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# DISTRIBUTION OF MICROBIAL CONTAMINANTS IN OPERATING THEATRES AND HEALTHCARE ENVIRONMENTS

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**Keywords**: Microbial Contamination, Particle Distribution, Deposition of Airborne Bacteria, Particle Modelling

## ABSTRACT

Contamination control in healthcare facilities against airborne pathogens is a challenging task to prevent nosocomial infections and the distribution of highly infectious diseases from one patient to another. In different areas and contamination protected areas like operating rooms, isolation wards and intensive care units, similar tasks for the ventilation scheme and knowledge about the distribution of pathogens in the airflow is needed. Most investigations and the standard test cases for acceptance tests consider particulate contaminants of small particle size that is completely airborne without gravitational effects. Most microbial contaminants like respiratory droplets and skin flakes have particle diameters of 1 to 20 µm. These particles are also affected by their gravitational settling and do not perfectly follow the airflow motion. The gravitational forces lead to significant increase of their deposition behaviour. Investigations that consider the microbial particulates as completely airborne have limited validity to predict the surface contamination inside the patient's wound field or on medical instruments and equipment. However, accurate prediction of the behaviour of the contaminants is fundamental for risk assessment and performance tests of ventilation systems. Numerical simulation models to calculate the particle motion and interaction to the airflow field provide more detailed information about the paths for contamination and infectious diseases. To develop and evaluate contamination control strategies for healthcare environments, the method to simulate the movement of pathogen contaminants has major importance. A CFD simulation is a resource-efficient approach. It provides valuable insights into the three-dimensional and transient behaviour of contaminants. Accumulation zones of contaminants in the air and deposition spots on surfaces can be located and the optimal positions of monitoring devices can be found. The state-of-the-art approaches in particle modelling and simulation as well as their advantages and limitations are presented. Within several research projects in the field of cleanrooms, health care facilities and contamination control, the exposure, distribution, deposition and resuspension of airborne particles ranging from 0.1 to 20 µm are investigated at the Hermann-Rietschel-Institut (HRI). In this range of diameter, the transition zone between airborne particles and particles which are highly affected by gravitation is particularly challenging.

## 1 INTRODUCTION

Contamination control of airborne microbial particulates is a major topic in different areas of healthcare facilities.

Patients need to be protected against nosocomial infections especially against surgical site infections (SSI) in operating rooms (OR). To protect patients from SSI, surgical procedures are conducted under clean air environments where it is attempted to keep the concentration of airborne microbial contamination as low as possible. Thus, big efforts are taken to remove airborne microbial contamination from the operating table and its immediate environment through OR-specific ventilation.

Different publications show that SSI result to an increase of the morbidity rate and in fatal cases higher mortality. In German hospitals, SSI occur after about 1.8 % of all performed operations (KISS, 2017) at $12.6 \cdot 10^6$ operations per year in total (Statistisches Bundesamt, 2006). This corresponds to $2.3 \cdot 10^5$ issues with $4.5 \cdot 10^3$ of them being fatal (Gastmeier and Geffers, 2008).

To protect other patients against particularly contagious diseases such as methicillin-resistant bacteria, humans infected with these pathogens are accommodated in isolation rooms. The intention is to prevent further distribution to other areas and cross-contamination.

## 2 PATHS OF AIRBORNE MICROBIAL CONTAMINATION

Nosocomial infections can be caused by direct contact, inhaled contaminated air or by deposition of microbial contamination on wounds or mucous membranes. Especially SSI may occur as the result of a pathogens transferred to an open wound. Besides the direct transfer by contact, pathogen carrying particles can distribute with the indoor airflow for long distances.One way are airborne pathogens that deposit directly in the wound. Another path for nosocomial infections are airborne pathogens that settle on instruments and devices and subsequently come into contact with the patient especially the wound field.

