RESEARCH ARTICLE

PREDICTIVE ANALYSIS OF SOLIDS FILTRATION WITH MULTI-LAYERED FILTERED MEDIA

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Manuscript Info

Abstract

Solid-liquid filtration, which is primarily reducing the amount of particulate contamination can be controlled either as a surface or as a depth filtration mechanism. While surface area control is quite common, understanding depth filtration is a bit more complex. Solid-Liquid filtration entails fine tuning of several parameters with respect to fluid flow and the filter media characteristics. The differential pressure across a given filter surface area that determines the life of a filter, in relation to these parameters, is explained by Darcy's law. The liquid permeability of the media is a characteristic of the filter properties such as pore size distribution, pore volume and depth of the media. Although multi-layered filters are well-known in industry, very few studies have systematically quantified their filtration performance, and even less have characterized the effect of multi-layered structure on depth filter performance. This study aims to determine the permeability of multi-layered filter media as opposed to that of the individual layers, so as to establish a predictive relation with the characterized properties of the layers included as well as operating conditions. The filtration efficiency and mechanism are studied for single versus multiple layers of non-woven melt blown media based on filter inlet and outlet fluid evaluations.

Introduction:-

Solid-liquid filtration is present in almost every industrial chemical process. It is hard to identify a chemical process that does not involve solid-liquid filtration. Solids find their way into liquid stream during storage, transport, chemical processes, corrosion of process equipment, etc. It is necessary to get rid of these solid particulates to ensure effluent fluid quality as well as process reliability by avoiding equipment plugging, fouling, and ultimately failure. Filtration performance can be tailored in many ways by controlling the filter structure, operation mode and composition of fiber material. Two efficient modes of filtration operation are dead-end filtration and crossflow filtration [1]. The flow is passed directly through the filter in dead-end filtration and tangentially in crossflow filtration. Filtration performance can also be altered based on the structure and configuration of the filter. Multi-layered structured filters with layers stacked on top of one another provides a way of sequentially separating out the particles [2-5].

Although Multi-layered filters are well known in the industries, very few studies have systematically quantified their filtration capabilities and their variance with the layer structure. In this study we analyze the effect of multi-layer on filtration parameters like pore size distribution, permeability, beta ratio and estimated filter life.

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Materials and Equipment:-
In solid-liquid filtration filter media made up of various materials are used. Some of the materials used as filter media include wet laid products such as cellulose and borosilicate glass as well as meltblown or spunbonded synthetic media such as nylon, polypropylene, polyester, etc. In this study we will be mainly focusing on the study of melt blown Polypropylene as the filter media. To determine the Pore size distribution, Capillary Flow Porometer CFP 1200AEXL-2R (PMI, Ithaca, New York) was used. The air permeability was determined by using the Frazier Test (Frazier Precision Instrument Co Inc, Gaithersburg, MD, USA). The β ratio, was calculated by determining the number of particles downstream/number of particles upstream at the specific micron rating. To determine the number of particles in both these process fluid streams, Accusizer A7000 (Particle Sizing System, Entegris, Florida) was used. The wettability of the samples used were determined using the DSA 25E (KRUSS, Germany). The process fluid, that was used as the filter feed in each case was a dispersion of medium test dust (Powder Technology Inc, ISO 12103-1, A3 Medium Test Dust) in distilled water. The inlet concentration was maintained at 0.2 g/L and the media flux rate was maintained at 0.5 gpm/ft^2.

Experimental Description:
Filter Selection and Media Layering:
Filters are often rated according to their performances in removing particles of a specific size from a fluid, particularly those filters used for the removal of contaminants [6]. Two (2) kinds of filter media aligned in nine (9) different configurations were analyzed for this study. One was a polypropylene media with basis weight 20 gsm and the second one was a polypropylene media with basis weight 25 gsm. For representative purposes the media with basis weight 20 gsm was labelled as media A and the media with basis weight 25 gsm was labelled as B. The nine different alignments in which the 2 medias were set up for testing were as follows: from upstream to downstream A, A+A, A+A+A, B, B+B, B+B+B, B+A, B+B+A, B+A+A. The first six configurations would allow us to study the effect of layering on filtration efficiency and estimated filter life. Additionally, the last three will help us study the gradient effect of media layering in filtration.

Figure 1. gives the schematic representation of the different filter configurations. A total of 9 different configurations which were made using 2 different media were studied. Both the filter media had different basis weights but were made of the same material, that is, polypropylene. Polypropylene medias were used due to its large-scale use in various industrial application.
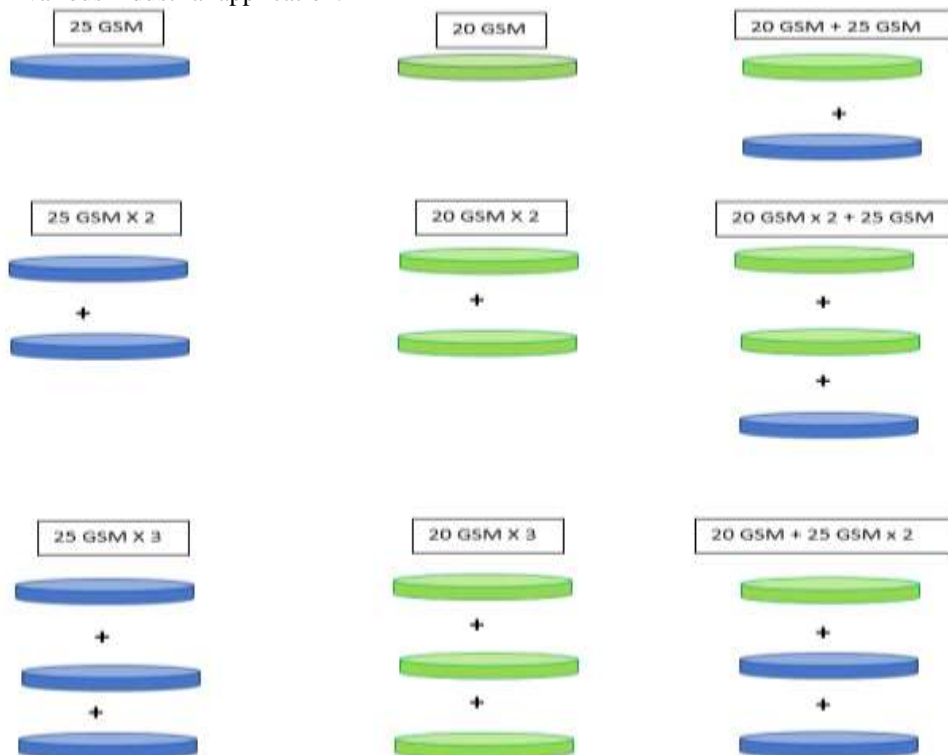

Figure 1:- Schematic representation of the different filter configurations that will be investigated.

