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Optical determination of filter effectiveness in potentially aerosol contaminated classrooms during the COVID-19 pandemic

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Abstract

Increasing COVID-19 infections are reason of concern for all the inside workplaces where physical presence is necessary for collaborating. Classrooms are one of the suspected places, where usually students are closely placed to learn together as in times before the pandemic. To reduce the infection rate in classrooms, an air purifier was designed around a commercial filter which removes 99,9% of particles with 3µm. A baseline optical study of air purification was carried out to ensure effectiveness of the purifier during operation in closed environment. With conclusive evidence of microscopic images, breathing tests and aerosol penetration test using oil, the filter effectiveness was recorded. Optical values for suspended particle counts are recorded for variations in air flow rates of the air purifier and the gradual change is helping to understand the filter performance. Already around 70% minimum effectiveness of one flattened tissue layer removed from the filter was recorded during the tests, where the functional filter is folded in zigzags and 25 times thicker than a single layer. Furthermore, microscopic images showed solids deposited on the filter fabric and fuzzy spots on the tissue could indicate possible dried aerosol spots. This could be the hint supporting the hypothesis that aerosols can be effectively filtered reducing the virus load thus also risk of super-spreading of potential infection risk to an acceptable level. Beyond this research, and with the same group, measurements were made finding out the degree of reduction in potential aerosols particles in a classroom with a continuously aerosol emitting person. On that basis from this and the other optical studies, it was concluded that the spread of COVID-19 virus can be mitigated through effective air purification systems in classrooms and students can continue learning smoothly during the ongoing pandemic.

1. Introduction

In the wake of COVID-19 pandemic, every workplace, schools, university, and community centers came to halt. In this ongoing digital era, work can theoretically be carried out on the internet, groceries could be brought online, and information spread over websites. However, conventional ways of education remain preferable for several reasons. The sudden closing of universities to control super-spreading of virus was new challenge for teachers of all backgrounds and ages to prepare, and deliver their lessons from home effectively, and in most of the cases with improper technical support [1]. Lengthy use of online interaction has revealed the many problems encountered by teachers and students. The online classes are problematic in certain topics where the content is abstract, while deep grasping of concepts is required. Learning profound notions often need real face to face interaction for complete discussing, understanding and comprehending. In multilingual settings reading the mouth movement is crucial. Relying on online interaction is disadvantageous to eyes and general body health of such online-learners too. Some students and teachers reported that lengthy interactions online were not at all helpful in understanding the concepts and real face to face interaction were preferred for some topics beyond information acquisition. [2]. Additionally, many people developed eye issues and other health complications such as back pain due to prolonged sitting in front of screens. In era of digital and e-learning, still many pupils were keener on taking blended learning courses or even better wanted to take lessons in person, while the pandemic requires the opposite. On the other side, spreading the Corona virus in classrooms is too risky.

Medical research till date found SARS-CoV-2 mainly transmitting via aerosol droplets that are produced when breathing, speaking, singing, coughing or sneezing. When that exhaled air gets inhaled or in direct contact [3] such classrooms could become a centre for superspreading. The COVID-19 virus loaded aerosol particles, which can accumulate in a room over time, cannot be prevented with mouth and nose covers alone. An effective filtration of aerosols might help and was therefore studied [4]. This could be also done through ventilation by opening windows, but in winter times, it is undesired to use window ventilation and more importantly the air-exchange is uncontrolled. Such opening of windows or passive airing as a means of exchanging air was already found highly depending on local weather around a building and the rooms geometry with the placement of heaters described by [4], since the continuous exhaled air lets aerosol concentrations drop only temporarily with an infectious person nonstop contaminating. Airing out by window opening depends on wind, heating, and the temperature difference to the environment. Also, the German Physicist Association found passive airing out by window to be less reliable than controlled filtering [5]. In fact, the Deutsche Physikalische Gesellschaft calculated a 4% risk of a teacher infecting one of his 30 pupils in a 190 m³ room in only one day, and that already with the wildtype virus.

However, air-filtering would actively remove aerosols from an inside room by pumping the room air through a filter with a sufficiently high flow rate. The involved pump would need to create an air stream with the purified air (downstream of the filter) and so displace the air. In this way, a circulation would be induced that fulfils two functions: Firstly, potentially contaminated air would be distributed to higher levels of room, whereby humans inhale between typically between 1,0 m and 1,8 m, and rooms are usually 2,5 m high. Secondly depending on the filter's quality and room air exchange rate ACH, potentially COVID-19 contaminated air would be removed sufficiently fast to prevent exposure of a too high virus load over a too long time period.

Additionally, air filtration has also an effect on the psychology of humans in such purified rooms. Air quality and presence of air-purifiers people feel to be in safe environment and helps influencing moods of the people in the room [6]. The situation to build trust among people to attend lectures safely inside classroom is not trivial. In early days of pandemic due to corona restrictions only 20 people were allowed inside a classroom by authorities like the Berlin educational authorities, which allowed students attending lessons in person, if every 15 minutes the classroom's windows were opened. In this situation, teachers and students still were exposed to a risk of getting infected and become a carrier for the virus.

To tackle this issue an air-purifier was designed, and optimal placement of air purifier was found out to minimise the potential risk of getting infected. The heart of the purifier is an air filter. This commercial nonwoven fabric filter [7] was selected as a core of purifier machine and then further analysed for effectiveness after it was built into a casing that sealed it with a fan blower. Since the effectiveness depends also on the positioning in a given classroom, an adjacent research was performed and published in the same conference, where this research is reported [8]. In complement, this article provides insight into the effectiveness of filter in potentially reducing the risk of infection via COVID-19 or similar virus aerosol particles in a closed and heated atmosphere. How does such filter need to perform?

2. Literature Survey

According to EN 1822, HEPA filters are High-Efficiency air filters with an efficiency (but actually effectiveness) reaching up to 99.9967% efficiency and usually taken for filtration of aerosol particles. Air filters are removing particles from an air stream that usually starts with straining, which is blocking the passage simply by a grid with an opening size. In the studied Philips filter, the strainer had a grid opening size of 0,5 mm, as measured under the microscope, as seen in images 5 and 11 Downstream of the strainer, four important principles act in removing particles namely, inertia impaction, interception, diffusion and electrostatic attraction as shown on the figure below.

