CFD analyses of filtering devices for indoor applications: HYLA EST purifier

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Summary

The purpose of this work is the analysis through CFD simulations of the fluid dynamic behavior of a commercial purifier within an indoor environment. The scenario is representative of a living room with and without the purifier, where the particles, with diameter between PM10 and PM0.1, is evenly distributed in the volume at the start of the simulation. The study analyses the trajectories of the particles and their residence time in the room, so as to characterize the performance of the device depending on the particle diameter class.

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Introduction

Particulate Matter (PM) indicates a mixture of solid and liquid particles found in the air. Such particles can consist of dust, dirt, soot or smoke and can be large enough to be seen with the naked eye. Others are smaller and can be detected only using a microscope (see Figure 1). PM10 is meant to identify coarse particles of 10 micron or smaller, but scientists are focusing in the last decades on the ultrafine particles such as PM0.1, with a diameter of 0.1 micron or smaller.

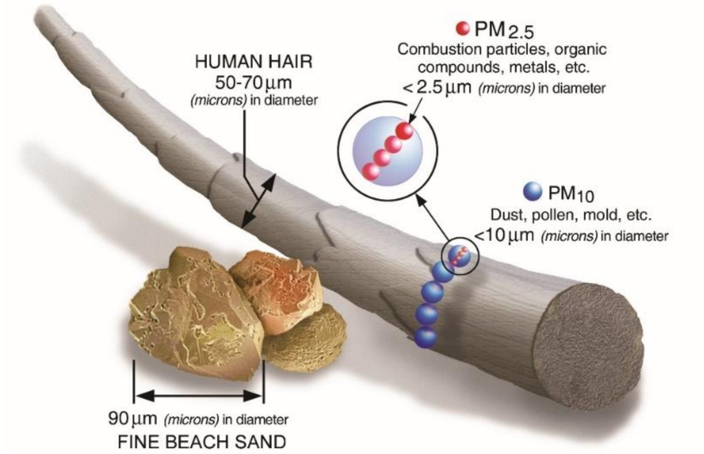

Figure 1: Size comparison from PM particles [1]

It is well known that the smaller the diameter, the more harmful is the effect on the human body. PM0.1 partially penetrates the body through the alveolar-capillary membrane, which separates air from the blood stream. It is believed however that such nanoparticles can penetrate via other routes, like the digestive and the dermal pathways.

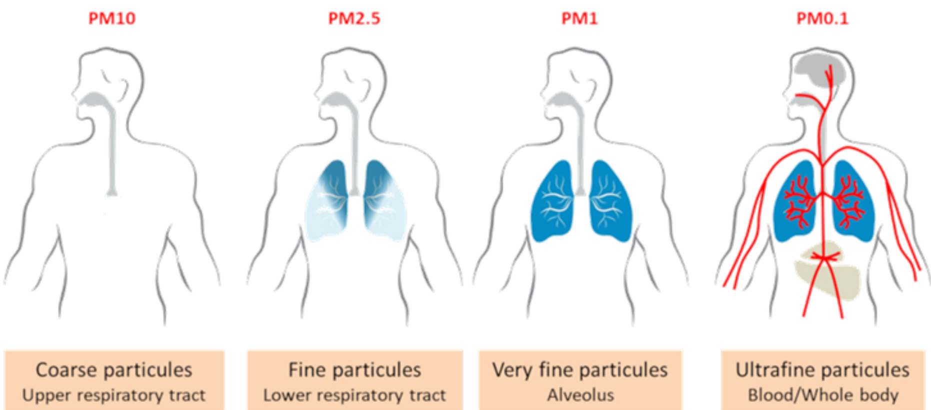

Figure 2: Levels of interaction if PM particles with human body [2]