Pore Size Distribution:
Filter media has a porous structure and it is made of large number of pores. Pore size is typically described with a single value, usually a diameter. However, the pore size is irregular in most of the medias. The variability of pore sizes is also dependent on the polymer. The pore sizes are averaged to determine a mean pore size assuming all pores are circular. The importance of this point is that, the efficiency of a filter should be measured above this point. In actual practices, pore size distribution is just a guide. The retained particle size distribution gives a better idea of the filtration process [7-8]. There are several methods by which pore sizes can be measured. Some of them include mercury porosimeter, gas adsorption, sieve analysis, optical counting analysis, laser diffraction method. The one that was used during this study was capillary flow porometry.

Capillary flow porometry is a characterization technique based on the displacement of a wetting liquid from the sample pores by applying air at increasing pressure. The air pressure and flow rates through wet and dry samples are accurately measured. The pressure required to remove liquid from the pores and cause gas to flow is related to the pore diameter and is expressed as

$$D = 4 \gamma \cos \theta / \Delta p$$

Where, D is the pore diameter, γ is the surface tension, θ is the contact angle of the liquid and Δp is the differential pressure. Based on the measurement of the air pressure and flow rates, the pore diameters and pore size distribution are calculated.

Particle Sizing:
To determine the filtration efficiency and β ratio using the different media layering Accusizer A700 was used. Accusizer A700 is an equipment used to determine particle counts in the upstream and downstream fluids. The A700 uses single-particle optical sensor system (SPOS) for measuring particles. The technique of SPOS is used to detect individual particles in a certain size range as each passes through a very thin "optical-sensing zone". Concentrated sample suspensions must therefore be diluted sufficiently so that the particles pass one at a time through the detection zone. There are two physical methods that traditionally have been used to implement SPOS technique:
1. Light Extinction (LE) Method - The LE method is based on the measurement of the decrease in the intensity of the light transmitted across a flow channel carrying particles suspended in a fluid.
2. Light Scattering (LS) Method – The LS method is somewhat complementary to the LE method. It measures the increase in the intensity of light due to the scattering from the particles which pass through the optical-sensing zone.
3. Combination method - This technique combines advantages of LE (large size range) with the advantage of the LS method (highly sensitive – lower diameter limit).

Filter Life and Filtration Efficiency:
Different filter media have varying properties that enable different contaminant capture profiles, quality of effluent and life of media/filter. Filterability testing helps compare the performance of different medias in terms of effluent quality, differential pressure profile and the time to reach terminal differential pressure. Upstream and downstream turbidities are noted as a measure of the particulates being captured by the filter. Based on the life and surface area of the filter media tested, the life of the filter element with a different surface area can be projected. Below is the picture of the filterability setup that was used for collecting the data.
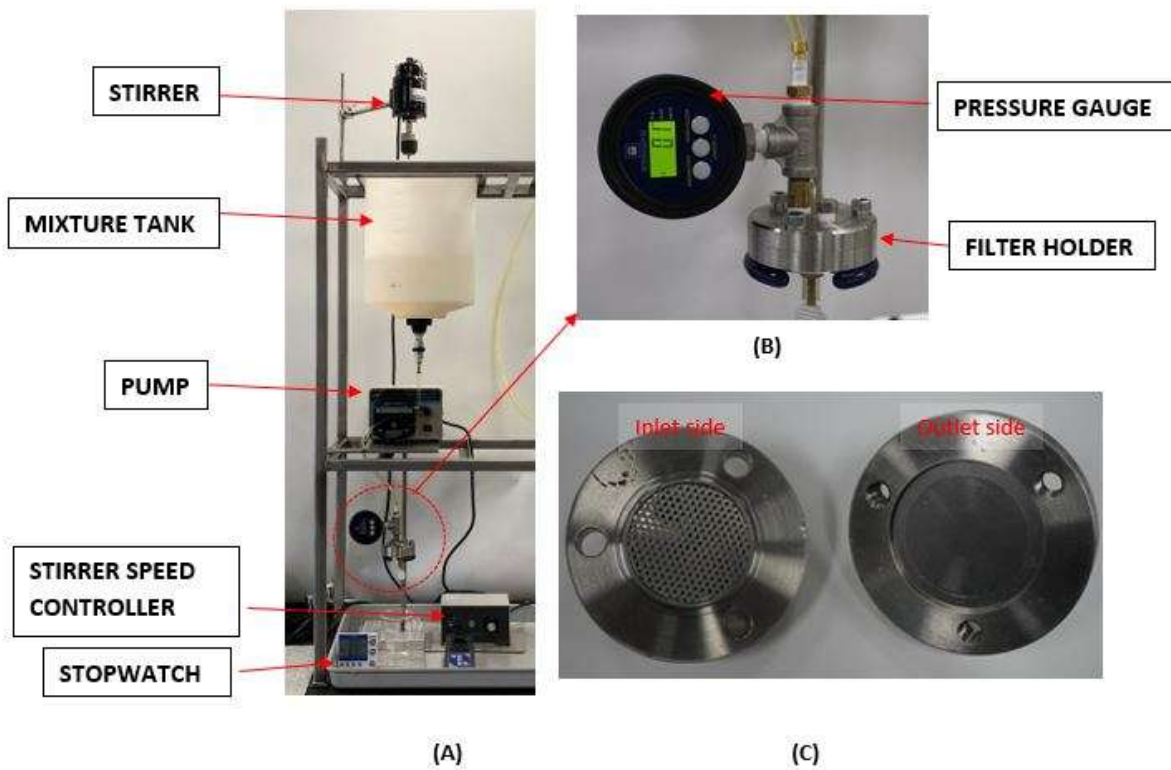
Figure 2:- (A) Filterability Setup (B) Zoomed in image of the filter holder and the pressure gauge (C) image of an open filter holder.

Although filtration theory states increased filter area will provide increased dirt holding capacity and longer life, this is not always the case. If a pleated filter is not properly designed and the media packing density is too great, it might result in little to no void space for the captured contaminants to form a cake. In such a situation some of the packed media is left unused before the terminal differential pressure is reached. Solid-liquid filtration can be divided into two main types: surface filtration and depth filtration. In case of surface filtration, the particulates are captured on the surface of the filter by diffusion, interception and impaction. These captured particulates now in turn act as the 1st layer of filter for the incoming fluid before it reaches the filter media. In surface filtration, as particulates form a cake on the surface of the filter media, the depth of the cake provides for some added filtration. This could accelerate the time to reach terminal differential pressure. In some cases, due to the deformable properties of the contaminants, no cake is formed. In the absence of cake building, depth filtration is used to capture particulates. Depth filtration is multiple layers of media, or a thicker media that forms a path to retain particles. This type of media normally retains larger particles at the surface level and then finer particles through the layers of thickness.

