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Determination of Particle Concentration in the Breathing Zone for Four Different Types of Office Ventilation Systems

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ABSTRACT

Many factors affect the airflow patterns, thermal comfort, contaminant removal efficiency and indoor air quality at individual workstations in office buildings. In this study, four ventilation systems were used in a test chamber designed to represent an area of a typical office building floor and reproduce the real characteristics of a modern office space. Measurements of particle concentration and thermal parameters (temperature and velocity) were carried out for each of the following types of ventilation systems: a) conventional air distribution system with ceiling supply and return; b) conventional air distribution system with ceiling supply and return near the floor; c) underfloor air distribution system; and d) split system. The measurements aimed to analyse the particle removal efficiency in the breathing zone and the impact of particle concentration on an individual at the workstation. The efficiency of the ventilation system was analysed by measuring particle size and concentration, ventilation effectiveness and the Indoor/Outdoor ratio. Each ventilation system showed different airflow patterns and the efficiency of each ventilation system in the removal of the particles in the breathing zone showed no correlation with particle size and the various methods of analyses used.

Keywords: Contaminant removal, indoor air, particle, air distribution, ventilation system.

1. INTRODUCTION

High concentrations of indoor contaminants are known to cause a range of problems, from physical discomfort to serious diseases, and the severity of these problems has increased over time. Contaminants in office environments can have many different origins. Outdoor contaminants from vehicles and factories (e. g., CO, CO2, SO2) enter the building through the ventilation system, doorways or windows. Indoor air contaminants arise from office furniture, which may contain chemicals, especially volatile organic compounds (VOCs). Printers and photocopiers can release ozone and VOCs. Dust and moisture accumulated in ventilation systems can provide a habitat for microbial contaminants [1, 2, 3]. These issues have motivated researchers to gain a greater understanding of ventilation, air distribution and pollutant transport in office buildings.

Commercial buildings typically have heating, ventilating and air conditioning (HVAC) systems for space heating and/or cooling. There are several types of HVAC systems used in commercial buildings. The type of system employed will have a significant influence on air flow patterns within the building and can have a significant impact on the indoor air quality. The air distribution systems most commonly used in commercial buildings are a) conventional air distribution system with ceiling supply and return; b) conventional air distribution system with ceiling supply and return near the floor; c) underfloor air distribution system; d) displacement system; and e) split system.

Indoor air quality (IAQ) and thermal conditions can be greatly affected by the type of air distribution system adopted. Airflow patterns and the extent to which supply air mixes with room air are further affected by operating conditions, how the system is used and the location and type of supply outlets and return inlets. Each of these factors can interfere with temperature distributions, contaminant removal and the age of air in the occupied zone, therefore affecting occupant responses to the office environment [4, 5, 6, 7, 8, 9].

Most of the studies that analyse the performance of air distribution systems are related to the thermal conditions produced by those systems and current literature provides very limited information on the influence of air distribution systems on airflow patterns and their impact on pollutant concentration and removal. As such, very little is known about the efficiency of the different air distribution systems used in modern open-plan offices, in terms of the reduction of particle concentration at the breathing zone. I addition, the IAQ in the breathing zone can vary for each system type. For example, a high particle concentration may exist inside, even if the air distribution system displays good ventilation efficiency.

The indoor ventilated environment is a dynamic system which is constantly affected by indoor and outdoor physical phenomena, with particle size being the most important parameter affecting particle fate during transport [10]. Due to the different sizes of indoor and outdoor particles, their dynamics will differ significantly and the influence of the ventilation system will be different for the different particle sizes. Zhao et al. [11] comments that particles with different sizes display different movement patterns in ventilated rooms, and while important studies have been published on the topic, they only analyse the performance of different ventilation systems for one specific particle size (e.g. [12] and [13]). Similarly, recent studies have analysed the performance of those systems for indoor gas contaminants (e.g., [14]–[16]), however particulate matter often behaves quite differently from gas phase pollutants [12]. Other studies have published results based solely on evaporative substances (e.g., [12] and [17]), however, evaporation will cause the particles diameter to change and consequently, the particles will display different movement patterns within the ventilated rooms.

