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DISPERSION AND SEDIMENTATION OF AIRBORNE PARTICLES AND GERMS IN LAMINAR AND TURBULENT AIRFLOW

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ABSTRACT

Several studies have shown that the lowest concentrations of contamination in operating theatres are achieved by using fabric covered laminar airflow systems. These systems are distinguished due to the low turbulence intensities in the protective areas. An examination in a special designed test facility was done to get further information about the relation between the turbulence intensity and airborne contaminations.

In a first stage the dispersion of airborne contaminations was examined. The measurements showed that because of variations in the airflow airborne contaminations can reach areas cross the main flux far away from their point of emission. The cross diffusion and the area in which the particles and germs are spread is reduced in a less turbulent flow.

In a second stage the sedimentation of germs under the influence of the turbulence intensity was examined. The measurements showed that a reduction of the turbulence intensity of 20% to 1% (laminar flow) halves the sedimentation rates of the germs.

Reducing the turbulence intensity leads to lower contamination of the ambient air at the wound site and lowers the chance of sedimentation. In conclusion the incidence of infection can be reduced.

KEYWORDS

Aerosol, air flow pattern, air quality, laminar flow, operating theatres, particles

INTRODUCTION

In recent years considerable efforts have been made to improve the air quality in sensitive rooms like clean rooms or operating theatres (OT). The main tasks of an air-conditioning system in an OT is to maintain thermal comfort and to abate pollution loads in the air. The most sensitive area for contaminations in an OT is the operating table with the wound site and the instrument table. The development of filters with high efficiency is a warrant for the supply of clean air in the OT. Problems occur due to people and machines working inside the OT. Depending on the activity level a person is able to emit up to several millions of skin squamae per minute with thousands of microorganisms on them (Schicht 1988; Gecsey 1996). Considering the fact that a standing person has a thermal plume up to 150m³/h (Fitzner 1989) one can easily see that the surgical team is one of the major pollutants in the OT. The particles emitted by the people get airborne and can lead to infections if they reach the wound site.

There are several studies showing the relationship between the number of microorganisms in the air and the risk of a postoperative infection. Lidwell et al. (1984) for example found that reducing the number of colony forming units (CFU) in the air of the OT by the factor 10 reduces the risk of infection by about 2%. This reduction seems to be very small but one should never forget that behind these percentages the fate of individual persons is hidden. At best the infections lead to a longer hospital stay, sometimes, however, people get disabled or even die. Therefore it is necessary to eliminate or at least reduce the contaminations to minimize the risk of infection. Regarding the OT this means that there should be a possibility to protect the patient against the aerosols, especially germs, in the air. In the last analysis not the airborne germs and particles are of importance but those who settle in the wound. The air supply system is responsible for the airflow patterns and determines whether an aerosol gets to the wound or not and if a settlement is possible or not. Physically it makes no difference if the aerosol is a particle or a microorganism. Both have the same behaviour in the air. Normally microorganisms attach to particles and are transported through the air with the particles. But if they approach a surface several forces have an effect on the aerosols which are responsible for the different behaviour between aerosols and gases. Mainly these forces are: the gravitational force which gains influence the larger the aerosols are, diffusion and electrostatic forces which become more important the smaller the aerosols are and in addition there is the thermophoretic force which influences the settlement of particles or microorganism. Therefore it is necessary not only to study the dispersion of aerosols in the air but also to draw attention to the process of sedimentation.

An estimation of the threats by aerosol contamination in an OT requires knowledge about the transport and sedimentation of aerosols. Thus the transport of aerosols is convective air flow patterns play a main role. Several authors (Koller 1988, Fitzner 1990; Milholland 1990) mentioned that not only the concentration of contaminations of the air has a great influence on the number of deposited aerosols. It seems that the turbulence intensity has a great impact on the deposition as well, even more than the influence caused by the air velocity (Detzer 1988).

