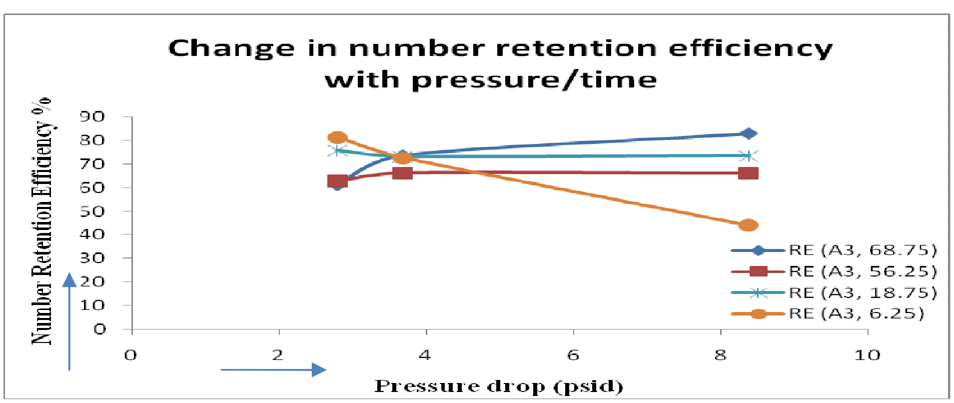


Figure 4.10 shows change in retention efficiency of A3 with pressure

Figure 4.10 shows the efficiency of A3 for the larger particles having average diameters of 68.75 µm and 56.25 µm, the graph is almost a straight line with an improvement in efficiency with time whereas for the smaller particles like those having an average diameter of 18. 75 µm and 6.25 µm, it shows a drop in the efficiency with time or with increase in pressure drop. This is in agreement with the results plotted in figure 4.8, where the % frequency of these particles in the filtrate is seen to increase.

Thus it can be said that amongst the three traverse ratios selected for the study, A3 may be advantageous due to lower pressure drop (life), better performance with time and more economical but at the same time A1 shows better retention efficiency than A3.

T-test was run for the above set using Microsoft Excel 97-2003, and it was found that there no significant differernce in the mean values of the number of particles observed in the filtrate at two different time intervals considered. This is justified because, the studies carried out by some of the researchers have reported a terminal pressure of 40 psi, while in the present study the pressure drop reached when the test was terminated may be roughly one-fourth this value. Had the tests been conducted till the terminal pressure, then there could have significant difference in the particles observed in the filtrate. From the next set onwards, compartive charts rather than individual will be considered, due to their suitability.

4.1.2 GROUP – II:

The next important winding variable which was varied for the study was the tension. Three different average tension levels were selected namely 145 gm, 252 gm and 360 gm. Figure 4.11 is a combined plot of change in pressure drop with time for the three different tension levels considered.

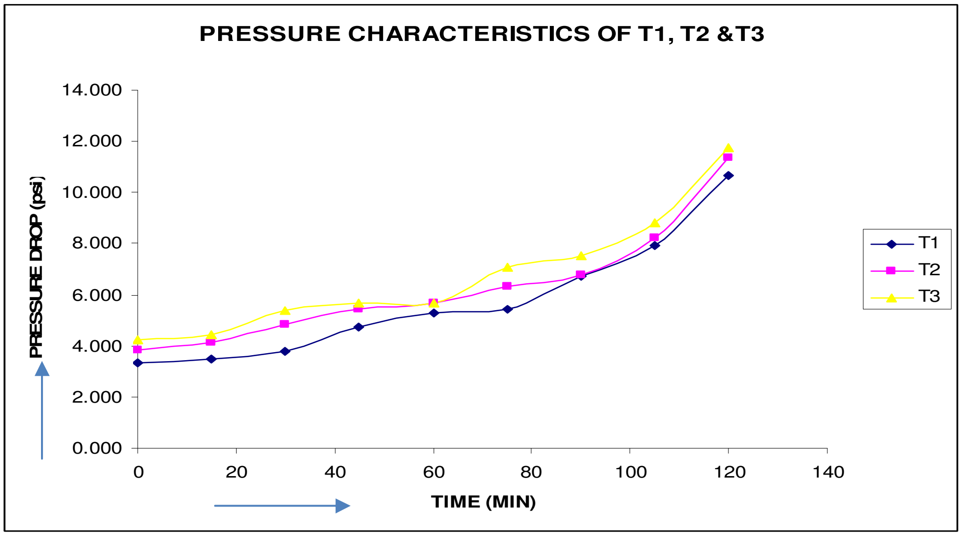


Figure 4.11 combined pressure characteristics of the three different tension levels with same number of coils/coil angles

All the three cartridges show the same trend, that is gradual increase in the pressure with time, but the increase in this pressure is steeper towards the end of the test for the cartridge wound with maximum tension of this set. This also indicates that the cartridge will get chocked earlier and its filtration behavior can also get affected. The cartridge wound with the least tension offers less resistance to the flow of slurry while the cartridge wound with higher tension offers greater resistance. As winding on tension increases, the yarn tends to sit firmly in its position making it difficult for the slurry to dislodge it; contrary to this will be the case of cartridge wound with lower tension level. Besides this the firmness of the cartridge or density of the cartridge also increases with increase in tension, which provides greater layers of resistance thus an improvement in the filtration behavior can be expected with an increase in the winding tension, which is proved by the plot shown in figure 4.12 and figure 4.13.

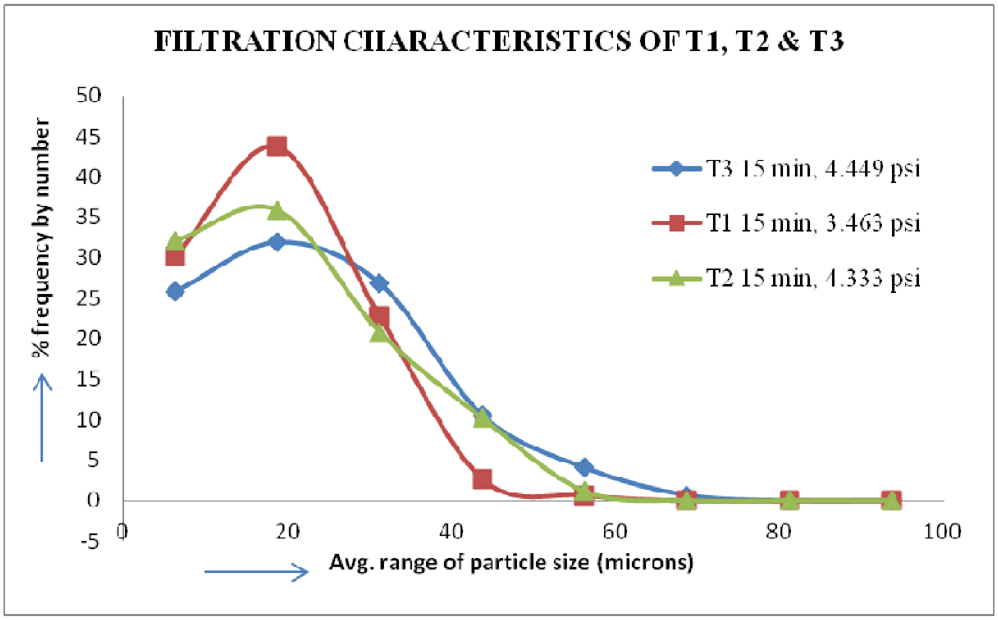


Figure 4.12 shows combined filtration characteristics of the three different tension levels after 15 min of test time

When the cartridges were wound with lower tension levels, it was observed that simply touching the cartridge a bit harshly resulted in the displacement of the coils. But with the increase in the tension the coils become somewhat locked in their respective positions. When such cartridges were placed inside the housing, a cartridge wound with greater tension would thus restrict the entry of the particles through the small openings between adjacent coils but this obviously resulted in an increase in pressure difference across the cartridge.

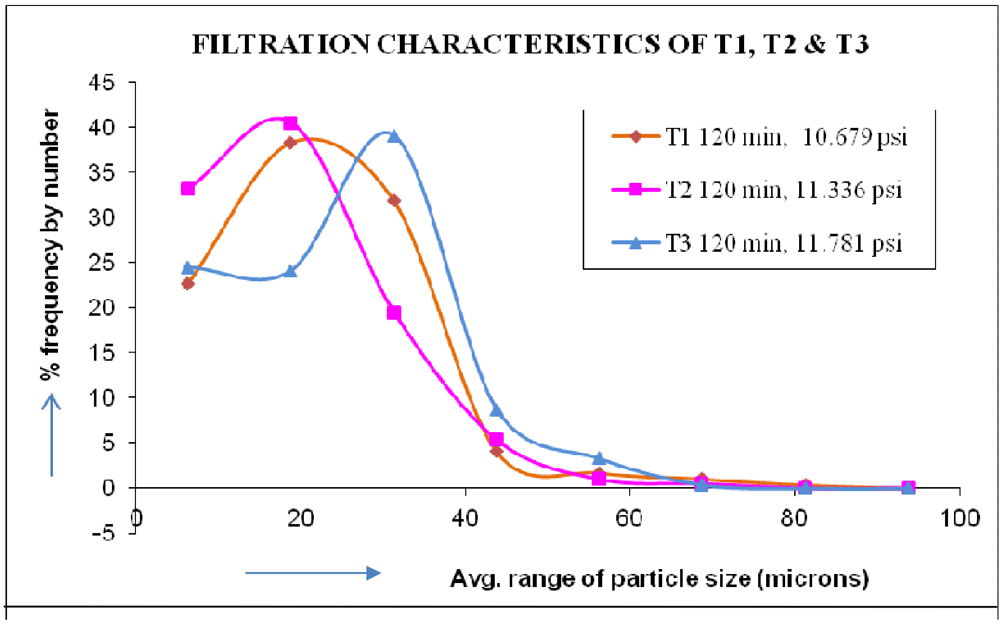


Figure 4.13 shows combined filtration characteristics of the three different tension levels after 120 min of test time

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The cartridge with higher tension shows better particle removal frequency, though the distribution becomes a bit spread implies that is in the range of around 20 µm for the sample taken after 15 min. The same trend is observed even after 120 min with reduction in the difference between T1 and T3 and the distribution of the cartridge wound with higher tension shifts to the coarser particle range especially around 31.25 µm. This shows that though the higher tension showed improvement in trapping the particles in the initial part of the test but with time it no longer remains effective. In fact the smaller particles showed an increase in the filtrate with the same logic as explained for the earlier group. This happens because; higher the winding on tension more will be the number of times for which the setting of bypass will have to be done. Adjustment of this valve becomes all the more frequent to achieve constant flow rate conditions hence greater will be the tendency of the cartridge to discharge the already trapped particles in the filtrate. The table 4.5 shows retention efficiency for Group – II where cartridges have been wound under three different tension levels.

As it can be seen from table 4.5 the retention efficiency of T1 is better than T3 for all particle sizes with time. Cartridge wound with least tension can be rated as 7 μm, whereas T2 and T3 can be rated as approximately to be 69 μm. The filtration behavior will show the possiblity of trapping the particles, which in case of T1 is better than T3 due to greater possibliity of the particles entering inside the matrix and getting arrested during its journey from outside to the core, whereas with T3, the cartridge structure is quite rigid hence greater will be its pressure drop.

Table 4.5 shows the Retention Efficiency (RE) by number for Group – II

Avg. dia	NUMBER RETENTION EFFICIENCY%								
	T1			T2			T3		
μm	15 min	45 min	120 min	15 min	45 min	120 min	15 min	45 min	120 min
93.75	100	100	100	100	100	100	100	100	100
81.25	100	100	80.76	100	100	100	100	100	100
68.75	100	93.26	80.76	100	58.04	85.50	91.24	85.74	86.49
56.25	94.28	91.58	91.99	69.91	52.05	68.86	73.72	64.34	39.20
43.75	88.06	86.81	89.96	-11.52	30.89	29.48	84.91	68.30	63.97
31.25	65.67	65.60	73.01	53.47	51.47	47.47	81.98	5.65	24.70
18.75	59.37	79.41	80.06	36.47	28.07	27.34	84.16	61.05	65.70
6.25	61.33	87.46	83.69	22.49	23.71	15.07	79.19	41.16	43.42

Higher tension causes the yarn to reduce in volume thus reducing the air spacing, the finer particles get arrested during their path through the cartridge which is because they get trapped inside the yarn structure. Since the porosity of a wound cartridge is too high therefore finer particles can get trapped only during their travel through the yarn but this gets hampered due to higher tension. Hence the finer particles entering inside the matrix do not get arrested and their arrest can only be because of mechanical capture[6] of particles, either sieving or bridging. And that is the reason why their frequency in the filtrate is greater, which is evident from figure 4.13.

4.1.3 GROUP – III:

The third variable considered which could have an influence on the filtration behavior was the gain. The gain has been calculated using three different values of yarn diameter namely 2.5 mm, 2.8 mm and 3.1 mm as per the calculations mentioned in Chapter 2. The figure 4.14 shows a combined plot pressure plotted for different gain values.

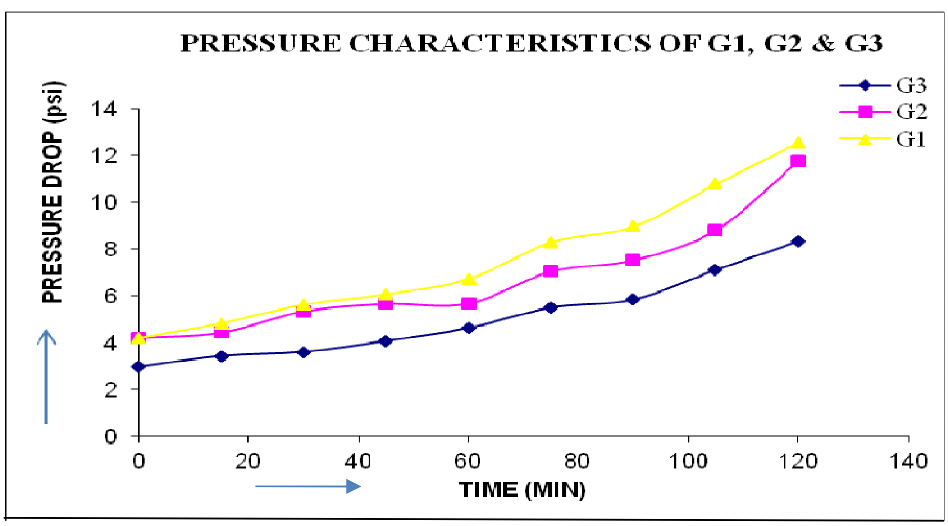

Figure 4.14 shows combined pressure characteristics of the three different gain values with same number of coils/coil angles

Out of the three, G1 is the closest while G3 is the widest in the group considered. When cartridges were produced with the different gain values the traverse ratios/coil angles was same. The tension was kept at the highest level since filtration behavior of cartridges wound with higher tension was found to be better. When coils are laid touching each other, it would be expected that the cartridge offers greater resistance to the path of the slurry. Hence the pressure drop for G1 recorded is greater compared to the other two gain values. The figure 4.15 and figure 4.16 show the filtration behavior of all the three different gain values plotted together.