Outdoor sources also play a role in determining indoor particle concentration and distribution, such that in the absence of strong indoor sources, the particles found in the indoor air are mainly of outdoor origin [18]. However in many previous studies, the effect of outdoor air has not been considered (e.g. [11] – [17]). Additionally, the influence of outdoor sources can make it difficult to directly quantify the extent to which indoor sources contribute to indoor particle concentration.

It is also important to highlight that, although split system ventilation is often utilised in offices, there are no published studies that examine the impact of the split system on indoor particle concentration and distribution, compared with different kinds of ventilation systems used in offices.

Thus, this paper aims to analyse the influence of different ventilation systems used in offices, on both the concentration and size of particles at the breathing zone. Outdoor air was the main particle source in the office analysed and particle concentration for a number of size ranges were analysed (0.3-0.5, 0.5-1.0, 1.0-3.0, 3.0-5.0, 5.0-10.0, >10 μm). The measurements were carried out under controlled conditions, in a 34.8 m^2 test chamber, which was representative of a real world office environment [19]. The measurements were also carried out using different types of air conditioning systems, including: a) conventional air distribution system with ceiling supply and return; b) conventional air distribution system with ceiling supply and return near the floor; c) underfloor air distribution system; and d) split system.

2. VENTILATION EFFECTIVENESS

IAQ is one of the most important indicators of air distribution system performance, particularly in terms of the concentration and distribution of airborne the contaminants. The effectiveness of the ventilation system is characterised by the efficiency of the air distribution system in removing internally generated pollutants from the ventilated space. Many definitions and indices have been used to describe the effectiveness of a ventilation system, most of which are a variation of two basic concepts: air change effectiveness and ventilation effectiveness. The concept of the air change effectiveness provides a measure of the degree to which the mixing of air takes place under a given set of conditions, whilst ventilation effectiveness (ε_c) quantifies the effectiveness with which the internal contaminant is diluted and removed [20]. The ventilation effectiveness can be obtained by calculating the relationship between the concentration of contaminants at the exhaust (C_e) and the concentration of contaminants in the breathing zone (C_i), according to the equation below:

$$\varepsilon_c = \frac{C_e}{C_i} \qquad (1)$$

Under ideal mixing conditions, where air quality will be the same at each location in the room, the ventilation effectiveness would be 1. Values above 1.0 indicate that the pollutant concentration of the return air is greater than the pollutant concentration of air in the breathing zone, indicating that the air quality in the breathing zone is better than in the return air. Values below 1.0 indicate that the pollutant concentration of the return air is less than the pollutant concentration of air in breathing zone, indicating that not all contaminated room air is exchanged by fresh supply air, thus the air quality in the breathing zone is worse than in the return air.

3. EXPERIMENTAL METHOD

In order to analyse the removal efficiency of each ventilation system and the impact on particle concentration in the breathing zone of an individual, measurements of particle concentration and thermal parameters (temperature and velocity) were performed in the test chamber under steady-state conditions, with the chamber empty, the door closed, and outdoor particles as the main source of particles inside the chamber. However, people walking on the carpeted floor of the chamber between measurements could have represented a potential source of contamination due to particle resuspention within the chamber. As such, once the equipment was set up, the air in the chamber was left to settle for 10 minutes before each set of measurements were conducted and as such, outdoor particles were the main source of particles inside the chamber.

The measurements were performed at several points inside the test chamber: at the breathing height of a person sitting within the workstation, at the air supply, at the air return and at the inlet of external air. At each point, temperature and air velocity were measured at the following heights: 0.1m; 0.6m; 1.1m and 1.8m [21]. For temperature and wind speed measurements, an analyser was placed at the workstation, in order to record the data while particle measurements were in progress. The measurement of outdoor particle concentration was carried out at an external point close to the outdoor air inlet. Particle concentration was measured only between 2:00 pm and 4:00 pm, for four consecutive days, starting on January 10-2006. In order to compare the performance of the systems for each particle diameter range, the concentrations were normalised, rather than using their absolute values. To obtain the normalised concentrations (Ci/Cm) for each system, the absolute values of particle concentration (Ci) were divided by the average of the concentration (Cm).