Smaller particles are almost completely airborne with non-significant sedimentation velocities. The motion of large particles is significantly influenced by gravitational forces and the sedimentation velocities can be of the same or higher magnitude as the airflow. Infectious germs may appear as airborne particles (single or small number of bacteria clusters) with particle sizes about 1 µm or they exist imbedded in droplets or on skin scales (Kappstein, 2009) with particle sizes up to 50 µm. These large particles like droplets and skin scales are not airborne and thus sink regardless of the ventilation. However, droplets may become airborne, if the water part evaporates. It can be assumed that the operating personnel is responsible for about 80 % of all contamination (non-viable and viable) in an OR with the head area being the main source location (Hottner, 1996). The operating personnel and the hospital staff in general are the main source of airborne bacteria-carrying particles (Tuomi, 2014). The typical range of particle size for these microbial contaminants in the room air of hospital wards and operating rooms is about 1 to 20 µm (Clauß 2015). The infectious agents in hospitals are usually bacteria such as Staphylococcus aureus or Enterococci.

The deposition of airborne bacteria onto the wound field and medical instruments is one of the possible reasons for SSI. The deposition of particles on protected surfaces should therefore be further investigated. In another case, for patients in isolation wards, the protection of the environment and the prevention of cross contamination are in the focus of the contamination control.

## 3 SIMULATION METHODS OF MICROBIAL CONTAMINANTS

### 3.1 AIRBORNE CONTAMINANTS

The effects of the surgeon's posture and the locations of contaminant sources in an operating room were previously studied using CFD simulations (Lichtner and Kriegel, 2014). The room is equipped with a laminar airflow inlet at the ceiling of 3.2×3.2 m² and a supply volume flow rate of 10.800 m³/h. In Figure 1, the local particle concentration relative to the exhaust concentration is shown for upright standing personnel (left) and bent-forward personnel (right). It can be clearly seen that the posture has a significant impact on the contaminant concentration on the operating table in case the personnel's facial areas are considered as particle sources.

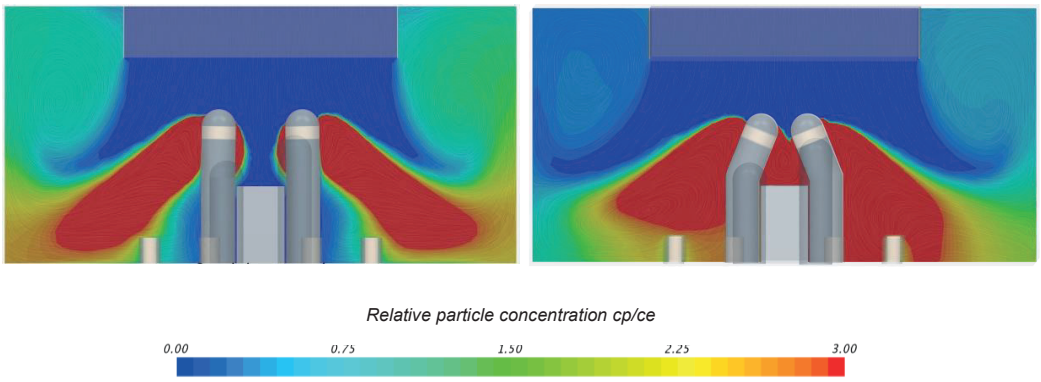


Figure 1: Relative local particle concentrations with upright standing personnel (left) and bent-forward personnel (right) (Lichtner and Kriegel, 2014).

Sadrizadeh and Holmberg (2015) also considered bent-forward operating personnel in their simulations and found an increased number of suspended particles in the surgical area, compared to upright standing personnel, even when using a local ventilation type OR where the fresh air is supplied horizontally near the patient. These simulations were done with a passive scalar to indicate the distribution of contaminants. With this method, the contaminant follows the fluid motion perfectly and is not influenced by gravitational settling and its inertial forces. Furthermore, there is no model to calculate surface interaction for a passive scalar to consider the deposition of contaminants on protected areas. The validity of this methodology is therefore limited and can give no information on how the settlement of pathogens to the wound field would change for different particle sizes. This is given as an example for a scientific question where the deposition rate should be considered instead of the concentration of airborne particles.

