Design optimisation of air filters using ANSYS fluent

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Abstract. This paper is based on the current status of research and development in the high performance air filters segment. This can be done by choosing an appropriate filter and operating it under optimized conditions. The present paper details the applicability of filters used in conjunction with metal screen for the purpose of classifying aerosol. In this paper, the analysis on applicability of centrifugal force for achieving enhanced collection efficiency without increasing the pressure drop has also been done. This paper endorses the proposition that the quality of air filters can be improved remarkably and suggests a methodology for achieving the same. The Hepa filter can capture with extraordinary efficiency of $0.01 \times 10^{-9}$ meter sized particles. The size of the Corona Virus Covid-19 is 125 nm. The preliminary study shows that covid-19 can become aerosolized and can remain in the air for hours. After analysis, the flow rate has been increased from an initial value of $21 \times 10^{-4}$ m$^3$/s (thickness 0.15 mm) to the optimized value of $92 \times 10^{-4}$ m$^3$/s (thickness 0.91 mm) which is a significant increase of 338% i.e. 3.38 times from initial value. For optimizing the material porosity, it has been found that the filter shows the maximum performance at a porosity value of 0.95.

Keywords: Aerosol Classification, Air Filtration, ANSYS, Measurement, Nanofiber Filter, Quality Factor

1. Introduction
The small size, portable air filters can clean and circulate the air. The air filters are very useful in cleaning air and can be used to separate out pollutants from the air. One of the most efficient and economic ways of achieving clear air is through filtration. One of the earliest recorded industrial uses of air filter dates back to 50 A.D where finely woven cloth was used to filter air in a mine for breathing purposes. A large number of issues raised in this treatise remain unresolved till this day. Accordingly, relevant areas of research under the umbrella of air filtration fall within the following three major topics:
(i) Developing High Performance Air Filters – with high collection efficiency and low pressure drop
(ii) Change in Collection Performance with dust load – Predicting life of filter
(iii) Collection of nanoparticles – thermal rebound of sub-10nm particles

As far as the first topic is concerned, the development of new manufacturing methodologies has garnered a newfound interest in nanofibers. The first part of this paper shall deal with this first topic. The second topic has been recently dealt with the readers refer to it. As far as the third and last topic is concerned, it was initially introduced its experimental verification is predicated upon the development of methods for generating well-defined nanoparticles as well as measuring of sub-10 nm particles. The review of the third topic, therefore, ought to be done after the said developments take place. In addition to their traditional applicability for the purpose of removing particles, air filters may also be employed for the purpose of classifying particles through the instrumentality of a proper filter media and operating it under optimized filtration. This classification can be achieved by tuning of the collection efficiency curve. The tuning, in turn, can be done through the adjustment of properties and conditions of filtration. For instance, in the case of an inertial filter, inertia is behind the collection of particles, this allows one to term the filter as an inertial classifier. If the filtration velocity is very high, a metal screen may double up as a sieve and collect aerosol through the inhibition of adhesion between particles. Thus, a centrifugal filter doubles up as an aerosol classifier in this example, with various cutoff sizes. The reason why air filters do and will continue to have multiple applications is rooted in the fact that there can be several permutations and combinations possible by choosing any porous media put under extreme filtration conditions and combining the same with different external force fields. Now more than ever, the time is opportune to think about different novel applications of air filters as various fiber-manufacturing techniques and new porous media exists today. Indoor air pollutants are unwanted, sometimes harmful in the air. They range from dusts to chemicals to radon. [1] Many air cleaners also include a bed of sorption material to remove gaseous pollutants in order to control the indoor air quality. Air cleaners removed the contaminants contained in the air like tobacco, dust, pollen, animal dander and volatile compounds present in the room. [2]

Air cleaners are classified according to the technology to remove various sized of the particles in the air. The general types of technologies available for use in air cleaners are: [3]
(i) Mechanical filters
(ii) Electronic air cleaners
(iii) Hybrid filters to capture the particles and the gas phase filters to control odors.
2. Literature Review
This paper covers the important research conducted in the field of air filter design as under:

Wonji Junga (2020). Through a comparative review and analysis, this paper has the capacity of the proposed filter for removing FPM and CPM from the source of pollution. It has also been demonstrated that low graphene oxide used in conjunction with 3D prorous filter has the ability of removing particulate matter by virtue of electrostatic force of attraction. Furthermore, a filter was designed using two rGO filters with a condenser and this filter succeeded in suppressing emissions of particulate matter from the source of pollution. As far as the usual FPM is concerned in emission gas, which demonstrated an efficiency of 99.9%. Subsequently, this is removed by the second rGO filter with a demonstrated efficiency of 93%. Furthermore, the durability and reusability factor of rGO filter are above average and ensure its long term operational viability. Not only that, it also has shown remarkable chemical and structural stability. This becomes especially pertinent in view of the fact that exposure to extreme temperatures and toxic acids is a frequent occurrence for the filters. Simply installing the filter onto a pollution source would exponentially reduce the emission. [3]

Zhuangbo Feng (2020). The impact of a fiber’s diameter, thickness, packing density, and face velocity on electro spun nanofiber filters’ efficiency of removing PM2.5 was considered in the course of this study. For this purpose, a partly-empirical model was designed on the foundation of a physical model supported by a hundred and twenty five sets of experimental data. [1]

Yuan Liao (2019). To summarize, the bead-on-string PAN filters that had been developed through electrospinning were found to be remarkable as air filters. This is because, they efficiently captured ultrafine solid and oil based particulate matter in the air. The requisite bead-on-string morphologies are produced by a combination of factors like, the imbalance between electric field’s repulsive force and the restrictive force generated due to the surface tension. Viscosity optimizations of PAN dope and relative humidity conditions are the other contributing factors. Ultrafine nanofibers present between the beads ought to further enhance the removal efficiencies. The open and interconnected channels of airflow courtesy of the nanobeads help in creating low levels of airflow resistance. Through the optimizaton of the mass weight, removal efficiency beyond 99% and a pressure drop as low as 27 Pa could be achieved by the bead-on-sting filter. Clearly, this is way better than what the commercial filters or other filters discussed in literature offer. Furthermore, its performance, mechanical robustness, and reusability are unmatched as far as practical applicability is concerned. Additionally, it is quite practical to scale up the production without the need of introducing new costs and changes. To sum it up, when it comes to varied applicability of air filters like, respiration, window-screen, and medical equipment, the filters designed in this paper may prove to be invaluable. [2]
B.F. Yua (2009) When it comes to indoor air quality, it is in everyone's benefit that it be safe and healthy. When it comes to regulating indoor temperature, the air conditioning technology has made great strides. However, when it comes to indoor air quality, it is still an up and coming area of research and application. Various different studies exist on the composition, sources, and characteristics of air pollutants found indoors and its impact on health of individuals. It is no secret that same levels of pollution affects different individuals differently, owing to their distinct physiological characteristics. It has to be acknowledged that the components of indoor pollutants are quite complex and varied. Interestingly, often chemical reactions occur among these components which leads to the creation of secondary pollutants which may prove to be all the more harmful. The level of research and study on secondary pollutants is even more limited at the present. The nature of interaction between these secondary pollutants and the human body is also relatively less known at the time. All of these issues and problems lie at the heart of the subject of indoor air quality. Therefore, it is apt to say that these systems save energy while providing a healthy indoor air quality [4].