Capture mechanisms:
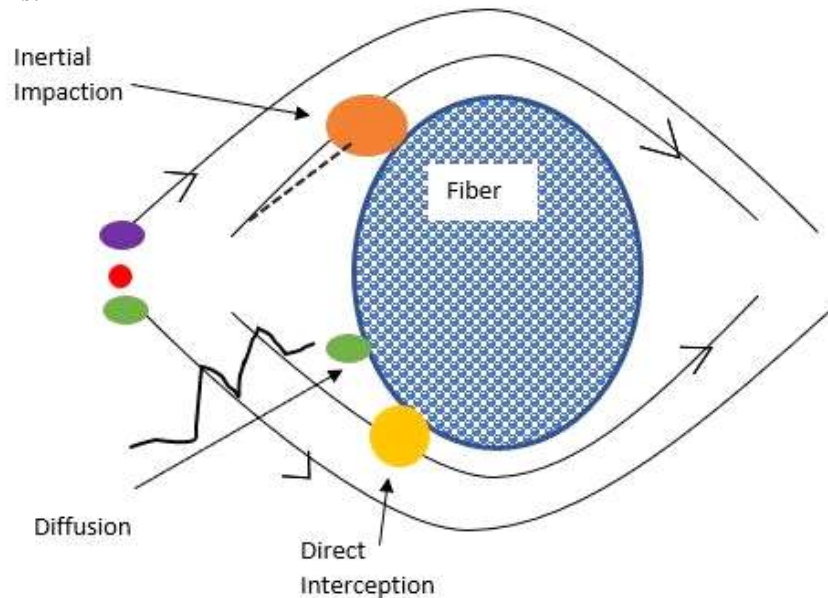
Figure 3:- Particle Capture Mechanism.

Basically, a filter medium is a porous (or semi-permeable) barrier placed across the flow of a suspension to capture most of the suspended materials. If the size of the perforations are smaller than the diameter of the particles to be filtered, most of the particles will be captured on the upstream surface of the medium. In a flowing medium, if a particle is brought sufficiently close to the fiber, it will be attracted to the fiber, and then the particle might stay put. These attractive forces are quite weak and are known as the van der Waal's forces, but are sufficiently strong to hold the particle on the fiber surface [9]. The fluid flow inside the medium is laminar and as streamlines bend round the obstacle, they carry particles with them. If in doing so these particles are taken to a distance half of its diameter from the fiber surface, they come into contact with the fiber and get trapped. This mechanism is known as direct interception, and, by definition, it must happen on the flanks of the fiber, not directly in front of it. Direct interception works on particles in the mid-range size. In turning their path to pass by the fiber the streamlines take the suspended particles with them. However, large particles have too much inertia and are unable to follow the streamline path. These consequently collide and are trapped by the filter. This mechanism is called inertial impaction. The smallest particles are captured by diffusion. Small particles are not held in place by the fluid and diffuse within the flow stream. As the particles traverse the flow stream, they collide with the fiber surface and are collected. The diffusion behavior of the small particles is largely caused by the Brownian motion of the carrier fluid [9]. These three are the three main mechanism by which particles are captured by the fibers but some particles can be an exception to these mechanisms. Consider the red particle in figure 3, it is going to find it difficult to determine which way to go around the fiber. It will probably be carried straight to the front face of the fiber but before it reaches its surface, it will become involved in the fluid eddy pattern that must exist just in the front of the fiber. Once it is involved in this pattern, it is likely to exit from this pattern either by getting into one of the by-passing streamlines or by getting trapped by the filter. These mechanism are depicted in Figure 3.

Single layer vs Multilayer:
A filter medium is thin and porous in structure. Particles having diameter larger than the size of the pore diameter are captured on the surface of the filter medium due to straining (or sieving). Some particles find their way past the first pore opening and are captured within the filter media. In some cases, the size of the particulates is such that they fit exactly into the pore openings on the filter media thus blocking off the pore. Liquid flows through channel with least resistance and saturates the surrounding filter medium of this preferential flow path. When an additional layer is introduced, the tortuousness is increased, and the channeling is mostly avoided as multi-layers offsets the channel alignment between consecutive layers [4]. This avoids preferential flow through continuous channels (Figure 4). Also, the addition of an extra layers provides increased fiber surface area through the depth maximizing filter-liquid contact. Now, when an extra layer is added the performance trait of the composite filter medium

depends on a number of factors such as, type of filter media, type of particulate, chemical composition & porosity of the particulate, stream flux rate, temperature, fluid viscosity, etc.
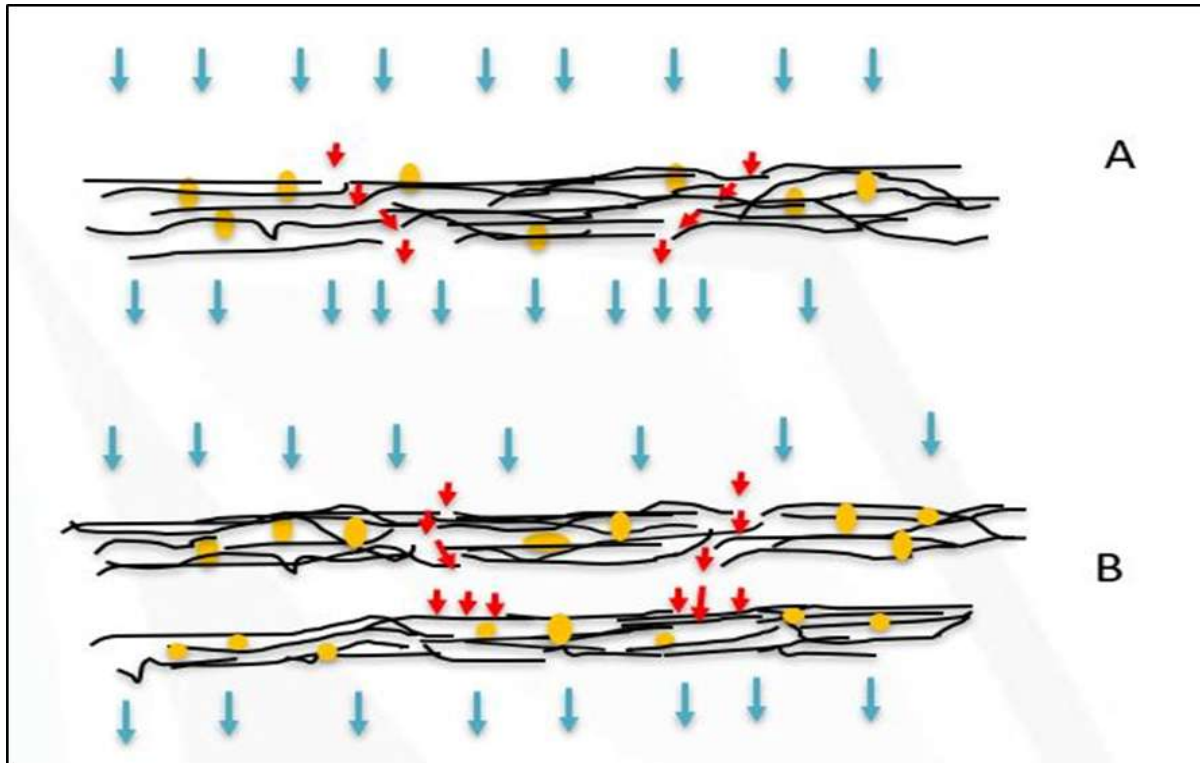