### 3.2 MICROBIAL PARTICLE DEPOSITION

The protection of other patients and the personnel from highly contagious patients in isolation rooms is another important topic for contamination control strategies in hospitals. The evaluation of the air concentration of perfectly airborne tracer particles such as Di-Ethyl-Hexyl-Sebacat (DEHS) represents the technical standard for experimental testing of contamination-controlled areas and the protective effect of the ventilation. To get a better picture of the distribution and deposition of the pathogens in the room and the contaminated areas, a more complex model approach was chosen to calculate the particle motion and interaction to the fluid and surfaces in a numerical simulation.

airborne pathogens the distribution and deposition of different sized particles in numerical simulations reliable models for the particle motion are needed.

The particle's size has major influence on the deposition of particles, which determines the influence of gravity on the particle distribution. Three particle size ranges can be distinguished by their deposition behaviour:

1. For small particles, deposition depends on the turbulence characteristics, especially molecular and turbulent diffusion
2. Medium size particles are more influenced by turbophoresis (gradient of turbulence intensity) and interception
3. Large particles are highly influenced by gravitation

The mentioned particles sizes for bacteria carrying particles are mainly in the range ofthe second and third category.

### 3.3 SIMULATION GEOMETRY

The simulation geometry and the computational surface mesh are shown in Figure 2. It consists of an isolation room with an area of 4×5 m² and a height of 3 m. The room is equipped with a single patient's bed and different tables and trays. On the bed, a computer simulated person (CSP) is sitting. Beside the bed, another cylindrical CSP is located which represents hospital personnel. The computer simulated persons have a convective thermal output of 34.5 W/m² (medium activity level with 1.6 met according ASHRAE (2013)). The supply air diffusers are arranged at the ceiling and the extract air openings are located in the bottom region for mixing ventilation regime. Additionally, a second air flow distribution with displacement ventilation and supply diffuser at the walls in the bottom region and extract openings in the corners of the ceiling is modelled. The airflow rate for all cases is constant at a value of 180 m³/h (air change rate of 3 $h^{-1}$). The vertical side of two 80 cm trays is cooled for one tray and heated for the other one. The heat flux of these surfaces is ±50 W/m².

