Experimental investigation of the contaminated volume around a person in a clean room

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Abstract. To monitor the particle concentration in a clean room, the measuring position is usually chosen based on a risk analysis and a monitoring plan. The demand zone is the area on the table, where the product is placed and where very clean air must be assured. Measuring the particle concentration in this working area is often difficult, as the measuring probe may obstruct the work flow. A situation that frequently occurs in a clean room is that of a person working at a work table. In this experimental investigation, the radial spread of particles, emitted by a dummy, is investigated. Particles are emitted from the proximity of the mouth region, with a source strength that is much higher than the normal particle emission of a human being when speaking. The aerosol distribution is measured with a laser particle counter at varying measuring positions. In the present case, the demand zone is defined as the area above the table in front of which the dummy is standing, 250 mm deep and 500 mm wide. Hot-wire anemometers are used to measure the velocity profile in the close-up range of the dummy. The influence of the distance between table and wall on the velocity and particle field is investigated, at varying inlet airflow velocities between 0.25 - 0.45 m/s. The results show that the table positioning has an influence on the flow velocities in the demand zone and that the table should be positioned in the room if possible.

Keywords: cleanroom, monitoring, unidirectional airflow, particle, anemometer.
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1. Introduction

People create a buoyancy current in the area of which particles can be stirred up. The supply air velocity in the cleanroom must ensure that the buoyancy current is effectively prevented, as particles can spread in this area. The particles are representative of contaminants of various origins that are emitted by people, either through their clothing, skin or when they speak.

Starting from the person, a volume of contaminated air is created, which depends on the activity and clothing of the person, as well as on the positioning of the person in the room, the inflow speed and possibly other obstacles in the room for the air flow, such as a table. A model for calculating the radius of contaminated air around a cylindrical particle source can be found in [1]. At an inflow velocity of 0.25 m/s, the maximum radius of contaminated air is $R_{\max} = 750$ mm, at an inflow velocity of 0.45 m/s, it is $R_{\max} = 400$ mm. According to an experimental study by [2], the buoyant flow of people in rooms with vertical piston flow can be effectively suppressed from a supply air velocity of 0.25 m/s.

The human particle emission rate was investigated by several authors. According to [3], the human particle emission rate, is $PM_{5.0} \approx 66$ particles/sec, when speaking at normal volume, and it could be up to 570 particles/sec when speaking loudly [4].

The heat output of humans is 100 W when standing and performing light laboratory work. Activity increases the heat output and thus the buoyancy flow along the person. In order to safely prevent the human buoyancy current, cleanrooms are usually operated with a supply air velocity of 0.45 m/s. The aim of this study is to investigate the particle and velocity distribution around a dummy for different boundary conditions.

There are specific recommendations for the table height of workstations, but not for the specific positioning of tables in the cleanroom. The height of a standard work table should be between 650 - 850 mm if mainly sedentary activities are performed and the height can be extended up to 1250 mm if standing activities are still performed [5]. According to DIN EN 14644-4, a table in a clean room should not be placed directly against the wall, but at a certain distance from it. [6] However, the decision on the selected distance lies with the operator. The recommentation according to the European Good Manufacturing Practice (GMP) is also very general, recommending "to ventilate production areas effectively with ventilation systems that are appropriate for the products handled there, the operations performed, and the external environment." [7] Therefore, two concrete table positions are to be investigated and their influence on the particle concentration in the requirement zone.

Cleanrooms with unidirectional airflow guarantee a very short residence time of airborne contamination. They are accompanied by a high air exchange rate and thus high energy consumption, but also meet the highest requirements for air quality. Concrete application cases for a person working at a table in a clean room with unidirectional airflow are packaging steps in the pharmaceutical industry or manual product inspections. The ventilation system assures a clean area in the demand zone on the table. Understanding the dynamic airflow distribution in this area helps to identify possible energy saving measures.

2. Research Methods

2.1 Experimental set-up

The experiments were performed in a cleanroom with vertical, unidirectional airflow, where the air change rate can be set of up to 540 times per hour. 16 Filter Fan Units (FFU) with terminal ultraclean U13 filters are mounted on the ceiling. A laminating mesh below the outlet ensures a very even flow. The air leaves the room through a perforated double floor, is filtered and fed back to the supply air. The floor space of the clean room is 4.8 x 4.8 m, the height is 3 m. A sketch of the test set-up is shown from above in **Fig. 1** and from aside in Fig. 2(a). The dummy was heated with an electrical power input of 100 W.