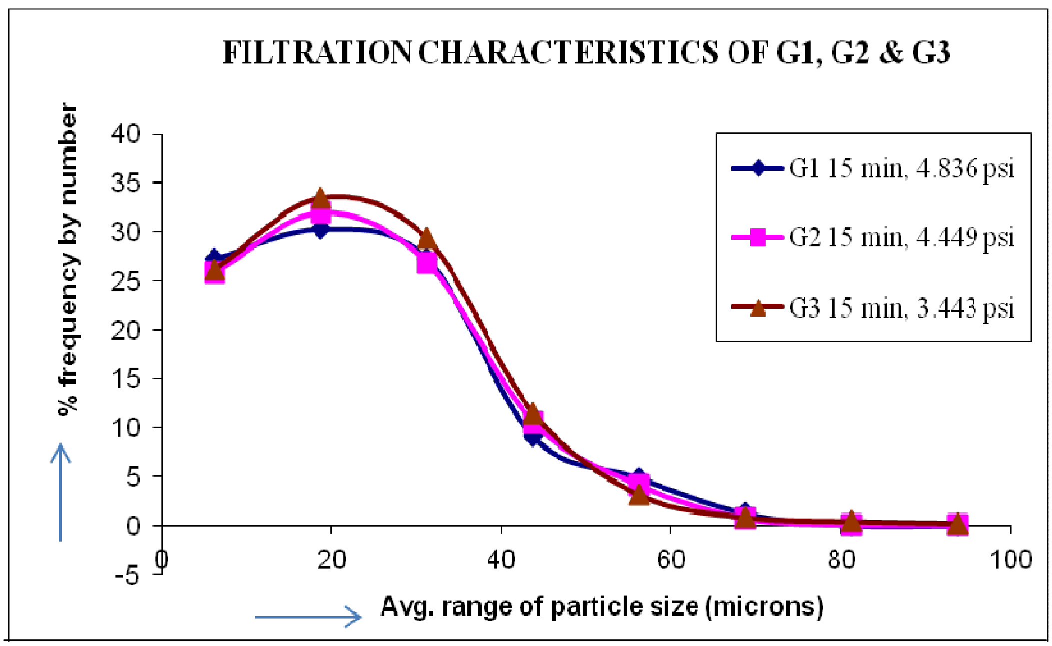

Figure 4.15 combined filtration characteristics of the three different gain values after 15 min of test time

. The results are obviously as expected, that is the cartridge wound with the closest gain gives better results. In fact there is reduction in the % frequency of particles collected in the filtrate when comparison is made with the earlier group of tension. This means that reducing the gain certainly improved the filtration behavior along with the increase in its pressure drop.

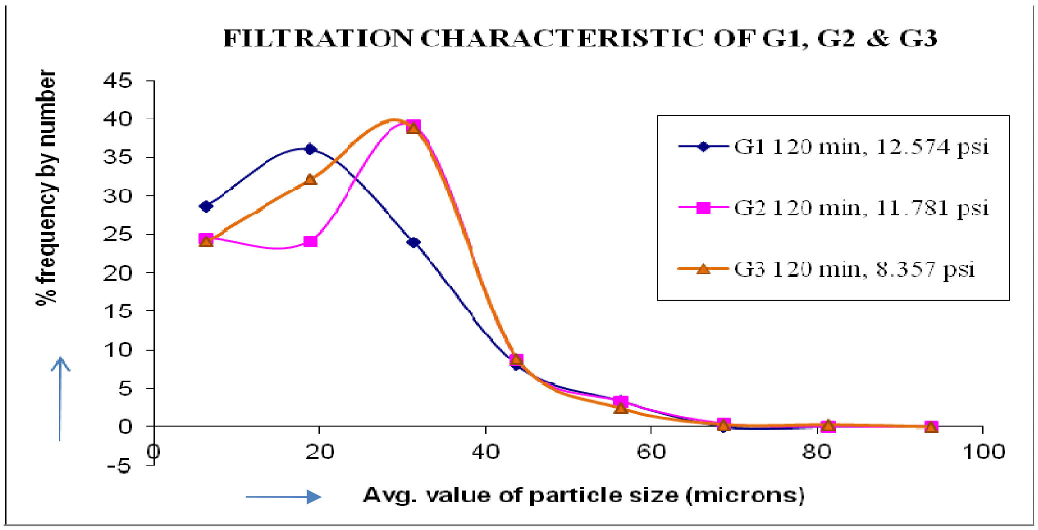

Figure 4.16 shows combined filtration characteristics of the three different gain values after 120 min of test time

In figure 4.15, the % frequency of particles observed in the initial part of the test, shows a nominal difference between the three cartridges of different values of gain. But in the later part of the test, figure 4.16, the influence of gain on the filtration behavior becomes all the more prominent. G1 still shows better retention, whereas for G2 and G3 the distribution shifts to the coarser side, more so for G3 where the coil spacing is highest amongst the three and the table 4.6 shows efficiency for Group – III .

Table 4.6 shows the Retention Efficiency (RE) by number for Group – III

Avg. dia µm	NUMBER RETENTION EFFICIENCY% G1 15 min	G1 45 min	G1 120 min	G2 15 min	G2 45 min	G2 120 min	G3 15 min	G3 45 min	G3 120 min
93.75	100	69.53	100	100	100	100	67.86	100	100
81.25	100	100.00	100	100	100	100	67.86	79.52	74.56
68.75	74.33	80.88	100	91.24	85.74	86.49	48.58	67.23	79.65
56.25	57.22	36.28	67.72	73.72	64.34	39.20	35.72	34.47	38.96
43.75	67.91	52.21	69.01	84.91	68.30	63.97	63.93	62.39	65.74
31.25	63.90	54.60	37.06	81.98	5.65	24.70	12.96	-13.48	-27.18
18.75	58.55	40.26	56.42	84.16	61.05	65.70	-0.43	-23.72	-37.77
6.25	41.66	11.37	39.43	79.19	41.16	43.42	-40.24	-45.95	-47.99

Looking at the above table it becomes clear that, higher the gain (open wind) greater will be the number of particles coming into the filtrate at the same time its retention would also be poor due to greater chances of particles coming through the openings present for the parameters selected for this cartridge. The ratings for all the three are different namely for G1 and G2 it can be said to be 69 µm, while for G3, it can be said to be 94 µm. Thus it can be said that the filtration behavior of the cartridge wound with closer coil spacing would give better results. Here though towards the end, the pressure drop in case of closer spacing reached is higher, but still its retention capacity does not reduce unlike in case of Group – I and II. In Group – I the number of coils were varied whereas here the number of coils remain the same. The structure of the cartridge becomes very compact. Due to higher tension level the coils are firmly placed and due to close wind, the coils a packed closely touching each other hence the scope of particles entering into the structure from between the neighboring yarn in reduced considerably. Besides the traverse ratio selected in this case was the one with higher number of coils where the limit of smaller particles being discharged due to increase in pressure is reached latter than that for lesser number of coils. Thus in this group the close wound cartridge shows better retention and fewer particles in the filtrate but the higher pressure drop is responsible for reduction in retention efficiency.

For intermediate gain and maximum tension the rating was approximately 69 µm and the same rating was also achieved for maximum tension and close wind thus gain is effective tool in removal of large as well as small sized particles, whereas tension plays an important role in removing the larger sized particles.

4.1.4 GROUP – IV:

The fourth variable considered for this study was the final package diameter. Three different package diameters were considered, namely 60 mm, 65 mm and 70 mm. The figure 4.17 shows a plot of change in pressure with time.

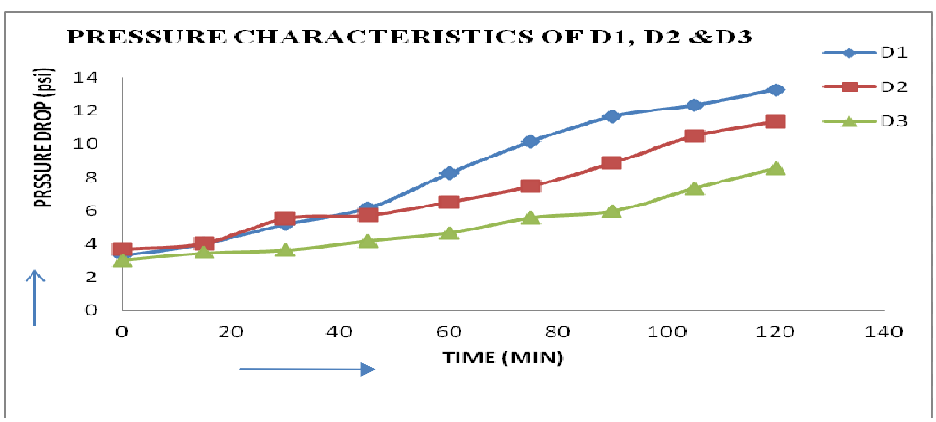

Figure 4.17 shows combined pressure characteristics of the three different diameters with same number of coils/coil angles

It has been found that the cartridge wound with the least package diameter of 60 mm showed the highest pressure drop, whereas the one with maximum diameter of 70 mm showed the least one. The cartridge with intermediate diameter showed intermediate pressure drop values. The figure 4.18 and figure 4.19 show the filtration characteristics at two different time periods during the test. When the cartridge is almost clean it can be observed that D1 shows greater frequency of particles in the downstream whereas D3 is better than the other two though its distribution is more towards the coarse particle size. But with time the scenario becomes quite different, with D2 consistent, D1 shows a shift in the retention distribution and D3 shows better results except the finer particles.

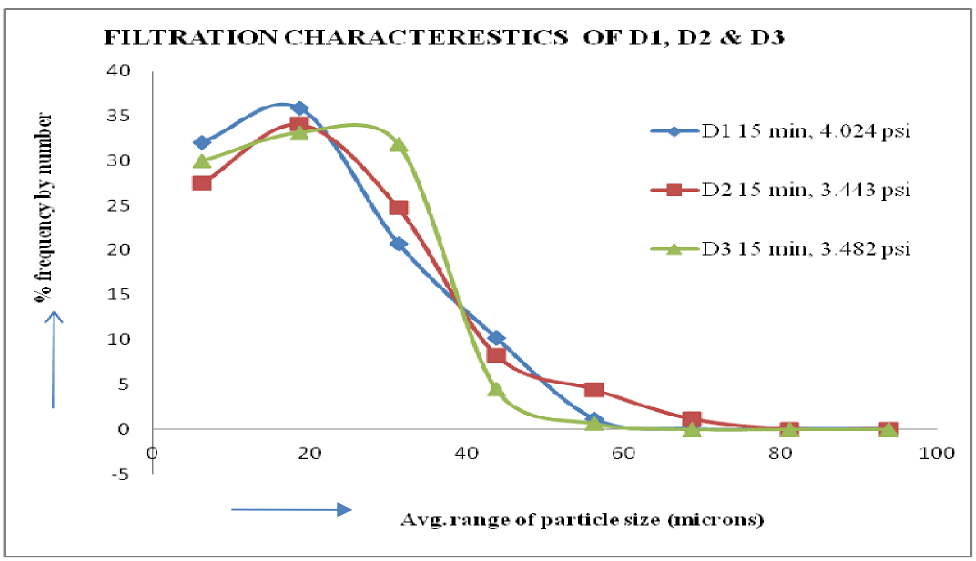

Figure 4.18 combined filtration characteristics of the three different diameters after 15 min of test time

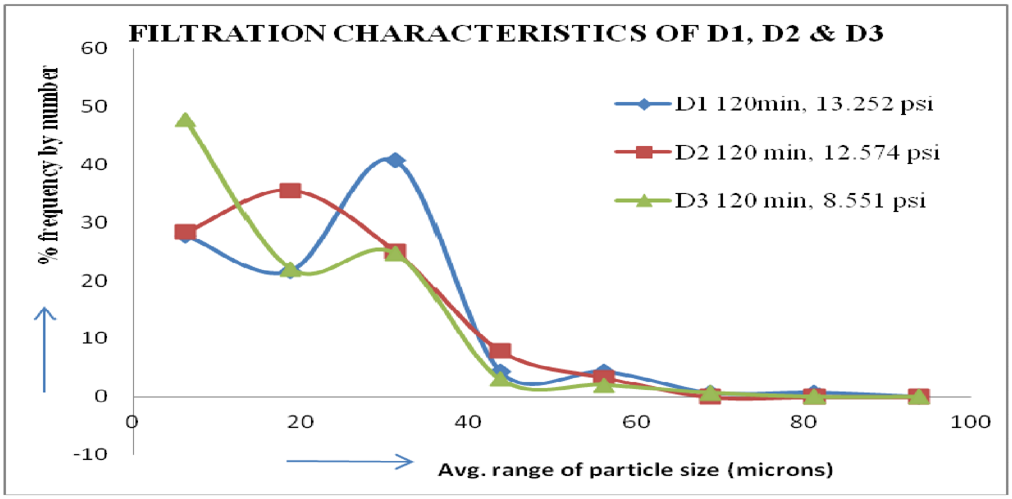

Figure 4.19 shows combined filtration characteristics of the three different diameter levels after 120 min of test time

The table 4.7 shows efficiency for Group – IV where cartridges have been produced with three different maximum diameters.