Figure 4:- Schematic illustration of flow through a A) Single layer B) Multi-layer (double layer in this case).

Figure 4.A shows a schematic illustration of flow through a single layer. Channeling can be seen in the regions of least resistance. Figure 4.B shows a schematic illustration of flow through a multi-layer. As compared to single layer the amount of channeling occurring here is very less.

Contact Angle and Surface Tension:
Wettability is the tendency of one fluid to spread on, or adhere to, a solid surface in the presence of other immiscible fluids. Wettability refers to the interaction between fluid and solid phases. Contact angle is the angle, conventionally measured through the liquid, where a liquid-vapor interface meets a solid surface. It quantifies the wettability of a solid surface by a liquid via the Young equation. Wetting depends on both the surface it comes in contact with and the intrinsic characteristics of the liquid [10-11].

Surface tension is a property of a substance where the molecules of the substance at the surface experience unbalanced intermolecular forces. The shape of a liquid at the interface highly depends on the surface tension of the liquid and the solid with which it is in contact. The liquid tends to minimize the surface free energy by maximizing the surface area. This is the reason why water droplets take spherical shape when they detach from the liquid stream. The potential energy per unit area of the surface film is called surface energy. It may also be defined as the amount of work done in increasing the area of the surface film through unity. The surface tension of a liquid is numerically equal to its surface energy. Surface energy and surface tension differ slightly thermodynamically but the terms and values quoted are often used interchangeably. Surface tension is often used to define fluid surfaces while surface energy is used to define solid surfaces.

Filtration Efficiency and Beta Ratio:
Beta (β) ratio refers to the efficiency (η) in which a given a filter media removes particles of a given size. The beta ratio is calculated based on ASTM F795-88:1995 The test involves adding particles of a known size to the test fluid until the fluid reaches a saturation point, and then bringing the filter online to remove particles in a single pass through the element. In this case the fluid was water and the particles were ISO medium size test dust. The slurry

that was passed across the filter had a concentration of 0.2 g/l. Beta ratio is often used when expressing filter efficiency for a given particle size. This, in simple terms, is the number of particles in the upstream (before filtration) divided by the number of particles downstream (after filtration) at a given micron rating and larger. In this case, the number of particles are measured using the Accusizer A700. Beta rating at 10 micron (β_{10}) was determined in each case. It can be determined using the below formula:

$$\beta_{10} = \frac{n_{upstream} \geq 10}{n_{downstream} \geq 10}$$

The efficiency determined for the conducted experiments is the initial efficiency and was calculated from the beta ratio.

Efficiency (%), $\eta = \left(\frac{\beta_{10}-1}{\beta_{10}}\right) * 100$

Results and Discussion:-
As mentioned in section 3.1 the filter media were tested in a total of 9 configuration. In each of the 9 configurations the media was tested for the below properties:
1. Pore Size Distribution
a. Minimum Pore size
b. Mean Pore size
c. Maximum Pore size
2. Air Permeability at 0.2 inches of H_2O
3. Contact angle for water on the media surface
4. Surface Tension (mN/m)
5. Filtration efficiency
6. Estimated filter life

Pore Size Distribution:
The pore size distribution for the 9 configurations of the media was determined and is shown in the figure 5. In each case, 3 test runs were conducted.
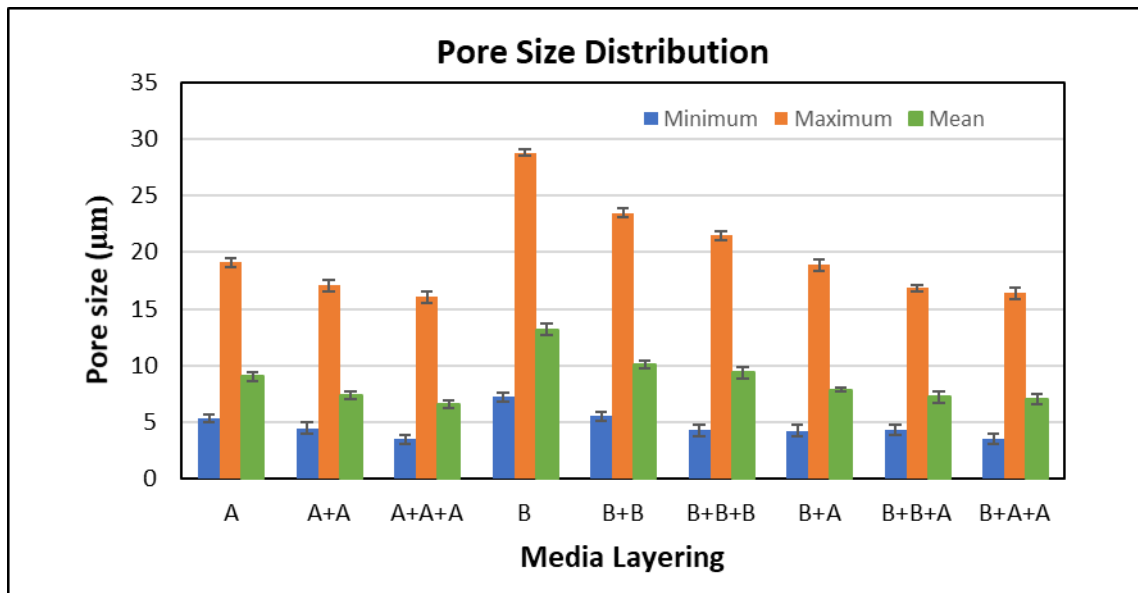

Figure 5:- Pore size distribution in micrometers for the various media configurations.