The device

The object of study consists of the HYLA EST purifier [3], a device for domestic applications designed by HYLA. From Figure 3 it is possible to notice some details of the device. The filtering system is based on water purification. Air is sucked from grills on the upper part of the casing and directed in a volume in the bottom part, where is pushed at high speed through the water. Here a sort of "geyser effect" mixes air (and dust) with the water, creating a mixture that captures the particles. On the top of the volume there is a rotating separator that, using the centrifugal force, separates the water and the captured dust from the purifier air, which ultimately leaves through a grill on the rear part of the device. As far as the flow rate is concerned, in the purifying mode the device is working with a flow rate of 15.9 L/s. In addition to this condition (entitled in this activity HYLA ON), an additional condition is considered, where the purifier is absent from the room (HYLA OFF)

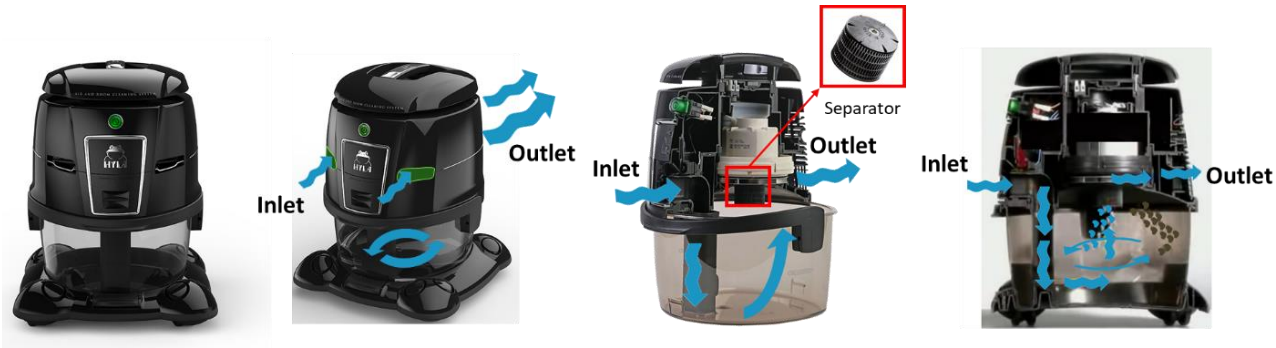

Figure 3: The device HYLA EST.

The scenario

The virtual environment in which the device was tested is represented by a living room of 4 m x 4 m x 2.5 m, corresponding to 16 m^2 and 40 m^3 (see Figure 4), including a mother on a sofa, a baby playing on the floor and other pieces of furniture such as scaffolds with a TV and a small coffee table. The most relevant object for the scope of the study is however the purifier, which is located in the corner of the room, close to the door.
The temperature of the room is considered equal to 25 °C, while different temperature values are applied to the people and objects in the room so as to recreate the natural convection deriving from temperature-driven buoyancy effect even when the purifier is absent. In particular, the window is set to 25 °C, the TV at 40°C, the mother and the baby at 35 °C.
Three different classes of diameter were studied for the particles entering the window: PM10, PM2.5 and PM0.1. The particles are visible in the same figure just after a few seconds from the start

of the simulation. Due to the lack of additional data concerning the filtration efficiency of the system, an ideal performance is assumed, meaning that all the dust intercepted by the purifier is removed and no particles are re-injected from the rear of the device.
As already introduced, the conditions studied in the activity are two: device working in purifying mode (HYLA ON) and absent purifier (HYLA OFF).

