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Research Article

Efficiency Analysis of Covid 19 Filtration with The Theoretical Approach Developed for Single Fiber Efficiency

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ABSTRACT

It is necessary to understand the efficiency of the filters, which are the most important part of the ventilation systems, in order to hinder the spreading of the Covid-19 virus. In this article, a model was created using theoretical solutions developed for single fiber efficiency and with this created model, the previous theoretical data were confirmed. Then, the theoretical data in the model created with the experimental data were compared. Also, factors such as fiber diameter, particle diameter, or flow velocity affecting single fiber efficiency were changed and the effects of these parameters were investigated. As a result of this investigation, it was seen that, as the Peclet number increased, the single fiber efficiency decreased, and the efficiency of the single fiber increased when the particle diameter increased. Finally, when the solidity, which can be considered as the fiber density in the filter, increased, the single fiber efficiency increased along with it. When solidity was increased from 0.011 to 0.03, single fiber efficiency increases from 0.023 to 0.0269. That is, there was an increase of approximately 16.9 %.

1. Introduction

Today, with the rise in the human population, the development of industry, and the advancement of technology, air pollution is increasing. Also, the removal of particles from the air is a huge problem and there is a need to reduce particles that endanger human health. Therefore, being able to fulfill this need is an industrially important issue. In addition to all these, due to the COVID-19 pandemic disease that swept the whole world in 2019, the ventilation of the environments we live in has become an increasingly important issue. Because COVID-19 disease spreads more in crowded and closed environments. [1]. So, breathing clean air is not a privilege but a general need.

The most important part of the ventilation system that provides clean air is the filters. Two filters' standards are extensively utilized. One of these standards is EN779 and the other is ASHRAE 52.2 (2007) [2]. In these classifications, for various particle sizes, dissimilar filter classification criteria were used. The dimension of particles that filters can filter vary in EN779:2012 and ASHRAE 52.2 standards. While 0.4 µm particles can be filtered in EN779:2012, ASHRAE 52.2 filters 0.3 to 10 µm particles [2]. Also, Also, due to the insufficient filtration standards of EN 779:2012, experts recommended a more advanced standard, ISO 16890. The ISO 16890 standard, unlike the EN 779 standard, takes the particle dimensions in the variety of 0.3 to 10 µm (Particle Matter = PM) into account for efficiency evaluation. PM 1, one of the classification names, refers to situations where the particle size is ≤1 µm, PM 2.5 refers to the particle size of ≤2.5 µm, and PM 10 refers to the particle size of ≤10 µm [3]. Apart from the classifications based on these particle sizes, many studies have been carried out on efficiency. The single fiber hypothesis was put forward by Hinds W.C. (1999). Many theoretical studies have been carried out to ease the correct understanding of the data obtained in the experiment or the measured data [2]. In these theoretical studies, mechanisms such as diffusion, interception, and impact are in examined, electrostatic filtration was not included in the studies [4]. Happel and Kuwabara have included cell models in addition to previous work. The single fiber hypothesis presented to explain the effect of neighboring fiber on efficiency in these cell models is widely used because it is easy to understand. According to this hypothesis, the flow lines and particle capture efficiency of the filter have been studied successfully. Stechkina and Fuchs were the first to examine neighbor fiber interference using the Kuwabara Happel flow field in their study [5]. The Kuwabara and Happel flow field was obtained utilizing the cell model and solved the viscous flow around the cylinder with the Navier-Stokes equations [5]. Kirsh and Fuchsun's studies in 1967 and Yeh's studies in 1972 showed that the Kuwabara flow field, which represents the flow around the fibrous filters, is preferred over the Happel flow field. Therefore, the Kuwabara flow area is preferred. Also, the Kuwabara flow field is preferred when the Reynolds numbers are low. [6] Lee and Liu (1980) and Wang and Kasper (1981) conducted many studies on the filtration efficiency of ultrafine particles without inertial impaction, they investigated by considering the diffusion and interception mechanisms [7]. People can be exposed to particles outdoors or indoors, and there are often ultrafine particles in the air they are exposed to inside buildings. [8] Indoor particle concentrations often exceed outdoor particle concentrations due to a combination of indoor emission sources and outside particle ingress [9]. Particles generally enter the human body through the respiratory tract and mostly affect the