In this paper an experimental approach to characterize the influence of the air flow pattern on the dispersion and sedimentation of aerosols is presented. In a first step the influence of the turbulence intensity and air velocity on the cross diffusion of aerosols is described. Also the influence of the aerosol diameter is examined. These examinations are necessary for a prediction about the possibility of aerosols reaching a surface. In the second step the settlement of microorganism under various flow conditions is studied.

The knowledge about the influence of the turbulence intensity, the aerosol diameter and the air velocity on the dispersion and deposition of aerosols help to predict contamination risks in an OT.

METHODS

To investigate the influence of air flow patterns on dispersion and deposition of aerosols the experiments are carried out in a special designed flow channel to get well defined environmental conditions.

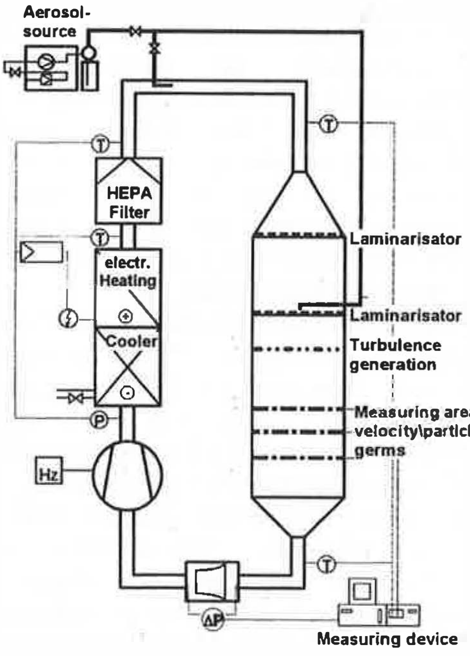

Figure 1: Schematic experimental set-up of the test facility

The test facility consists of a duct system in which the test chamber is integrated. An electrical heater and a water cooler allow to adjust steady temperatures during the tests. The air is drawn through the channel by a ventilator with adjustable speed to get different air velocities.

Because of the two fabric covered laminarisers the airflow gets unidirectional and laminar. The use of grids enables to produce different levels of turbulence intensity. Generated aerosols introduced into the air stream at various points as a small thread are widely spread and are measured with a measurement grid at different distances from the laminarisers and the point of emission of the aerosols, respectively. The measurements are done with the following aerosols:

- particles generated with a salt suspension
- test germs of the species Micrococcus Luteus.

The particles are measured with a normal laser particle counter. The measurements of the germ dispersion are done with 6-stage Anderson-Impactors and the measurements concerning the deposition of Micrococcus Luteus are done with TS-Agar plates, which are placed horizontally in the channel. The germs are hatched for 24 hours with a temperature of 36±1°C.

RESULTS

Aerosol distribution

The measurements of the dispersion of aersols in the different measuring planes with different distances from the point of emission show that in a certain distance the aerosol distribution of a peak emission in the center of the channel results in a Gaussian distribution. The main stream velocity for all cases is about 0.25m/s and constant across the section, a usual flow velocity under laminar flow ceilings in OT's.

The following figures show the distribution of aerosols for two different distances between the point of emission in the center of the test channel and the measuring plane. The cross diffusion, as expected, increases with the raise of turbulence intensity which is documented by broader and flatter curves. In a turbulent flow the aerosols move in all directions following the ups and downs of the air stream. In contradiction the aerosols move in a laminar flow only on the parallel path lines with no exchange between these. An increase of the degree of turbulence leads to more variable airflows and cross movements which can be documented by greater dispersion areas of aerosols.