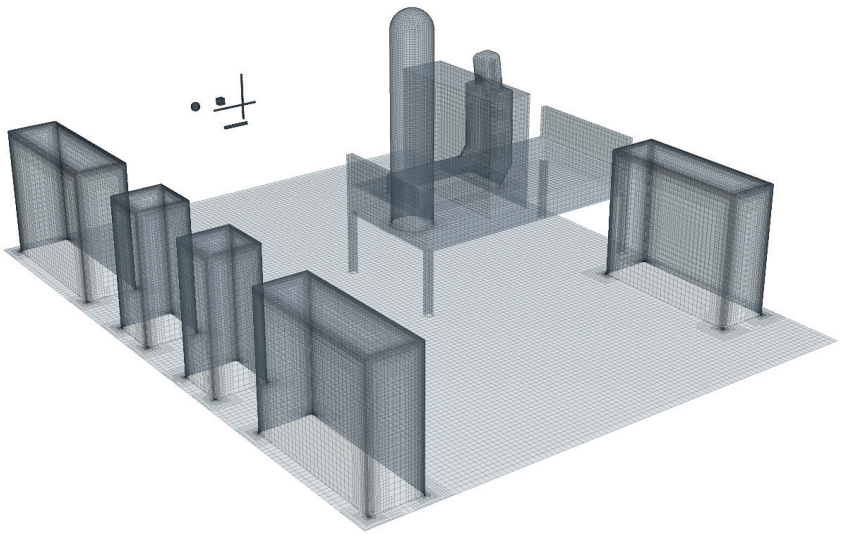

Figure 2: Geometric surface grid of the isolation room

### 3.3 PHYSICAL MODEL

Table 1 gives an overview of the simulation parameters. The flow field is computed using an Eulerian framework. It is assumed as three-dimensional and turbulent with friction and the influence of the gravitational field. The ideal gas equation is utilized as the thermal equation of state and heat transfer is simulated by calculating convection and conduction forces. The turbulence model is a k-ω SST two-layer model for statistical modelling. The Reynolds-Averaged-Navier-Stokes equations (RANS) are discretized into algebraic equations by the finite volume method with the commercial CFD software STAR-CCM+ 12.06.010 (double precision solver).

The governing equations are solved sequentially through a segregated approach. The distribution and deposition of particles are calculated using the Eulerian Dispersed Multiphase Model. Two additional phases for particle sizes of 0.5 µm and 18 µm with a density of 1000 kg/m³ are injected with a mass flow inlet at the facial region of the patient. The particles that impinge to a solid wall or body surface escape from the solution domain and are calculated as deposited on that surface. The deposition rate is the mass flux of particles of each size going through the surface per unit area and time.

Table 1: CFD-Parameters

| Parameter | Setting |
|---|---|
| Turbulence model: | k-ω SST, all y+ wall treatment |
| Multiphase model: | Dispersed Multiphase Eulerian |
| Solver settings | Segregated, implicit unsteady, time step: 0.05 s |
| Mesh | 2'440'588 cubic cells, base size 4 cm, structured |

### 3.4 RESULTS AND DISCUSSION

#### *Deposition on different shaped objects*

When particles deposit on health care instrumentation, they can cause cross contamination to other clinical areas. The shape of the objects has important impact on the particle deposition. In Figure 3, the deposition on different object shapes is shown for the 0.5 and 18 µm particles. All objects have the same surface area but in different volume geometry with different length of the edges. The small particles deposit mostly on edges of any orientation while large particles show high deposition rates over the whole area of horizontal surfaces. The reason for that is the bigger influence of turbulent fluid forces on the smaller particles. The flow separation of the turbulent boundary layer results in an increase of the particle deposition in this separation region. Bigger particles are only dominated by gravitational settling. This effect is smaller at round edges or round objects.

