STUDY ON DOORWAY AIRFLOW FOR MAINTAINING CLEAN ENVIRONMENT

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Abstract
Room pressurization is an approach to ventilation that prevents airborne contaminants from moving from one room to another. It is applied in clean room, chemical lab, hospital operating room, and so on. At aperture as large as door openings, airflow of the suitable wind velocity is appropriate. For room pressurization design, doorway airflow is evaluated by measuring the concentration of airborne particles and number of microbes that invade through the doorway when the door is open. The number of airborne microbes and concentration of particles that invade from the adjacent room are associated with the doorway airflow. Thus, it would be possible to reduce the risk of contamination by controlling the doorway airflow speed in the desired direction. The doorway airflow speed should be more than 0.05 m/s, at least for airborne particles larger than 5.0 μm.

1. Introduction

Room pressurization is a ventilation approach that prevents airborne contaminants from moving from one room to another. It is applied in clean rooms, chemical labs, hospital operating rooms, and so on. There are various techniques to establish room pressurization. One of these techniques is implemented as the differential pressure control system. The pressure difference between a pressurized room and some reference space is monitored, and the pressure of the room is directly controlled by dampers that regulate the volume of air in and out of the room in a feedback operation. If the system maintains the designed pressure difference, the airflow between the spaces will always move in the desired direction. However, if a door that separates two rooms with different cleanliness levels is opened, the desired pressure difference maybe lost and the de-contamination function may deteriorate.

One of the solutions to this problem was described by Dale (1994). If a door is opened, the feedback system is stopped in his way. Another solution is the use of the pressure data averaged over a long period for control. However, by stopping or weakening the feedback system while a door is open, the airflow through separations and the doorway is extremely weakened and becomes unable to prevent contamination. The use of an airlock or anteroom is another solution for keeping contaminants out of the room, but it is no longer a feasible option for each door due to its cost, traffic complications, and consumption of extra space.

Wiseman (2003) recommended using an airlock or anteroom whenever possible, since door swing causes eddies. Matsudaira et al. (2004) visualized flow behavior by utilizing PIV measurements. Honda et al. (2004) measured airborne particle concentrations and calculated the mass transfer of airborne particles by door opening and closing operations. Considering the movement of airborne particles caused by a swinging door, an airlock is likely the best solution. Yet, as described by Wei (2004), to replace the old room air, even if the clean air at a rate of 60 air changes per hour (ACH) is supplied, a “one minute” wait is required in the airlock. This is not acceptable for most users.

The authors (2008) introduced a new technique that combined differential pressure control and differential volume control between the supply air and exhaust air, called a hybrid pressure control system. When a door is closed, differential pressure control is applied, and when it is opened, differential volume control is applied to ensure the desired directional airflow and prevent contamination at the doorway. As stated by Wei (2004), a differential air volume between the supply air and exhaust air is the primary cause of airflow at a doorway.

Wei (2004), Anderson (1987), and Coogan (1996) suggested an air volume calculation method for obtaining desired directional airflow and designed room pressurization when a door is closed; this method cannot be applied to the case when the door is opened. As described by Coogan (1996), it is necessary to consider the required airflow speed to prevent contamination.

Shaw and Whyte (1974) reported on air movement through a doorway caused by a difference in temperature under natural convection conditions. However, an alternative approach is required to understand air movement in a clean room under forced convection conditions.

The authors have evaluated doorway airflow by measuring airborne particle concentration and the number of airborne microbes invading through an open doorway in an experimental room. This study was conducted for application to the case of a pharmaceutical manufacturing facility. The experimental results described in this paper are useful for room pressurization design, and serve to constitute fundamental data for future studies.

2. Experiment

A unidirectional airflow was formed in the doorway of our clean room by controlling the exhaust air volume and constant supply air volume, and the speed of this unidirectional airflow was changed to various values. We evaluated the amount of pollutant entering the high-cleanliness room from the low-cleanliness room.

Our experimental environment and the distribution of the inlets and outlets of the conditioned air are shown in Fig. 1; other conditions are summarized in Table 1. The door was always open, and a unidirectional airflow passed through the doorway. We measured the airborne particle concentration and airborne microbe variation in the high-cleanliness room as the unidirectional airflow speed was changed. Atomized pollutants were generated at the doorway to act as pseudopollutants from the low-cleanliness room.