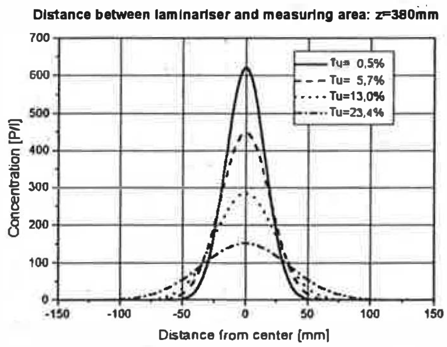

Figure 2: Concentration of aerosols for different turbulence intensities; source intensity: 500 P/s; distance from point of emission: z=380mm

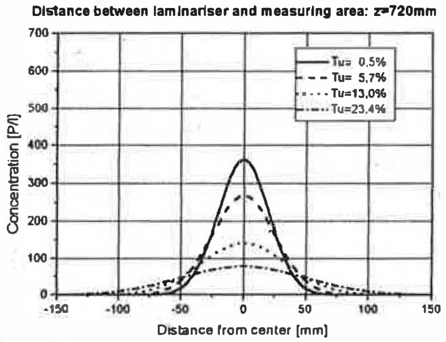

Figure 3: Concentration of aerosols for different turbulence intensities; source intensity: 500 P/s; distance from point of emission: z=720mm

Higher turbulence intensities lead to greater areas of dispersion as well as the distance between the laminariser or point of emission has an influence on the dispersion. A greater distance between the point of emission and the measuring area leads also to broader areas of dispersion. Because of the not ideal laminar flow inside the test chamber the turbulent fluctuations increase in value. This leads to a greater intermingle between the air and the aerosols, which get spread downstream over a bigger area. With the help of these curves it is possible to determine the standard deviation of the Gaussian distribution curves as a characterizing figure for the cross diffusion.

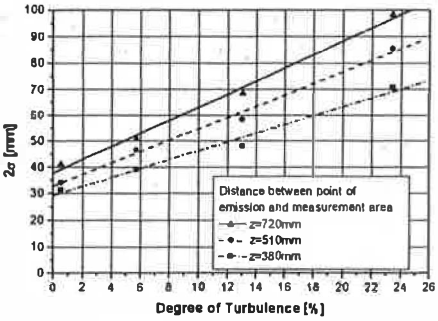

Figure 4: Relation between standard deviation (σ) of the Gaussian distribution and turbulence intensity for a velocity of 0.25m/s

In Figure 4 the relation between the standard deviation and the turbulence intensity is shown. The aerosol distribution transverse to the main flux described by the standard deviation of the Gaussian distribution curves increases with the raise of the turbulence intensity. Aerosols are spread over a broader area as was also shown in Figure 2 and 3. Therefore the aerosols can reach areas within the room which are quite far away from the point of emission if they are emitted in a more turbulent flow. A fact that explains the better performance of laminar flow compared to a mixing ventilation system in an OT.

The measurements presented in Figure 2-4 are representative for a main flux velocity of 0.25m/s. An increase of the velocity up to 0.3m/s and 0.4m/s does not change the results. In the range between 0.2m/s and 0.4m/s there seems to be no influence of the air velocity on the distribution of aerosols. There is also no significant difference detectable whether the measurements are carried out with particles or with germs of the species Micrococcus Luteus.

In Figure 5 the relation between this standard deviation and the distance from the point of emission is shown. As mentioned above the standard deviation of the Gaussian distribution as characterizing figure for the dispersion of aerosols increases with a greater distance from the point of emission. With the help of the measurements it was possible to find an empirical formula in the range of Tu=0% up to Tu=25% for the prediction of the standard deviation when a punctual emission source is used:

$$\sigma = \frac{1}{2} \cdot (\Delta x + z \cdot \mathrm{Tu} \cdot k) \qquad (1)$$

where

σ = standard deviation, characterizing the cross diffusion of aerosols [mm]
Δx = extent of the emission source [mm]
z = distance between aerosol source and measuring area [mm]
Tu = turbulence intensity [%] (relative standard deviation of the velocity)
k = empirical factor

Figure 5 shows the comparison between the measured data and the calculated. The empirical factor used for this graph is k=1/175. The deviation from 0 is explainable considering the fact that the emission source is not ideal punctual but has a certain extent, in this case about 25mm.