Table 4.7 shows the Retention Efficiency (RE) by number for Group – IV

Avg. dia	NUMBER RETENTION EFFICIENCY%								
	D1			D2			D3		
µm	15 min	45 min	120 min	15 min	45 min	120 min	15 min	45 min	120 min
93.75	100	100	100	100	66.42	100	100	100	100
81.25	100	100	55.32	100	100	100	100	100	100
68.75	100	100	55.32	71.26	86.57	100	100	90.09	86.95
56.25	82.11	53.21	55.32	52.10	55.23	/55.06	93.55	85.13	80.42
43.75	18.62	66.55	70.96	73.06	74.82	67.64	59.37	91.08	73.57
31.25	29.03	7.58	29.20	64.07	71.65	56.86	20.49	32.78	40.46
18.75	-4.64	50.12	70.96	71.26	67.77	53.40	37.12	0.55	57.17
6.25	-16.26	37.44	47.02	63.67	61.52	47.89	26.27	-49.51	-13.51

D1 has diameter of 60 mm that is a cartridge with least media thickness. Its retention efficiency for smaller particles is obviously poor and can be rated as 94 µm while D2 has a diameter of 65 mm that is a cartridge with intermediate value of media thickness amongst the three diameter values chosen. Its rating is approximately 69 µm whereas for cartridge with the largest diameter chosen, results found were not very encouraging and can be rated approximately as 81 μm. D1 and D3 both show poor retention and logical explanation for the same can be that when the cartridges reaches a diameter of 70 mm, the coil angle reduces to 6°, which is a typical characteristics of precision winding system. That is to say for each of the cartridges in this set, when winding is commenced the coil angle set was approximately 15° and by the time the package reaches its maximum package diameters of 60mm, 65mm and 70 mm, the coil angle reached would be approximately 8° 29', 7°51' and 7°17' respectively. At 60mm the coil angle is slightly greater than half of the starting value of desired coil angle, but for 70 mm it becomes almost half of the original value. Thus these values clearly show that by the end the cartridge approaches parallel winding and reduction in coil angle will be more in case of larger diameter of cartridge. The advantage of cross winding due to reduction in coil angle is completely lost in this case, especially when the coil angle selected is less (desired coil angle 15°) and more so with larger diameter. Hence in practice, cartridges of such low coil angles especially if larger diameters have to be provided are less preferred due to poor performance in spite of having greater yarn content.

Thus the increase in the thickness of the media can influence the filtration behavior provided a suitable coil angle/traverse ratio is selected.

4.1.5 GROUP – V:

The fifth parameter considered was the circumferential diamonds. Cartridge with one diamond means there will be one starting point around the circumference of the cartridge, two would mean two starting points and so on. More the number of circumferential diamonds more will the number of starting points and crossing points around the circumference of the cartridge, hence greater the scatter. For this group the three values of circumferential diamonds selected and denoted are 1 (/1), 2 (/2) and (/4) respectively. The figure 4.20 shows the pressure characteristics of cartridges wound with different circumferential diamonds.

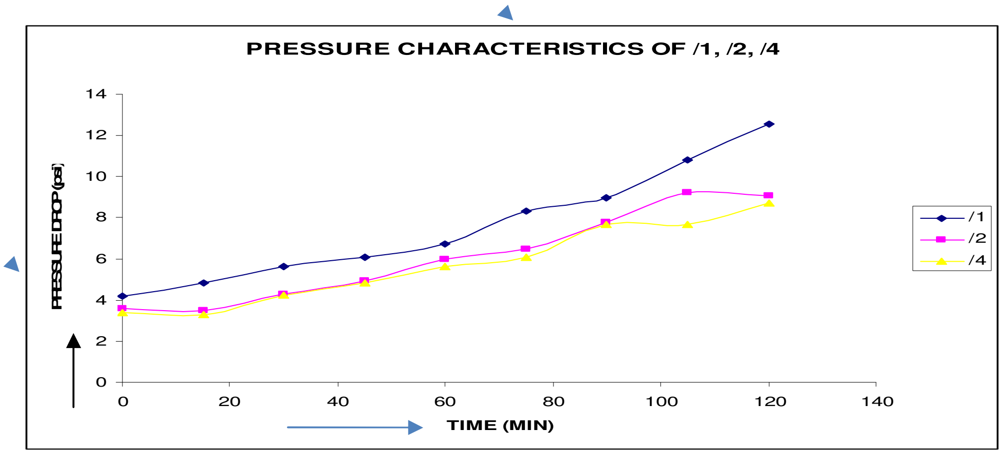

Figure 4.20 shows combined pressure characteristics of the three different circumferential diamonds with same number of coils/coil angles

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The cartridge with one circumferential diamonds shows the maximum pressure drop and steeper rise in the curve is observed towards end of the test while the one with four circumfernetial diamonds shows the least. The figure 4.21 and figure 4.22 shows the filtration characteristics taken at two different time intervals. Cartridge with one diamond shows lesser frequency of particles coming in the downstream whereas with the two diamond and four diamond, though, two is better than four but their behaviour can be considered to be very close to each other. Towards the end of the test the retention of smaller particles is poor in case of both two and four circumferential diamonds, though four exhibits better retention of coarser particles that two. The one diamond cartridge is still able to exhibit comparatively better retention.

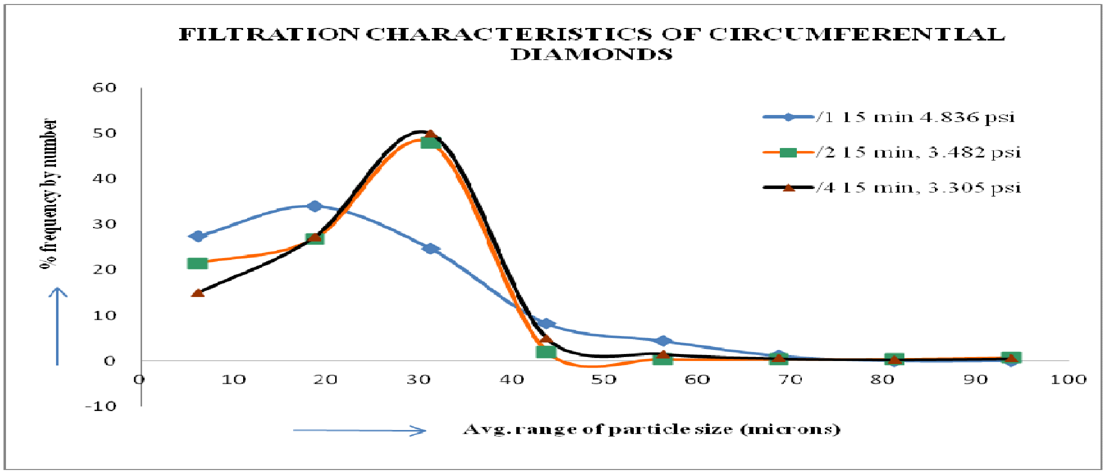

Figure 4.21 shows combined filtration characteristics of the three different circumferential diamonds after 15 min of test time

Thus as the number of circumferential diamonds increase even though the pressure drop developed is less, the number of crossing points present on the same area are more. Hence there are greater number of entry points available for the slurry to pass through them. Thus it can be said that with change in the number of circumferential diamonds the nature of porosity of the cartridge also changes.

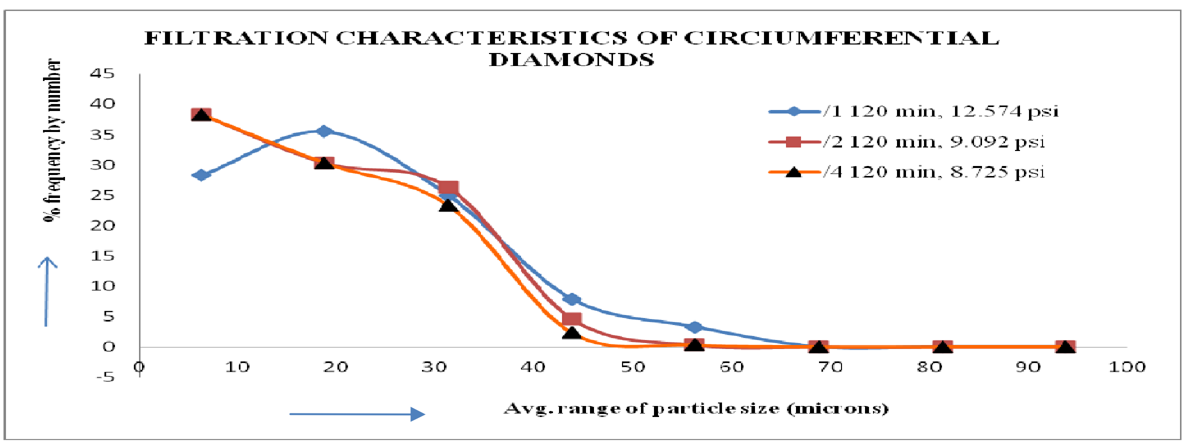

Figure 4.22 shows combined filtration characteristics of three different circumferential diamonds after 120 min of test time

Hence with time they show an increase in the % frequency of number of particles coming in the filtrate. Higher number of circumferential diamonds may be selected if a compromise is to be reached with the pressure drop. The table 4.8 shows efficiency for Group – V where cartridges have been produced with three different circumferential diamonds.

The table 4.8 shows efficiency of the cartridges produced with the three different values of circumferential diamonds. Cartridge with one and two circumferential diamond may be rated as approximately 56 µm while the one with four circumferential diamonds as approximately 69 µm.

Table 4.8 shows the Retention Efficiency (RE) by number for Group – V

Avg. dia	NUMBER RETENTION EFFICIENCY%								
	/1			/2			/4		
µm	15 min	45 min	120 min	15 min	45 min	120 min	15 min	45 min	120 min
93.75	100	69.53	100	42.60	203.99	100	23.77	100	100
81.25	100	100	100	82.81	135.99	100	87.30	100	100
68.75	74.33	80.88	100	91.41	102.00	100	87.30	85.64	84.15
56.25	57.22	36.28	76.86	92.63	135.03	86.41	67.33	63.08	72.83
43.75	67.91	52.21	61.55	88.54	22.84	50.68	71.77	74.47	68.30
31.25	63.90	54.60	54.34	14.27	-29.78	12.63	11.36	-3.18	17.05
18.75	58.55	40.26	45.93	54.67	-51.79	4.89	54.35	-14.55	-2.43
6.25	41.66	11.37	24.85	56.00	-35.72	-45.84	69.51	-3.38	-52.18

Though their ratings may not be very different, the retention efficiency is quite different. All the three show good retention efficiency till an average particle size of approximately 56.25 µm but as the particle size becomes finer; the efficiency of cartridges towards the end of the test for two diamonds reduces and drops even further in case of four circumferential diamonds. The pressure drop reached by one circumferential diamond was more so it is expected that had the cartridge with four circumferential diamonds been tested till it reached the same pressure drop as the one diamond then there would be further deterioration in its retention efficiency. Some values in the 120 min also show negative readings, which indicates that the number of particles coming in the filtrate is larger than the number of particles in the inlet. With the particle size distribution remaining same, this should not happen but it can happen only due to the release of already trapped particles and that too due to pressure rise. Cartridges in this group have been produced with maximum tension and close wind. It has already been established in the earlier group wise conclusion that higher tension has resulted in the poorer retention efficiency of smaller sized particles while gain is effective in trapping the larger particles only. Hence with this combination owing to the higher tension, retention of particles inside the yarn structure will be less and greater number of crossing points also becomes potential sources through which finer particles can easily pass.

4.1.6 GROUP – VI:

The sixth variable considered was the rotational speed of the cartridge. The cartridges were produced at three different rotational speeds namely 225 rpm, 425 rpm and 625 rpm. The figure 4.23 shows a plot of pressure characteristics of the three speeds in this group. Here one thing should be noted though that this group was designed to find the effect of rotational speed. Hence the tension level selected was 145 gm, which was maintained at all the speed levels. Tension is manifestation of speed. When a cartridge is rotated at higher rotational speed, its surface speed will also be high. Thus with the increase in package diameter, tension on the yarn also increases.

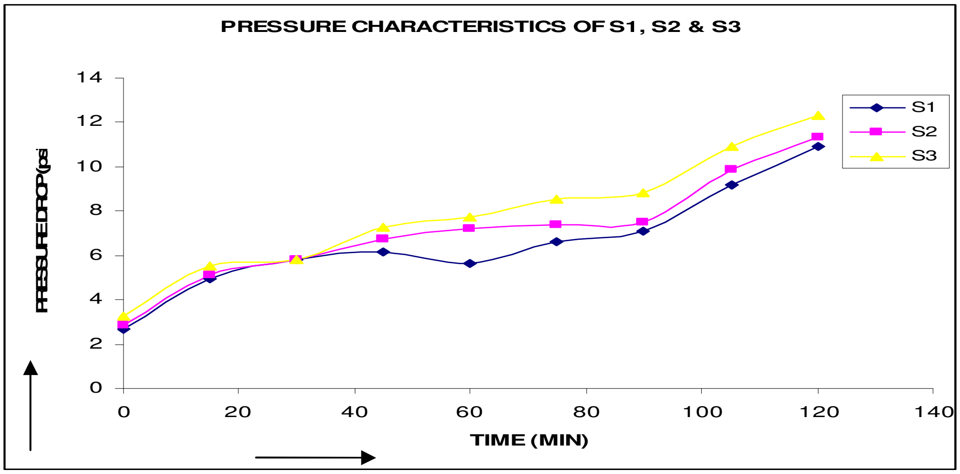

Figure 4.23 shows combined pressure characteristics of the three different speed values with same number of coils/coil angles

The figures 4.24 and 4.25 show filtration characteristics of cartridges tested at different speeds and at two different time periods. The cartridge wound at higher rotational speed would develop higher tension due to which the cartridge would be compactly wound, which is also reflected in the % frequency of particles collected in the filtrate.