Stephen N. Rudnick (2004). More often than not, HEPA filters are found contained in most portable fan-filters for indoor use. The author postulated that fibrous filters are more effective at dealing with sub-micrometer sized indoor aerosol, including, tobacco smoke, particles from cooking, viruses, as well as radon decay. This is due to the higher penetration of fibrous filters. This postulation was found to be correct. Borrowing from the filtration theory, the thickness of the filter was optimized at a fixed energy consumption and filtration area so as to maximize the rate of clean air delivered. Optimal collection efficiency was hypothesized to be at 82% as far as very small particles with less than 0.1 \( \mu m \) diameter were concerned. For them, diffusional deposition was mainly responsible for collection. Therefore, optimal filter penetration was found to be 600 times more compared to a HEPA filter. As far as bigger particles are concerned with diameter close to a fibrous filter’s most penetrating size, deposition due to direct interception was also factored-in. One of the plus-sides of particles of this size is that the rate of clear air delivery will be higher for both smaller and larger particles than the size for which the thickness of the filter was optimized. This is an efficient way of achieving good indoor air quality at less cost, material and method [5]

3. Research Methodology

The research methodology for optimizing the air filter can streamlined by considering a simple metallic body to house the cartridge consisting of some good filtering fibrous material like hepa. It is important to calculate the pressure drop due to filtering resistance and its efficiency. The numerical model should stand constant throughout the research. No standard method is available to tell the pressure drop and efficiency. The results might vary and therefore appropriate model has to adopted. But the methodology being used in
this work may be easy to adapt for accurate predictions. The physical and practical constraints must be applied in air filtering machines like size, energy requirements, amount of the air and its efficiency. In some countries there are power limits. In India a single phase connection cannot have more than 2 KW load. The realistic model should consume minimum power like 250 watt. The CADR of the fibrous filter must be optimized. If the basis of optimization is the distribution of the particle size then quantifying process must be specified for example by mass or by number. Another issue is the settlement of the particles on filtering medium changes the composition of the filter. This in turn reduces the pressure and efficiency. It is easy to use pre filter with separate out big size particle [6][7]

Pressure Drop across the filter

Based on a theoretical analysis the pressure drop and flow field velocity in and ideal fiber filter, the pressure drop $\Delta pt$ can be mathematically given by

$$\Delta pt = 16\alpha\eta t V/d f^2$$  \hspace{1cm} (4.1)

Where $\alpha$ is solidity (fraction of filter volume that is fibrous), $\eta$ is the air viscosity, $t$ is the thickness of the filter $df$ is the fiber diameter. $V$ is the interstitial velocity, the mean velocity within the filter medium:

$$V= V_0/(1-\alpha)$$  \hspace{1cm} (4.2)

$V_0$ is the face velocity, the mean velocity which flows upstream and perpendicular to the filter medium :

$$V_0=Q/A$$  \hspace{1cm} (4.3)

$$Q=(1-\alpha)AV$$  \hspace{1cm} (4.4)

Where $Q$ is airflow rate, $A$ is filtration area, $K$ is Kuwabra hydrodynamic factor:

$$K= \alpha - \alpha^2/4 - (\ln \alpha/2) - (3/4)$$  \hspace{1cm} (4.5)

Power Consumption

The power required to resist the resistance of the filter (H) is given by:

$$H = Q\Delta p$$  \hspace{1cm} (4.6)

$$He = H/\eta m \eta \tau$$  \hspace{1cm} (4.7)

Where $\eta m$ is motor efficiency and is fan full efficiency energy into rotating mechanical energy to kinetic and pressure energy of the air. This work will be making the use of Solid Works to model a filter. All the parts will be modelled and then the parametric assembly would be created using ANSYS FLUENT 6.3 tool.

The solid works Software also has SIMULATION WIZARD to model all the air filter parts including the porous material like HEPA. The air flow can be simulated and it can pass through the porous material. The porous material can be modified to some suitable material available in the market. All the flows can be controlled and measured. The graphical simulation and its results can be verified against the mathematical model of the proposed filter [1], [8].
4. Simulation by ANSYS Fluent 6.3

4.1. Flow Modeling & CFD Simulation

Fluent software contains the broad, physical modeling capabilities needed to model flow, turbulence, heat transfer and reactions for industrial applications. The range from airflow over an aircraft wing to combustion in a furnace, from bubble columns to oil platforms, from blood flow to semiconductor manufacturing and from clean room design to wastewater treatment plants. Fluent spans an expansive range, including special models, with capabilities to model in-cylinder combustion, aero-acoustics, turbo-machinery and multiphase systems [9][10]. X and Y are considered to keep the simulation easy. The value of X and Y depend on many quantities, only the thickness in Z direction (unit mm) has the role in pressure variation.