In the present case, the demand zone is defined as the area above the table in front of which the dummy is standing, 250 mm deep and 500 mm wide. The influence of the following aspects was investigated:

1. Table position: distance of the table from the wall
2. Supply air velocity

1. Table position

The table used was a common work table with a length of 1560 mm, a width of 780 mm and a height of 772 mm. There were two 2 options chosen for varying the distance Δx between the wall and the table:

(a) $\Delta x_1 = 15$ mm

(b) $\Delta x_2 = 900$ mm

First, the table was placed very close to the wall. And then a little further away, whereby the table was positioned at the 2nd position so that the dummy was centrally below a Filter Fan Unit (FFU) outlet. Both table positions are shown in **Fig. 1**. The dummy was positioned centrally below the FFU outlet.

2. Supply air velocity

The supply air velocity v_0 and the corresponding air change rate ACR were varied as follows:

v_0 (m/s) = 0.25 – 0.30 – 0.35 – 0.40 – 0.45
ACR (1/h) = 300 – 360 – 420 – 480 – 540

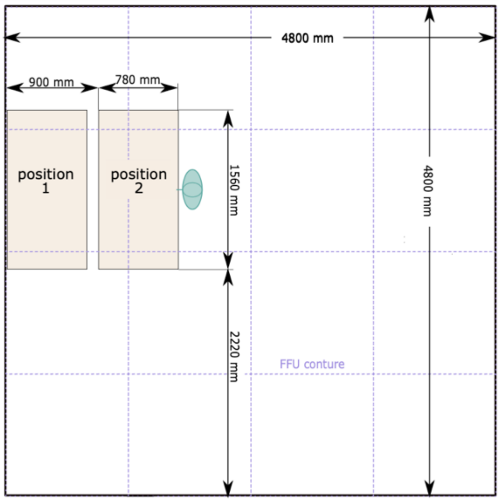
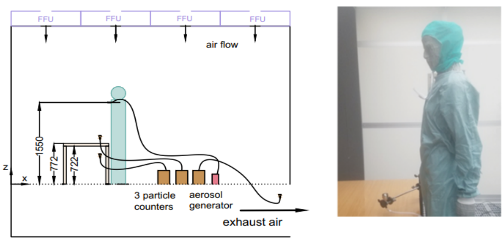


Fig. 1 - View from above: Test stand with a person standing at the table, for 2 different table positions.



a) b)

Fig. 2 - a) View from aside: test stand with a dummy standing at the table, with the table-wall distance Δx_2=900 mm. b) Photo of the dummy.

2.2 Velocity measurements

In a first step, velocity measurements were carried out. Therefore, omnidirectional hot wire anemometers were used (type Schiltknecht ThermoAir 6). The measuring principle of this anemometer is based on a Negative Temperature Coefficient (NTC) resistance. The hot wire is heated to a constant excess temperature to ambient and the power required to maintain this temperature is measured. It measures the magnitude of the velocity in a range 0.01 – 1 m/s with an accuracy of ±1,5% from the measured value at a room temperature of 22°C.

The supply air velocity was measured continuously centered below a FFU, 250 mm below the ceiling. The velocities around the dummy were measured at a height of 150 mm above the table, i.e. 922 mm from the raised floor. The results of the velocity measurements were evaluated in Python, with the Tricontour function.

2.3 Particle countings

To investigate the distribution of particles, emitted by a dummy, Di-Ethyl-Hexyl-Sebacat (DEHS) particles were artificially generated using an aerosol generator (type Topas ATM 225). The aerosol outlet was positioned close to the breathing zone, 778 mm above the table surface. The aerosol outlet was located 60 mm from the dummy. The distance between the dummy and the table was 40 mm, and the aerosol was introduced at a horizontal distance of 20 mm from the edge of the table. The flow rate of the aerosol generator was 0.150 m^3/h. The generated particles have a particle size distribution as shown in **Fig. 3**, with most particles generated at a size of 0.23 µm.

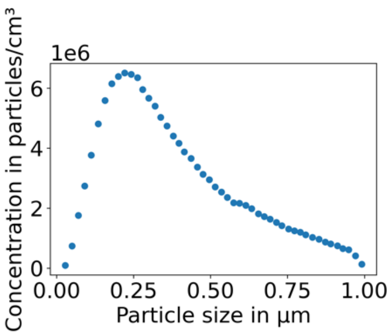


Fig. 3 – Generated particle size distribution [8]

The particle counts were performed with 3 mobile laser particle counters (type LDCP 5-10P0 from kmOptoelektronik).