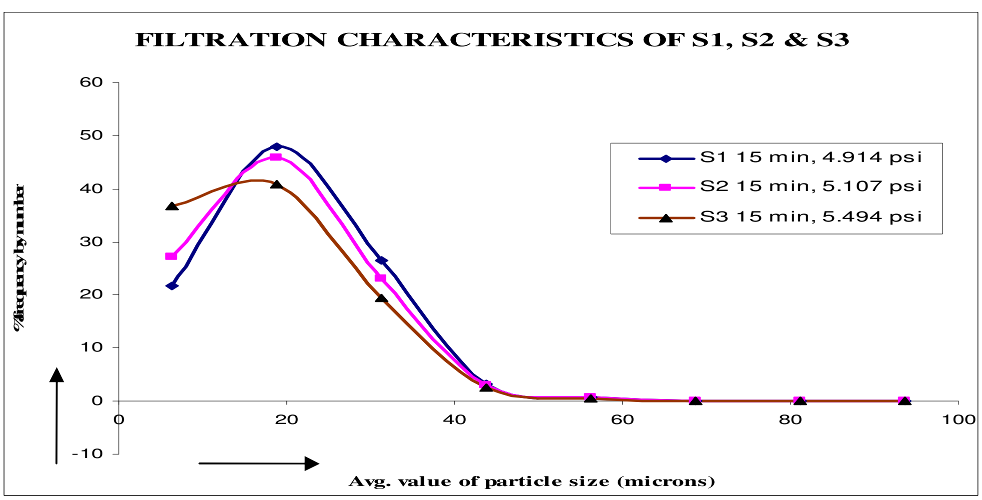

Figure 4.24 combined filtration characteristics of the three different speed values after 15 min of test time

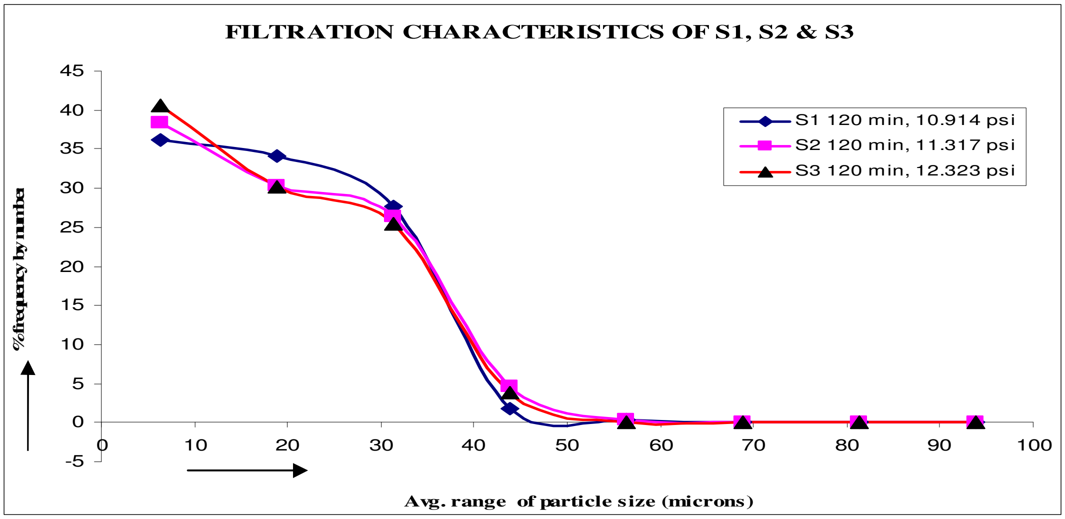

Figure 4.25 combined filtration characteristics of the three different speed values after 120 min of test time

The poor retention of finer particles can be attributed to the fact that with the increase in the rotational speed the yarn, causes an increase in the winding on tension due to which the yarn more compact hence does allow the slurry to pass through it very easily and hence come out in the filtrate. With increase in pressure it becomes more likely that the smaller particles which were trapped within the filter media are forced into the filtrate. The distribution also shows a swing to the coarser particle size. Thus this effect is in close adherence to the results obtained for cartridges tested at different tension levels.

Table 4.9 shows retention efficiency for Group – VI, where cartridges have been wound at three different rotational speeds. The ratings of cartridge wound at 225 rpm could be approximately 44 µm whereas the cartridges wound at 425 rpm and 625 rpm would be approximately 56 µm. There is no significant change in the rating of the cartridges.

Table 4.9 shows the Retention Efficiency (RE) by number for Group –VI

Avg. dia	NUMBER RETENTION EFFICIENCY%								
	S1			S2			S3		
µm	15 min	45 min	120 min	15 min	45 min	120 min	15 min	45 min	120 min
93.75	100	100	100	100	100	100	100	100	100
81.25	100	100	100	100	100	100	100	100	100
68.75	100	82.44	100	100	100	100	100	78.54	100
56.25	88.38	86.83	93.73	87.39	93.45	94.73	91.76	91.06	100
43.75	75.74	83.97	83.64	71.18	66.33	57.88	67.03	70.19	57.00
31.25	30.26	23.75	13.25	42.53	34.36	36.81	39.03	44.14	28.43
18.75	22.59	47.81	37.50	15.93	38.17	46.76	16.11	42.52	44.71
6.25	51.45	39.33	3.80	28.37	-2.66	3.12	-18.41	22.92	-17.19

The cartridges wound with at slower rpm come under less amount of tension level hence retention efficiency observed is better at the same time less pressure drop is achieved due to which, at least the trapped particles do not get discharged into the filtrate. As speed increases the tension also increases along with the increase in pressure drop with time. This results in the greater amount of smaller particles being present in the filtrate.

4.1.7 GROUP – VII

The seventh variable considered was the count of the feed material. Three different counts have been considered for this group namely 0.4's Ne, 0.6's Ne and 0.8's Ne. These counts were readily available and hence have been selected. The figure 4.26 shows the combined pressure characteristics of cartridges wound using feed yarn with different counts. C3 is the finer yarn while C1 is coarser yarn and C2 stands for the intermediate yarn count. The pressure drop across finer is higher than the coarser. The figure 4.27 and figure 4.28 show the filtration behavior of cartridges wound with different count of the feed material. The number of finer particles coming in the filtrate for C3 is almost same as the other two counts.

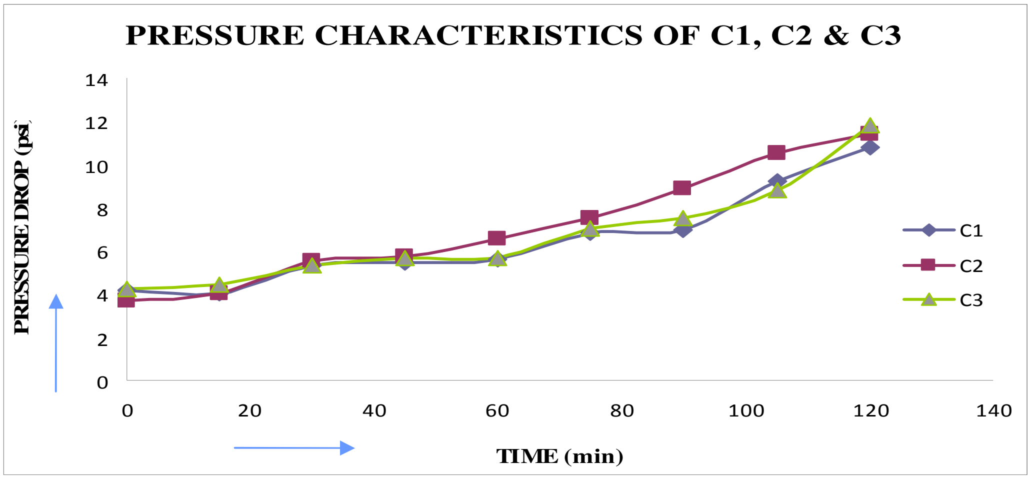

Figure 4.26 shows combined pressure characteristics of the three different count values with same number of coils/coil angles

The distribution of C1 and C2 is rather on the coarser side. But at the same time the pressure developed across C3 is the highest amongst the cartridges produced by winding three different yarn counts.

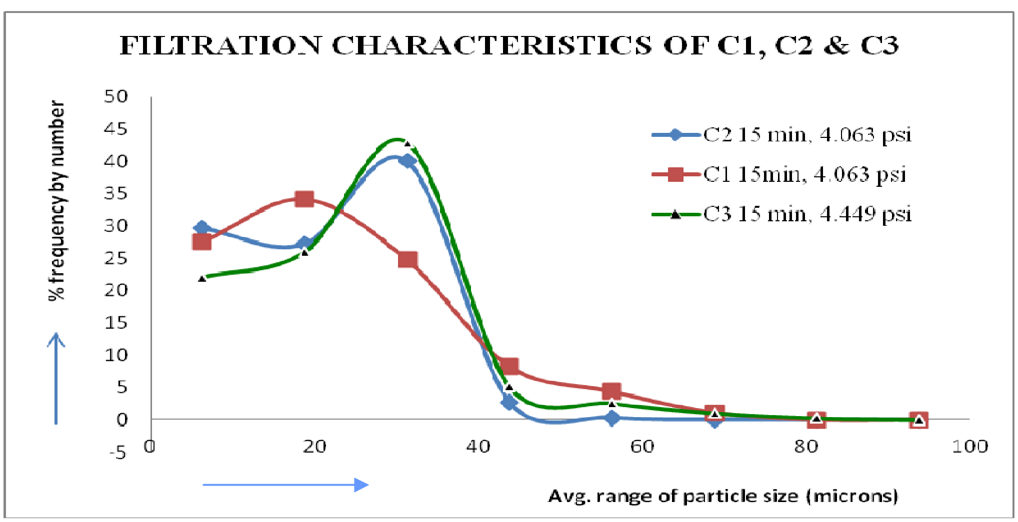

Figure 4.27 shows combined filtration characteristics of the three different count values after 15 min of test time

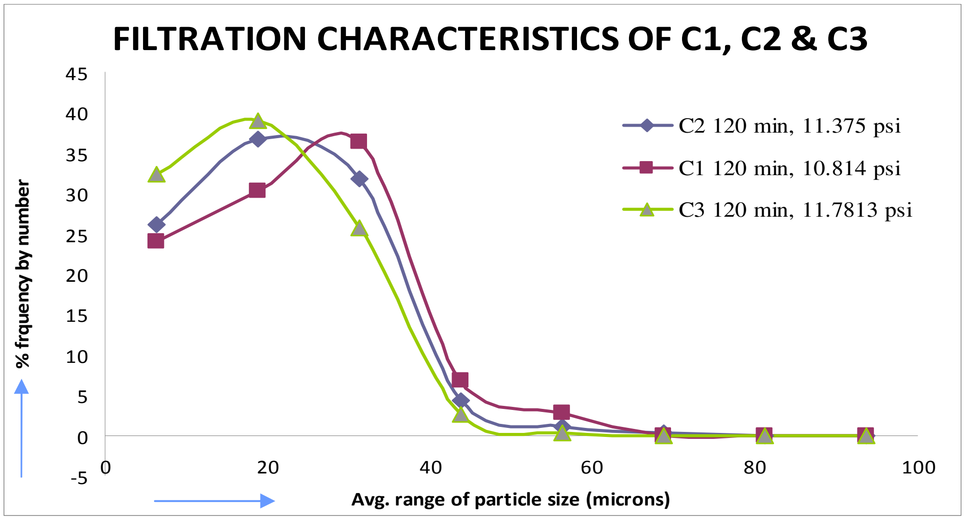

Figure 4.28 shows combined filtration characteristics of the three different count values after 120 min of test time

The table 4.10 shows efficiency for Group – VII where cartridges have been wound with three different counts.

Table 4.10 shows the Retention Efficiency (RE) by number for Group –VII

Avg. dia	NUMBER RETENTION EFFICIENCY%								
	C1			C2			C3		
μm	15 min	45 min	120 min	15 min	45 min	120 min	15 min	45 min	120 min
93.75	100	69.53	100	100	-25.32	100	100	100	100
81.25	100	100	100	100	100	100	70.73	65.31	100
68.75	74.33	80.88	100	100	100	77.43	53.17	72.25	100
56.25	57.22	36.28	59.95	89.62	100.00	72.91	58.18	90.09	86.67
43.75	67.91	52.21	61.55	56.31	60.42	38.22	46.78	49.55	40.62
31.25	63.90	54.60	54.34	-50.46	-3.39	-9.48	-20.74	-35.27	-63.30
18.75	58.55	40.26	45.93	18.84	-35.25	-0.12	38.38	-67.95	-108.24
6.25	41.66	11.37	24.85	-10.17	-43.89	10.83	27.88	-87.00	-138.02

C1 shows better retention of finer particles than C3. When finer yarn is wound, in order to achieve the same package diameter, the number of strokes made are higher. The yarn content is more as the yarn is more compact, but due to this, it offers greater resistance to flow of the slurry and also is not able to trap the finer particles efficiently. It does not show improvement in the filtration with time and its reason is related to spinning of the yarn. Practically in the industry, when the count of yarn is to be changed, the feed and the delivery speeds are adjusted with the number of doublings remaining the same. With an increase in the speed the yarn becomes compact due to reduction in the number of fibers in the cross section which implies that there will be lesser number of fibres in case of finer fibers to resist the flow hence inspite of greater yarn content. It shows poor retention of finer particles because these cartridges have been wound with maximum tension level and close wind. If the fiber denier is changed (finer) then only the filtration would be improved in this case.

4.2 Comparative study under taken to find whether the cartridges produced on the fabricated winder is at par with the cartridge produced on commercial winders.

4.2.1 Introduction:

In the initial chapters already discussion was made regarding the fabrication and development work under taken to establish and alternative to cam traversing method of yarn traverse. Though the system developed was satisfactory it was necessary to establish whether it was equivalent to the already existent winders. Hence trial work was carried out at KBS filters G.I.D.C at Makarpura in Vadodara. The trial was restricted to two winding parameters namely the traverse ratio and the tension. The main aim was only to establish whether the results obtained using newly developed winder were close enough to the ones obtained using commercial winder. So this was the real test of the new winding machine and the new testing apparatus which was fabricated. While taking trials the other winding parameters like speed, gain, package diameter etc. were maintained almost identical as the newly developed filter winder.

4.2.2 Group – I

In this group cartridges of identical coil angles/traverse ratios were selected so that comparison could be made. CW 1 indicates commercial winder and 1 stands for ATR of 16.89. The pressure characteristics are similar to the ones for the cartridges produced on newly developed filter winder. Here also the outlet pressure is almost constant, inlet steadily increases and the pressure drop also shows similar trend as inlet.