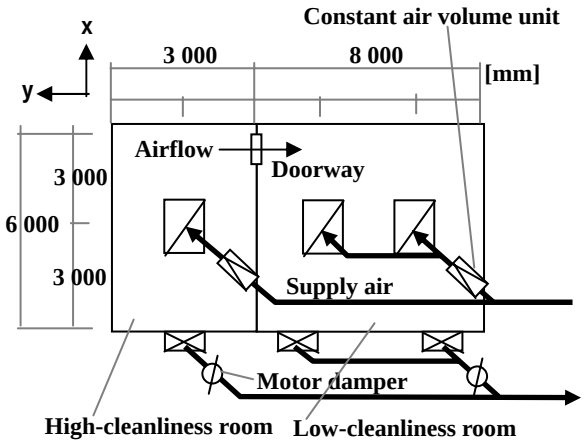

Figure 1 Schematic illustration of experimental setup

The air changes per hour were set at 20 ACH in each room. The unidirectional airflow speed was controlled by changing the exhaust air volume with motor dampers. When atomized pollutants were not generated, the airborne particle concentration was measured as less than 1000 counts/m^3. Germs were detected at less than 10 CFU (Colony-forming unit)/m^3, and mold was not detected.

The coordinate axis is decided for the explanation as follows. The x, y, and z axes are perpendicular to each other, with the origin located at the lower left of corner the doorway. The x axis is parallel to the door frame. The doorway from the low-cleanliness room to the high-cleanliness room is the positive direction of the y axis. The z axis is vertical to the floor.

Table 1 Experiment environment conditions

	High-cleanliness room	Low-cleanliness room
Room size	6 × 3 × 3.7 [m]	8 × 6 × 3.7 [m]
Door size	0.86 × 2.05 [m] (door is open)	
Air conditioning system	Supply ：Constant air volume units, HEPA Filters Return ：Motor dampers	
Air volume (Air changes per hour)	1 300 m^3/h (20 ACH)	3 600 m^3/h (20 ACH)
Room pressure to room surroundings	13 ± 2 Pa (Around the room 0 Pa)	
Airborne particle concentration < 0.5 μm	< 1 000 counts/m^3	< 1 000 counts /m^3
Airborne microbe	Mold： not detected Germ：< 10 CFU/m^3	Mold： not detected Germ：< CFU/m^3

Table 2 Measurement apparatus

Measurement item	Apparatus	Specification
Velocity sensor	Anemometer Model : WA-390 Kijo Sonic Co., Ltd TR-90 T Probe	Range : 10 m/s Accuracy : 0.005 m/s
Airborne microbes	(Shown in Table 3)	(Shown in Table 3)
Airborne particles	Airborne Particle Counter KR-11A Rion co., ltd	90° sideway light-scattering method 2,83 L/min

First, to confirm whether the experimental environment was appropriate, we verified the airflow profile at the doorway with a 3-dimensional velocity measurement apparatus, the specifications of which are shown in Table 2. Measurements were taken for 10 min at intervals of 0.1 s, and 9 measurement points were selected, as shown in Fig. 2.

Even if the desired directional airflow is only slightly formed in the doorway, some amounts of pollutants may invade the high-cleanliness room. Even even a small quantity of contaminants poses a problem. To evaluate the effect of airflow more clearly, we generated pseudopollutants at the doorway and set their initial speed at 0.5 m/s in the direction counter to the doorway airflow. This speed (0.5 m/s) represents the speed of the air movement caused by swinging the door or by the motion of people.

Figures 3a and b shows situations where the airflow speeds at the doorway were 0.0 m/s and 0.05 m/s, respectively. Figure 3a shows that pseudopollutants invaded the high-cleanliness room freely. In Fig. 3b, the pseudopollutants were turned back to the low-cleanliness room under the influence of the doorway airflow.

The pseudopollutants were located, as shown in Fig. 4, at the center of the doorway and the 1000-mm in height. The airborne microbe flocks that invaded the high-cleanliness room were counted.

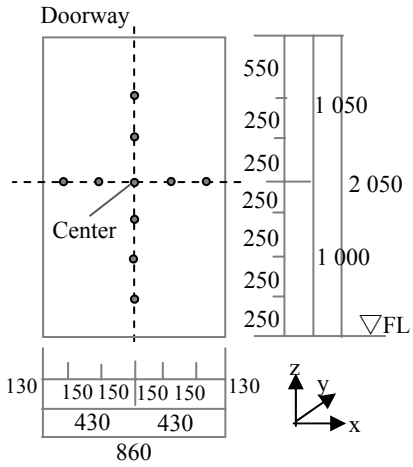

Figure 2 Distribution of velocity measurement points

The measurement point was 500 mm away from the atomization point, and both heights were the same. Airborne microbes were caught in an air sampler medium, cultivated, and counted. The airborne microbe measurement conditions are listed in Table 3. It was presumed that any mold was removed by the HEPA filter (high-efficiency particulate air filter) under background conditions. Since mold would not form usually in the indoor environment of an actual clean room, only germs were used as the objects for this verification. *Bacillus spizizenii* was used as the pseudopollutant; it has comparatively low toxicity and environmental impact.