As the number of layers of same media type increase, both the minimum and mean pore size seem to decrease. This points to the possibility that pore sizes get reduced at the interface between the layers. The reduction in the mean

pore size is of the order of 10-25%. In case of the gradient configuration, it is evident from the graph that as the layers of the tighter media increase in the configuration the size of the pore openings decreases. B+A+A has pore openings relatively smaller than B+A and B+B+A. The pore size distribution gives us an idea regarding the micron rating and filtration efficiency of the coupons as at the same concentration the tighter configuration would tend to reach the terminal differential pressure faster. It also points to the micron rating and predicted filtration efficiency. Table 1 gives the pore size distribution for each of the 9 configurations.

Table 1:- Pore Size Distribution for the 9 configurations.

Media Layering	Minimum Pore size	Maximum Pore size	Mean Pore size
A	5.342 ± 0.3	19.081 ± 0.4	9.011 ± 0.4
A+A	4.457 ± 0.5	17.079 ± 0.5	7.386 ± 0.5
A+A+A	3.508 ± 0.4	16.029 ± 0.5	6.572 ± 0.3
B	7.230 ± 0.4	28.774 ± 0.3	13.165± 0.5
B+B	5.519 ± 0.4	23.473 ± 0.4	10.097 ± 0.3
B+B+B	4.273 ± 0.5	21.495 ± 0.4	9.349 ± 0.5
B+A	4.233 ± 0.5	18.878 ± 0.5	7.853 ± 0.2
B+B+A	4.309 ± 0.5	16.831 ± 0.3	7.223 ± 0.5
B+A+A	3.532 ± 0.5	16.376 ± 0.5	7.031± 0.4

Air Permeability:
The air permeability for the media A is lower than that for media B. Also as predicted, the tightest configuration which is the triple layer of media A has the lowest air permeability. The air permeability results align well with results for the pore size distribution. In both the cases the prediction that the multilayer (triple layer) configuration of media A out of the 9 configurations is the tightest is justified by lowest air permeability and smallest minimum, maximum and mean pore sizes. The air permeability and pore sizes for a single layer of media A are more than that for triple layer of media A.
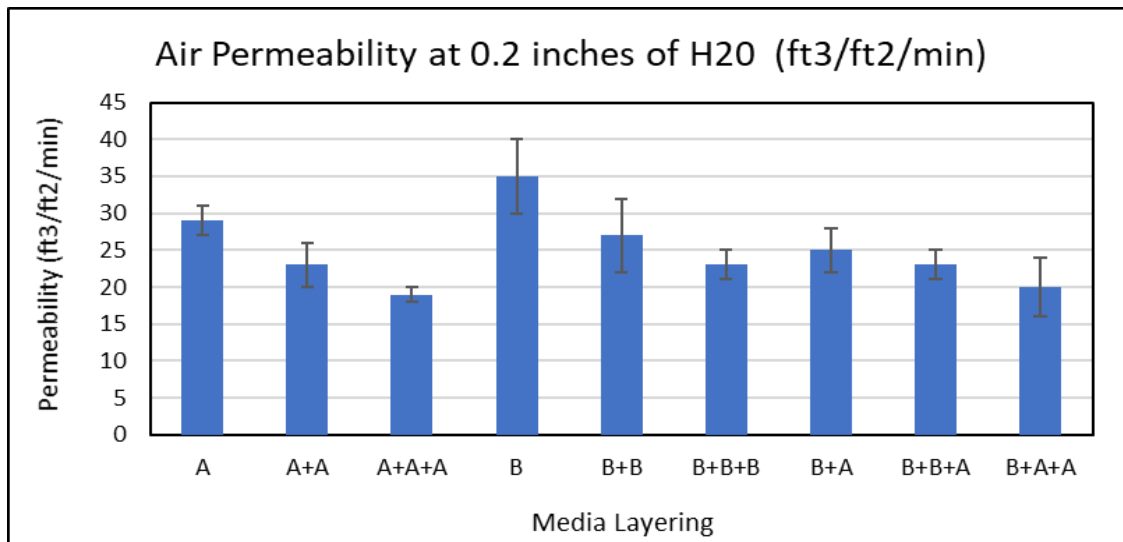

Figure 6:- Air Permeability at 0.2 inches of H_2O for the different layer configurations.

Double layer for media A has permeability and pore sizes intermediate of its single and triple layer. The highest air permeability numbers are recorded for single layer of media B. The trend followed by multilayering media B is the same as the trend followed by multilayer media A. In case of the ones with gradient configuration, the configuration with a single layer of media B and 2 layers of media A shows to have least air permeability and pore sizes. Figure 7. Gives a graphical representation of the air permeabilities and the pore sizes for the various configurations.
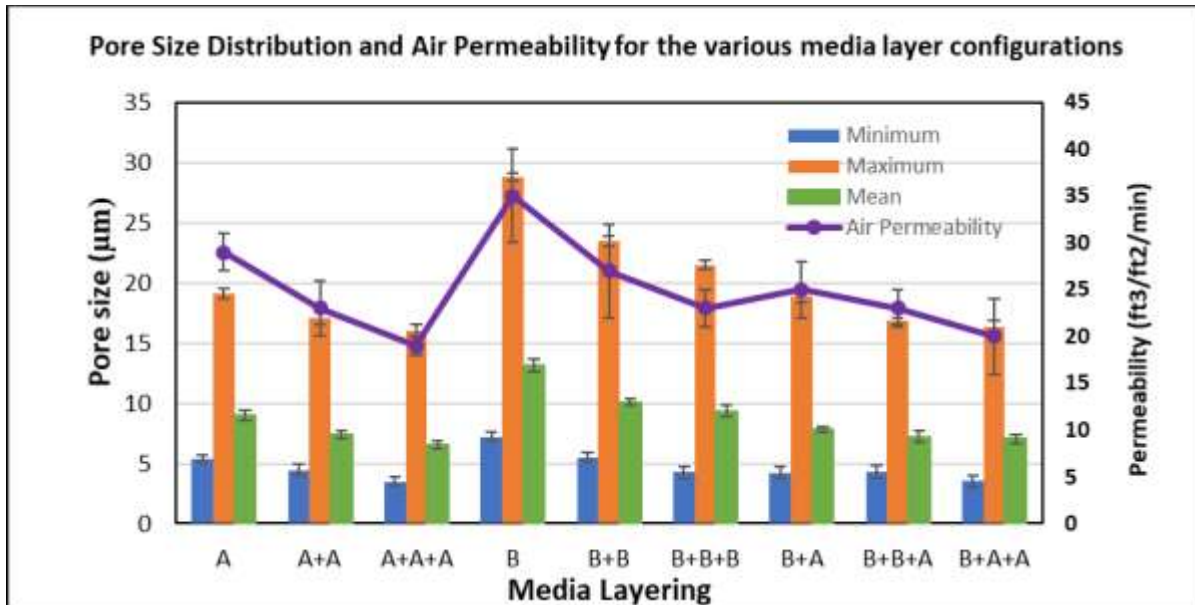
Figure 7:- Graph showing the data alignment for the pore size and permeability of the 9 configurations.

