CHAPTER – II

REVIEW OF

LITERATURE

PERTAINING TO THE

PRESENT WORK
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.
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 (\(\text{\(\mu\)}\)) range of the three different types of filtration techniques commonly adopted.

<table>
<thead>
<tr>
<th>0.0001(\mu)m- 0.001(\mu)m</th>
<th>0.2(\mu)m</th>
<th>10(\mu)m*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1(\text{A}^0) &lt;--------</td>
<td>10(\text{A}^0) &lt;--------</td>
<td>200(\text{A}^0) &lt;-------------</td>
</tr>
</tbody>
</table>

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 75\(\mu\)m, the smallest pencil dot a human eye can see is 40 \(\mu\)m, and a yeast cell is 3 \(\mu\)m whereas a common bacterium is of 0.2 \(\mu\)m. 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.
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.
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:
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. Coalescing Filter Rating: 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: 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/water 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.
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 mm to 150 mm, 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\textsuperscript{39}
Fig. 2.40 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
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\textsuperscript{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
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

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.
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\textsuperscript{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\textsuperscript{7, 11} & \textsuperscript{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.
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\textsuperscript{25} \&\textsuperscript{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
suffer from bypass 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\textsuperscript{25} &\textsuperscript{19}
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

Typical applications include:

1. Activated Carbon for the removal of chlorine, taste and odor.
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)\textsuperscript{20, 35, 36 & 39} Dr. Graham Rideal and et.al\textsuperscript{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\textsuperscript{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.
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.

$$P = \frac{4k \cos \theta}{d} \sigma,$$

Equ 2.5.1

where, $P =$ bubble point pressure, $d =$ pore diameter, $k =$ shape correction factor, $\theta =$ liquid- solid contact angle, $\sigma =$ 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.
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 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
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.

\[
DF = \frac{K(P_1 - P_2)A \times P}{L}
\]

Equ 2.5.2

where, \(K\) = Diffusivity/Solubility coefficient, \(P_1\) and \(P_2\) = 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.
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:

\[
\text{Pressure hold test formula} = \frac{D \cdot (T)(Pa)}{V_h} = \Delta P
\]

Equ 2.5.3

where, \( D \) = Diffusion rate (cc/min), \( T \) = Time (minutes), \( Pa \) = Atmosphere pressure (1 Atm. or 14.7 psi), \( V_h \) = Upstream volume of apparatus (cc), \( \Delta P \) = 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.
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 shows a typical glass bead test apparatus
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 contaminants 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 shows a typical apparatus showing single pass test method.
A 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 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 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
The 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 (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 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\textsuperscript{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.

<table>
<thead>
<tr>
<th>Liquid Retention Ratings (μm) (by ASTM F-795 Test)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Single Pass</strong></td>
</tr>
<tr>
<td>0.5</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td>3</td>
</tr>
<tr>
<td>10</td>
</tr>
<tr>
<td>25</td>
</tr>
</tbody>
</table>

Figure 2.16\textsuperscript{10} shows comparison between different test types.
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. 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.
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\textsuperscript{20} using water. C.J. Williams and Edyean\textsuperscript{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 at least 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.
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. 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>
<thead>
<tr>
<th>Sr.</th>
<th>ISO 12103-1</th>
<th>Micron size</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>A1 ultra fine</td>
<td>0-10 microns</td>
</tr>
<tr>
<td>2.</td>
<td>A2 fine</td>
<td>0-80 microns</td>
</tr>
<tr>
<td>3.</td>
<td>A3 medium</td>
<td>0-80 microns (0-5 micron content&lt; than A2)</td>
</tr>
<tr>
<td>4.</td>
<td>A4 coarse</td>
<td>0-180 microns</td>
</tr>
</tbody>
</table>
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\textsuperscript{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.
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

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)
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.

DISTANCE AB IS CALLED SINGLE TRAVERSE. THE NUMBER OF COILS LAID ARE 2 HENCE THE PACKAGE IS PRODUCED WITH A WIND OF 2

AFTER COMPLETING THE SINGLE TRAVERSE, THE YARN REVERSES AND TAKES THE PATH FROM B TO A, PUTTING TWO MORE COILS. THUS THE TRAVERSE RATIO BECOMES 2+2=4

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
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$^2$ shows random winding system  
Figure 2.23 shows precision winding system
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.

\[
\text{Surface speed} = \pi \times d \times n, \quad \text{Eq. 2.7.1}
\]

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.

\[
\text{Traverse speed} = 2 \times L \times n \times \frac{p}{q}, \quad \text{Eq. 2.7.2}
\]

Where \( L = \) traverse length, \( n = \) rotations/min (rpm) of the package and \( \frac{p}{q} = \) 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.

\[
\text{Winding speed} = \sqrt{(S.S)^2 + (T.S)^2}, \quad \text{Eq. 2.7.3}
\]
The coil angle ($\theta$) is a function of traverse speed and the surface speed.

$$\tan \theta = \frac{T.S}{S.S} \quad \text{.........................} \quad \text{Equ. 2.7.4}$$

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 in that case.

$$T.R = \frac{q}{p} \quad \text{.........................} \quad \text{Equ. 2.7.5}$$

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 lengthwise 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, lengthwise 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 lengthwise diamonds will be 12.5 while two diamonds will be formed.
traverse ratio is \(8\frac{1}{2}\), 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 \([(48\times20)/(20\times20)]\) 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 \(9/2\) (4\(\frac{1}{2}\)). 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:
But R.G is a better known quantity which is written as follows,

\[ R.G = L.G + \text{circumference of the package} \]  \hspace{1cm} \text{Equ. 2.7.6}

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

\[ R.G = \text{yarn diameter} + \pi \times d \times \sin \theta \]  \hspace{1cm} \text{Equ. 2.7.7}

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

A.T.R = N.T.R – gain \hspace{1cm} \text{Equ. 2.7.8}

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
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
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 \( X_1^* (X_1^*<X^*) \). 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 \( X_2^* (X_2^*<X^*) \). 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.
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.
inding 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

<table>
<thead>
<tr>
<th>Sr. No</th>
<th>Method to rotate Package</th>
<th>Method to traverse</th>
<th>Manufacturer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>International</td>
</tr>
<tr>
<td>1.</td>
<td>Surface contact</td>
<td>Grooved drum/ plain drum with separate traversing arrangement like cam or propeller blade</td>
<td>Autoconer, Murata, Savio, SSM</td>
</tr>
<tr>
<td>2.</td>
<td>Spindle drive</td>
<td>Cam</td>
<td>Scharer, Schweiter</td>
</tr>
</tbody>
</table>

Table 2.3 Cartridge winder manufacturers (National and International)

<table>
<thead>
<tr>
<th>Sr no</th>
<th>Manufacturer</th>
<th>Traverse type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Dietze Shell</td>
<td>Chain traverse</td>
</tr>
<tr>
<td>2.</td>
<td>M/s Avon international</td>
<td>Cam traverse</td>
</tr>
<tr>
<td>3.</td>
<td>M/s Aishwarya marketing</td>
<td>Cam traverse</td>
</tr>
<tr>
<td>4.</td>
<td>M/s Prakash engineering</td>
<td>Cam traverse</td>
</tr>
</tbody>
</table>
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\textsuperscript{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.
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\textsuperscript{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
Servomotor, 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-
items, 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.