Figs. 1, 2 and 3 shown the modular office configuration installed in the isolated test chamber. This area represents a fraction of a typical office building floor and reproduces the real characteristics of a modern office space, including the type and layout of equipment and partitions, as well as the location of people. The test chamber floor was a raised floor made of metal plates, covered with carpeting. Together with the slab, these plates make up the inferior plenum for the conditioned air distributed in the environment. On one of the walls there was a light panel to simulate solar radiation on a glass surface, which can have a thermal load equivalent to the worst solar radiation condition (160 x 40W incandescent light bulbs with adjustable power). Heat loads were also provided to simulate typical office load distributions and densities, with overhead lighting fixtures, personal computers and printers placed on three desktops. The average heat density in the chamber was 121 W/m2, which is comparable to the heat density in typical office environment. Table 1 presents a breakdown of the values of the internal heat sources.

Table 1. Internal heat sources

Computer (4)	390.4 W
Human simulators (4)	399.6 W
Lamps (16)	696 W
External Heat transfer (80 lamps)	2723.1 W.
Total	**4,209.1 W**
Heat Density	121 W/m^2

The laboratory contains an automated direct expansion air conditioning system that supplies the environment with chilled air. The air distribution system permits ducted or plenum air to be supplied to and returned from the test chamber at any combination of ceiling and floor locations. It consists of the following basic components: a) a test chamber, with underfloor or ceiling air distribution; b) an air conditioning unit; c) an automation and control system; and d) a data acquisition system in the environment. The air conditioning system has a 5 TR chiller that supplies a fan coil with a nominal 5 TR refrigeration load and a 3,420 m^3/h airflow rate capacity. In the hydraulic plant, between the chiller and the fan-coil, a three-way valve (chilled water bypass) was installed so that, by altering water flow, it can ensure an air discharge at constant temperature, satisfying the need for a steady-state condition. The outdoor air entered the plant room, where it was mixed with the return air from indoors, to form mixed air. The mixed air was then fan forced through a fan-coil unit, consisting of filters (MERV 11) and cooling coils, to become supply air, which was then delivered into the room through an air ducting system. The total air exchange rate was 1800 m^3/h (26 ACH), with fresh air accounting for 144 m^3/h (36 m^3/h/person x 4 people) (ASHRAE 62.1, 2004).

The relative significance of deposition was not investigated because the effect of processes associated with particles dynamics, such coagulation, condensation and deposition, are considered to be less significant than particle losses due to filtration and ventilation (Zhao et al., 2004; Jamriska et al., 2000, Jamriska and Morawska, 1999; Nazarof et al., 1993).

4. INSTRUMENTATION

4.1. Airborne particle concentrations

Airborne particle concentration was measured with three light scattering automatic particle counters, calibrated by the manufacturer (MET ONE), which yielded counts of particles in six size ranges: 0.3 µm to 0.5 µm, 0.5 µm to 1.0 µm, 1.0 µm to 3.0 µm, 3.0 µm to 5.0 µm, 5.0 µm to 10.0 µm, and >10 µm, with a flow of 0.1 cfm (2.83 L/min).

4.2 Thermal parameters

The measurement of temperature was performed using a thermoresistance transducer PT100, which measures temperatures from 0 to 50^{o}C with an uncertainty of 0.2^{o}C. For the measurement of wind speed a thermo-anemometer was used, with a measurement range of 0.03 to 3 m/s and uncertainty of 0.04 m/s + 3%.

5. RESULTS

This work analysed the influence of four different types of air conditioning systems used in offices, on the concentration and size of particles at the breathing zone. Measurements were carried out for particle concentration and size, and vertical profiles were obtained for air velocity and temperature. Although the work did not aim to compare the ventilation systems in terms of thermal comfort, air temperature and velocity, these were also analysed because the air distribution system affects airflow patterns and the extent of air mixing, which in turn affect the IAQ and thermal conditions in the space. Thus, a deeper knowledge of the distribution fields of air temperature and velocity can increase our comprehension of the factors concerning indoor air quality.