Contact Angle and Surface Tension:

The contact angle and surface energy were determined using the Drop Shape Analyzer - DSA25 by KRὐSS. The Young-Laplace fit method was selected to determine the contact angle and surface tension. Figure 8 gives the image of a water droplet on the surface of media A. Since, contact angle and surface tension both are surface properties, adding media layer below the top layers has no effect on either of the properties. The values in Table 2 make it clear that, in a triple layer media only the topmost surface layer was responsible for the two properties. In all the cases distilled water was used as the liquid and the droplet volume was 5µl.
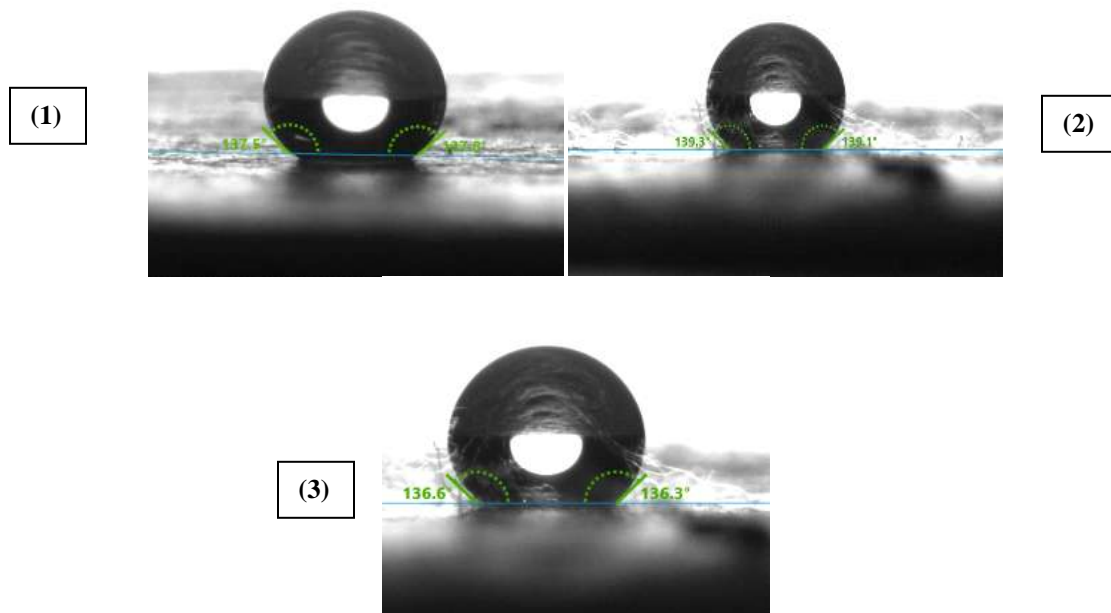

Figure 8:- Images of a 5µl water droplet on media (1) B (2) B+B (3) B+B+B and having similar contact angles.

Table 2:- Contact angle and Surface Tension for Various Media Layering.

Media Layering	Contact Angle (°C)	Surface Tension (mN/m)

A	**134.70 ± 3**	**170 ± 7**
A+A	134.70± 3	175 ± 5
A+A+A	134.70 ± 3	174± 9
B	136.45 ± 3	135 ± 6
B+B	136.45 ± 3	142 ± 5
B+B+B	136.45 ± 3	148 ± 3
B+A	137.65 ± 2	147 ± 8
B+B+A	137.65 ± 2	145 ± 7
B+A+A	137.65 ± 2	149 ± 8

Filtration efficiency and Beta ratio:
Table 3 gives the Beta ratio at 10 microns and filtration efficiency for the 9 different filter media configurations. Among the 9 configurations, as predicted the triple layers have higher Beta ratios followed by the double layers and the single layer. Consequently, the triple layers have the highest initial efficiency followed by the double layers and the single layer have the lowest efficiency. Each media configuration was run 3 times.

Table 3:- Efficiency and Beta rating for 10-micron particles for all the 9 Filter Media configurations.

Media Layering	β_{10}	**Efficiency (%)**
A	5	80.0
A+A	30	96.6
A+A+A	200	99.5
B	2.5	60.0
B+B	22	95.5
B+B+B	200	99.5
B+A	25	96.0
B+B+A	40	97.5
B+A+A	50	98.0

It can be inferred from the data from Table 3 that the tightest media layup has the highest initial efficiency. The triple layer configuration gives more depth to the filter media to capture the particles and thereby increases the effective fiber contact surface area. For media A and media B addition of every layer reduces the pore size diameter and as a result is able to capture higher concentration of smaller particles which a single layer is unable to capture.