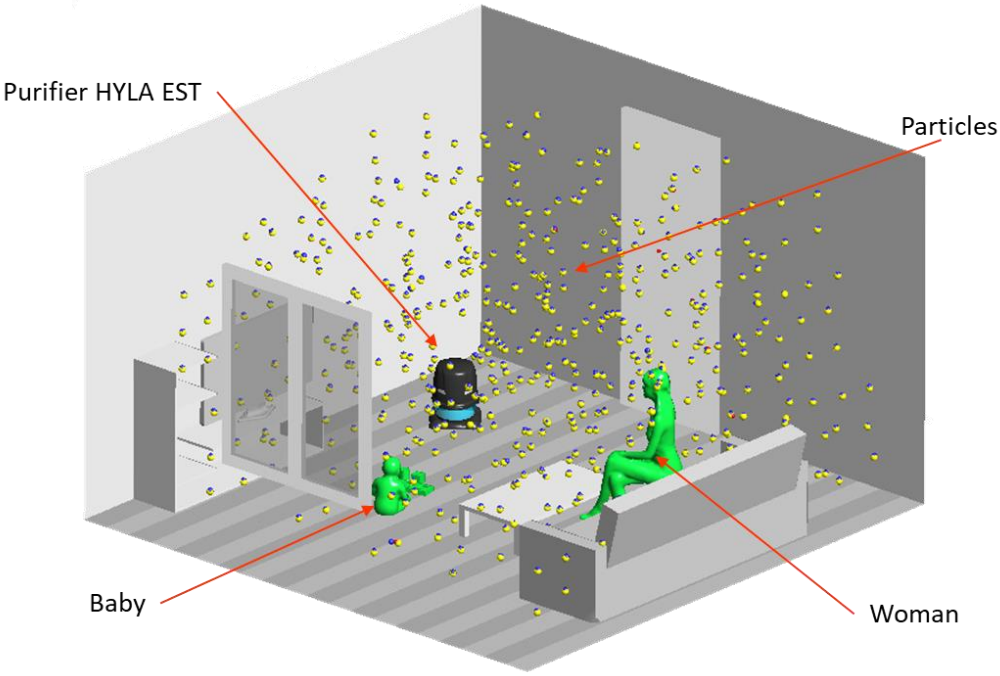

Figure 4: Environment under investigation

Numerical methodology

The tools used in this activity belongs to the suite of commercial software produced by ANSYS. The computational grid (Figure 5) was generated with ANSYS Meshing, which allowed to create a tetrahedral mesh with 2.4 million elements and about 0.4 million nodes. Refinement zones were added in the proximity of the purifier to characterize more accurately the velocity gradient in the region.