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respiratory tract. The movement and impact of particles in the human respiratory system depend on the features of the particles like shape, dimension, density, or reactivity. Particles that can reach the human lungs are the ones below 10 µm. Most of the particles are larger than 10 µm and approximately 60-80% of particles between 5 and 10 µm are retained in the throat and nose area. These particles are trapped and expelled in the upper respiratory system by precipitation, inertia, and direct impact mechanisms. [10] When the particle concentration in the substance increases, especially when PM 2.5, that is, its diameter is smaller than 2.5PM, or ultra-fine particles (the diameter of which is less than 100 nm.) human health is adversely affected [11].

The particle size of the COVID 19 virus, which is today's pandemic disease, is also very small. Therefore, it is of great importance to prevent the entry of this virus into our body. The COVID 19 virus spreads more in crowded environments, and the virus spreads faster in poor ventilation systems. Therefore, the authors evaluated the development of heating, ventilation and air conditioning (HVAC) systems in hospitals and buildings as factors that may prevent the spread of the virus [12]. The control and efficiency of these ventilation systems is of great importance for human health. Filters, one of the most important parts of ventilation systems, come to the fore at this point. Many authors have set up and tested different test setups to evaluate the effectiveness of the filters. However, N. Zacharias, A. Haag et al. did not utilize SARS-Cov-2 virus. They utilized bacteria or viruses instead of SARS-CoV-2 [13]. Cindy Wenke et al. [14] used 6 different pathogens in their study. The mean diameters of these pathogens differ from each other. Using these pathogens, they conducted a series of experimental tests to substantiate whether or not booth air filters and air filters types G4, H14, F8, and M5 may cease the unfold of SARS-CoV-2.2. Leonard F. Pease, Na Wang et al. [15] evaluated the infection concentrations and probabilities by creating a model in a building with an HVAC system. According to the results, the infection risk was calculated as 0.2% in the room where the MERV-8 filter was connected, while the infection risk was calculated as 1.5% in the rooms where it was not connected.

In this study, the change in filter efficiency, which has been examined before, is examined theoretically under different conditions to facilitate the understanding of the factors affecting the efficiency, and these factors. These parameters are fiber diameter, particle diameter and velocity of a fluid. As a result of this examination, it was determined which parameters affect the efficiency and how. Since no theoretical work has been done on the effect of the COVID-19 virus, which has affected the whole world in 2019 and affected our lives so much, on the filter systems that can prevent the spread, a study has been carried out on this subject. The parameters used in previous studies on the COVID-19 virus are different (such as examining the pressure change). Experimental data were obtained in the examination of pressure variation. This study includes a theoretical approach.