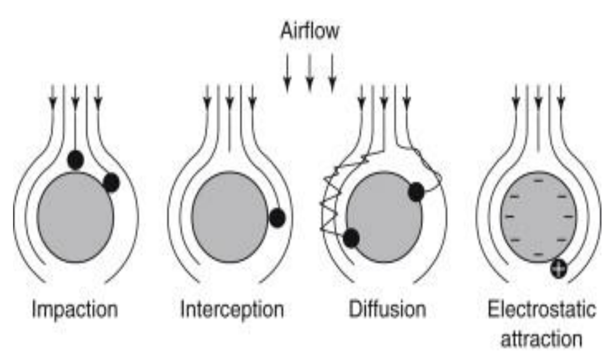

***Figure 1**: Four filtering mechanisms according to Mann + Hummel.*

Inertial impaction and interception are the dominant collection mechanisms for particles greater than 0.3 microns, and diffusion is dominant for particles less than 0.3 microns. The electrostatic charging and attraction is often applied during the production phase and lost over the duration of utilization and so also in the studied filter. However, the dust collected in the filter during that early stage of use increases the surface and therefore the filtering effect remains constant. Together and in theory, these four mechanisms allow filters to catch particles, which are both larger and smaller than a certain target size [9]. In any case, during the penetration of particles into the filter's fabric, the airspeed slows down, and solid particles settle, presumably on the downwind side of fibres. Liquid aerosols are experiencing a split of larger particles to smaller ones until the liquid evaporates. There is therefore reason to assume that the liquid droplets settle on the fibres on the downwind side. Cohesion will probably spread the liquids along the fibres, and so settle the virions. It is furthermore assumed by this research group that the liquids evaporate until virions settle on the surface, where they become inactive.

Such filters are widely used for medical operation theatres and intensive care facilities to remove maximum number of aerosol particles, where 18 times an OP theatre's volume is filtered per hour. Ultrafine filters (ULPA according to European norm EN1822) are even used to remove radioactive particles. In the context of this research, HEPA rating according to EN1822 are given to a filter depending how effectively the filter to removes particles that are greater than 0,3 µm. Most of the bacteria and fungi are greater than 0,3 µm hence, they get filtered absolutely. However, the viruses of interest here are a hundredth of the aerosol's size, in the range from 0,003 to 0,05 µm [10]. When exhaled, virus generally take a habitat of a surrounding mucus layer, which makes their size bigger. Depending on the condition of the contaminating person and how breathe is exhaled by speaking, singing or other, an amount of aerosol with a certain virus load is brought into the environment [11]. Inside rooms, which is the condition of interest, such aerosol can accumulate with up to 1 m^3 per person in quarter of an hour, corresponding to up to $4m^3$/person per hour. The aerosol is a combination of different sizes between 0,1 and 20µm. Since humans are warm the aerosol rises slightly, but in a completely still standing room the aerosol tends to sink with 3mm /sec as RWTH reported [12]. However, Stadnytskyi found the sink rate depending from the diameter is given with 6,8cm/sec for 50 µm to 3,5 mm/sec for 10 µm [13]. Stadnytskyi also described the probability of passing on an infection being proportional to the duration of staying airborne times the probability of carrying at least one virion, i.e. the diameter of the aerosol droplet. Once heating is considered or moving people in a room, the aerosol's movement gets complex and hard to predict.

In any case and despite the small size of Virus, the hundred-time larger aerosol particles are easier to capture, in such a filter to effectively capture them. Question remains however, what happens to the virus, but the assumption is discussed in further below to which degree aerosol particles are captured in the studied filter. The reason to believe that COVID-19 contaminated aerosol is getting stuck on the woven fabric is due to the necessity of the virus requiring a moist environment to remain infectious. In other words, the virion membrane material requires a moist environment [14] [15]. Additionally, even if some infectious virions remain, the aerosol droplets are mostly kept inside the filter and after three days the COVID-19 virus are generally inactive. A virus load possibly reaching humans subject to infection is therefore likely to remain lower than the necessary threshold. Literature reports that 500 to 2000 virions are necessary to raise the probability to infect a person in average.

When such woven fabric filters clubbed downstream with activated carbon, air purification gets more effective. Activated carbon filters, mostly remove volatile organic compounds and odour from the air as woven fabric filtration is only effective on particulate filtration. Activated carbon can adhere particles especially due to its huge inner surface of the carbon matrices [16]. This is all the more effective, the longer the dwell time in the filter is. The researched filter had a 1,5 cm thick layer with activated carbon pellets, which has a dwell time of 2 seconds.

3. Methodology

Given the theoretical considerations in chapter two, this chapter describes the method to substantiate the assumption that filters pose a necessary condition to effectively protect persons in the inside i.e., classrooms and lecturing halls. and sustain the effectiveness of the nonwoven fabric filter installed in the air-purifier designed. This general assumption that appears at least partially shared in literature was tested in one specific filter.

3.1. Material introduction

In this research an air purifier of the Philips Nano brand, Series 3 FY4440 was studied. That filter is operated in the commercial Philips 4236, which is designed to process up to 500 m³/hr. The filter inside has a structure of a nonwoven fabric filter equivalent to a HEPA H13 followed by and activated carbon layer, which totals to six layers. First, a mesh of Polypropylene (0,1 mm), second the nonwoven fabric filter of 25 mm thickness, third, fabric separation mesh (0,1 mm), fourth the activated carbon layer in pellets (15 mm), fifth another fabric separation mesh (0,1 mm) and finally the metallic mesh (1 mm). These layers, all together, guarantee the trap of particles up to in size 0,003 µm as well as Volatile Organic Compounds, vapors, and smells. Taking into consideration that COVID-19 does not come by itself, always in water droplets, dust or even bigger particles in our environment.

Considering that nonwoven fabric filter material can be a combination of different polymers like Polyester, PET, PBT, PP, PA or PE, this research is unable to determine the exact composition. However, the exact material is less relevant given the virion's adhesion to all the surfaces with its structure being made by staple fibers or filaments in a complex manner. The type of interconnection of the fibers in the nonwoven is the form fit (by entanglement) and / or the cohesion and / or the adhesion, whereby the character-determining fibers in the nonwoven can be oriented or randomly arranged. This interconnection of continuous fibers achieve that the particles can be trapped easily. Since it has several chaotically stacked layers, one after another that makes it difficult to penetrate.

To study that, a filter was cut into two and the next picture shows the thickness of the different layers, structure, and material.