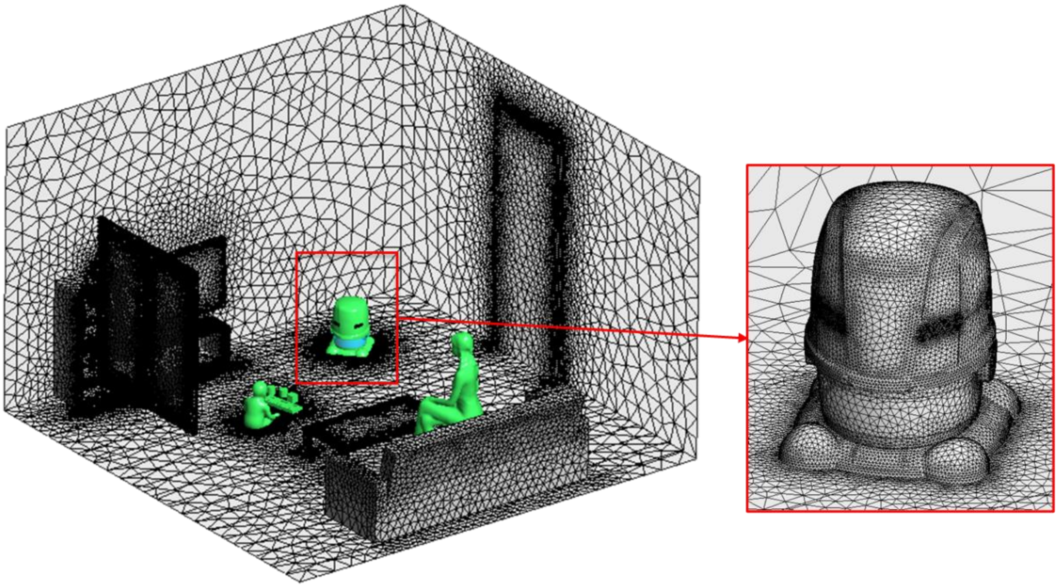

Figure 5: Computational grid

The simulations were carried out with Fluent Release 2019 R3 [4]. The numerical setup was chosen based on the state-of-the-art in literature and previous experiences of the authors [5]. Air was treated as an ideal gas, considering its properties as constants due to the small temperature differences. Gravitational effects were included. As regards the Eulerian phase, consistently with previous experience, the effects of turbulence on the flow field were included by means of the k-ε RNG model [6–8]. The air discharge section of the purifier was considered as mass-flow-inlet, while the air intake section was considered as mass-flow-outlet. The mass flow rate applied is the same on the two patches to ensure the mass balance. All walls are treated as no slip, smooth and adiabatic, except for the people, the TV and the window, on which a fixed temperature was applied. Particle motion was solved with the Lagrangian Particle Tracking. The approach followed involves a 1-way coupling, with the Eulerian flow field influencing the Lagrangian transport, but without any effect of the presence of particles on the former (due to their small size). Stochastic Tracking was included in the modelling, using the Discrete Random Walk model. The particles are initialized as uniformly distributed in the volume and with a velocity of zero. The population was considered monodisperse (i.e. diameter with constant value) and divided into 3 classes PM10, PM2.5, PM0.1). Particles were treated as spherical and for surfaces a trap condition for particle contact was considered for all the surfaces (i.e. the particle is removed when reaches a surface), except for walls and ceiling which are considered reflecting.

The stationary simulations were carried out by means of the SIMPLE solver until the convergence of the calculation. Subsequently, the Lagrangian computation was performed as a postprocessing on the Eulerian field to track the motion of the particles.

Results

The time evolution of the particles after entering the room is depicted qualitatively in Figure 6. The figure reports the snapshots of the three-dimensional position of the particles considering three different time points with a 10 minute interval (from left to right) and the two operating conditions (from top to bottom). The particles are displayed changing size and color to highlight the difference in diameter: PM10 (big, yellow), PM2.5 (medium, blue), PM0.1 (small, red). The scenari start from the same condition at the initial time but later gradually diverge, producing a clear reduction in the amount of particles when the purifier is active.