![Figure 1. Air flow along filter thickness in Z direction](image1)

![Figure 2. Air filter with dimensions in mm](image2)
### Table 1. Data for Change in Filter Thickness

| Thickness of filter (t) mm | Pressure drop (ΔP) Pa/m | Volumetric flow rate (Q) m³/s | Air power (H) PW | CADR (Q) | Dimensionless X | Dimensionless Y |
|---------------------------|-------------------------|-------------------------------|------------------|----------|----------------|----------------|
| 1.50E-04                  | 159.8006                | 2.18E-03                      | 3.49E-01         | 2.18E-03 | 3.84E+00       | 5.09E-01       |
| 2.00E-04                  | 184.5218                | 1.88E-03                      | 3.47E-01         | 1.89E-03 | 5.13E+00       | 4.41E-01       |
| 2.50E-04                  | 206.3017                | 1.63E-03                      | 3.37E-01         | 1.66E-03 | 6.46E+00       | 3.93E-01       |
| 3.00E-04                  | 225.9922                | 1.43E-03                      | 3.23E-01         | 1.49E-03 | 7.83E+00       | 3.57E-01       |
| 3.50E-04                  | 244.0994                | 1.31E-03                      | 3.19E-01         | 1.37E-03 | 9.17E+00       | 3.30E-01       |
| 4.00E-04                  | 260.9533                | 1.18E-03                      | 3.08E-01         | 1.26E-03 | 1.06E+01       | 3.07E-01       |
| 4.50E-04                  | 276.7827                | 9.74E-04                      | 2.70E-01         | 1.11E-03 | 1.23E+01       | 2.85E-01       |
| 5.00E-04                  | 291.7546                | 8.41E-04                      | 2.45E-01         | 1.00E-03 | 1.40E+01       | 2.67E-01       |
| 5.50E-04                  | 305.9948                | 7.28E-04                      | 2.23E-01         | 9.13E-04 | 1.58E+01       | 2.52E-01       |
| 6.00E-04                  | 319.6012                | 7.73E-04                      | 2.47E-01         | 9.20E-04 | 1.67E+01       | 2.44E-01       |
| 6.50E-04                  | 332.6514                | 8.34E-04                      | 2.77E-01         | 9.37E-04 | 1.76E+01       | 2.38E-01       |
| 7.00E-04                  | 345.2087                | 4.29E-04                      | 1.48E-01         | 6.60E-04 | 2.22E+01       | 2.12E-01       |
| 7.50E-04                  | 357.325                 | 3.16E-04                      | 1.13E-01         | 5.56E-04 | 2.55E+01       | 1.98E-01       |

### Table 2. Filter Properties

| Porosity (1-α) | 0.97 | Temp of air at inlet (T_i) k | 298 |
| Solidity (α)   | 0.03 | Density of filter (ρ_f) kg/m³ | 215 |
| Viscous resistance (C_o) Ns/m² | 3.85E+07 | Dynamic viscosity of air (η) Ns/m² | 1.85E-05 |
| Inertial Resistance (C_2) V/A | 20.414 | Cross sectional area of filter (A) mm² | 2.32E-02 |
| Initial thickness of filter (t_i) mm | 5.00E-04 | Density of air (ρ_a) kg/m³ | 1.225 |
| Static press of fan (P_i) N/m² | 150 | | |
Table 3. Assumptions in Filter Design (UNIT SI)