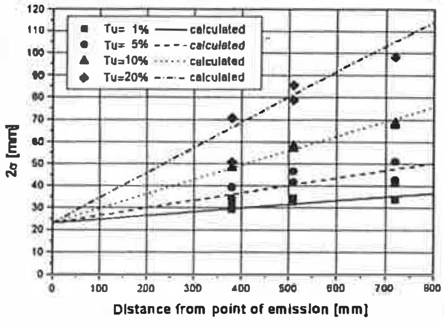

Figure 5: Comparison between calculated and measured standard deviation for different turbulence intensities

The comparison between the calculation and measurement shows a high correspondence. With the help of this empirical approximation it is possible to predict the enlargement of the area the aerosols reach in a more or less turbulent air flow. On this basis a statement is possible whether aerosols reach a surface or not. If they get near the surface, like an operation table, the question is under what circumstances they deposit and which influence the airflow patterns play in this process.

Deposition of aerosols

If aerosols get near a surface the boundary layer on the surface becomes important. In the boundary layer the concentration decreases from a concentration in the outer air flow to zero at the surface. The difficulty is to determine proper values for the thickness of the boundary layer. It depends on flow mechanics, velocity boundary layer and the size of the aerosols (Hinds 1982). Regarding this a practical way to solve these problems is chosen. The results in form of the number of deposited CFU's are of interest. The variations of the airflow patterns lead to a change within the boundary layer which is documented in different settling rates. All measurements concerning the deposition of test germs (Micrococcus Luteus) showed significantly an increase in the number of deposited germs when the turbulence intensity is raised.

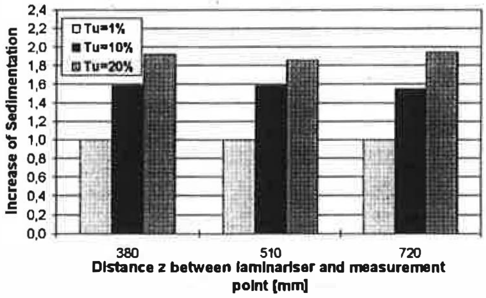

Figure 6: Increase of the sedimentation rate for different turbulence intensities

Figure 6 shows the increase of the deposition rate of the test germs for different turbulence intensities in relation to the case for Tu=1%. An increase of the turbulence intensity from 1% to 10% results in 1.6 more deposited CFU's. If the turbulence intensity is increased up to 20% the number of deposited CFU's is even raised by 1.9. The results are shown for different distances between the laminariser as the point where the airflow is unique and parallel and the measuring point. Figure 7 shows explicitly the influence of this distance. The values are related to the number of deposited germs at a distance z=380mm. The maximum increase of the deposition rate origin from a greater distance is about a factor of 0.15, much lesser than the increase of the sedimentation rate caused by higher turbulence intensities.

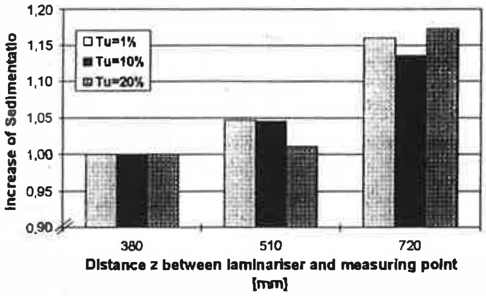

Figure 7: Increase of the sedimentation rate for different distances between laminariser and measurement point

Figure 8 shows a combination of the two factors found to have a great influence on the number of deposited CFU's.

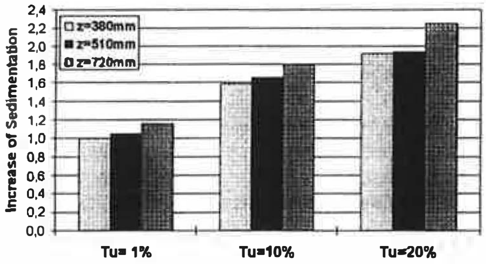

Figure 8: Increase of the sedimentation rate for different turbulence intensities and different distances between laminariser and measurement point

The influence of the turbulence intensity is much higher than the influence caused by greater distances of the measuring point. The number of deposited germs depends on the turbulence intensity of the airflow. An increase of the turbulence intensity from 1% up to 20% results in a two times higher sedimentation rate.