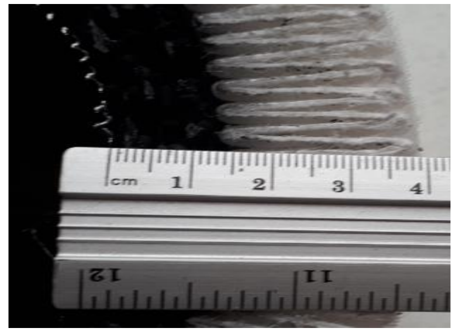

Figure 2: Cut through the filter: The thickness of the 6 different layers of the studied Filter amounts to 40 mm.

3.2. Microscopic images

The filter was sequentially analyzed for parameters like distance between two points, diameter, and perimeter of a void. The measurements were recorded using a digital microscope Keyence VHX-6000. Microscopic images helped in analyzing the filter material on scales up to 1000 µm, which gave idea of possible virion travel path inside the filter.

The next picture shows the perimeter of the out layer of the nonwoven fabric filter material, it was taken with a 1000 µm scale.

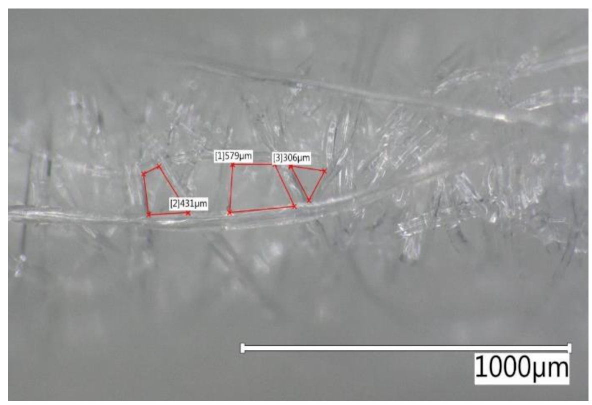

Figure 3: Perimeter of the different porous shapes into the fibre arragement,306 µm as minimum to 579 µm as maximum, out layer of the nonwoven fabric filter.

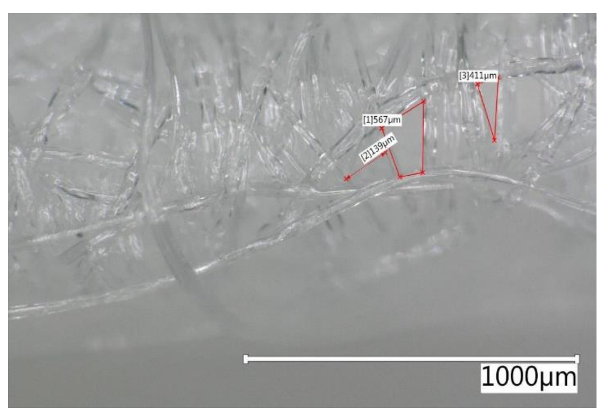

Figure 4: Perimeter of 411 µm as minimum and 567 µm as maximum, and the middle length of 139 µm.

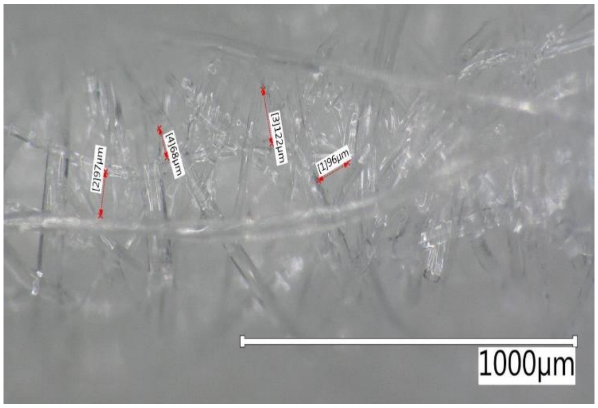

***Figure 5**: Porous mid-layer.*

The figure below represents the first mesh layer of the filter which is primarily responsible for straining of the big dust particles from the stream if air entering the air filter.

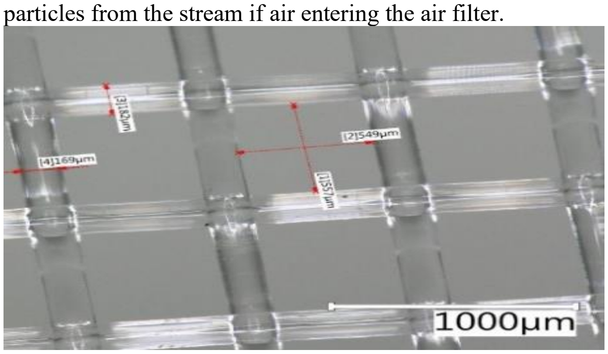

Figure 6: ***Strainer: first outer layer mesh and its dimensions. Small, squared shapes with (549 to 557) µm as width.***

3.3. Shape of the filter and air behavior

In process of filtration, geometry plays an important role in effective results. The nonwoven fabric filter had a cylindrical geometry with multiple folds of fabric filter at the inlet. The fold mechanism is advantageous as it increases overall surface area in contact, approximately five-fold to around 2,44 m^2. it also helps in reducing the speed of emerging air inside the purifier device, distorting the flow pattern of approaching foreign unwanted particles in air. The shape of filter makes environment difficult for particles to penetrate deep inside the filter layers and it is during this phase they get trapped in successive layers of non-woven fabric layers. Additionally, fold mechanism also helps in reducing air pressure at inlet surface.

***Figure 7**: Zigzag shape in nonwoven filter.*

It can be assumed that the air flow is turbulent while passing through and because of the zigzag surface and more importantly because of the chaotic fabric shown in picture 4. Also, we can consider that the pressure in the inlet is about 50 to 70 Pa, which was verified by comparing assumption with results in a breathing test.

3.4. Aerosol Oil Penetration test

Aerosol oil test is conducted on the filter specimen to determine the effectiveness of the filter against aerosol particle penetration. PALAS PMFT 1000 machine, which specifically tests respiratory masks, was used to determine the efficiency of filter specimen. This exact analysis of filter mask has the efficiency from 100 nm up to 40 µm. It has as parameter the predetermined size of SARS-CoV-2 of 120 nm to 160 nm.

In the next figure, we can see the analysis of filter and filter mask effectiveness against COVID-19 loaded aerosols.