| Length of cylindrical fiber (lf) mm | Dia of cylindrical fiber (df) mm | Volume of a single fiber (Vf) m³ | Surface area of a single fiber (Sf) m² | Sphericity (ϕ) mm |
|----------------------------------|---------------------------------|---------------------------------|---------------------------------------|-----------------|
| 0.03                             | 7.00E-07                        | 1.15E-14                        | 6.60E-08                              | 3.74E-02        |

| Dia of virus (dp) mm | Interception parameter (R) m/s | Slip correction factor (Cc) s | Particle diffusion coefficient (D) | Kuwahara hydrodynamic factor (K) | Direct interception parameter (f) |
|---------------------|--------------------------------|------------------------------|-----------------------------------|---------------------------------|----------------------------------|
| 1.25E-07            | 1.79E-01                        | 1.08E+02                     | 2.04E-08                          | 1.03E+00                        | 9.41E+02                         |

5. Results & Discussion

5.1. Variation of CADR with Filter Thickness

![Figure 3. Volumetric Flow Vs. CADR](image)

Note: Volumetric flow rate is proportional CADR

5.2. Variation of Pressure Drop with Filter Thickness
Figure 4. Pressure Vs. Thickness of filter fiber

5.3. Comparison of Initial and Final Filter Thickness

Figure 5. Thickness of filter fiber before optimisation and after optimisation

5.4. Variation of Pressure Drop with Filter Thickness
5.5. Variation of Dimensionless $Y$ with Dimensionless $X$

The X and Y direction have no effect. Simple number is considered as it is a ratio between two lengths.
5.6. Variation of CADR with Filter Material

Figure 8. Graph of volumetric flow rate

Note: Volumetric flow rate is proportional CADR

5.7. Variation of Pressure Drop with Filter Material

Figure 9. Pressure drop Vs. Porosity

5.8. Optimizing the Design of Room Air Filters for the Removal of Sub Micrometer Particles (Improvements after Optimization)

1. At the expense of pressure drop in optimized design, the discharge was maximized, for the same air power.
2. The flow rate has been increased from an initial value of 21E4 m³/s (at thickness 0.15 mm) to the optimized value of 92E4 m³/s (at thickness 0.91 mm) which is a significant increase of 338% i.e. 3.38 times from initial value.

3. Optimizing for the material porosity, it was found that the filter shows the maximum performance at a porosity value of 0.95

4. These factors will result in lower power consumption, enhanced Q<sub>cad</sub>, filtration efficiency, and hence the overall effectiveness of room air filter\[8\]

Various performance improvements are depicted below:

5.9. Pressure Distribution

![Figure 10. Pressure Vs. Distance in Z full domain](image1)

![Figure 11. Pressure Vs. Distance in Z along](image2)
Figure 12. Velocity (w) distribution in full domain

Figure 13. Velocity (w) distribution in Z along

Figure 14. Velocity (v) distribution full domain

Figure 15. Velocity (v) distribution in Z along
6. Conclusion

The Hepa filter can capture with extraordinary efficiency of $0.01 \times 10^{-9}$ Meter sized particles. The size of the Corona Virus Covid-19 is 125 Nano Meter. The preliminary study shows that covid-19 can become aerosolized and can remain in the air for hours. Therefore, the hepa filter can protect the hospitals where patients are vulnerable to any similar type of infection. But person-to-person contact is the chief source of spreading the deadly disease as the virus can remain in the air up to 6 feet and thereafter it settles down. At the expense of pressure drop in optimized design, the discharge was maximized, for the same air power. The flow rate has been increased from an initial value of $21E4$ m$^3$/s (at thickness 0.15 mm) to the optimized value of $92E4$ m$^3$/s (at thickness 0.91 mm) which is a significant increase of 338% i.e. 3.38 times from initial value. Optimizing for the material porosity, it was found that the filter shows the maximum performance at a porosity value of 0.95. These factors will result in lower power consumption, enhanced Qcad, filtration efficiency, and hence the overall effectiveness of room air filter.

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