DISCUSSION

The present results show clearly that the influence of the turbulence intensity cannot be neglected. Raising the turbulence intensity leads to better cross exchange and broader areas of aerosol dispersion and in consequence to higher sedimentation rates. The results presented in this paper show these relations. However the ranges concerning aerosol size, air velocity and turbulence intensities in which the measurements are done have to be regarded.

The data from Detzer (1988) and Fitzner (1996) and the measured values presented in this paper show a good correspondence. Figure 9 shows a comparison between the measured data of Detzer and Fitzner and the calculation according to equation (1).

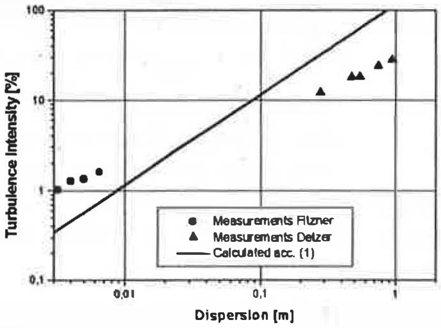

Figure 9: Comparison of calculated data with former measurements

Comparing the data it has to be considered that Detzer and Fitzner measured the turbulence intensity at the same height where the aerosols were injected. In objection to this the calculated data is based on the evaluation of the turbulence intensity at the measuring plane for particle dispersion and not at the point of particle emission. In addition Detzer used a tracer gas instead of particles and germs for his measurements. Detzer and Fitzner measured the distribution at a distance of 3m left and right from the point of emission while the maximum distance for the measurements presented in this paper is 720mm. The calculated data in Figure 9 is based on Equation (1) for a distance of 3m although the referring measurements are done at different heights. Nevertheless the calculated data fit well between the measurements and calculated data presented in this paper. A transfer of the data for greater distances is possible. The data concerning the distribution of aersols can be used to predict the dispersion area of contaminants in a laminar or turbulent flow in the above-mentioned range.

If aerosols get near a surface because of their convective transport in the air it is quite possible that they deposit on the surface. Speaking about operating theatres a deposition of aerosols in the wound or on instruments is one of the major infection routes. The measurements with test germs of the species Micrococcus Luteus show a dependence of the deposition process from the turbulence intensity of the ambient air. The results presented in this paper show high accordance to results of Fischbacher (1991).

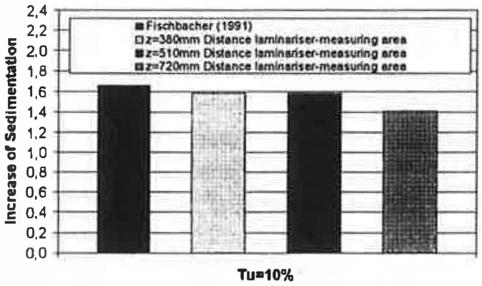

Figure 10: Comparison between measured data and experimental data by Fischbacher (1991)

Fischbacher measured the increase of sedimentation on a horizontal wafer in a clean room when the turbulence intensity is raised from Tu=1% to Tu=10%. The distance between the measuring point and the point where the laminar flow gets disturbed is not mentioned. But there is little difference between his data and the values for the increase of sedimentation based on the measured values presented in this paper.

Consequences for operating theatres

The normal German test routine DIN 4799 (1990) for air supply systems for operating rooms defines a degree of contamination which describes simplified the relation between a concentration of contaminations at the measuring point (e.g. operating table) to the concentration in the exhaust air. The evaluation of nine acceptance tests for air supply systems from different manufacturers done at the Hermann-Rietschel-Institute in the DIN test facility is pictured in Figure 11. The tested supply systems range from fabric covered laminar flow ceilings to systems with turbulent displacement flow. Although the correlation is not quite clear it is obvious that the degree of contamination is dependent on the turbulence intensity.