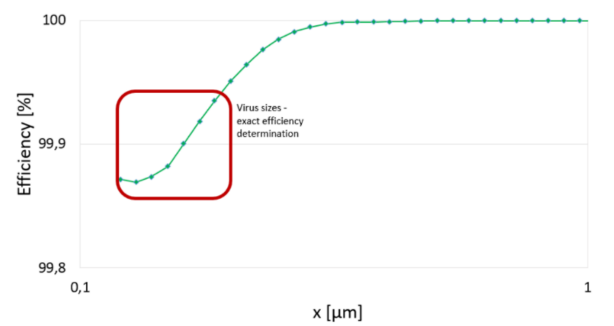

***Figure 8**: Graph from PALAS showing the 99,99% "efficiency" into the particle size for CoVID19.*

Furthermore, a dilution test was performed called "oil penetration", which is relevant for the virus' fat-based shell.

Material Characteristics

- PALAS PMFT 1000 machine.
- Test specimen, non-woven filter material, dimensions (138mm x 1 mm x 225 mm) LWH, which from this surface **a flattened 100,29 cm^2 was analyzed.**
- DEHS (Dioctyl sebacate), oil aerosol, Target value for mass concentration according to standard EN 149 is 20 mg/m3 +- 2 mg/m^3 (**normal range: 15 to 25 mg/m^3**).
- Aerosol generator PLG 1000 PALAS.
- Main air (95 liters/min).
- Generator air (2,30 liters /min).
- Dilution System, VKL 10 PALAS.
- Aerosol Spectrometer Promo 1000 PALAS.
- Media holder adapter (diameter 113 mm).

A unit sample was cut-out from the original filter and mechanically flattened for analysis. The specimen was carefully placed on the media holder adaptor and the filter holder immobilizes the filter medium during the measurement made by PALAS PMFT 1000 machine. Further, a computer software assesses the aerosol assessment through the fabric and report the result in graphical format as well as in numeric values.

The spectrometer has an optical sensor with a detection of 45-degree light scattering, which measures the particle electrical mobility diameter in (µm) and the particle concentration (P/cm^3).

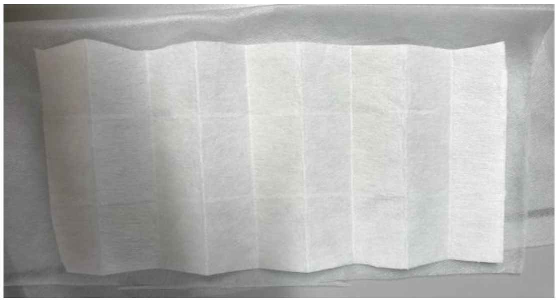

***Figure 9**: Test specimen: The zigzagged tissue was flattened.*

3.5. Breathing resistance

"Breathing Resistance" test is another method that was used to measure the filter's pressure drop and as well as to prove the effectiveness of it, by making a simulation of inhalation (upstream) and exhalation (downstream) similar to testing for protective face masks according to EN149 using PALAS PMFT 100 machine. This is a test stand as a reference to compare the pressure in the inlet and outlet of the filter. The parameters of the test are as follows:

Description	*Main air (L/min)*	*Upper limit (Pa)*
Upstream 1	28,86 liters/min	70 Pa
Upstream 2	95,18 liters /min	240 Pa
Downstream	159,87 liters /min	300 Pa

***Table 1:** The main air has set points (30, 95 and 160 liters/min) respectively and the upper limits to ensure the test analysis.*

Note: Here we used the same material and the same sample

3.6. Particle Counter Test

In this test a calibrated accurate particle counter, Aero Trak 9306-04, which is generally used to monitor cleanrooms. It is compliant to ISO 21501-4. It tracks down particle contamination sources. The particle counter has size range from 0,3 to 25 µm and flow rate of 0,1 CFM (2,83 liters/min). the device can measure up to six channels of simultaneous data and observations were taken for particle size of: 0,3; 0,5; 1,0; 3,0; 5,0 and 10,9 µm in a volume of 1,9 liters air.

***Figure 10**: Particle counter test: Upstream and directly downstream of the purifier, the particle concentration was measured.*

4. Observations

In this section, observations are described for various tests and discussed briefly.

4.1. Microscopic imaging

The perimeters and middle length of the outer layer mesh as well as in the nonwoven fabric filter were observed. After multiple measurements, observed values were averaged to form a result and further interpretation was carried out.

Specimen	**Perimeter [µm]**	**Middle Length [µm]**
Nonwoven fabric filter	458,8	104,4
Outer layer Mesh	2165	551

***Table 2:** The average results from the microscopic captures and measurements taken from the 2 different chosen layers.*

The pictures show that the fibers in the nonwoven fabric filter make a perimeter of 458,8 µm, which indicates the very outer layer only. It needs to be considered that nonwoven material has continuous interconnected fiber layers one behind another making the porous openings smaller and smaller. The first layer of mesh shows as well a micromanometer protection of 551 µm in the middle length average and 2165 µm in the average perimeter, which is significant for removing coarse dust from the incoming air.

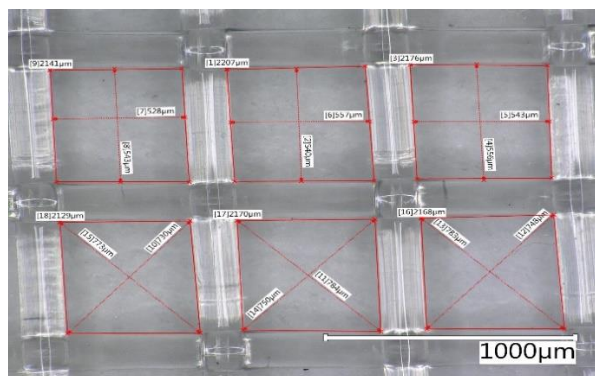

Figure 11: Measurements in the outer layer mesh or strainer.

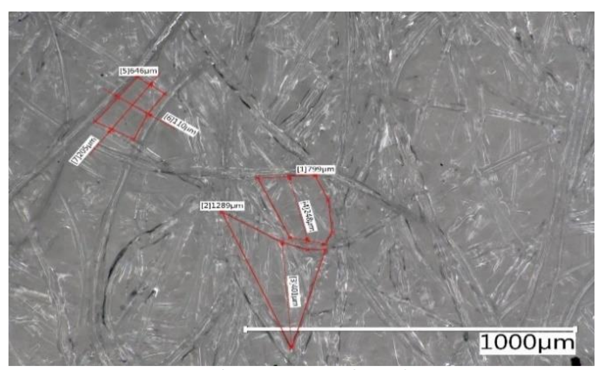

Figure 12: Measurements of the nonwoven fabric filter.