2. Air Filters Capture Mechanism

Air filters have multiple capture mechanisms. These mechanisms show different effects on single fiber efficiency under other conditions. Firstly, according to the inertial impaction mechanism, which is one of these mechanisms, when the airflow rotates, the fine particles in the air are under the effect of inertia. They are separated from the airflow direction. After that, it starts to form residues on the fiber membrane by multiplying. Accordingly, inertia generally ensures that the particles have higher filtration efficiency. The efficiency is greater in case of inertial impact mechanism at high flow rate and when the size of particles is greater than 0.3-1 µm. [16,17]. Secondly, in the sieving mechanism, the distance among the fibers of the filter is smaller than the size of the particles, and thus the passage of particles is not allowed. [18] If the pores of the filter media through which the air flows are smaller than the particle from which the air is removed, the particle is retained. The filtration, in this case, is done on the face of the filter so that the filter can be very thin (typically about 100 µm) [19]. Thirdly, according to the interception mechanism, if the distance from the middle of the mass of the particle to the fiber surface is equal to the radius of the particle or smaller than that distance, it is possible to catch the particle [20]. According to the interception mechanism, there is touch and attachment of particles to the fibers of the filter. Particles are held in the fiber by a molecular surface gravitational force known as the Van der Waals force [21]. The collecting efficiency of the single fiber owing to interferences is at that point basically the proportion of the liquid stream rate limited inside the two critical particle directions to the entire stream rate captured by the fiber [21]. The particle capture attempts instrument gets to be critical when the particle measure is not irrelevant relative to the fiber estimate [21]. Finally, the captur mechanism that greatly affects the single fiber efficiency is diffusion. By botanist Robert Brown, the random motion of pollen on the water was initially discovered in 1827, and soon after it was discovered that the movement of small smoke particles in the air was the same [22]. This basis implements to very slight particles that behave like gas molecules. Particles smaller than 1 micron collide with gas molecules in the airflow and move in random trajectories (Brownian motion). However, for large particles, the total net intermolecular force is not sufficient to generate such motion. It is feasible to keep such randomly acting pieces by placing dense obstacles on their path. In order to provide efficient filtration, a large number of particles must be able to collide with the media fibers. For this, a very low speed of 0.02 m/s inside the media should be used. A tensile force is present to keep the particles on the middle fiber. The name of this force is Van der Waals. In this case, the smaller and lighter the particle size, the more efficient the principle. This principle is of paramount importance in air filtration engineering and is primarily used in medium and high-efficiency extended surface filters, as most atmospheric particles are less than 1 micron. [22]. Modeling of the filter capture mechanism described is shown in Figure 1.

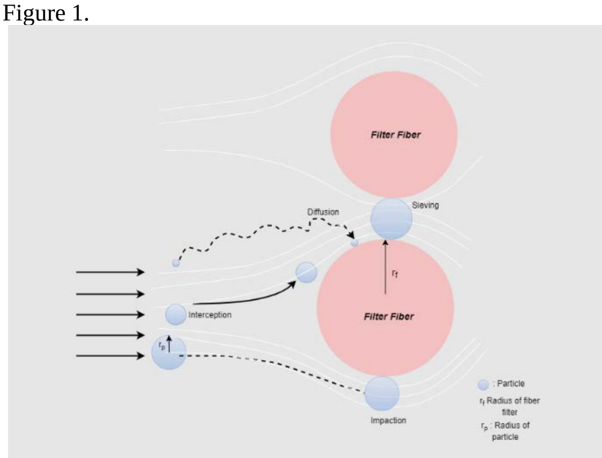

Figure 1. Air Filter Capture Mechanism

3. Classical Filter Theory

Examining the efficiency of single fiber filters (SFFE) is the greatest method to measure the filtration of fiber filters. SFFE can be described as the number of particles caught by the fiber and the number of particles discrete from the fiber [23]. There are two basic components of the collection in a filter. The hypotheses created generally include standard filtrations, and most researchers who have worked in this field have independently examined the capture mechanisms and evaluated the filtration efficiency.

4. Methods and Theory

In order to better understand this subject, first of all, it is necessary to understand the concept of efficiency. Efficiency in filters can be evaluated as the particle capture capacity. Single fiber efficiency refers to how much a particle is captured as it passes through the fiber of the filter. The number of particles passing through the filter fiber is related to the porosity of the filter fiber. The more porous the filter fiber (the lower the density pack), the higher its permeability. This study examined the transmission of the COVID-19 virus, which is one of today's new problems, in fiber filters. When the studies are concerned, the diameter of the COVID-19 virus is approximately between 20 nm and 120 nm. It is vital for us to keep such a small virus in filters. In this context, the studies of Lee and Liu analyzed diffusion and interception mechanisms separately for the efficiency of the filter and then combined them [6]. Lee and Liu's studies have been taken into account because the theories used in Lee and Liu's studies, which is one of the recent studies, are more accurate when compared to experimental data.