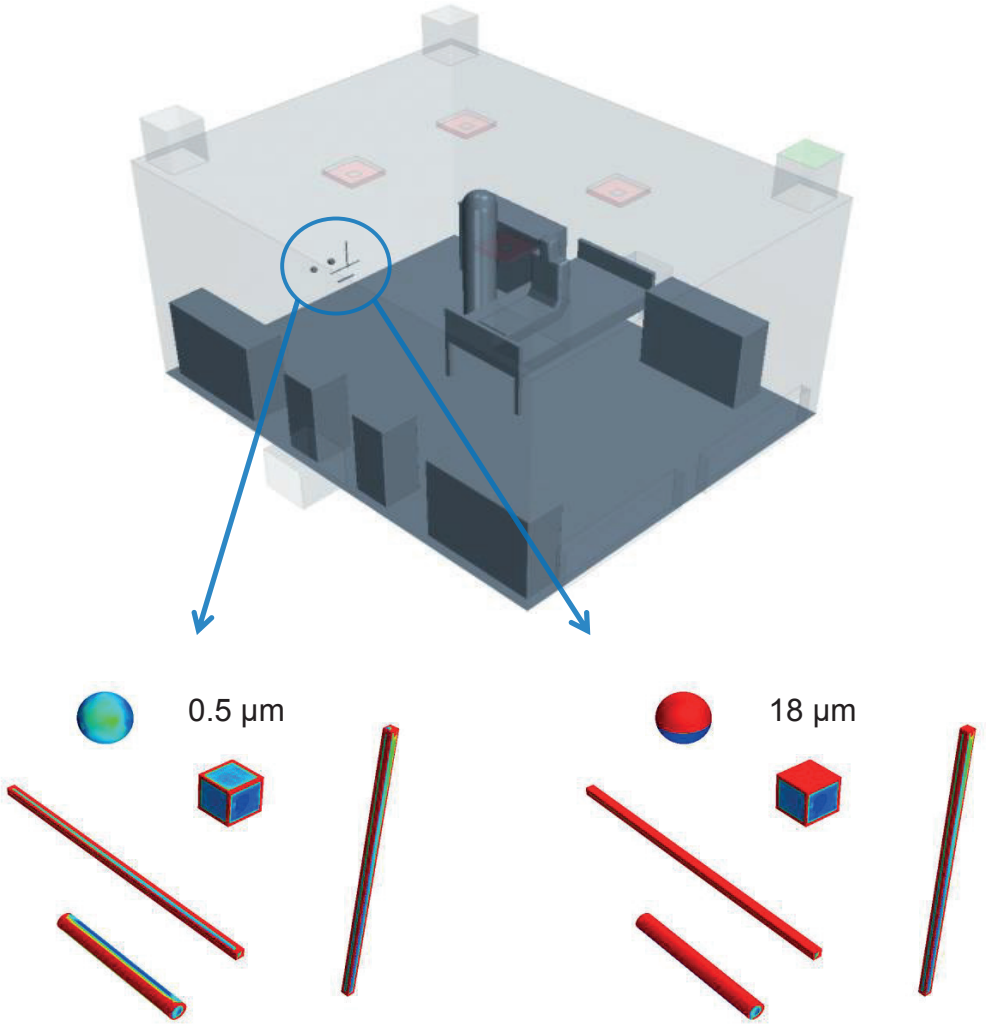


Figure 3: Deposition of particles on different shaped objects

***Deposition on non-isothermal surfaces***

To evaluate the influence of non-isothermal surfaces on the deposition of particles, the deposition on a cooled and heated vertical is investigated. The heated side shows increased deposition rates at the bottom while the cooled surface shows increased deposition at the top. In both cases, a higher deposition rate can be observed where the boundary layer is small. With an increase of the boundary layer (further away in the flow direction) the deposition rate decreases. Figure 4 shows the overall deposition pattern on the vertical surfaces of the furniture opposite to the patient.

Figure 5 and Figure 6 show the relative deposition rate for the heated and cooled surface. The relative deposition rate in that case is the mass flux of particles to the surface per time. For better visualization, the deposition rate is de-dimensionalized by a constant value of $9.0 \cdot 10^{-14} \frac{\mathrm{kg}}{\mathrm{m^2 s}}$. The graphs for the heated and cooled surface area show an opposite behaviour of