The airborne particle concentration was measured by a particle counter, the specifications for which are shown in Table 2. The particle size ranges were 0.3 - 0.5, 0.5 - 1.0, 1.0 - 5.0, 5.0 - 10.0, 10.0 - 25.0, and >25.0 μm. The sampling point was located at the same point where the airborne microbes were measured.

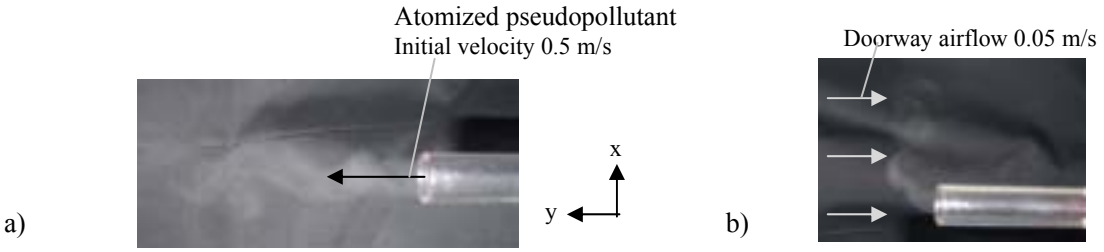

Figure 3 The flow of atomized pseudopollutant (a) via 0.0 m/s of doorway airflow and (b) via 0.05 m/s of doorway airflow

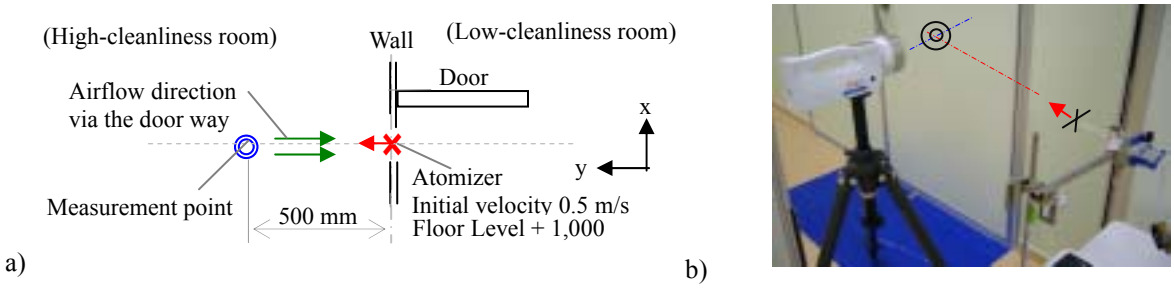

Figure 4 (a) Geometry of atomizer and air sampler and (b) the apparatus

Table 3 Airborne Microbe Measurement Conditions.

Atomizing condition	
Pseudo-pollutant	MicroBioLogics Inc. Bacillus spizizenii Epower ATCC 6633 1.0E+5—6 CFU
Atomizer	Kinoshita Type Atomizer J-753 15mmφ
Compressor	Kinoshita Chemistry Industry Co. Hypower-mini-pomp KP-20-A, Max 13 l/min, 20 kPa
Sampling condition	
Air sampler	Biotest ltd. RSC HIGH FLOW, 100 L/min
Medium	Germ: TC SCD-LP, Mold: YM Rose Bengal
Cultivation condition	
Incubator	Advantec Tokyo Kaisha Ltd. F1-45T 0.5kW Germ：37℃ 24—48 hours, Mold:27 ℃ a week

3. Result

3.1 Airflow Profile at Doorway

The measurement data of the negative y-direction components of the velocity at one of the measurement points are shown in Fig. 5a. The frequency distribution of Fig. 5a is shown in Fig. 5b. The solid line in Fig. 5b is a frequency function of a normal distribution, and it is mostly in agreement with the measured values. Consequently, it can be presumed that the wind velocity measurement data had approximately a normal distribution, and it can be presumed from the characteristics of a normal distribution that approximately 95% of the data exists within twice the standard deviation range from the average value.