One of the important parameters used in Lee and Liu's studies is the diffusion coefficient. The diffusion coefficient affects the diffusion efficiency of a single fiber. The diffusivity D (diffusion coefficient), which depends on the gas features, can be defined as follows [24];

$$D = \frac{kTC_c}{3\pi\mu d_p} \quad (1)$$

where k is Boltzmann's constant ($1.38x10^{-23}\ JK^{-1}$), d_p is particle diameter, μ is the dynamic viscosity of air ($\mu_{air} = 1.81 \times 10^{-4}$ g/cms), T is the absolute temperature in K (the temperature specified here varies depending on the ambient temperature, 298.15 Kelvin is acceptable for a normal room temperature.), and C_c is a Cunningham slip correction factor for small particles. $C_c = 1 + (0.167 / d_p$ [μm]), for air approximately.

The higher the diffusion coefficient, which is attached to the particle dimension and the properties of the fluid, the faster the mass transfer process to push particles moving from higher concentrations to lower concentrations [25].

One of the other important parameters is the Peclet Number. Peclet Number is described as the proportion of the rate of the transfer of heat by the flow of fluid of a physical quantity by the rate of diffusion (matter or heat) of the identical amount driven by a suitable gradient [26]. Peclet Number is defined [27];

$$Pe = \frac{U_0 L_{char}}{D} = \frac{Convection\ Transport}{Diffusion\ Transport} \quad (2)$$

In terms of filtration parameters, say, velocity (U_0), characteristic length (L_{char}), and diffusion coefficient (D). In this study, the diameter of the fiber filter d_f is taken as characteristic value, ($L_{char} = d_f$)

In previous studies, mechanisms such as diffusion, interception, and impaction were examined separately. Later, these capture mechanisms were combined. In accordance with the hypothetical research of Lee and Liu in 1982, the efficiency expression for the diffusion capture mechanism is as follows [6]

$$\eta = 2.6\left(\frac{1-\alpha}{K}\right)^{\frac{1}{3}} Pe^{-\frac{2}{3}} \quad (3)$$

Where α is defined as the solidity, volume fraction, or packing density. Packing density depends on the shape of the particles. K in cell model is Kuwabara hydrodynamic factor, which is represented by $K = -\frac{ln\alpha}{2} - \frac{3}{4} + \alpha - \frac{\alpha^2}{4}$ [25]. The single fiber efficiency expression obtained above is valid only for the diffusion mechanism and valid for Pe ≥100 [6].

As mentioned before, in the interception mechanism, if the distance between the center of the particle and the fiber surface is less than the radius of the fiber, the particles are caught [23]. Lee and Liu in 1982 [5] obtained the following single fiber efficiency for the interception mechanism by using the Kuwabara flow field in their work [6]. The single fiber efficiency due to interception η_R, is defined,

$$\eta_R = \frac{1+R}{2K}\left(2\ln(1+R) - 1 + \alpha + \left(\frac{1}{1+R}\right)^2\left(1-\frac{\alpha}{2}\right) - \frac{\alpha}{2}(1+R)^2\right) \quad (4)$$

R is the rate of particle diameter to fiber diameter ($R = \frac{d_p}{df}$). Since this resulting equation was too long, Lee and Liu decided to convert it to a simpler form. As a result of Lee and Liu's studies, the fiber efficiency originating from the interception mechanism is as follows [6] ,

$$\eta_R = \frac{1-\alpha}{K}\frac{R^2}{1+R} \quad (5)$$

One of the best ways to combine two separate efficiencies is to add the two efficiencies together. In this application, one of the mechanisms is dominant and the effect of the other is very small. This application has been found suitable for diffusion and interception mechanisms. As shown in Equation 3, a rise in particle diameter causes a reduction in diffusion efficiency. In addition, increasing particle size increases the efficiency resulting from holding. Assuming the effect of the impaction is negligible, the single fiber efficiency obtained from the studies of Lee and Liu [6] is as follows,

$$\eta = \eta_D + \eta_R \quad (6)$$

If equations (3) and (5) are substituted in Eq. (6), the single fiber efficiency can be found as ;

$$\eta = 2.6\left(\frac{1-\alpha}{K}\right)^{\frac{1}{3}} Pe^{-\frac{2}{3}} + \frac{1-\alpha}{K}\frac{R^2}{1+R} \quad (7)$$