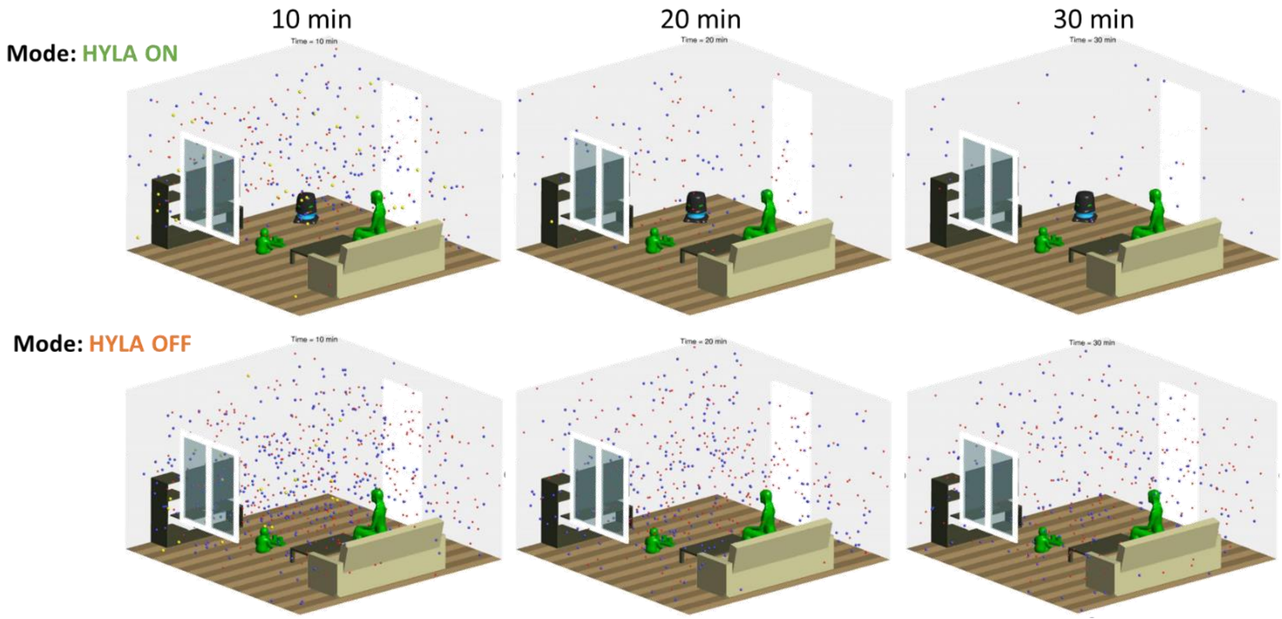

Figure 6: Qualitative time evolution of the particles depending on the operating mode for PM10 (big, yellow), PM2.5 (medium, blue) and PM0.1 (small, red)

To better understand the effect of the operating mode and the diameter of the particles, it is possible to refer to the graphs shown in Figure 7, which report the cumulative trend of the residence time of the particles inside the room. It is important to point out that the effect of the particle

diameter involves the variation of orders of magnitude in the residence time. This effect confirms that smaller diameter particles tend to remain in suspension for significantly longer times.
In addition, it is possible to note how the operating mode of the purifier mainly impacts the residence time of the smallest particles (PM2.5 and PM0.1), while for the biggest ones (PM10) there is only a minimum deviation between the curves. This effect is justified by the characteristics of these particles, which due to their greater weight, tend to deposit earlier, without being intercepted if far enough by the device. As expected, the trend is also generally asymptotic, with residence times that are stretched exponentially to remove 10% of the remaining particles inside the room.

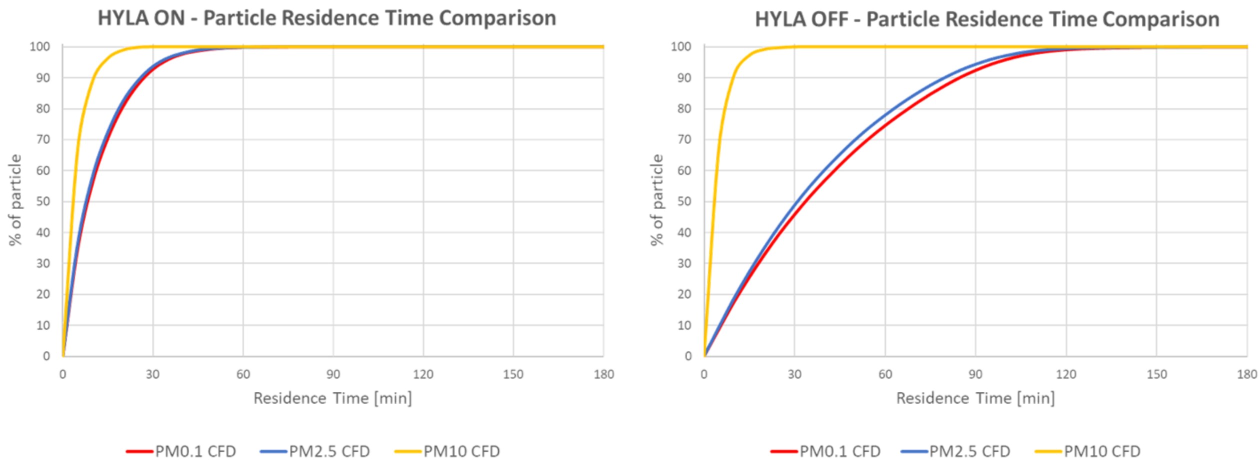

Figure 7: Cumulative distribution of the residence time of particles for the two operating conditions, depending on the particle diameter