As described in section 3, in the whole structure of the nonwoven fabric filter is followed by a layer of activated carbon that we analyzed by the microscopic images. We noticed that some particles greater than 0,3 µm get trapped in the surface, which was depicted below. This also leads to observation that even if the 25 mm thick layers of nonwoven fabric is passed before the air emerges to activated carbon layer, there is a minute possibility that particles greater than 0,3 µm would get adsorbed on and in the activated carbon. Taking into consideration that its actual function is the adsorption of gases, vapors, odors, and smokes by its wide inner surface area in the grand order of 500 to 1500 m²/g.

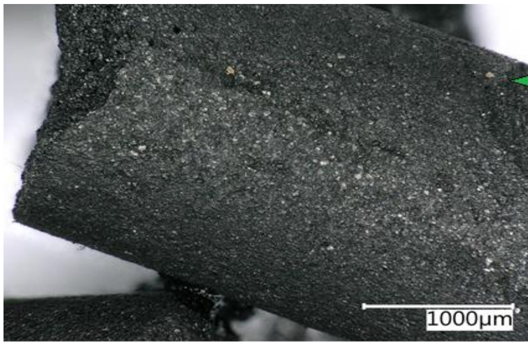

Figure 13: Particles trapped on activated carbon surface.

The notable observations of microscopic study were that filter even though the filter has high porosity as compared to virus size, the successive layers improve effectiveness of filter. It was observed that smaller particles get trapped into nonwoven fibers and bigger particles get trapped into the pores of the filter. In Fig. 15 it can be clearly seen that particle get attracted towards the fiber due to electrostatic force while in Brownian motion inside the filter layers

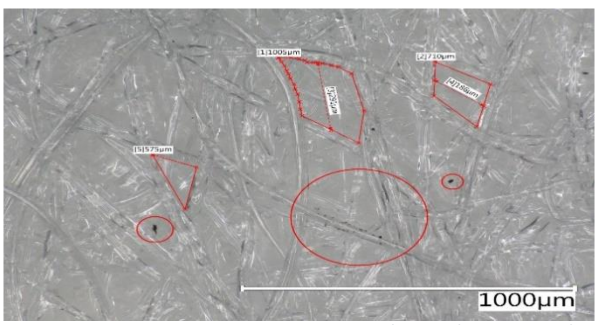

Figure 14: Trapped-charged particles in the fibres of nonwoven fabric material.

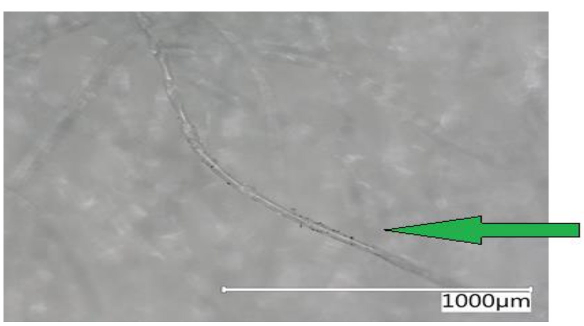

Figure 15: Close up of trapped-charged particles into the fibres of nonwoven fabric material. (magnification in annex).

4.2. Aerosol Oil Penetration

The flow of process that the machine performs while the test is shown in Fig. 18, which is a screenshot from the PALAS Software. It shows the parameters into the set points and the actual values in sample, that is, 92,29 l/min as main airflow, aerosol flow 2,30 l/min and 108 Pa in the pressure difference:

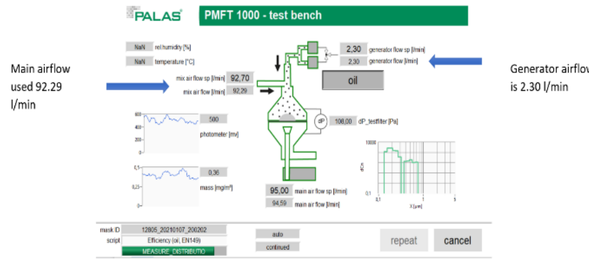

Figure 16: PALAS test bench. (Magnified copy in annex).

Through the flattened fabric, it was observed that around 30,43% of the particles with 0,15 µm (particle size diameter of CoV-2) are penetrating through the filter layers. Also, the optical sensor with 45 degree light scattering measures the distribution of particles by concentration and particle diameter size. Around 4,11% of the particles in the range of 0.3 µm to 5 µm are penetrating the filter layer as compared to the upper limit of 6%. While such fabric would not be considered suitable for face masks, the zigzag wrapped fabric followed by activated carbon, like in the studied filter is over 99% effective.

Result

Penetration	Measurement	Upper limit	Result
P_SARS_CoV-2 (0.15 µm)	**30.43 %**		
P_m	**1.95 %**		
P_Ph_45°	**4.11 %**	6.00 %	pass

Figure 17: Oil penetration results showing 30,43% of the particles of 0,15µm size are passing through the flattened filter tissue.

By the test conditions the mass concentration is 22,31 mg/m³, which is in the range concentration normal for FFP2 face masks.

In Fig. 18 the measurement of the particle size distribution up- and downstream of the filter. It shows that from the initial 9000, some 500 Particles/cm³ of the diameter size of 0,3 µm (COVID-19 relevant size) are penetrating. The rate of penetration decreases in concentration (P/cm³) with particles below 1 µm. Above that size, practically no particles penetrate the filter, which corresponds to the producer's specification.

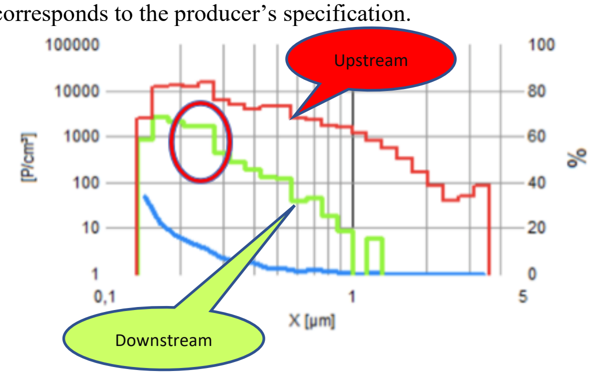

Figure 18: Particle Size distribution upstream (red) and downstream (green) of the filter. The blue line displays the proportion of passing particles [in %]. A larger diagram copy is shown in the annex. (magnification in annex)

4.3. Pressure drop test

In this test the parameter pressure drop is measured, similar to the inhalation (upstream) and exhalation (downstream) in a facemask. For the tested filter it is relevant, since the pressure drop depends on the volumetric flow rate. The figures 19 and 20 show screenshots from PALAS software while the test is in progress performing:

Upstream test

During the upstream test it was noted that a maximum airflow used was 28,88 l/min from main air, with a differential pressure of 32,43 Pa.