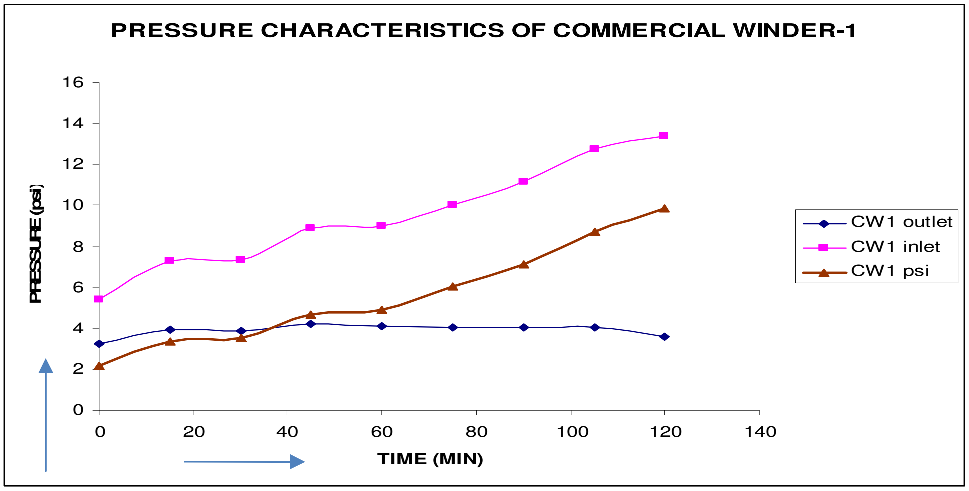

Figure 4.29 shows pressure characteristics of cartridge with desired coil angle/no. of coils 15°/16.89

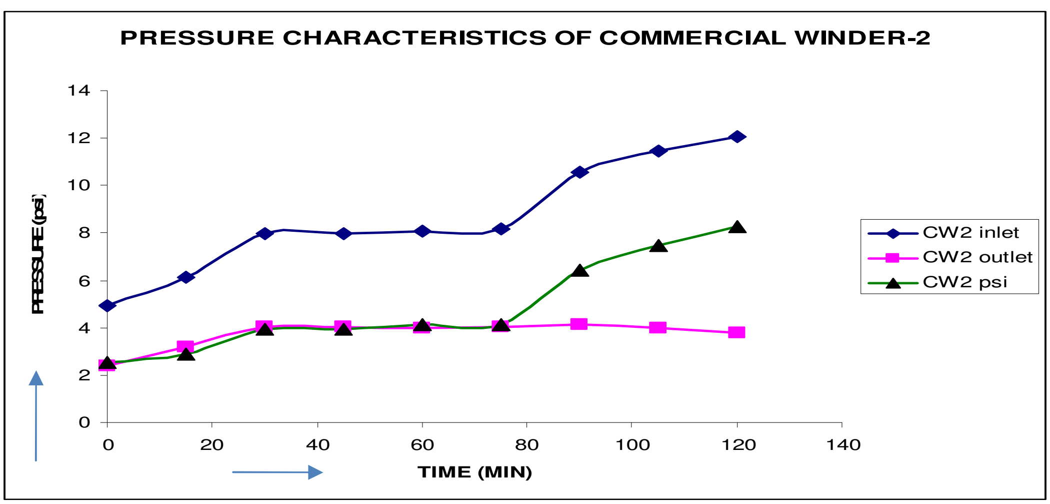

Figure 4.30 shows pressure characteristics of cartridge with desired coil angle/no. of coils 25°/9.9357

Figure 4.30 shows pressure characteristics for commercial winder producing cartridge with ATR with of 9.9357 and 2 stands for 9.9357. CW-3 is the cartridge that wound with ATR of 6.9512 and shows the least pressure drop. The next figure 4.31 shows a combined plot of pressure characteristics of the three different coil angles/traverse ratios together. The figure 4.32 and figure 4.33 shows the combined plot of filtration behavior of the cartridges wound with three different coil angle/traverse ratio, reported over a definite time period. The cartridge with highest number coils shows a distribution on the coarser size range than the other two traverse ratios. CW-2 and CW-3 show poor retention of smaller particles. But overall these two cartridges are close to one another and are markedly different than CW-1.

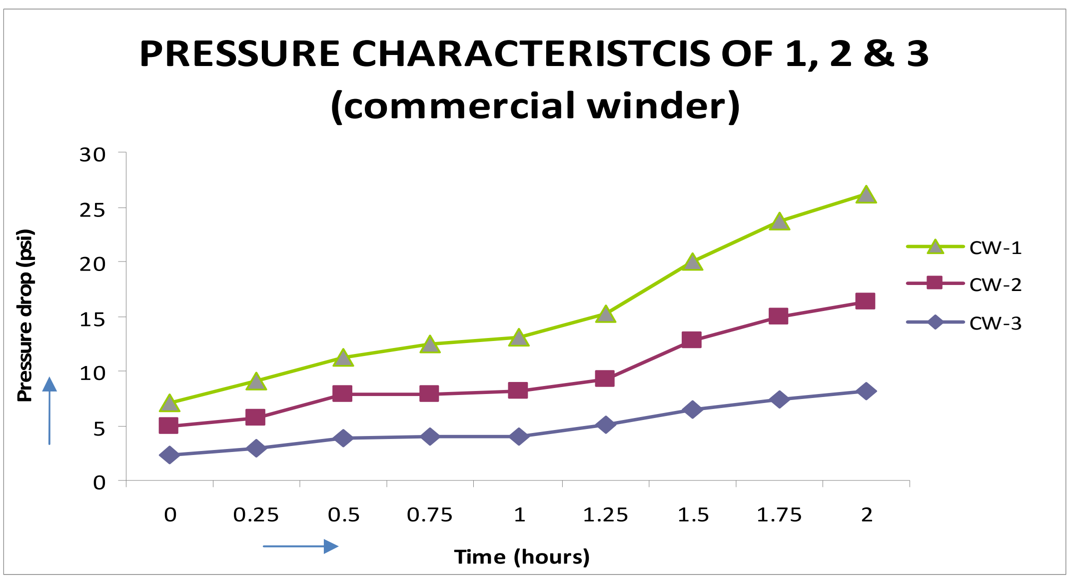

Figure 4.31 shows combined pressure characteristics of the three different number of coils/coil angles

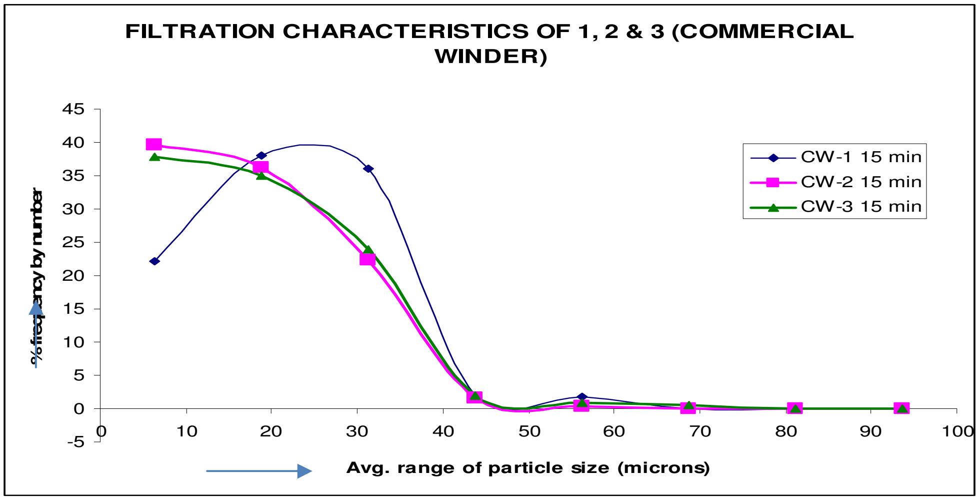

Figure 4.32 shows combined filtration characteristics of three different coil angles after 15 min of test time

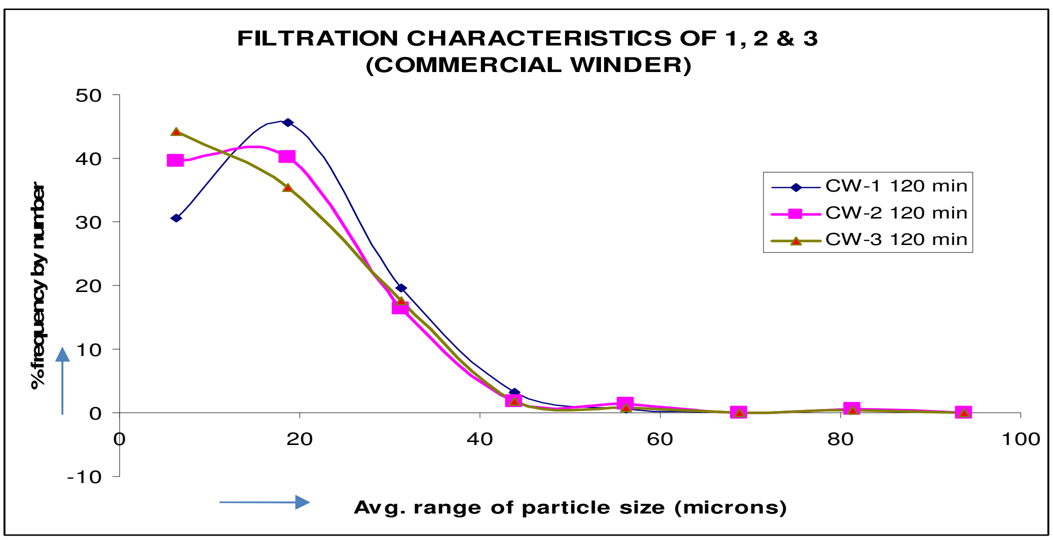

Figure 4.33 shows combined filtration characteristics of three different coil angles after 120 min of test time

Figure 4.34 shows comparative pressure plot of cartridges with same traverse ratio produced on commercial winder and those produced on newly developed filter winder.

They are very close to each other only thing is that the cartridge produced on newly developed filter winder shows a rapid increase in pressure towards the end of the test.

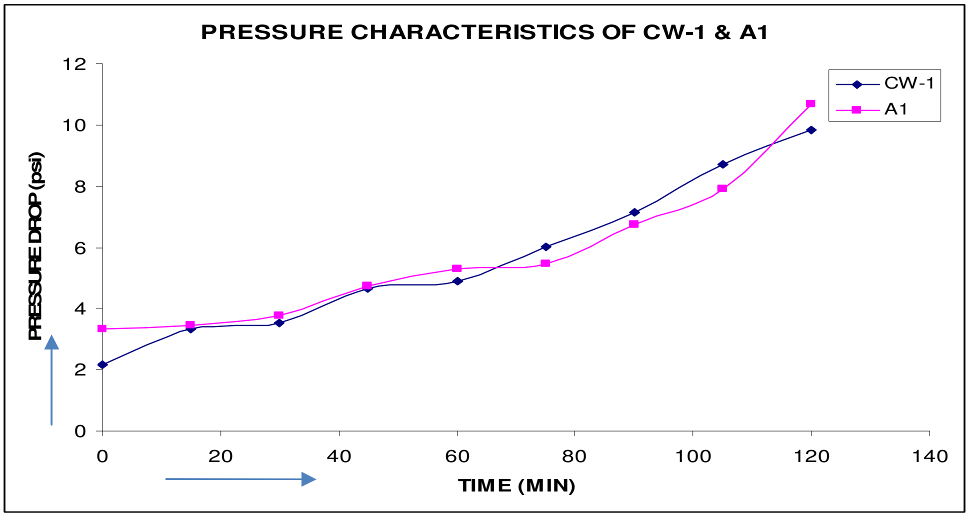

Figure 4.34 shows comparative pressure characteristics of cartridge wound with same coil angle but produced on two different winding machines

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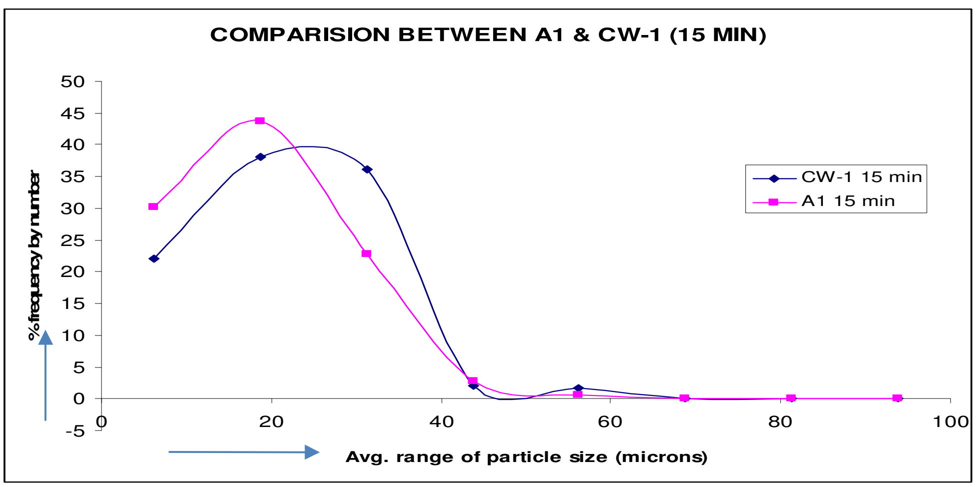

Figure 4.35 comparative filtration characteristics of cartridge wound with same coil angle (ATR=16.894) but produced on two different winding machines (15 min)

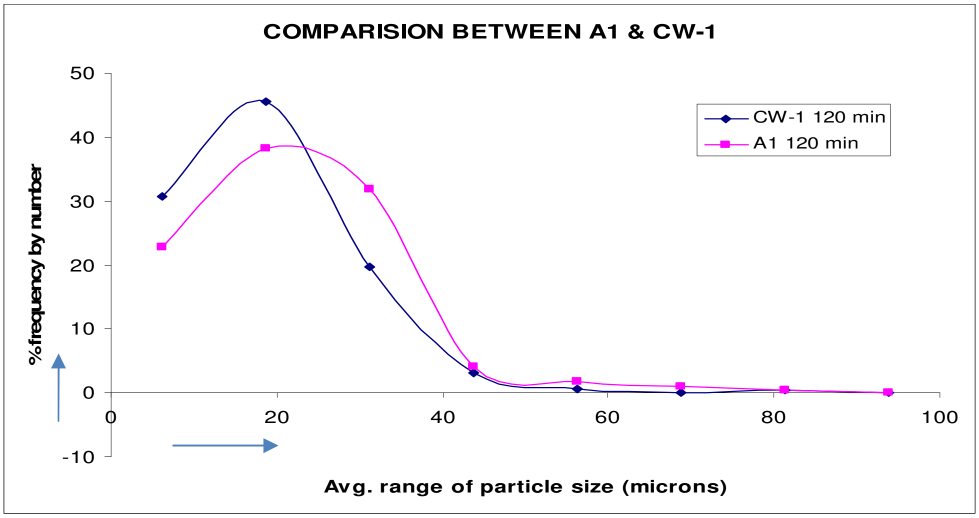

Figure 4.36 comparative filtration characteristics of cartridge wound with same coil angle (ATR=16.89) but produced on two different winding machines (120 min)