5. Verification of The Model

The model equations, Eq. (4) and (5) are coded in MATLAB. The verification of the model were performed based on the parameters presented in Table 1 and the comparison of the results obtained in this study using MATLAB with the results exist. The values under the Simulation title are the values obtained from MATLAB in this study. It is observed that the deviation between the results of this study and the one in the literature [6] as follows. The values used in the comparison are theoretical approaches. The values are also very close to each other. Therefore, it is concluded that the model equations can be used in the parametric analyses.

According to the information obtained by the studies in the literature, a small-scale test setup was prepared for eight full-scale bag filters supplied from the international filter manufacturer and checked in this setup. The characteristics of the tested filters are summarized in Table 2. The values given in this table were used in the present study.

Table 1. Verification of the Interception Efficiencies

	Solidity	Diameter Ratio (R)	Hydrodynamic Factor (K)	Efficiency Using the Original Flow (Equation 4)		Efficiency of Interception (Equation 5)	
No	Reference [6]	Reference [6]	Reference [6]	Reference [6]	Simulation	Reference [6]	Simulation
1	0,001	0,05	2,70490	0,00089	0,0008938	0,00088	0,0008793
2	0,001	0,1	2,7049	0,00347	0,0034665	0,00336	0,003357
3	0,005	0,05	1,9042	0,00126	0,0012643	0,00124	0,001244
4	0,01	0,1	1,5626	0,00594	0,00594	0,00576	0,005759
5	0,1	0,1	0,4988	0,0168	0,016809	0,0164	0,016403
6	0,1	0,2	0,4988	0,063	0,062989	0,0602	0,060144
7	0,2	0,2	0,2447	0,112	0,1119	0,109	0,10897
8	0,3333	0,01	0,1049	0,00063	0,000629	0,00063	0,0006292
9	0,3333	0,1	0,1049	0,0577	0,05763	0,0578	0,05777
10	0,5	0,01	0,0341	0,00145	0,00144	0,00145	0,0014517
11	0,5	0,1	0,0341	0,1283	0,1283	0,133	0,13329

Table 2. Properties of Used Filters [2]

	Filter Code	European Standard EN779	US Standard ANSI/ASHRAE 52.2	Effective Fiber Diameter (μm)	Thickness (mm)	Packing Density (α)
1	GF	M5	MERV 9-10	6,20	3,7	0,01
2	US	M6	MERV 11-12	2,5	1,8	0,01
3	GF	M6	MERV 11-12	5	4,1	0,01
4	US	M6	MERV 11-12	2,5	2	0,44
5	GF	F7	MERV 13	2,2	3,5	0,01
6	US	F7	MERV13	2	0,6	0,03
7	GF	F8	MERV14	1,4	2	0,01
8	CS	F8	MERV14	1,50	0,9	0,01
9	US	F8	MERV14	1,5	1,2	0,02
10	GF	F8	MERV14	2	4,3	0,012
11	GF	F9	MERV15	2	4,3	0,011
12	CS	F9	MERV15	2	1,4	0,015

GF: glass fiber; CS: charged synthetic fiber; US: uncharged synthetic fiber.

6. Results

Considering the studies of Lee and Liu [6], single fiber efficiency calculation will be made according to equation 3. The simulations do not contain any electrostatic filtration mechanism.