There were two measuring points which were measured continuously, a position below the table and the concentration in the exhaust air. And there was a third measuring probe, whose position was varied at a height of 150 mm above the table. There were different distances to the aerosol outlet chosen, to detect the radial particle range as shown in **Fig. 4**.

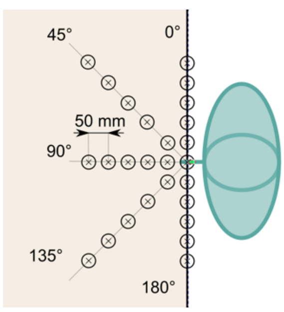


Fig. 4 - View from above: Scattered measuring positions for the particle countings above the table.

3. Results

3.1 Velocity measurements

The velocity field was measured at several points around the dummy at a height of 150 mm above the table, as shown in **Fig. 5**. In a) and b), the velocity fields are shown for the incoming velocities of 0.35 and 0.45 m/s at a table-wall distance of Δx_1 = 15 mm. And in c) and d), the velocities are plotted for a distance of Δx_1 = 900 mm. It can be seen in all 4 cases that the flow velocities decrease significantly towards the centre of the table. There, a stagnation area forms, where the flow velocity is about 1/3 of the inflow flow velocity and thus significantly lower. This is particularly clear frontally to the dummy. At the same time, there is an acceleration in the lateral direction of the dummy, along the edge of the table. The velocity gradient is stronger at the higher velocity of 0.45 m/s than at the lower velocity of 0.35 m/s. When the table is positioned more closely to the wall (Δx_1 = 15 mm), the velocities are also lower in the immediate vicinity of the dummy and the velocity gradient to the side is more distinctive.

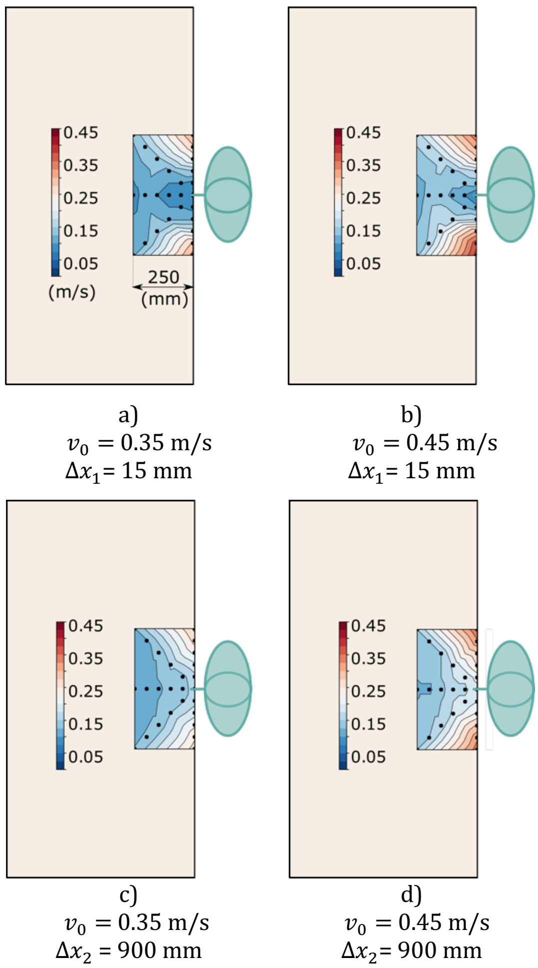


Fig. 5 - Flow velocities (in m/s) around the seated dummy at an incident flow velocity of a) v_0 = 0.35 m/s and b) v_0 = 0.45 m/s at a table-wall distance of Δx_1 = 15 mm and c) v_0 = 0.35 m/s and d) v_0 = 0.45 m/s at a table-wall distance of Δx_2 = 900 mm.

3.2 Particle countings

The particle counts examined how they spread radially from the aerosol outlet. The results are shown in **Fig. 6**. The following cases were investigated:

(a) grey: table close to wall ($\Delta x_1 = 15$ mm)
(b) orange: table inside room ($\Delta x_2 = 900$ mm)

The different colour gradations indicate the different velocities. The dots in the plot show the mean particle concentration as a function of the radial, horizontal distance of the measuring probe to the position of the aerosol outlet. The lower the incident flow velocity, the higher the concentration close to the dummy. This applies to both cases, whether the table is close to the dummy or it is positioned in the middle of the room.