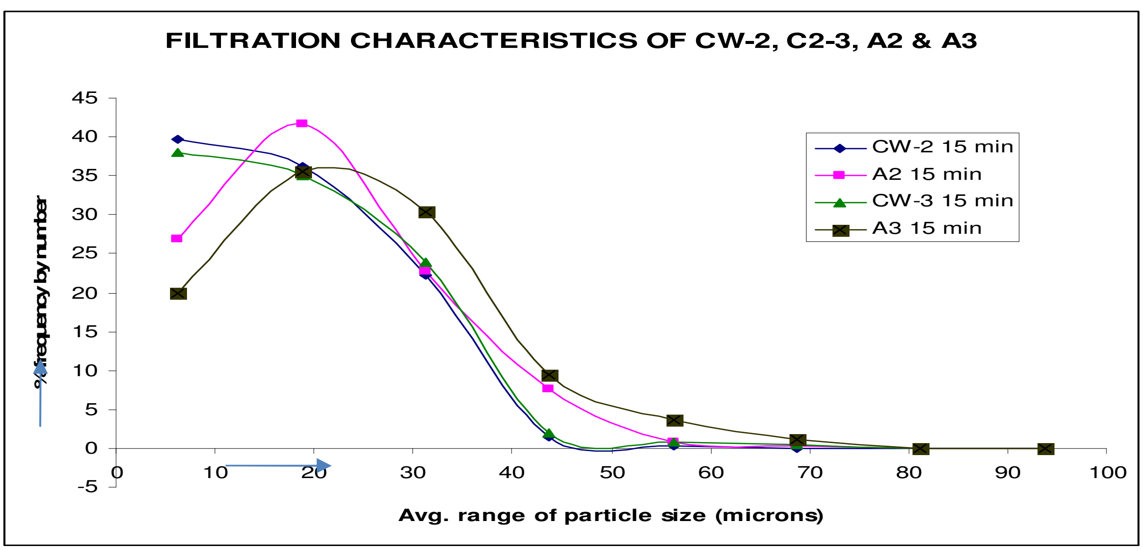

Figure 4.37 comparative filtration characteristics of cartridge wound with same coil angle but produced on two different winding machines (15 min)

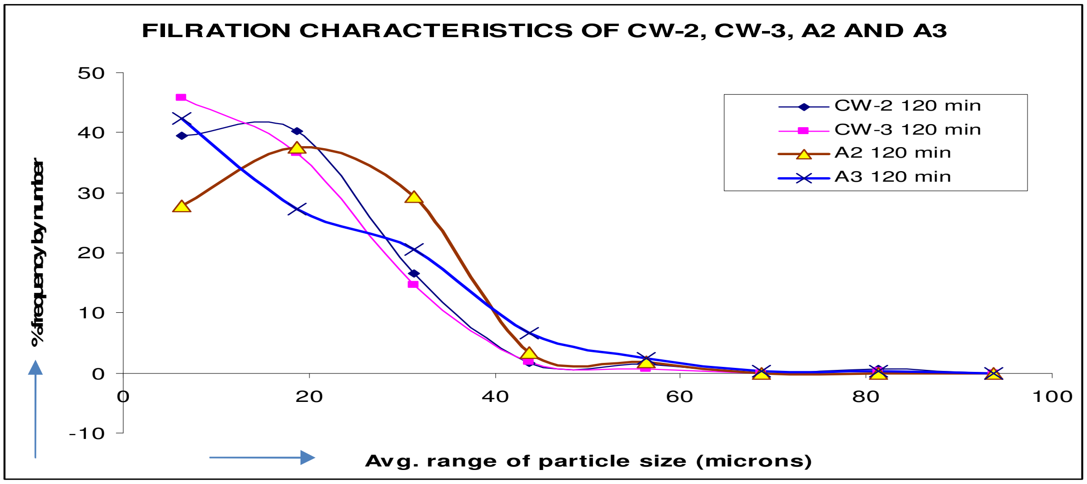

Figure 4.38 comparative filtration characteristics of cartridge wound with same coil angle but produced on two different winding machines (120 min)

Figures 4.35 and 4.36 show the filtration characteristics of cartridges produced on commercial and fabricated winders of the same coil angle, whereas figure 4.37 and figure 4.38 shows the filtration characteristics for the cartridges produced with the other two coil angles at test time of 15 min and 120 min respectively. In the initial stage the cartridge produced on newly developed filter winder shows greater % frequency of particles coming in the filtrate but with time it shows improvement and also shows a slight shift in the distribution on the coarser particle size. This can be due to higher pressure build up in case of cartridges produced on newly developed filter winder; coarser particles would be forced through the media matrix into the filtrate. All the three cartridges produced with different traverse ratios/ coil angles and can be rated as approximately 69 µm. Thus a tremendous difference in the ratings of the cartridges prodced on fabricated winder and commerical winder is seen. On newly developed filter winder, the cartridge denoted as A1 gives a rating of 7 µm and for A2 and A3 it is approximately rated as 69 µm. This can only be attributed to the difference in the pressing arrangement used on both the winding machines. The cartridges produced on newly developed filter winder and the commercial winder show a similar trend of the particles found in the filtrate. With time (120 min), the finer particles being captured by the cartridge produced on commercial winder may be less but larger particles are trapped better. Similarly for the other coil angle the particles with an average diameter of 6.25 µm may be found less for the fabricated winder but between 18.75 µm and 31.25 µm, commercial cartridge retention is better after which they are showing similar contour.

4.2.3 GROUP-II

In this group the next important winding variable namely, tension has been considered. The packages wound on commercial winder were wound at almost identical conditions. The figure 4.39 shows a combined plot of pressure characteristics during trials of cartridges wound with three different tension levels. The one with minimum level of tension shows the least pressure drop.

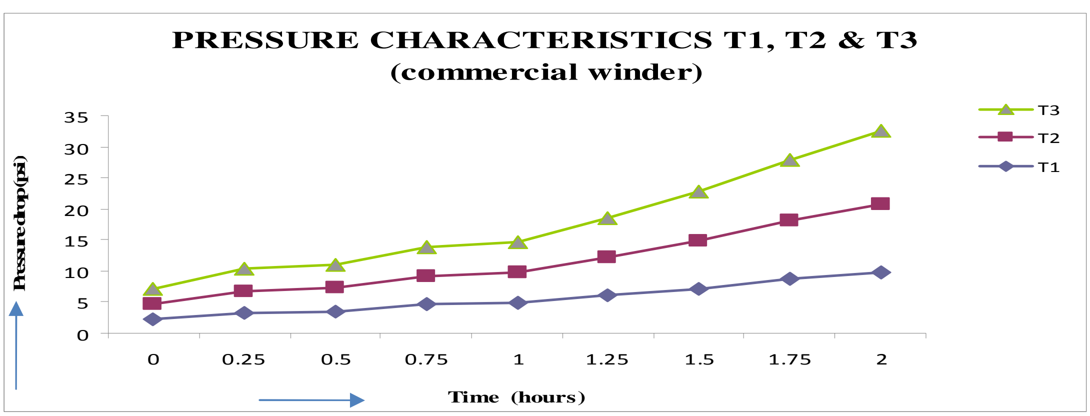

Figure 4.39 shows pressure characteristics of cartridge produced at three different tension levels

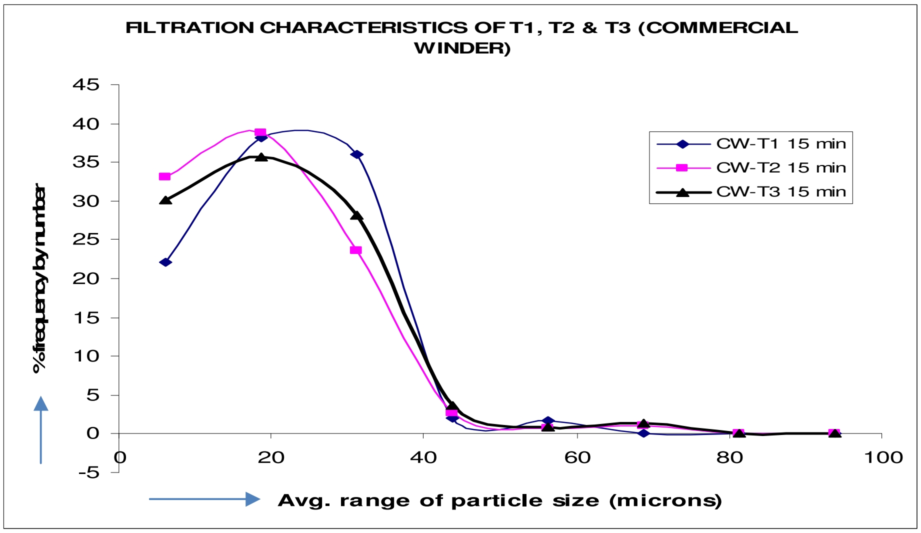

Figure 4.40 filtration characteristics of cartridge produced under three different tension levels after 15 min of test time

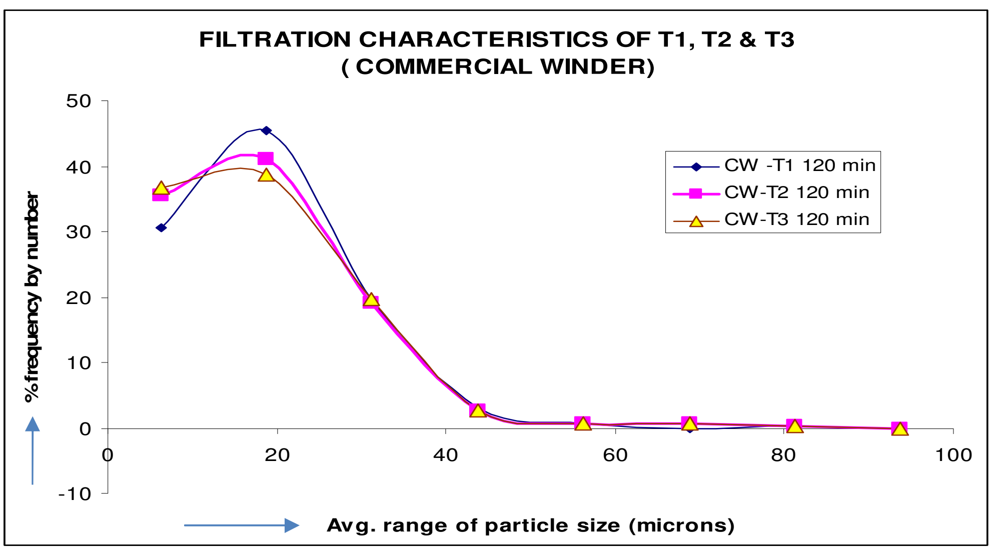

Figure 4.41 shows filtration characteristics of cartridge produced at three different tension levels after 120 min of test time

The figure 4.40 and figure 4.41 show the filtration characteristics of the cartridges wound on commercial winder under different tension levels. During the initial part of the test the cartridge with highest tension shows better retention and is maintained, even towards the end of the test. The cartridge wound with maximum tension level shows broader distribution initially and is different for all the three cartridges tested but towards the end of the test the distributions match. Figure 4.42 and figure 4.43 shows a comparison between cartridge wound on commercial winder and newly developed filter winder with same coil angle and tension at time intervals of 15 min and 120 min. Though the % frequency of particles in the filtrate is greater, the distribution is on the finer particle range for cartridge produced on newly developed filter winder. But in figure 4.43, the particle size distribution for the cartridge produced on newly developed filter winder after 120 min shows improvement though retention of particles of average diameter of 31.25 μm is poorer than that in case of cartridge produced on commercial winder.