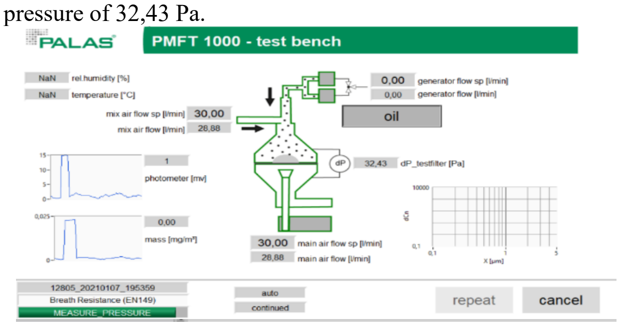

Figure 19: PALAS Upstream test. (Magnified copy in annex).

Downstream test

During the downstream test it was noted that a maximum airflow used was around 159,87 liters/min from main air, at a differential pressure of 182,96 Pa.

The results are corresponding to the pressure drops that can be recognized in the fan blower machine.

Result

Description	Main air	Differential pressure	Upper limit	Result
Inhalation 1	**28.86 l/min**	**32.39 Pa**	70.00 Pa	pass
Inhalation 2	**95.18 l/min**	**108.00 Pa**	240.00 Pa	pass
Exhalation	**159.87 l/min**	**183.10 Pa**	300.00 Pa	pass
Valve test	**NaN l/min**	**NaN Pa**		

***Figure 21:** Overall results from breathing test showing the pressure drops.*

4.4. Particle Counter results

One more hint of effectiveness is the particle counter test, where the particles up- and downstream the entire or intact filter are compared. The next table shows that in particles with size of 0,3 µm there are 22 290 000 P/m³ aspired into the filter but coming out just 43 571 P/m³ so an of effectiveness of 99,80% can be stated.

Filter input in [particles / m³] upstream of filter	Particle size	output in [particles / m³] downstream of filter	Filter effectiveness %
22 290 000	0,3 µm	43 571	99,80%
15 544 286	0,5 µm	4 643	99,97%
330 000	1,0 µm	0	100,00%
16 786	3,0 µm	0	100,00%
4 286	5,0 µm	0	100,00%
357	10,0 µm	0	100,00%
		Total effectiveness	**99,96%**

***Table 3:** Particle test of complete filter up- and downstream showing the effectiveness per particle size.*

Taking the particles with size of 0,5 µm, we observed that 1 016 786 P/m³ was going inside and just 4 643 of particles coming out the filter so here we have 99,96% of effectiveness. Taking in consideration that COVID-19 does not come by itself, it comes with aerosol droplets or dust, this increases the perimeter of the size particles greater than 1 µm and for this size the nonwoven filter is nearly fully effective.

Given the highest proportions of aerosol droplets exhaled between 0,1 and 1 µm size [9] [10], the filter needs to perform accordingly. Large size aerosol droplets will simply be larger than the grid opening dimension and be blocked. That was confirmed by the particle counting measurement, where no particle larger than 1 µm passed. Smaller than grid size droplets have passed through the filter with 4 643 particle/m³. However, this amount of small particles needs to be seen in relation to the faster evaporation and dehydration of smaller aerosol particles. As discussed in chapter 2, [13] found the probability of transmission proportional to the aerosol droplet size. Since only particles of 0,3 µm and smaller can pass to a 0,04% proportion, the probability is smaller. Because of Asadi's research measurement showing a relatively small proportion of all aerosols being of the 0,5 µm size and smaller, the filter is likely to let pass only the less infectious aerosols. One more argument can be added in that the observed small 4 643 particles per m³ might come out of the filter but might also contain less contagious material than when it entered the filter. It can be assumed that larger aerosol particles cascade through the filter and break apart during their passage. In that breaking up process many virions get slowed down and virions adhere to the fiber material or inside the activated carbon pores. What counts is keeping the viral load downstream of the filter below the threshold to stay safe of an infection.

5. Implications and Discussion

5.1. Implication

- Minimum efficiency of a single flattened filter tissue was already 70%. This effectiveness in terms of particles removed per input grows when folded like the specimen.
- The filter effectiveness of a single flattened filter tissue for particles above 0,5 µm amounts to 100% which means that all aerosol particles larger than 0,5 µm are filtered.
- The folded nonwoven fabric filter is followed by an activated carbon catching further aerosol, where particles were found on the surface. Inside the AC pellets the inner surface with over 500 m²/g.
- The complete filter's and overall particle effectiveness of was confirmed to be >99,97% as the producer states.

5.2. Filter effectiveness in concert with filter positioning

In this research the degree to which particles are removed from an air stream that passes through a filter is studied. That is the necessary condition of purifying air in a potentially contaminated classroom. The filter performing its task inside a purifying device needs to transport the clean air towards the persons to be protected. Reversely, potentially contaminated air needs to be aspired by the purifier and sucked through the filter, so that clean air is produced. However, besides the effectiveness of the filter the *position* of the purifier as well as the *direction* in which clean air is directed by the purifier matters significantly.

That is done in the adjacent research [17], which analysed by different methods, like: smoke shadow imaging, Schlieren imaging, particle counting and FLIR imaging, the best location of a filter depending on the volume and geometry of a room.

The main findings of these experiments are on the following page:

-The direction of the blower should be with an elevation angle of α=60º, because a purifier positioned along the long axis of a room facilitates a circulation of air in the entire volume.

-Given a rectangular room, and assuming a 60° forward blowing setup, positioning the purifiers at the extremes is superior to central positions.