If the table is close to the wall, the black markers, at the speed of 0.45 m/s the concentration is also very low even close to the dummy. This striking influence of the flow velocity is less pronounced when the table is positioned in the room, the orange markers. Here the concentration close to the dummy is in a similar range for all air velocities. With increasing distance from the aerosol outlet, the velocity decreases, especially strongly at the high air velocity of 0.45 m/s.

For this study, particle counts were conducted at various intervals between 70 mm - 450 mm. The results of the particle counting were grouped as follows: they are grouped into the 4 quantiles of the distance from the aerosol outlet. At the 1st point at approx. 150 mm, the mean value of the measured values of the 1st quantile (<=25%) is thus plotted. At the 2nd point, at 255 mm the mean values of the 2nd quantile (<= 50%) are plotted. At the 3rd point, at 357 mm radial distance the mean values of the 3rd quantile (> 50% and <= 75%) are plotted and at the last point at 426 mm distance the results of the 4th quantile (> 75% and <= 100%) are plotted.

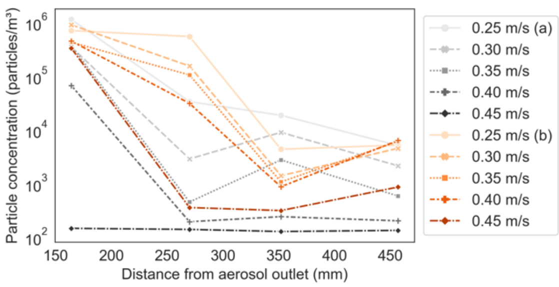


Fig. 6 - Measured mean particle concentrations at different distances between the measuring position and the aerosol outlet. The grey markers indicate that the table was positioned close to the wall (a), $\Delta x = 15$ mm, the orange markers indicate a wider distance (b), $\Delta x = 900$ mm.

2. Discussion

The measurements of the air velocity show that there is a stagnation area of the flow above the table. The air velocity decreases significantly towards the centre of the table and this occurs already a few centimetres from the edge of the table. When the flow velocity is increased from 0.35 m/s to 0.45 m/s, this stagnation area is weaker, as the air velocity in the requirement zone is higher overall.

There are several reasons for this. First of all, there are two currents which act in opposite directions. The buoyant flow, caused by heat near the dummy and the desired downward flow, caused by the FFU. At the higher speed of 0.45 m/s, the buoyant flow is clearly prevented and there is a smaller area where the flow is impaired.

Second, there is a loss of momentum in the vertical direction, when the supply air propagates to the surface of the table. This is expected to happen earlier at lower supply air velocities and we measure lower velocity magnitudes over the table at 0.35 m/s compared to 0.45 m/s.

If the table is positioned in the middle of the room instead of directly against the wall, the stagnation area is also smaller. This could be due to the fact that there is better air exchange to all sides of the table. The vertical air movement downwards is thus not additionally impaired by the vertical room wall.

In the radial dispersion of the particles, it can be seen that at low air velocities (0.25 - 0.30 m/s) the particles disperse in high concentrations, up to a distance of about 275 mm. After that, the concentration up to a distance of 450 mm is about 1/100 of the value in the close-up area around the aerosol outlet.

When positioning the table on the wall (black markers), it was noticeable that the measured particle concentration at the speed of 0.45 m/s was very low for all distances. For lower speeds, the overall particle concentration decreases less with increasing distance from the aerosol outlet. This is consistent with the velocity measurements, as here too the stagnation area is more pronounced than when the table is positioned in the room.

When the table was positioned in the centre of the room, the concentration in the vicinity of the aerosol outlet was quite as high as at the lower air velocities, but then dropped more sharply to 1/1000 of the initial concentration, from a distance of approximately 350 mm on.

3. Conclusions

Overall, the results show that the stagnation area is more pronounced when the table is positioned against the wall. It is therefore recommended to position the table with some distance to the wall in the cleanroom. This way, the buoyancy volume flow of the human is better suppressed and the particle concentration in the requirement zone is lower. The flow velocity should be at least 0.35 m/s so that the emitted particles only reach the requirement zone in low concentration. It can therefore be seen that a very small distance between the table and the wall of 15 mm is not sufficient to prevent a backflow of the flow above the table. the selected minimum distance between the table and the wall, according to the recommendation of DIN EN 14644-4, should therefore be significantly greater and better in the range of 900 mm.

4. Acknowledgements

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a.The datasets generated during and/or analysed during the current study are available in the DepositOnce repository, http://dx.doi.org/10.14279/depositonce-15371