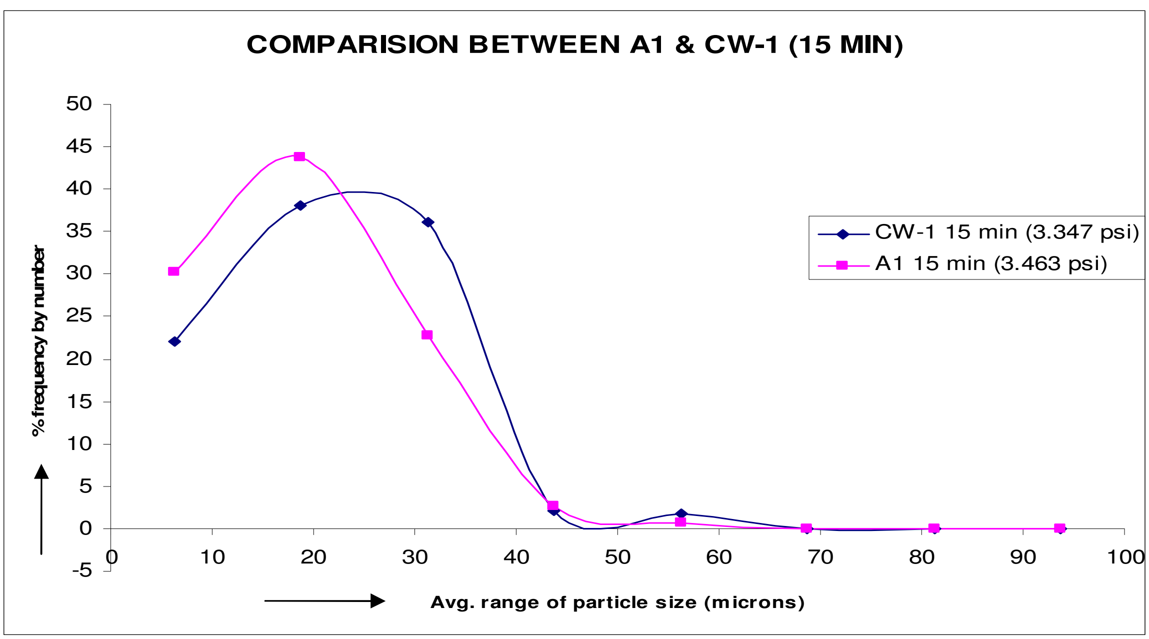

Figure 4.42 shows comparative filtration characteristics of cartridge wound with same coil angle but different tension and produced on two different winding machines

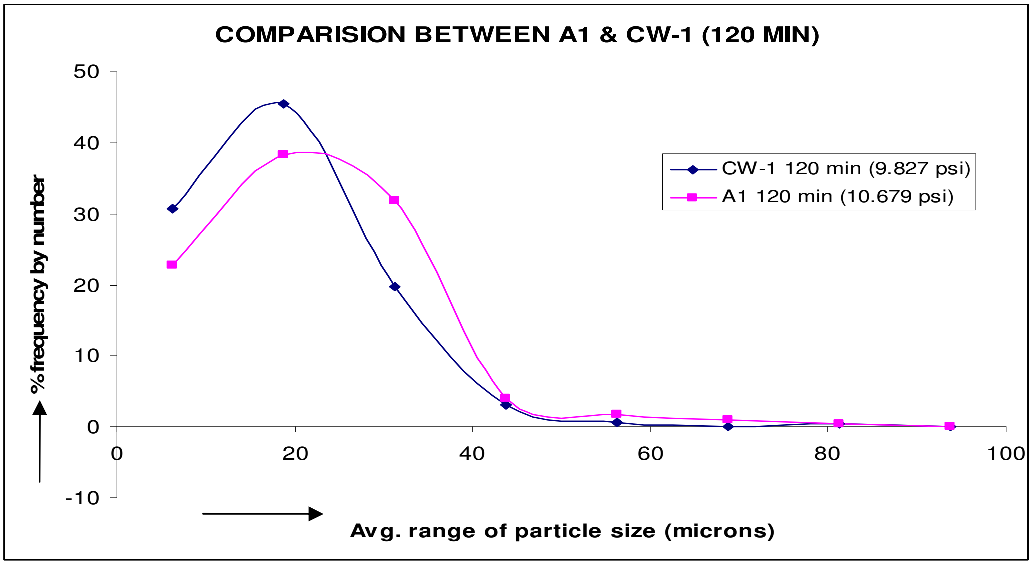

Figure 4.43 shows comparative filtration characteristics of cartridge wound with same coil angle but different tension and produced on two different winding machines

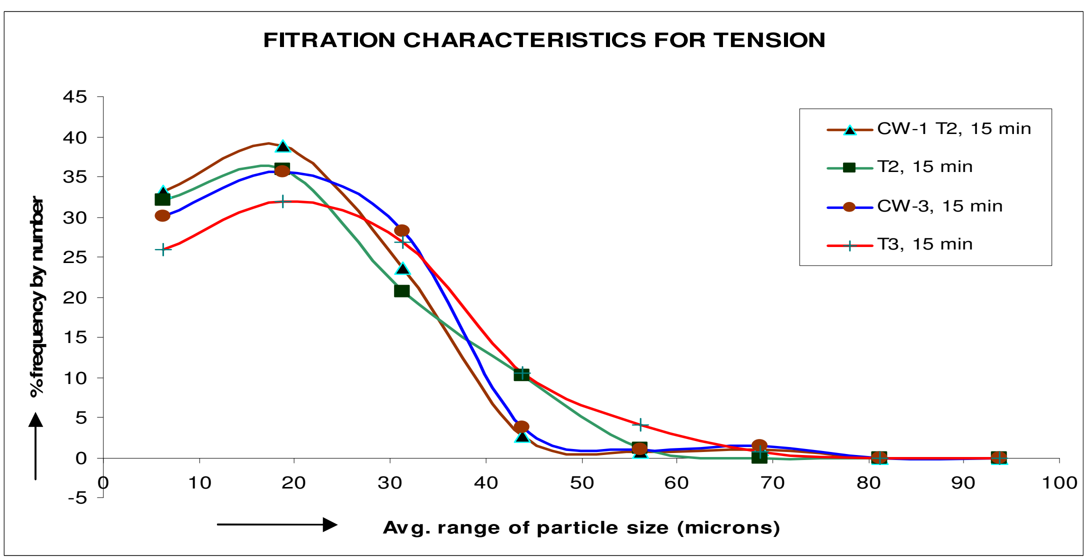

Figure 4.44 combined plots for cartridges produced under different tension levels after test time of 15 min

The figure 4.44 and figure 4.45 show combined plot of % frequency of particles in the filtrate of the cartridges produced on commercial and newly developed filter winder wound under different tension levels and at 15 min and 120 min respectively.

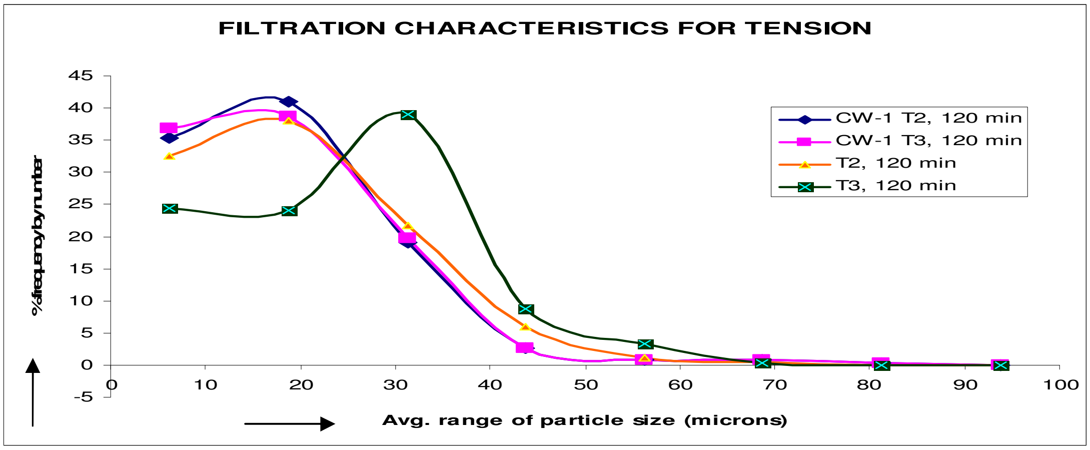

Figure 4.45 combined plots for cartridges produced under different tension levels after test time of 120 min

It will be observed that the trend exhibited in each case match with one another. The cartridge produced on newly developed filter winder exhibit lesser % frequency of particles in the filtrate. But with time the retention efficiency of particles having an average diameter of 31.25 µm in case of cartridge wound with maximum tension produced newly developed filter winder shows deterioration. A change in distribution is observed.

Thus it can be said that the cartridges produced on the newly developed filter winder and commercial winder show similarity in their results. Hence both the systems are comparable and that the newly developed filter winder developed is equivalent to that of the commercial winder. The most important feature of the newly fabricated winder is that it can even be operated on the step precision winding principle.

CHAPTER – V

SUMMARY

AND

CONCLUSION

5.1 Summary:

The group wise work discussed in chapter – IV gives an insight into the influence of winding parameters on the performance of cartridges. Group – I was designed to make comparison between cartridges of three different traverse ratios. There is significant difference not only in their filtration behavior but also in their ratings. The retention efficiency for the smaller sized particles and rating was less for cartridges wound with fewer coils than that of cartridges wound with greater number of coils. The reason is quite clear here that a cartridge which has more amount of yarn offers greater resistance to the flow of fluid under the given test conditions, in spite of the fact, that such a cartridge is able to retain large amount of dust (final package weight with dust and retention efficiency), but during test conditions the build-up of pressure occurs at a faster rate due to which it discharges greater amount of particles in the filtrate. Such cartridges not only have different ratings; but they also have the capacity to capture smaller sized particles with better efficiency than the cartridges wound with greater coil angle or with lesser number of coils. Thus cartridges with more number of coils show better micron rating at the same time their retention efficiency is better. The greater % frequency of particles by number observed in the filtrate can be related to the test method adopted. The test rig developed was to work on single pass method, where the flow rate had to be maintained constant. During the trials it was observed that the by pass valve needed to be closed so that the flow rate remained constant. The moment this valve was adjusted, changes in the fluid dynamics would definitely occur, though they were not visible due to non-transparent housing. And by chance if it coincided with sample withdrawal, this would result in untrue conclusion. So care has been taken to prevent this thing from happening. Gradual build up in pressure would force the already trapped particles to come into the filtrate; hence filtrate shows greater frequency of particles. Thus more the number of coils finer would be the cartridge's micron rating but poorer would be its service life.

In the second group the coil angle/traverse ratio was maintained constant, but the winding on tension was increased. It was observed that the cartridges which were wound under the minimum tension and minimum coil angle (highest number of coils), showed a greater tendency of bad edges and similar trend is seen for cartridges wound on commercial winder also. The edges significantly improved upon increasing the tension and coil angle. Cartridges wound with larger coil angles shows perfect edges and there was considerable amount of reduction in the disturbance of coil lay. The cartridges with smaller coil angle showed a sort of disturbed appearance due to reduction in coil angle towards the full package diameter stage. The filtrate samples collected in the initial part of the test for cartridges wound with different tension levels showed that the one wound with higher tension showed greater frequency of particles in the filtrate but with time though the frequency of particles is less, the peak point of the distribution shifts notably on the coarser side. Due to tension the yarn becomes more compact, there by reducing its area, hence the number of particles which can get loaded inside it also reduces and hence with time it is rendered incapable of trapping the smaller sized particles effectively. Cartridge wound with least tension also shows much higher rating than that of those wound with higher tension.

But instead gain shows a clear cut trend. When the coils are closely packed the particles coming in the filtrate are comparatively less and with time the different gains show tremendous difference in their performances. Though these cartridges are not significantly differently rated, the % frequency of particles in the filtrate is less as compared to the cartridge with open wind.

The increase in package diameter though did not give the required results due to the selected winding variable. The increase in circumferential diamonds could not show improvement in the filtration characteristics, but the pressure drop is much less. Thus the change in the circumferential diamonds is one of the ways in which the porosity of the cartridge wound with same number of coils can be changed. Speed has an effect of increasing tension, the tensioning arrangement being set to apply the same tension, the cartridge wound at highest speed, show better results. The count, as it became finer did not show improvement in the retention of finer particles, the number of fibers in the cross-section reduces; hence the filtration efficiency also reduces.

5.2 Conclusion:

When comparison is made between different coil angles, the coil angle with most inclination shows better filtration behavior in terms of particles collected in the filtrate. But retention efficiency of cartridge with more number of coils observed is more. There is still scope of improvement in the filtration apparatus by using a valve which can give a smooth change in pressure, since the amount of particles in the filtrate is greatly dependent on the pressure and the time at which the sample is drawn. With higher winding on tension the retention of larger particles improved but the smaller ones were seen in larger numbers and that is due to the yarn getting more compact when it is wound with higher tension. But a cartridge wound with less tension definitely shows a better rating than the one with higher tension. Within the same coil angles, gain and the winding on tension shows significant effect on the filtration behavior. It has been clearly seen in the results that increasing the coil spacing on the cartridge definitely reduces the retention efficiency for larger as well as the smaller sized particles. The retention efficiency of both the intermediate as well as close wound cartridge improves but tension is more significant with respect to removal of finer particles and rating. Cartridge with intermediate gain and close wind do not show any significant difference in their retention efficiencies. The diameter increase for the examined traverse ratio does not show improvement in trapping the smaller particles, but may change if the coil angle is increased. The increase in layer thickness can be significant for larger coil angles. The circumferential diamonds due to increase in the number of starting points along the circumference become incapable of trapping particles over a longer time period but the porosity definitely changes due to the change in circumferential diamonds. Count could have showed significant improvement had the denier of the fiber also become finer. Similar trend is observed for cartridges wound on commercial winder but show lower pressure drop due to different arrangements to apply pressure at the nip point on the fabricated winder and the commercial winder. It was not possible to find out the contact pressure between the cartridge and the press roller and hence the actual significance cannot be judged. Besides the yarn was supplied by the industry and could also be responsible for the results. The yarn was less compact compared to the yarn used for winding the cartridges produced on the fabricated winder.

The newly fabricated winder is definitely having an edge over the commercial winder because it can be operated on step precision winding system. Due to this advantage it can be very easily possible to produce graded filters. The ordinary cam operated winder would be incapable of working on this principle. The machines working on step precision winding principle require a very complicated system which can be very costly. That is the reason why they have not become commercially popular though the system has advantage of maintaining constant coil angle. The changes in the traverse length, traverse ratio, gain, and speed are so simple. The changes in commercial winders require the change of a minimum of four change gears for changes in traverse ratio and gain. Minor changes in the traverse length may be possible but with mechanical adjustment. Tension level can also be adjusted easily. Regarding speed normally on any machine the ratio of driver to driven pulley becomes a key factor. Hence on such types of winding machine a large set of gears and pulleys of different diameters would be required. The fabricated winder can very easily produce graded filters. The traverse ratio can be said to be the most promising of all the different winding parameters tested in this work.

LIST OF PAPERS PUBLISHED/ACCEPTED

1. Kanade P S, Bhattacharya S S and Pandey A B. Cad Software based design of yarn guide profile. *ISOR Journal of Mechanical and Civil Engineering (ISORJMCE)* 2012; 2: 43-47
2. Kanade P S, Bhattacharya S S. Designing a cartridge winder with electronic controls. *Journal of Engineered fibers and fabrics (in press)*
3. Kanade P S, Bhattacharya S S. Influence of winding parameters on performance of string wound filter cartridge - part-I. (Accepted for publication in Filtration journal)
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APPENDIX – I

The filtrate samples collected at definite time intervals were analyzed for particle size using microscope. These numbers obtained had to be converted to mass and volume fraction so that the mass per liter or number per liter could be calculated. The particles were counted and were assigned a particle size range[33]. This range had to be converted into the average diameter which was in microns. Assuming the particle to be spherical, its volume was calculated using the standard formula to find volume of sphere. From the theoretical volume obtained, mass of the particles in a particular range was calculated by multiplying it with the density of dust. The density of dust was supplied by the manufacturer.