Filter life:
Filterability testing was carried out for each of the 9 media layer configurations to determine the filter life for each media lay-up. In each case the filterability testing was run till it reaches a terminal differential pressure of 15 PSI. The upstream consisting of water + medium test dust was maintained at a concentration of 0.2 g/L for all the experiments. Effluent turbidity measurements were recorded at every 5 minutes. Figure 9 shows the pressure profile and the effluent turbidities in case of single, double and triple layer of media A.
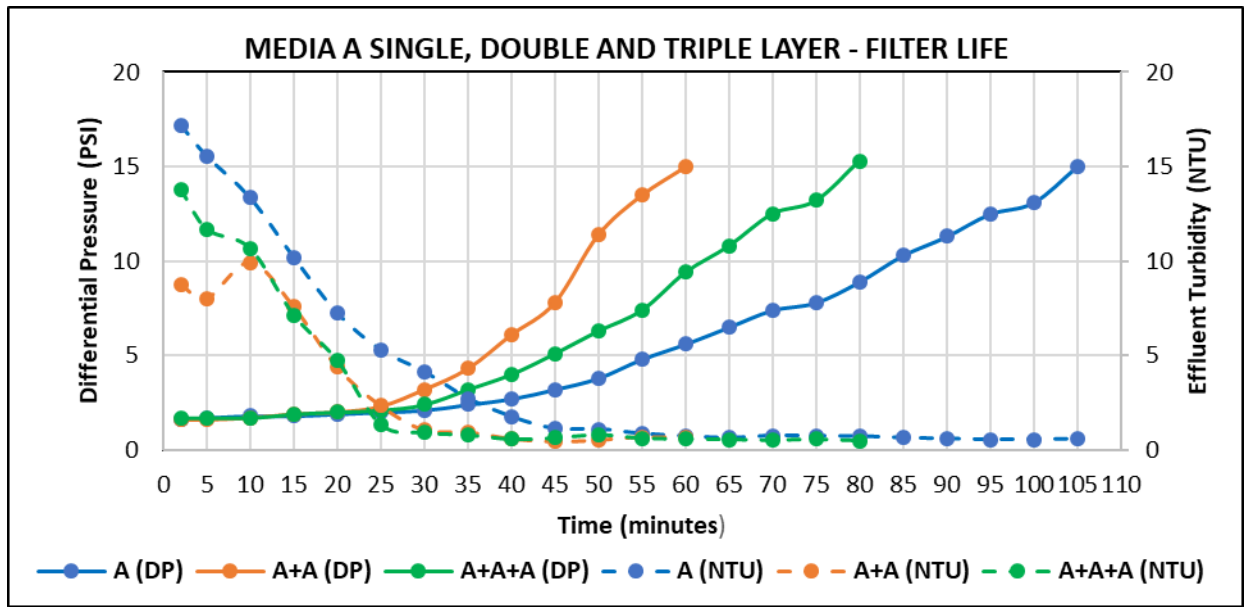
Figure 9:- Pressure build-up over time and effluent turbidities after every 5 minutes in case of single, double and triple layer for media A.

Single layer of media A lasted for 105 minutes, a double layer of media A lasted for 60 minutes and a triple layer of media A lasted for 80 minutes. Single layer of media A ran for the maximum time before it reaches the terminal DP, however a single layer media A has the lowest efficiency out of the three (Table 3). The higher effluent turbidity of single layer media A is also indicative of its lower capture performance. Both 2 layers and 3 layers of media A present higher efficiencies. Between the two, the 3-layer runs for a longer duration. This can be attributed to more "effective" fiber area in case of a triple layer. The triple layer gives the additional depth and surface area for capture of the tiny particles that have made their way through the first two layers. A similar trend is followed by single, double and triple layer configurations of media B (Figure 10).
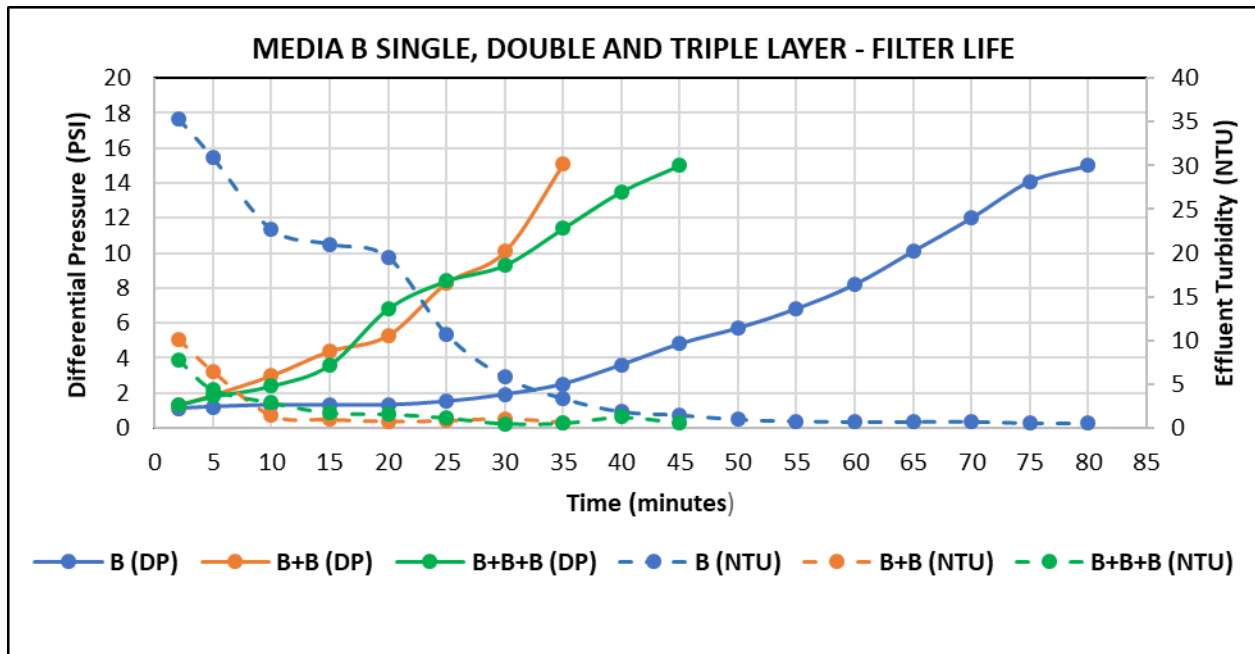

Figure 10:- Pressure build-up over time and effluent turbidities after every 5 minutes in case of single, double and triple layer for media B.