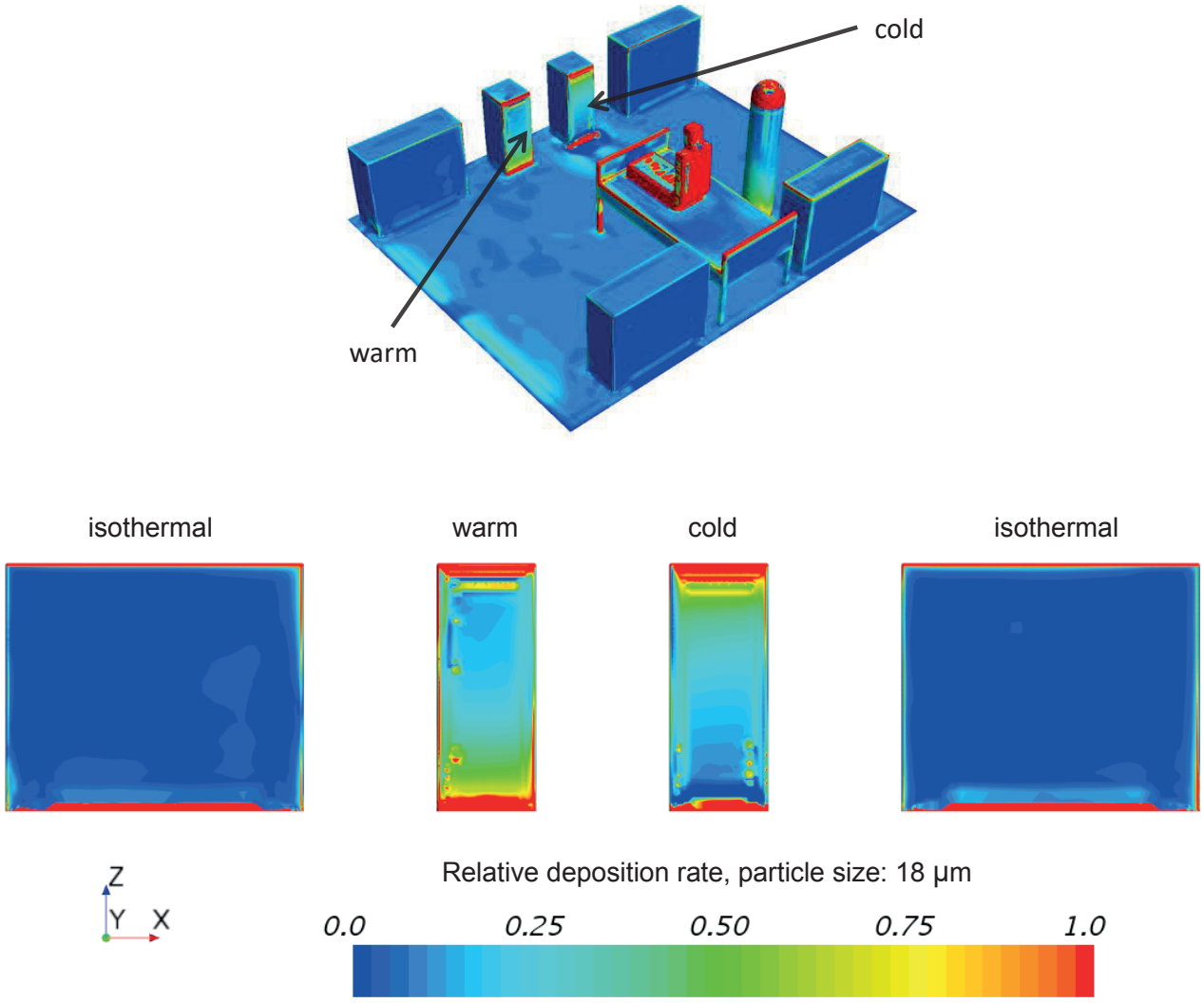


Figure 4: Deposition of particles on non-isothermal surfaces

the deposition rate over the height of the surface area. Both graphs show no significant difference for small and large particles. Comparing the gradients for the different particle sizes, no differences can be observed. In this case, the temperature gradient is the dominant parameter for deposition on the surface.