The cumulative distributions were replotted in Figure 8 to better highlight the influence of the purifier on each diameter class. Again, PM10 particles show small effect of the operating mode and small residence time due to fast deposition. The purifier is capable of intercepting part of the population, but its presence also introduces some perturbations in the flow field in the room. The air re-injected from the rear of the device can in fact slow down the natural deposition process, thus offsetting the removal process. Particles of PM2.5 and PM0.1 are instead very affected by the purifier, with a strong reduction when the purifier is activated.
In addition, residence time was extracted to consider the 90% of the particles. As it is possible to observe from the figure, PM10 is removed in 10-11 minutes, without a significant role of the purifier. However, the small-size particles are removed by the purifier in less than 30 minutes (compared to 80-85 minutes without it).

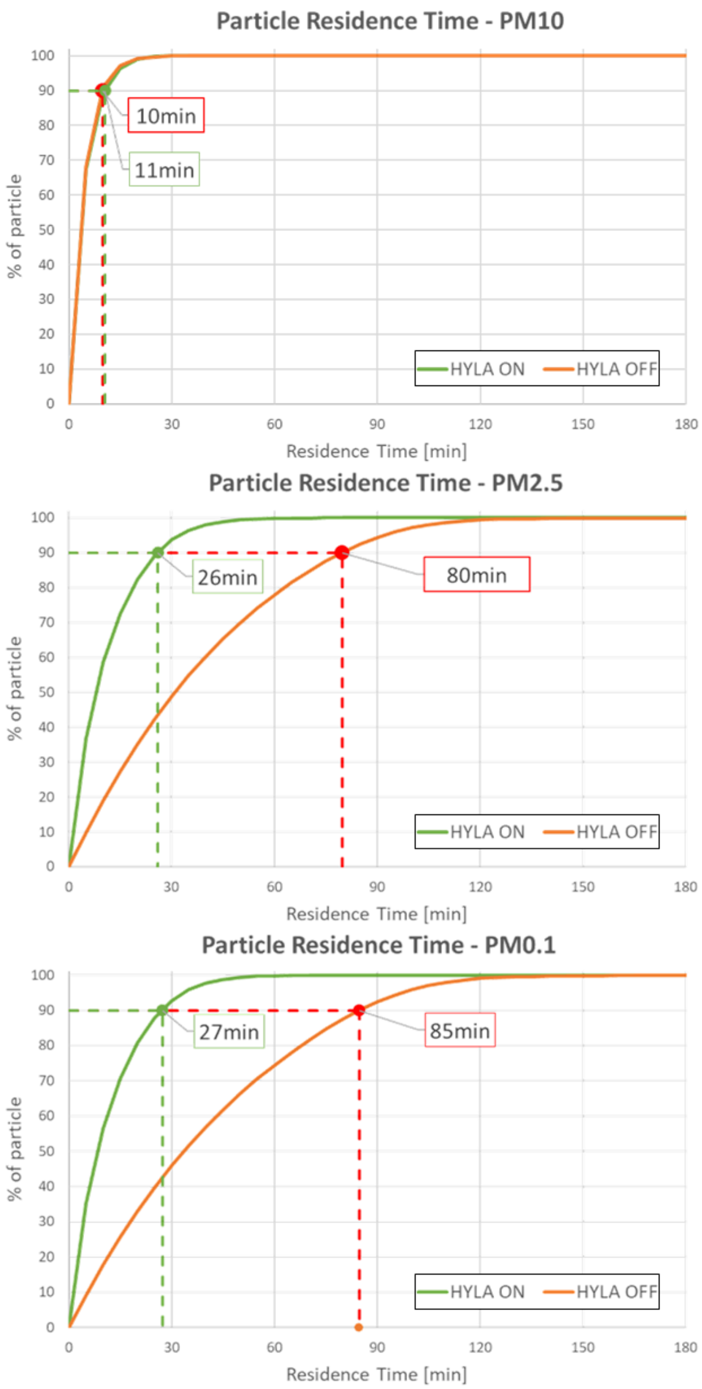

Figure 8: Cumulative distribution of the residence time of particles for the tree particle diameter classes, depending on the operating condition