A single layer media B ran for 80 minutes and a double layer and triple of media B ran for 35 minutes and 45 minutes respectively.
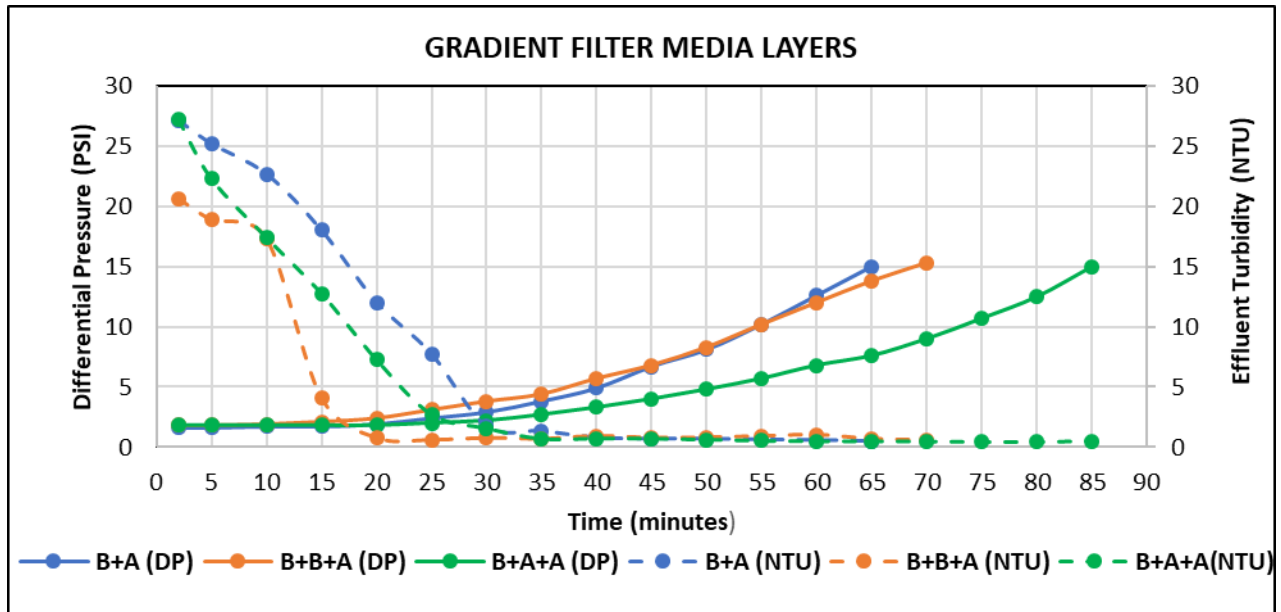

Figure 11:- Pressure build-up over time and effluent turbidities after every 5 minutes in case of single, double and triple layer for the media configuration of B+A, B+B+A and B+A+A.

In case of configuration with gradient effect, the media lay-up with the tightest pore structure B+A+A (Figure 5) has the highest efficiency (Table 2) ran for 85 mins. The media lay-up B+A which is the most open among the three ran for 65 mins and the intermediate configuration of B+B+A which has an intermediate efficiency and pore size structure ran for 70 minutes.

In Figure 9 and Figure 10 it is seen clearly that the single layer ran longest but the effluent turbidity is also higher throughout as compared to the double and triple layer. The tighter configurations, that is, the double and triple layer due to the tight nature and more effective fiber contact surface area and smaller pore openings start capturing particles faster, and capture more particles, especially the smaller ones that easily pass through in case of single layer structure. However, due to relatively higher capture of contaminants, the differential pressure also increases relatively faster in case of a double or triple layer as compared to a single layer. In Figure 11 one is double layer configuration and the other two are a triple layer configuration. All the three,display good initial efficiency (Table 3). As the lay-up is changed and the fiber area and pore structure are altered, the filter life is varied. The one with highest fiber surface area ran the longest, and lay-up with least fiber area ran for the least time among the three under consideration.

Summary and Conclusion:-
Two different type of medias namely polypropylene media with basis weight 20 gsm (media A) and polypropylene media with basis weight 25 gsm (media B) where analyzed in nine different configurations consisting of single, double and triple layers. The parameters that were tested included pore size distribution, air permeability, contact angle, surface tension, beta ratio, initial efficiency and filter life.

Being surface properties, contact angle and surface tension were dependent only on the upstream layer of the media lay-up configuration.

As the layers of the media in a configuration is increased, the diameter of pore openings was reduced. More layers also mean more depth and more fiber contact surface area. This results in capture of more particles and cleaner effluent, hence the higher beta ratio and initial efficiency for multi-layer configurations. The increased layer provides for a longer life of filter at efficiency which would then present economic benefits by way of reduced filter changeouts or continued filter expenses. This cost savings typically more than offsets the cost associated with

adding a few extra layers of media. Layering can affect many variables like and also affects filter performance, micron rating, %efficiency. Study of layering would help in optimization of filters for many specific applications.

Future Work:
There is a large scope for future work and analysis in multilayer filter media. Designing optimized parameters for various layers and predicting the final performance is something that can be targeted. The above work deals with, the effect of different media configuration on the pore size distribution, air permeability, contact angle, filtration efficiency and beta ratio. The study can be further expanded by studying the effect of flux rate, particulate concentration, different types of filter media, etc. on the filter medias. Also, the type of filtration that was mainly seen in the above experimental work that was conducted was surface filtration. Single layer vs multilayer filter media performance in case of depth filtration can have a significant impact on filtration performance which warrants further investigation. The study can be instrumental in designing filters with more than one layer. Not all filter applications are the same and custom layering can result in optimizing filter life.

Refrences:-
1. Liderfelt J., and Royce J. (2018). "Chapter 14 - Filtration principles," in Biopharmaceutical Processing (Elsevier), 279-293.
2. Rijn, C.J.M.V. (1998). Membrane Filter and a Method of Manufacturing the Same as Well as a Membrane. US Patent No US5753014A.
3. Saekflow, K.H.W.M.W.K. (1995). Filter for Liquor Filtration. US Patent No US5462667A.
4. Onur,A., Ng, A., Batchelor, W., Garnier, G. (2018). Multi-Layer Filters: Adsorption and Filtration Mechanisms for Improved Separation. Frontiers in Chemistry. 6, 417-427. doi: 10.3389/fchem.2018.00417
5. Sparks,T., Chase,G., "Chapter 1 – Filtration- Introduction,Physical Principles and Ratings,"in Filters and Filtration Handbook (Elsevier) , 1-50.
6. Svarovsky,L. (2001) " Chapter 2- Characterization of particles suspended in liquids,"in Solid-Liquid Separation (Elsevier), 30-65.
7. Behera,B.K., Hari, P.K. (2010). "Chapter 23- Application of woven fabrics,"in Woven Textile Structure (Woodhead Publishing), 413-435.
8. Nakao,S. (1994). Determination of pore size and pore size distribution:3.Filtration membranes. Journal of Membrane Science. 96, 1-2, 131-165. doi.org/10.1016/0376-7388(94)00128-6
9. Sutherland, K. (2008). "Chapter 1 – Basic Principles," in Filters and Filtration Handbook (Elsevier), 1-28.
10. Bandekar, A., Chase,G. (2016). Coalescence of Water Drops in Water-ULSD Dispersions via Electrowetting. Journal of Coating Science and Technology. 3, 41-49. DOI: 10.6000/2369-3355.2016.03.01.5
11. Radke, Clayton. (2007) Wetting and Spreading Dynamics. Surfactant Science. 138.