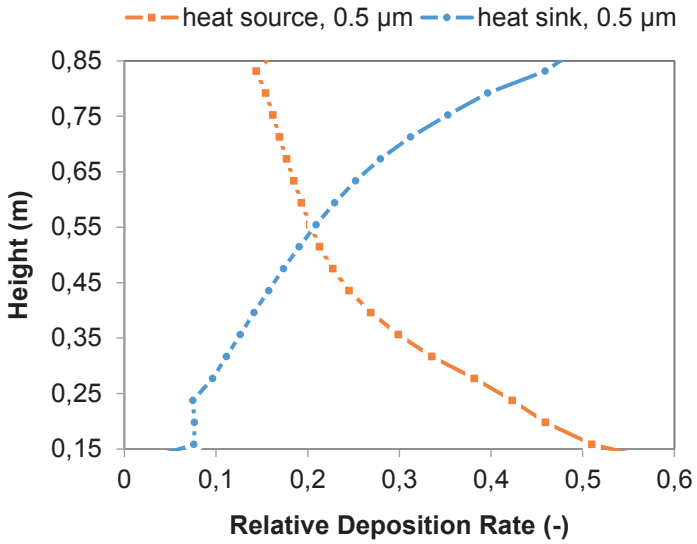


Figure 5: Particle deposition on non-isothermal surface for 0.5 µm particles

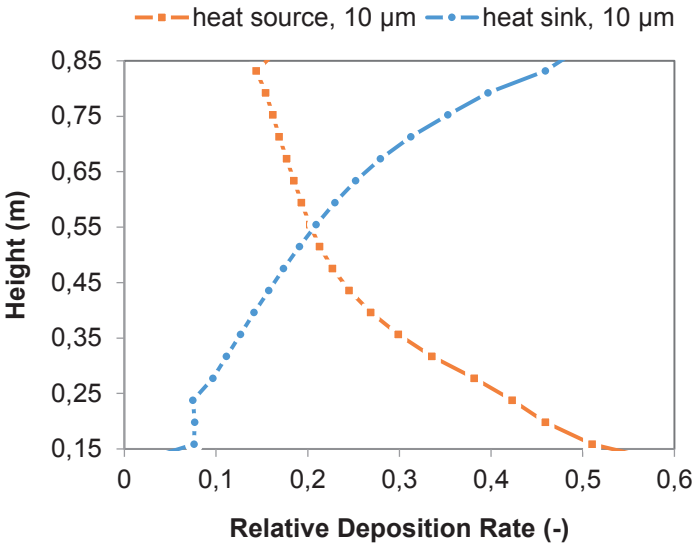


Figure 6: Particle deposition on non-isothermal surface for 18 µm particles

### 3.4 DOOR MOVEMENT

Another possible contribution to room air contamination is infiltrated air from less clean areas. In operating theatres, local effects such as door and person movement can cause contaminated backflows despite the pressure cascade. At the HRI, contaminated backflows between two cleanrooms (with an area of 5 x5 m² and 3 m height) with a pressure difference of 10 Pa are investigated by means of numerical flow simulation (Askan & Kriegel, 2016). A vertical and a horizontal sliding door and a revolving door with three door movement modes are considered. The three door motions are: elliptical increasing rotation (slow open, slow close), linear rotation and elliptical decreasing rotation (fast open, fast close). In all cases, the opening and closing time is 3 seconds each, with a pause of 0.5 seconds between opening and closing. The boundary conditions of the simulations are shown in Table 1. For further information about the used methods and conditions see (Askan & Kriegel, 2016).

Table 2 Boundary conditions of the transient simulation with door motion

| | |
|---|---|
| **Supply air high pressure room** | Volume flow rate: 750 $m^3/h$ (corresponds air change rate of 10 $h^{-1}$)<br>Passive scalar: 0 (uncontaminated air) |
| **Supply air low pressure room** | Volume flow rate: 750 $m^3/h$ (corresponds air change rate of 10 $h^{-1}$)<br>Passive scalar: 1 (contaminated air) |
| **Exhaust air high pressure room** | Volume flow rate: 397,5 $m^3/h$ |
| **Exhaust air low pressure room** | Volume flow rate: 1102,5 $m^3/h$ |
| **Passive scalar source term low pressure room** | Equals passive scalar term in low pressure room always to 1 (contaminated air) |

The results show that despite the existing pressure difference, local, contaminated backflows occur due to the door movement, which transport a significant amount of contaminated air against the impressed pressure gradient. Furthermore, it can be observed that the door operation mode has a decisive influence on the contaminated reverse current quantity.