6. Conclusion and recommendations

6.1. Conclusion

Based on a series of tests, described in this paper, sufficient observations were collected, which indicate that the studied filter is very likely effective in reducing potential risk of infection in a closed surrounding. Microscopic images show minimal perimeter length of 458,8 µm and middle length of 104,4 µm. Despite large inter-fabric length, the studied filter effectively captures particles of significantly smaller size due to the electrostatic and other filter mechanisms. The aerosol test leads to the conclusion that minimum filter effectiveness of one layer already amounts to at least 70% while the full filter has 25 times thicker non-woven fabric, and while the zigzag fold is inclined. Across one layer already, only about 4% of potential aerosol particles in range of 0,3 µm to 5 µm were found passing through the filter layers. Finally, particle counter tests verified that only 4 643 particles out of 15 544 286 P/m^3 were found emerging out of the device. Qualitatively, filter material was found 99,96% effective in removing the unwanted or potentially risk infectious aerosol particles. Even with the newly found mutations like the B1.1.7 being 35% more infectious [18], the mechanics of the filter and its effectiveness remain. But one should not forget that air filtration is derivative of positioning of the device, hence optimal position of device is also necessary to achieve highest efficiency and effectiveness in air filtration process. Air filtration could prove useful under the sustaining COVID-19 pandemic conditions, especially indoor. While a residual risk cannot be excluded yet, this research has affirmed the hypothesis that super-spreading can mitigated sufficiently to socially and politically acceptable levels. This is especially relevant in classrooms, where young generations need to learn effectively and in a safe environment how to solve issues, even once this pandemic was resolved.

6.2. Recommendations

- A biological survey should confirm the filter effectiveness with real but safe virus material and a lower and hopefully more efficient ACH of at least 2,5.
- If so, most students and especially children would benefit by allowing them back to classrooms if sufficient purifiers are installed.

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Annex

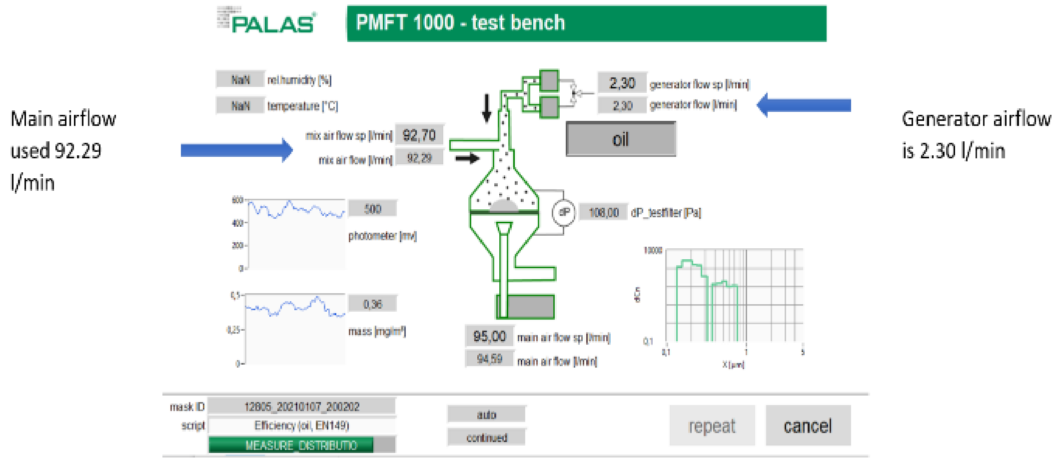

Figure 16: *PALAS test bench. (Magnified)*

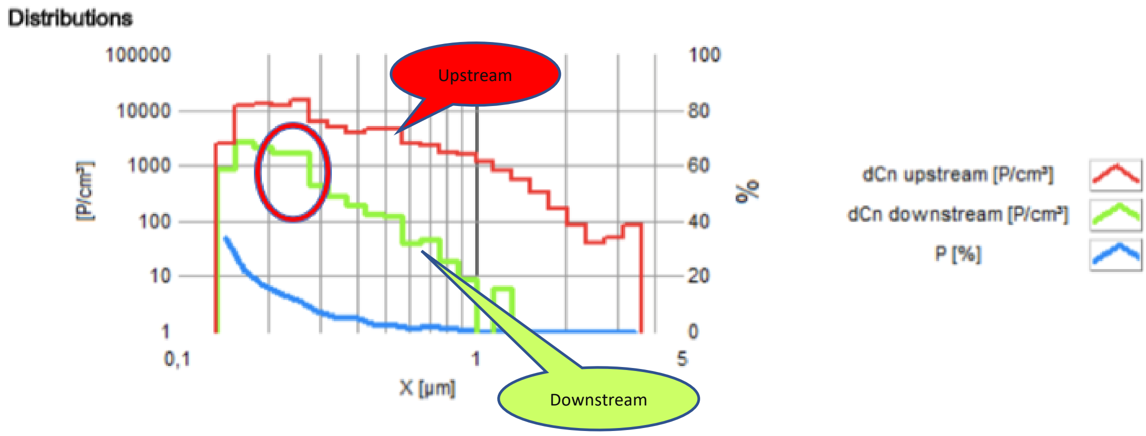

Figure 18*: Particle size distribution upstream (red) and downstream (green) of the filter. The blue line displays the proportion of passing particles in %. (Magnified)*