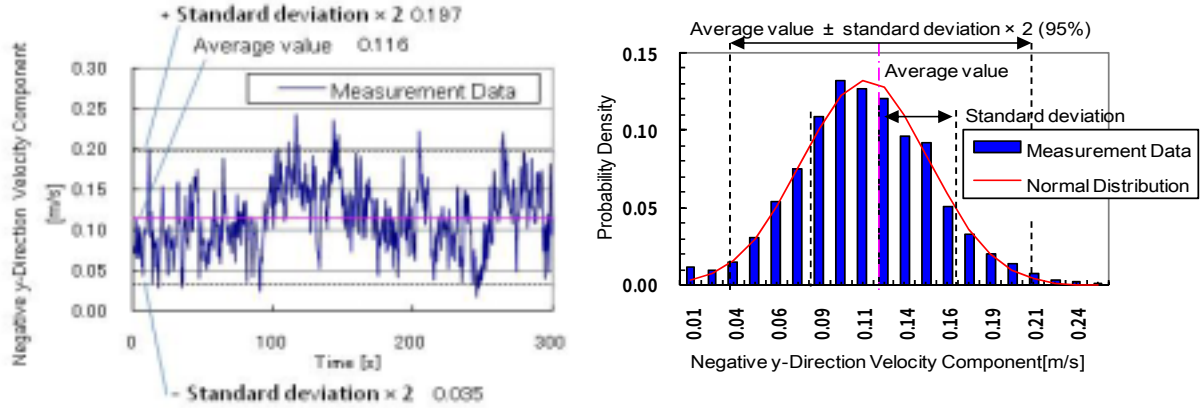

Figure 5 (a) The measurement data for a negative y-direction velocity component and (b) the frequency distribution of the measurement data

The vector of the average airflow velocity in the door opening is shown in Fig. 6. The starting point of the vector shows the measurement point. The dotted line shows the points whose distance from the average value is twice the standard deviation. In the following experiments, the values of the negative y-directional components of the velocities measured at the center of the doorway were used.

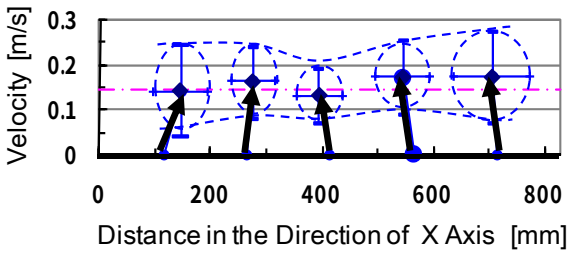

Figure 6 Airflow velocity distribution of xy section

3.2 Airborne Microbes

The measurement results of airborne microbes with doorway airflow speed variation are shown in Fig. 7a. The number of germs was determined to be less than 10 CFU/m3 under background conditions. The germs invaded from the adjacent room decreased with increasing the doorway airflow velocity.

An index approximation was performed for the measurement data that exceeded the background value. The

coefficient of determination was approximately 0.97. Here, the ratio divided by the measured value under 0.0 m/s doorway airflow is defined as the "transported contamination ratio (TCR)." The TCR values for airborne microbes with various doorway airflow speeds are shown in Table 4. This means that the probability that airborne microbes will move into a higher clean class room can be reduced by controlling the doorway airflow. For example, it was necessary to maintain a doorway airflow speed of 0.10 m/s to maintain a TCR of 1%. However, this result was a numerical value for *Bacillus spizizenii.* Further examinations would be required for an actual application, taking into consideration the characteristics of the target bacillus.