For sliding door motions, no backflows are detected. To compare the contaminated return flow rate between the individual door modes (linear, elliptically decelerated and elliptically accelerated), the volume flows are integrated over time (see equation 1 and figure 7). As a result of these integrations, the elliptically accelerated mode of operation with 0.104 m³ has the lowest return flow rate. In contrast, with an elliptically slowed door movement with 0.369 m³, the largest backflow takes place. The linear operation shows a backflow volume of 0.265 m³.

$$\dot{V}_{\mathrm{Backflow}} = \int_{t_1}^{t_2} \dot{V}(t)\mathrm{d}t \qquad (1)$$

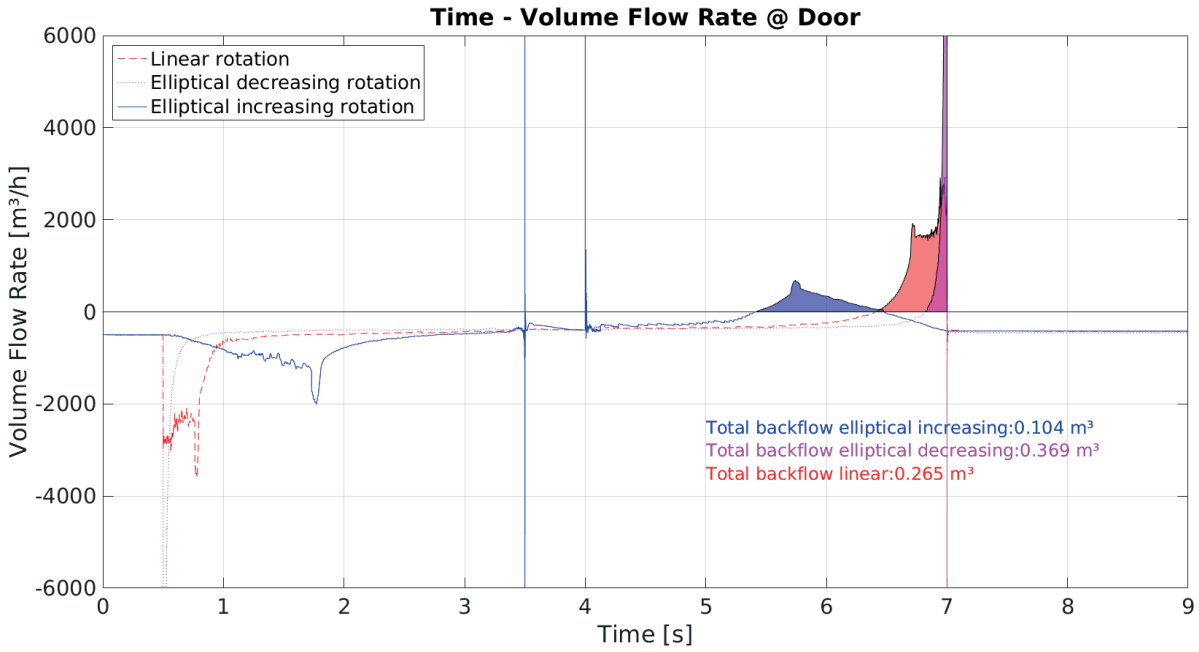


Figure 7: Amount of backflow by rotating door motion

The reason for the backflow is the induced air motion by the door movement. With the beginning of the closing, a vortex develops. This vortex moves with its vacuum area in the direction of the door tip during the closing process. Immediately prior to the door closing, the vacuum area is located in the area of the door gap and provides a sufficient local pressure difference for the backflow. As a result, the backflow takes place. Such door-induced reverse current structures occur during the door movement in different time periods and in different areas behind the door. This results in the contaminated volumes. Backflow duration and quantity vary with the way the door is operated.

## 4 CONCLUSIONS

Modelling particulate contaminants with a passive scalar approach gives a prediction for the distribution of airborne contaminants. That can be assumed for particles smaller than 1 µm but bigger particles show a different behaviour in their resulting motion interacting with the fluid and their deposition. The Dispersed Multiphase Model provides a reasonable approach for the calculation of particle distribution and deposition for the relevant particles. To validate the simulation model, additional experimental data is needed. The distribution and deposition of pathogen particulates is characterized by various multifactorial dependencies. To predict the risk of infections or cross contamination, a holistic approach must be chosen that takes all dominant influences into consideration.

## ACKNOWLEDGEMENTS

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