To better quantify the impact of the operating mode based on the particle diameter, the data reported in Figure 8 were further elaborated to derive the reduction in maximum residence time required to remove the first 90% of particles in the room. The results, highlighted by means of histograms in Figure 9, shows that generally the smaller the diameter of the particles, the longer the time they remain suspended in the air. The activation of the purifier (HYLA ON) has a small effect on PM10, but significant for PM2.5 (-67.3%) and PM0.1 (-67.8%).

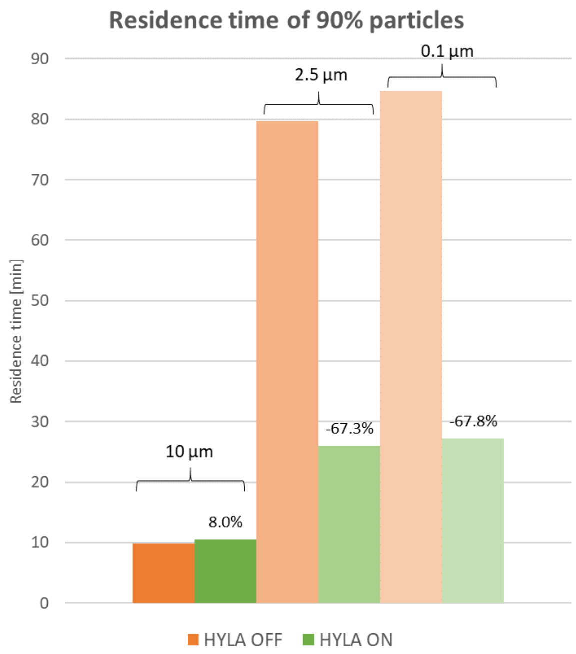

Figure 9: Residence time of 90% particles depending on the operating condition and particle diameter

Conclusions

This report summarizes the main results of the CFD analyses carried out to characterize a home purifier. The virtual tests were carried out in a living room in which particles are initialized as uniformly distributed in the volume and then transported by the natural convection in the room. The study therefore provides a representative estimate of the effect of the device on the fate and residence time of the particles. The performance was characterized considering two scenarios, namely absent/present purifier and three classes of particle diameter, namely PM10, PM2.5 and PM0.1.

Although the results are affected by some arbitrary choices, including the layout of the room and the position of the purifier, the used computational methodology is robust and based on models and inputs derived from the scientific literature and previous experiences of the authors.
Ultimately the main results can be summarized in:

- The dynamics of particles is profoundly influenced by the diameter.
- The heaviest particles (PM10) tend to deposit faster due to the greater weight and can be hardly intercepted by the purifier, especially if this is located far from the source of the pollens.
- The lightest particles (PM2.5 and PM0.1) remain in suspension for longer, but on the other hand they can be transported by air and therefore intercepted by the purifier with greater ease.
- In the absence of any removal device, the residence time of the first 90% of the particles varies between about 10 minutes (PM10) and 80-85 minutes (PM2.5 and PM0.1).
- When the purifier is present, the residence time of 90% of the smallest particles (PM2.5 and PM0.1) is reduced up to 67%.

Based on the data obtained during this numerical survey, it is therefore possible to state that, in the context of a use consistent with the assumptions made in the study, the device is particularly effective in removing particles of size ranging between PM2.5 and PM0.1. This type of particles is particularly relevant for human health as, unlike heavier particles, they tend to remain suspended in the air without depositing, as well as to penetrate deeply into the pulmonary alveoli. Compared to the condition of absent/switched-off purifier, the presence of the purifier leads to a reduction of the particle residence time in the room of 67%.

Appendix

Documents provided at the end of the activity:

- PowerPoint presentation and videos for the two modes.

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