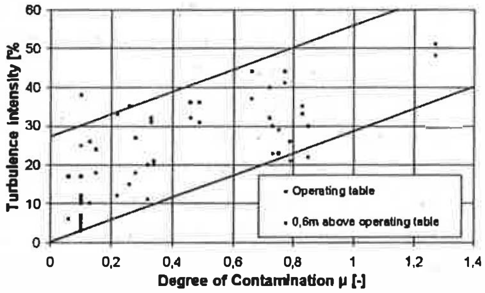

Figure 11: Degree of contamination and turbulence intensity for different OT supply air ceilings

An increase of the turbulence intensity leads to higher values of contamination. This test procedure only describes the performance of a supply air system for steady state conditions. In addition there is no assertion about the number of sedimented particles. Therefore Jung and Zeller (1996) described a modified test procedure. Besides the steady-state testing they recommend to examine the contamination removal effectiveness if there are abrupt spreadings of contaminants, for example door openings. But even with this additional testing there is no description possible whether aerosols reach the operating table and deposit there or not. Evaluating the turbulence intensity under the air supply system helps to predict the range of the area in which a contamination is possible. The knowledge about the relation between the dispersion of aerosols and the turbulence intensity makes it feasible to predict on which area on the operating table contaminations are to be expected. If these contaminations reach the operation table there is the threat of sedimentation compared with the incidence of infections.

Even if contaminants reach the operating table it is necessary to control the turbulence intensity. If it is reduced from 20% to 2% the number of deposited germs is halved. A lower number of deposited particles minimizes the pollution load of the wound area and in conclusion the incidence of infection. Nevertheless the discipline of the surgical teams presents one of the major factors influencing the air quality in operating theatres. But using fabric covered laminar flow supply air systems reduces the turbulence intensity significantly and is one step closer in reaching the best possible conditions for the patient.

Displacement flow as proposed for operating theatres is widely used in clean-rooms for ventilation. Because of the developments in clean-technologies it is necessary to gain more and more control over the air flow patterns in a clean-room to achieve the demanded air qualities. In recent years the diameter of particles which can cause damage on the products gets smaller and smaller. The normal installations in clean-rooms to create a displacement flow are the so called filter ceilings. The air reaches the room through a HEPA or ULPA filter and the flow conditions are more or less uniform. Several investigations (Lippold and Reichert, 1988; Fujii et al. 1992) showed that the pleated filters lead to local disturbances of the uniform air flow. Those can end in inreases of turbulence intensity. In this case particles generated by people and machines inside the clean-room are spread over a broader area in the room and the incidence of product contamination gets higher. The use of fabric covered laminar flow ceilings could also in this case help to reduce this risk. If the area in which the aerosols are spread is smaller the risk of product contamination gets smaller. Despite this fact the displacement flow origin from a fabric laminariser produces stable flow conditions and the additional costs which may occur because of a higher installation grade are neglectible compared to the costs of a higher loss of production.

SUMMARY

Generally spoken the laminar flow is a powerful tool in an integrated approach to lower the incidence of contamination, whether the contamination is in the air or on a surface. With low turbulence intensities in the air achievable with laminar flow systems it is possible to diminish the zone of contamination in the air and in consequence the area in which harmful aerosols can deposit. The deposition process itself is also influenced by the turbulence intensity. Lower turbulence intensities in the air result in lower deposition rates.

The normal hygienic control in OT's requires long and extensive measurements of the amount of CFU's in the air. Normally the results of measurements are achievable only with a time gap between measurement and result, on-line monitoring is not possible. With the knowledge that any aerosol can be a potential carrier for infections and the results presented in this paper it is much easier to control the route of infections with a normal optical particle counter (OPC). In clean-rooms the OPC is widely used for a direct monitoring of the air quality. It is a small step to use the OPC to monitor the air contamination in an OT during an operation. If the routes of infections are known it is possible to start counter-measures to prevent the patient from infections. Nevertheless it is necessary to reduce the turbulence intensity in the protective area to reduce not only the air contamination but also the deposition rate of harmful particles in the wound. All efforts including the above mentioned should be taken to create the best possible prerequisites for a successful work in the operation theatre.

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