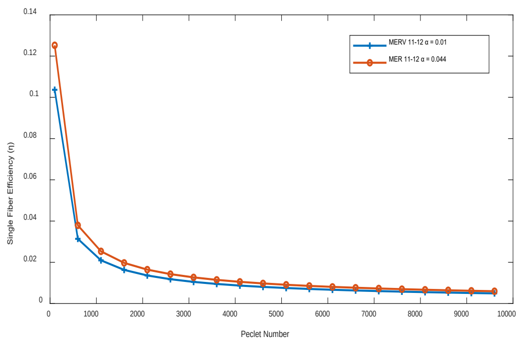

Figure 2. Investigation of the effect of packing density on yield according to the change of peclet number

The Figure 2. shows the relationship between Peclet number and single fiber efficiency. While examining this relationship, filters which is selected according to ASHRAE standards is used. The solidity of these selected filters is different from each other. When this graph is examined, it is observed that the efficiency of the MERV (Minimum Efficiency Reporting Value) 11-12 filter decreases when the Peclet number increases, that is, when the velocity of the flowing air increases. (It was mentioned in section 5 table 2 that the peclet number depends on the speed, fiber diameter and diffusion coefficients.) By examining in Figure 2, it is understood that as packing density increases, the holding capacity also increases. In addition, when the Peclet number is greater than approximately 6000, the curve remains stable. The efficiency studied here applies only to diffusion, excluding interception.

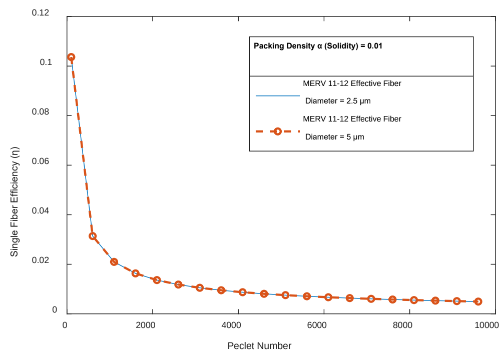

Figure 3 Investigation of the effect of effective fiber diameter on yield according to the change of peclet number

As in Figure 2, Peclet number and single fiber efficiency are investigated in Figure 3. In the Figure 3., the solidity of the filter and the particle diameter are kept constant and the fiber diameter of the filters are changed. As can be understood from Figure 3, the lines overlap in the graph. The reason for this is that the fiber diameter of the filter is not important when examining only the diffusion mechanism. According to this graph, no matter how much the fiber diameter of the filter is changed, if other parameters are kept constant, it is going to not have any effect on the single fiber efficiency.

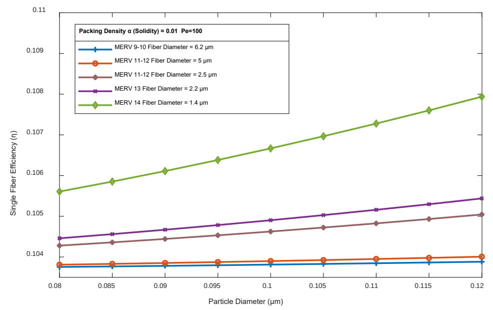

Figure 4. Investigation of the effect of fiber diameter on efficiency according to the change of particle diameter

In Figure 4, the Peclet number has been accepted as 100 from Lee and Liu's study and the packing density (solidity) has been taken as 0.01.[2] Here, it is thought that the particle diameter of the Covid 19 virus varies between 0.08 μm and 0.12 μm. In addition, not only diffusion but also interception with diffusion has been considered. It is clearly observed that the efficiency of the single fiber increases as the fiber diameter of the filter decreases because as the diameter decreases, the number of particles that will pass through that diameter decreases. In addition, it seems that the single fiber efficiency grows as the diameter of the particle increases. The reason for this is that the larger the particle diameter, the more difficult it is for the filter to pass through the fiber diameter.