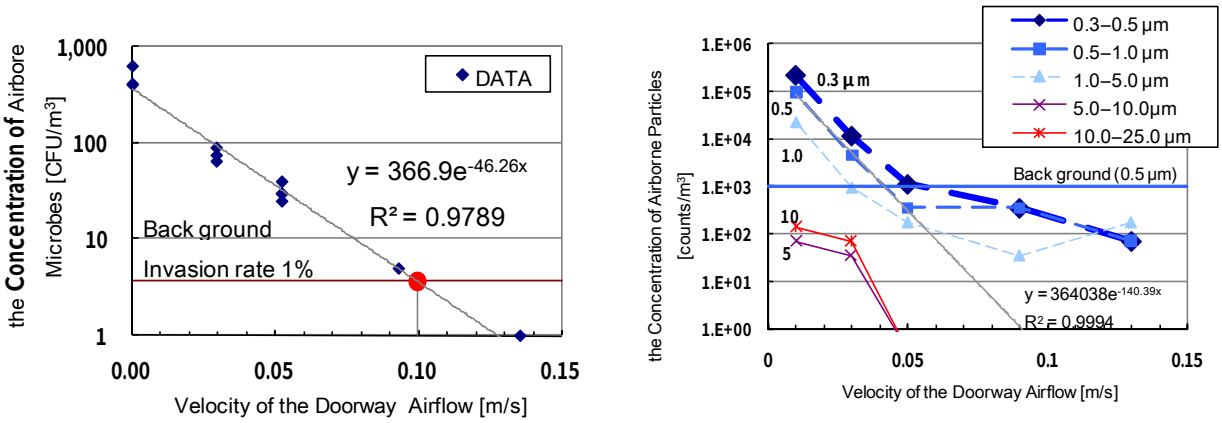

Figure 7 (a) Airborne microbe variation by doorway airflow velocity and (b) airborne particle concentration variation by doorway airflow veloc

Table 4 TCR of Airborne Microbes.

Airborne Microbe Invasion Rate (TCR)	Velocity of the Doorway Airflow [m/s]
0.001 %	0.25
0.01 %	0.15
1 %	0.10
10 %	0.05
100 %	0.0

Table 5 TCR of Airborne Particle Concentration.

Airborne Particle Concentration Invasion Rate (TCR)	Velocity of the Doorway Airflow [m/s]
0.001 %	0.075
0.01 %	0.058
1 %	0.042
10 %	0.026
100 %	0.0

3.3 Airborne Particle Concentration

The measurement results with various doorway airflow speeds are shown as Fig. 7b. The declinations of the 0.3–0.5, 0.5–1.0, and 1.0–5.0 µm particle concentrations are almost the same. The 5.0–10.0 and 10.0–25.0 µm particle concentrations almost leveled off within 0.0–0.03 m/s and decreased greatly after that. In the case of more than 0.05 m/s, they were not detected. It is considered that the 5.0–10.0 and 10.0–25.0 µm particle concentrations were more strongly influenced by the force of inertia than by the flattery nature to a circumference airflow, and that if the counter airflow blew at a speed of 0.05 m/s or more, the initial speed would not be able to be maintained and the particles would fall. The concentration of particles larger than 25.0 µm was not determined.

For example, in the case of the concentration of 0.5 - 1.0 µm particles, the index approximation was performed using the measurement data of Fig. 7b, which exceed the background value, 1000 counts/m^3. The TCR was also defined, and is shown in Table 5. In this case, the doorway airflow speed had to be 0.042 m/s to maintain a TCR of less than 1%.

4. Discussion

It is concluded from this experiment that the number of airborne microbes and the airborne particle concentration in air that invade from an adjacent room are related to the doorway airflow speed, and that it would be possible to reduce the risk of cross-contamination by controlling the doorway airflow.

With respect to airborne particles larger than 5.0 μm, the doorway airflow speed must at least be greater than 0.05 m/s. The result described in this paper could not be applied to every kind of germ. It should be noted that these results were found when targeting *Bacillus spizizenii*.
Under our experimental conditions, the doorway airflow profile was orderly. Under conditions where the airflow profile is not orderly because of inlet airflow influence or other reasons, the design must limit the reverse airflow and the doorway airflow must be evaluated at the point of the weakest speed.
In an actual case, various contamination risks must be considered, including the influence of door swing, the airflow that follows people, and so on.

5. Conclusions

The aim of a room pressurization design is to prevent the contamination or establish a complete isolation of a control object. A directional airflow regulated by room pressurization is generated at the separation between two rooms. The speed of directional airflow required to prevent contamination is yet to be determined. Certainly, this will be determined on the basis of room usage and room grade level. Fundamental data is required to make such a determination. For small separation, it is sufficient to just ensure the direction of the airflow. For large separation, such as door openings, an airflow with a suitable velocity is effective.
Doorway airflow was evaluated by measuring the concentration of the airborne particles and the number of airborne microbes that invaded through the doorway in the case of an open door in our experimental room. The following conclusions was summarized：
1. The number of airborne microbes and the concentration of the airborne particles that invade from an adjacent room are related to the doorway airflow speed, and it would be possible to reduce the risk of cross-contamination by controlling the doorway airflow.
2. The doorway airflow speed must be greater than 0.05 m/s.

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