The test was conducted for 2 hours. The calculations have been formulated on basis of two hours of operation.

$$\text{solids in} = \text{solids retained} + \text{solids in filtrate (drained)} \qquad \text{Equ. 1}$$

Here solids in, represents the weight of the solid that is present in the inlet of the slurry.

The concentration of the feed slurry was 0.1 gm/l and the flow rate was maintained constant at 400LPH. Since the amount of dust that was added to the known volume of water was not changed hence, the concentration of the slurry also did not change and then the value of solids in can be calculated as follows:

$$\text{solids in} = 0.1\frac{\text{gm}}{\text{l}} \times 400\left(\frac{\text{l}}{\text{hr}}\right) \times 2\,\text{hr} = 80\ \text{gm} \qquad \text{Equ. 2}$$

This therefore means that when the test is stopped after two hours the weight of dust that was fed to the system was 80 grams. Now depending upon the construction of the cartridge the amount of dust retained would change.

$$\text{solids retained} - \text{increase in wt of filter (bobbib + yarn + dust)} \qquad \text{Equ. 3}$$

$$\text{solids in filtrate} = \text{solids in} - \text{solids retained} \qquad \text{Equ. 4}$$

The above logic holds true since the flow rate is maintained constant. The solids in filtrate have been called mass/l (MIL) and the solids in filtrate divided by 800 lit, would give MIL. To convert MIL into number per liter (NIL) following formula has been used.

$$\frac{\textbf{number}}{\textbf{lit}} = \frac{\frac{\textbf{mass}}{\textbf{density}}}{\textbf{vol. of 1 particle}} \qquad \text{Equ. 5}$$

where density means density of the particle. A typical table of how the calculation was done for A1 is shown below. Since the table was spread over a large number of columns, hence at end of every 9 columns and 11 rows contd. Symbol has been used to indicate its continuity in the horizontal direction. While plotting the graphs the % NIL value has been plotted in each case.

Table – I Calculation table for A1 (15°/16.99) is shown

				A1T1D2G2S1/1				
particle size				OUTLET		(n)(d³)	mass gm	% freq
(microns)		inlet	15 min	45 min	120 min	inlet	inlet	mass. in
≤100&≥87.5	93.75	3	0	0	0	0.002471924	0.006550598	22.83028
≤87.5&≥75	81.25	1	0	0	1	0.000536377	0.001421399	4.953888
≤75&≥62.5	68.75	3	0	1	3	0.000974854	0.002583362	9.003585
≤62.5&≥50	56.25	12	2	5	5	0.002135742	0.005659717	19.72536
≤50&≥37.5	43.75	23	8	15	12	0.001926025	0.005103967	17.78845
≤37.5&≥25	31.25	67	67	114	94	0.002044678	0.005418396	18.8843
≤25&≥12.5	18.75	109	129	111	113	0.000718506	0.001904041	6.636001
≤12.5&≥0	6.25	79	89	49	67	1.92871E-05	5.11108E-05	0.178133
66.0123	92.6743					0.010827393	0.02869259	Contd MIL*
					gm/lit	0.0125		

MIL* gm/l	cc/lit	vol. of 1	NIL	% freqNIL	(n)(d³)	mass gm	% freq	MIL
inlet	inlet	particle	inlet	inlet	15 min	15 min	15 min	15 min
0.02283	0.0086	0.000431432	19.96884	1.010101	0	0	0	0
0.004954	0.0019	0.000280846	6.656281	0.3367	0	0	0	0
0.009004	0.0034	0.000170144	19.96884	1.010101	0	0	0	0
0.019725	0.0074	9.31893E-05	79.87537	4.040404	0.000355957	0.000943	9.028423	0.001129
0.017788	0.0067	4.38463E-05	153.0945	7.744108	0.000669922	0.001775	16.99176	0.002124
0.018884	0.0071	1.5979E-05	445.9708	22.55892	0.002044678	0.005418	51.8608	0.006483
0.006636	0.0025	3.45146E-06	725.5346	36.70034	0.000850342	0.002253	21.5679	0.002696
0.000178	0.0001	1.27832E-07	525.8462	26.59933	2.17285E-05	5.76E-05	0.551118	6.89E-05
0.1	0.0377		1976.915		0.003942627	0.010448		0.000131
								Contd cc/lit*

cc/lit*	NIL	%freqNIL	(n)(d³)	mass gm	%freqNIL	MIL	cc/lit	NIL
15 min	15 min	15 min	45 min	45 min	45 min	45 min	45 min	45 min
0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0
0	0	0	0.000325	0.000861	4.854652	0.000607	0.000229	1.345877

0.000426	4.569933	0.677966	0.00089	0.002358	13.29467	0.001662	0.000627	6.729387
0.000801	18.27973	2.711864	0.001256	0.003329	18.76573	0.002346	0.000885	20.18816
0.002446	153.0928	22.71186	0.003479	0.009219	51.97505	0.006497	0.002452	153.43
0.001017	294.7607	43.72881	0.000732	0.001939	10.93117	0.001366	0.000516	149.3924
2.6E-05	203.362	30.16949	1.2E-05	3.17E-05	0.178721	2.23E-05	8.43E-06	65.948
4.93E-05	674.0651		0.006694	0.017738				397.0339

Contd
% freq NIL*

%freqNIL*	(n)(d³)	mass gm	%freqNIL	MIL	cc/lit	NIL	%freqNIL
45 min	120 min	120 min	120 min	120 min	120 min	120 min	120 min
0	0	0	0	0	0	0	0
0	0.000536	0.001421	7.623443	0.000953	0.00036	1.280403	0.339
0.338983	0.000975	0.002583	13.85544	0.001732	0.000654	3.841208	1.017
1.694915	0.00089	0.002358	12.64791	0.001581	0.000597	6.402013	1.695
5.084746	0.001005	0.002663	14.28224	0.001785	0.000674	15.36483	4.068
38.64407	0.002869	0.007602	40.77171	0.005096	0.001923	120.3578	31.864
37.62712	0.000745	0.001974	10.58677	0.001323	0.000499	144.6855	38.305
16.61017	1.64E-05	4.33E-05	0.232486	2.91E-05	1.1E-05	85.78698	22.712
	0.007036	0.018645				377.7188	

Table II: % frequency by number for cartridges produced with different tension levels

PERCENTAGE FREQUENCY BY NUMBER										
Particle size(microns)		A1T1G2D2S1C1/1			A1T2G2D2S1C1/1			A1T3G2D2S1C1/1		
Range	Avg. dia	15 min	45 min	120 min	15 min	45 min	120 min	15 min	45 min	120 min
≤100&≥87.5	93.75	0	0	0	0	0	0	0	0	0
≤87.5&≥75	81.25	0	0	0.33898	0	0	0	0	0	0
≤75&≥62.5	68.75	0	0.338983	1.01695	0	0.440529	0.543478	0.680272	0.344828	0.364964
≤62.5&≥50	56.25	0.677966	1.694915	1.69492	1.132075	1.762115	1.086957	4.081633	1.724138	3.284672
≤50&≥37.5	43.75	2.711864	5.084746	4.0678	10.18868	6.167401	5.978261	10.54422	6.896552	8.759124
≤37.5&≥25	31.25	22.71186	38.64407	31.8644	20.75472	21.14537	21.73913	26.87075	43.7931	39.05109
≤25&≥12.5	18.75	43.72881	37.62712	38.3051	35.84906	39.64758	38.04348	31.97279	24.48276	24.08759
≤12.5&≥0	6.25	30.16949	16.61017	22.7119	32.07547	30.837	32.6087	25.85034	22.75862	24.45255

Table III: % frequency by number for cartridges produced with different gain values

		PERCENTAGE FREQUENCY BY NUMBER								
Particle size(microns)		A1T3G1D2S1C1/1			A1T3G2D2S1C1/1			A1T3G3D2S1C1/1		
Range	Avg. dia	15 min	45 min	120 min	15 min	45 min	120 min	15 min	45 min	120 min
≤100&≥87.5	93.75	0	0.367162	0	0	0	0	0.209644	0	0
≤87.5&≥75	81.25	0	0	0	0	0	0	0.419287	0.229358	0.26738
≤75&≥62.5	68.75	1.098901	0.575912	0	0.680272	0.344828	0.364964	0.838574	0.458716	0.26738
≤62.5&≥50	56.25	4.395604	4.607299	3.28947	4.081633	1.724138	3.284672	3.144654	2.752294	2.406417
≤50&≥37.5	43.75	8.241758	8.638685	7.89474	10.54422	6.896552	8.759124	11.5304	10.3211	8.823529
≤37.5&≥25	31.25	24.72527	21.88467	25	26.87075	43.7931	39.05109	27.25367	30.50459	32.08556
≤25&≥12.5	18.75	34.06593	34.55474	35.5263	31.97279	24.48276	24.08759	31.44654	33.25688	34.75936
≤12.5&≥0	6.25	27.47253	29.37153	28.2895	25.85034	22.75862	24.45255	25.15723	22.47706	21.39037

Table IV: % frequency by number for cartridges produced with different full package diameters values

		PERCENTAGE FREQUENCY BY NUMBER								
Particle size(microns)		A1T3G1D1S1C1/1			A1T3G1D2S1C1/1			A1T3G1D3S1C1/1		
Range	Avg. dia	15 min	45 min	120 min	15 min	45 min	120 min	15 min	45 min	120 min
≤100&≥87.5	93.75	0	0	0	0	0.367162	0	0	0	0
≤87.5&≥75	81.25	0	0	0.66667	0	0	0	0	0	0
≤75&≥62.5	68.75	0	0	0.66667	1.098901	0.575912	0	0	0.342466	0.657895
≤62.5&≥50	56.25	0.896861	3.424658	4.33333	4.395604	4.607299	3.289474	0.636943	1.027397	1.973684
≤50&≥37.5	43.75	6.278027	3.767123	4.33333	8.241758	8.638685	7.894737	4.458599	0.684932	2.960526
≤37.5&≥25	31.25	21.07623	40.06849	40.6667	24.72527	21.88467	25	31.84713	18.83562	24.34211
≤25&≥12.5	18.75	40.35874	28.08219	21.6667	34.06593	34.55474	35.52632	33.12102	36.64384	23.02632
≤12.5&≥0	6.25	31.39013	24.65753	27.6667	27.47253	29.37153	28.28947	29.93631	42.46575	47.03947

Table V: % frequency by number for cartridges produced with different package rotational speed

PERCENTAGE FREQUENCY BY NUMBER

Particle size(microns)		A1T1G1D2S1C1/1			A1T1G1D2S2C1/1			A1T1G1D2S3C1/1		
Range	Avg. dia	15 min	45 min	120 min	15 min	45 min	120 min	15 min	45 min	120 min
≤100&≥87.5	93.75	0	0	0	0	0	0	0	0	0
≤87.5&≥75	81.25	0	0	0.34247	0	0	0	0	0	0
≤75&≥62.5	68.75	0	0.325733	0.68493	0	0	0	0	0.641026	0
≤62.5&≥50	56.25	0.790514	0.977199	0.34247	0.766284	0.3861	0.333333	0.431034	0.641026	0
≤50&≥37.5	43.75	3.162055	2.28013	1.71233	3.065134	3.474903	4.666667	2.586207	3.205128	3.773585
≤37.5&≥25	31.25	26.48221	31.59609	29.7945	22.98851	25.48263	26.33333	19.39655	24.35897	25.4717
≤25&≥12.5	18.75	47.82609	35.17915	32.5342	45.97701	32.81853	30.33333	40.94828	38.46154	30.18868
≤12.5&≥0	6.25	21.73913	29.64169	34.589	27.20307	37.83784	38.33333	36.63793	32.69231	40.5660

Table VI: % frequency by number for cartridges produced with different fineness of feed material (yarn count)

PERCENTAGE FREQUENCY BY NUMBER

Particle size(microns)		A1T3G1D2S1C1/1			A1T3G1D2S1C2/1			A1T3G1D3S1C3/1		
Range	Avg. dia	15 min	45 min	120 min	15 min	45 min	120 min	15 min	45 min	120 min
≤100&≥87.5	93.75	0	0.367162	0	0	0.363636	0	0	0	0
≤87.5&≥75	81.25	0	0	0	0	0	0	0.25974	0.3367	0
≤75&≥62.5	68.75	1.098901	0.575912	0	ss0	0	0.326797	1.038961	0.3367	0.35461
≤62.5&≥50	56.25	4.395604	4.607299	3.28947	0.344828	0	0.980392	2.597403	0.3367	1.06383
≤50&≥37.5	43.75	8.241758	8.638685	7.89474	2.758621	2.181818	4.248366	5.194805	2.693603	2.48227
≤37.5&≥25	31.25	24.72527	21.88467	25	40	24	31.69935	42.85714	26.26263	27.30496
≤25&≥12.5	18.75	34.06593	34.55474	35.5263	27.24138	39.63636	36.60131	25.97403	38.72054	37.58865
≤12.5&≥0	6.25	27.47253	29.37153	28.2895	29.65517	33.81818	26.14379	22.07792	31.31313	31.20567

Table VII: % frequency by number for cartridges produced with different circumferential diamonds

		PERCENTAGE FREQUENCY BY NUMBER								
Particle size(microns)		A1T3G1D2S1C1/1			A1T3G1D2S1C1/2			A1T3G1D3S1C1/4		
Range	Avg. dia	15 min	45 min	120 min	15 min	45 min	120 min	15 min	45 min	120 min
≤100&≥87.5	93.75	0	0.367162	0	0.671141	0	0	0.5	0	0
≤87.5&≥75	81.25	0	0	0	0.33557	0	0	0.25	0	0
≤75&≥62.5	68.75	1.098901	0.575912	0	0.33557	0	0	0.5	0.306748	0
≤62.5&≥50	56.25	4.395604	4.607299	3.28947	0.33557	1.013514	0.333333	1.5	0.920245	0.352113
≤50&≥37.5	43.75	8.241758	8.638685	7.89474	2.013423	2.702703	4.666667	5	2.453988	2.464789
≤37.5&≥25	31.25	24.72527	21.88467	25	47.98658	27.36486	26.33333	50	31.59509	24.64789
≤25&≥12.5	18.75	34.06593	34.55474	35.5263	26.84564	40.87838	30.33333	27.25	37.11656	32.04225
≤12.5&≥0	6.25	27.47253	29.37153	28.2895	21.47651	28.04054	38.33333	15	27.60736	40.49296

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