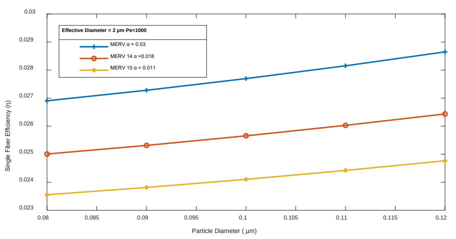

Figure 5 Investigation of the effect of packing density on yield according to the change of particle diameter

In Figure, the fiber diameter of the filter is kept constant, the Peclet number is accepted as 1000 from Lee and Liu study [6] and the effect of packing density on single fiber efficiency is examined. According to this graph, as the packing density increases, the efficiency increases. The packing density referred to here is the ratio of the capacity of the particles to the total capacity of the packaging. What is meant is that the higher the packing density, the closer the volume of the particles becomes to the total volume size, and the less the void becomes. The fewer the voids, the fewer the particles can pass through. In this case, the single fiber efficiency increases.

7. Conclusion

Considers the effect of fibers immediately adjacent to the flow field on the streamline, according to the cell model used in Kuwabara and Happel's studies, and the fiber's volume ratio is also taken into account in order to actually use the model. In the present study, the studies of Lee and Liu were taken into account. In their experimental studies, Lee and Liu have used velocity between 1cm/s and 300cm/s. [28]

They have found the Peclet number here and have given a certain range. The obtained equations are used in the range of this Peclet Number. (100≤Pe≤10000). In this study, single fiber efficiency examined for different parameter. These are particle diameter, fiber diameter, solidity of the filter. The values of the parameters examined were taken from the studies in the literature [2].

It is clearly observed that the efficiency improves as the solidity, which can be considered as the density of the inside of the filter, increases. It can be said that the results here are in agreement with other studies. When diffusion and interception are considered together, the efficiency of the filter increases with rising diameter of particle. This is because larger particles are more difficult to pass through the fiber diameter. In Figure 4, when the packing density is taken as 0.03, the particle diameter is 0.08, the single fiber efficiency is 0.0269, and when the particle diameter is 0.012, it is 0.028. Efficiency also increases when the number of Peclet and fiber diameter are kept constant, and the packing density is increased. In Figure 4, if the particle diameter is 0.08, when the packing density is 0.011, the efficiency is 0.023. On the same figure, it is seen that when the packing density is 0.03, the single fiber efficiency is 0.0269. In addition all of above, when the diffusion is considered alone, it seems that the diameter of the fiber has no effect on the efficiency in the results obtained. However, if diffusion and interception are examined together, it is seen that the effect of fiber diameter on efficiency is very huge (Figure 4.). As the diameter of the fiber decreases, the particle holding capacity increases. According to the values taken from the Figure 4 when diffusion and interception are examined together, the fiber diameter is 6.2 μm, the single fiber efficiency is 0.1037, while the fiber diameter is 1.4 μm, the single fiber efficiency is 0.1056.

When all the results are examined, the efficiency of fiber filters is affected by the mechanism of diffusion and interception. In order to enhance single fiber efficiency, the fiber diameter must be reduced, or the solidity must be increased. The results of this study show that when the particle diameter increases the single fiber efficiency rises. Also, the increase in particle velocity decreases the efficiency as it causes an increase in the Peclet Numbers.

Declaration of conflicting interests

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Nomenclature			
D	Diffusion Coefficient	***Greek symbols***	
k	Boltzmann's Constant,	η	Single Fiber Efficiency,%
T	Absolute Temperature, K	η_R	Efficiency of Interception Mechanism,%
d_p	Particle Diameter, μm	η_D	Efficiency of Diffusion Mechanism,%
d_f	Fiber Filter Diameter, μm	μ	Dynamic Viscosity of Air, kg/ms
C_c	Cunningham Slip Correction	α	Packing Density (Solidity)
C_0	Concentration,	***Subscripts***	
H	Channel of Width, m	PM	Particle Matter
Pe	Peclet Number	UFP	Ultrafine Particles
K	Kuwabara Hydrodynamic Factor,	SFFE	Single Fiber Filter Efficiency
R	The Ratio of Particle Diameter to Fiber Diameter, μm	MERV	Minimum Efficiency Reporting Value
U_0	Velocity, m/s		
L_{char}	Characteristic Length, m		

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