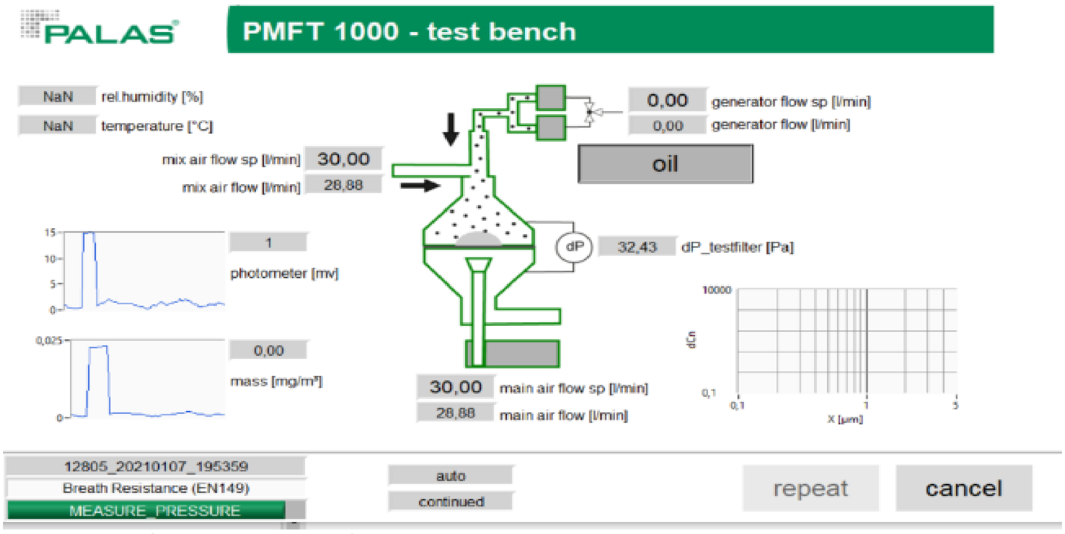

Figure 19: *PALAS Upstream test. (Magnified)*

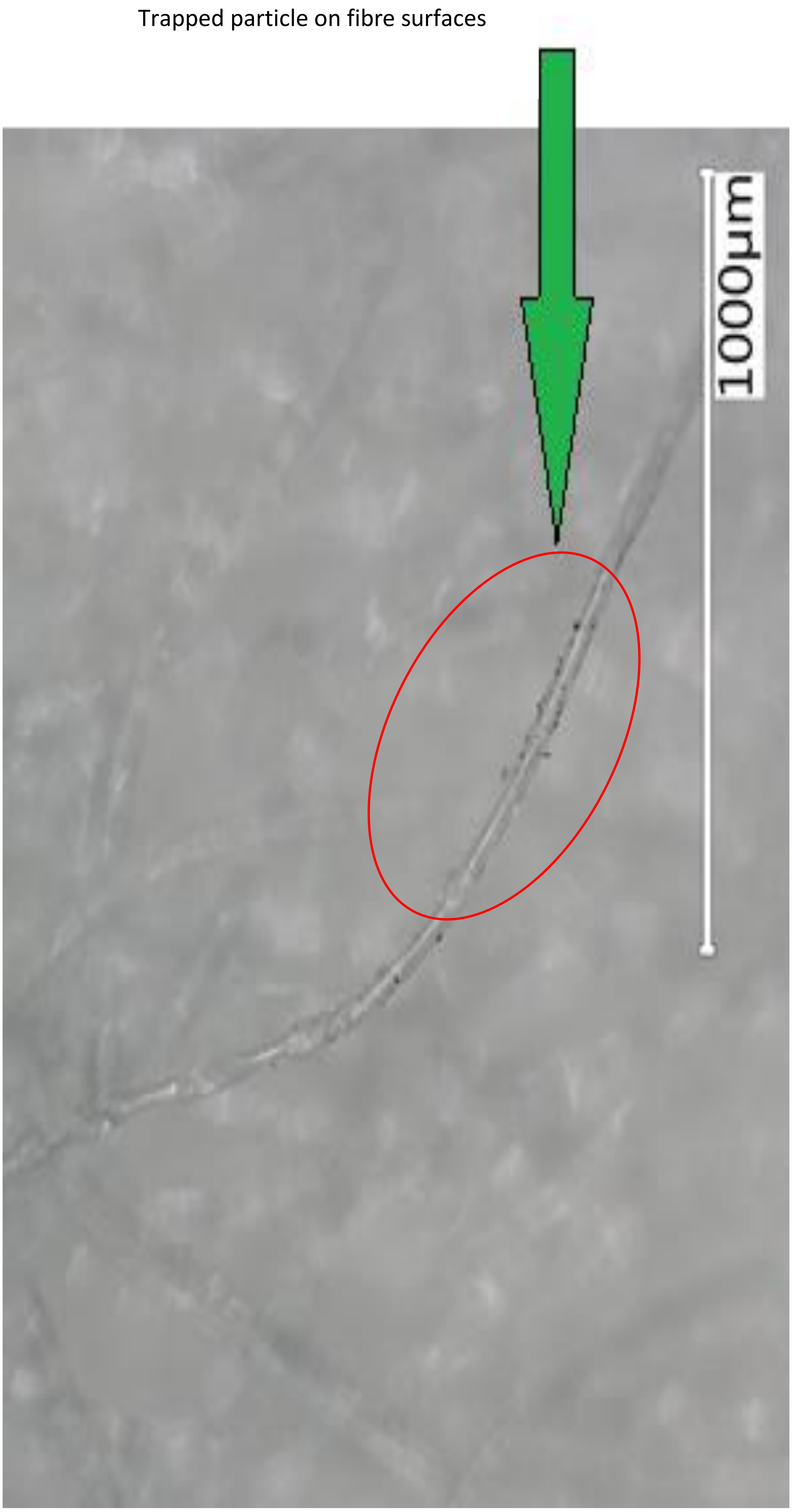

***Figure 10**: Magnified close-up of trapped-charged particles onto the fibres of nonwoven fabric material.*

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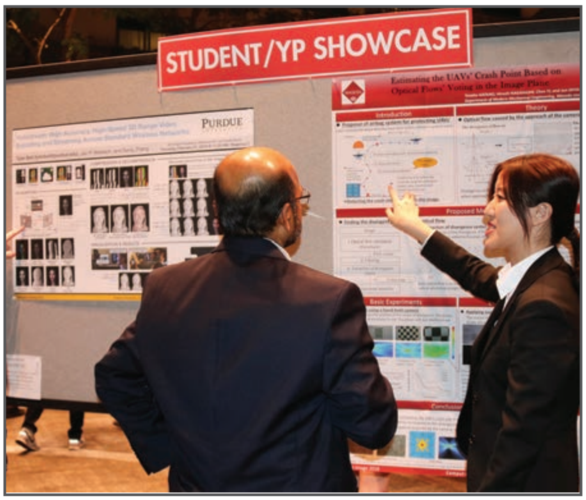

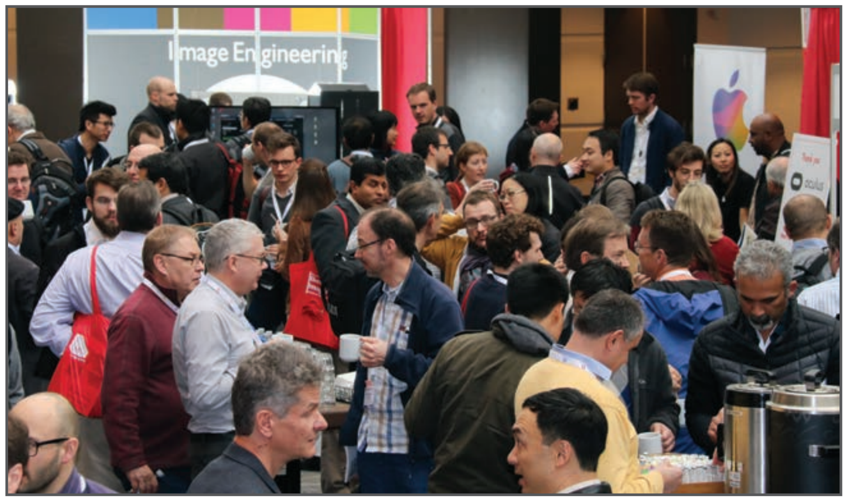

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