5.1. Thermal parameters

5.1.1. Air temperature distribution

The vertical temperature gradient in the occupied zone is one of the most important parameters to evaluate in terms of comfort. Fig. 4 presents the vertical temperature gradient at and slightly above the occupation zone for a sitting person. For all ventilation systems, there was an increase of temperature along the vertical axis between the 0.1 and 1.1m, as expected, with the overall vertical difference in temperature being less than 1°C. For all systems, a small temperature gradient in the breathing zone is acceptable for thermal comfort. Overall, the split system showed the largest temperature variation above the breathing zone and according to ANSI/ASHRAE Standard 55-2004, the upper limit for the vertical temperature gradient is 3 °C/m.

5.1.2. Air Velocity Distribution

Velocity is another important thermal comfort parameter. Fig. 5 presents the vertical velocity gradient for each system and it can be seen that all of the ventilation systems did not show any great variations, with air velocity values very close to 0.1m/s. This velocity is far below velocity values that can cause discomfort. However, the split system did show velocity peaks of about 0.3 m/s above the breathing zone.

5.2. Indoor air quality parameters

Particle concentration in the breathing zone is an important parameter for the evaluation of indoor air quality. Fig. 6 compares the ventilation effectiveness of all systems, as a function of particle size. The underfloor air distribution system displayed the best ventilation effectiveness for all particle size ranges and was most efficient at removing particles in the size ranges of 3-5 μm and 5-10 μm, with a ventilation effectiveness value of 1.6. This system was less effective for removal of the small particle (0.3-0.5 μm), with a ventilation effectiveness value of 1. The split system displayed the second best ventilation effectiveness value for particles in the size range 0.3-3.0 μm and was least effective for particles > 10 μm in diameter. For this system, the ventilation effectiveness decreased with particle size. The ceiling supply and return near the floor system showed very little variation in ventilation effectiveness for the different particle size ranges, with a common value of 0.4. This system had the worst ventilation effectiveness for particles in the size range 0.3-5.0 μm. The ceiling supply and return system displayed the second best ventilation effectiveness value for particles > 3.0 μm.

Fig. 7 compares particle concentration for all of the ventilation systems, as a function of size. The split system produced the largest particle concentration in the breathing zone for all particle diameters. For smaller particles (0.3-0.5 μm and 0.5-1 μm), the underfloor air distribution system had the smallest particle concentration in the breathing zone, and for larger particles (> 1 μm) it had the second largest particle concentration. The ceiling supply and return near of the floor system had the second largest concentration of small particles in the breathing zone and overall, had the smallest concentration of particles > 1 μm. Although the ceiling supply and return system showed little variation of particle concentration in the breathing zone, the particle concentration did fall slightly with an increase in particle diameter.

From Figs. 6 and 7 it can be seen that although the split system had the largest particle concentration in the breathing zone for all particle diameters, its pollutant removal effectiveness was still quite good, particularly for smaller particles. In the split system, air leaves the evaporator and is delivered directly into the room, returning directly to the evaporator to be distributed again, without fresh air regeneration or filtration. As a result, this type of equipment tends to maintain higher particle concentrations in the air.

The underfloor air distribution system had the greatest ventilation effectiveness out of all of the ventilation systems, yet it had the second largest particle concentration in the breathing zone for particles > 1 μm. This system distributes air directly into the occupied zone at numerous locations that are substantially closer to the occupants. As a result, improvements in the ventilation efficiency in the breathing zone are more easily achieved. However, whilst the localisation of the air inlets means that the smaller particles tend to remain below the breathing zone and are drawn directly towards the return vents, the lager particles stay suspended in the air as a result of the low air velocity. One possible explanation for this low particle concentration was that the smaller particles tended to follow the direction of the airflow directly towards the ceiling. However, in the case of the larger particles, their tendency to settle was inhibited by the directional air flow towards the ceiling and as such, they remained suspended in air for longer, thus contributing to their high concentration at the breathing zone.

Conversely, the ceiling supply and return near the floor system that had the smallest particle concentration in the breathing zone for larger particles, > 1 μm. This was caused by the localisation of the supply and return vents, whereby the airflow tended to bring the particles towards the return vent, assisted by the settling behaviour of those particles.

Figs. 8 to 11 show the results of the tests applied for each type of air ventilation system. Each Fig. shows particle concentration as a function of size for all systems. As expected, and in accordance with other studies, it is possible to observe that, for all systems, particles of different diameters present various concentrations in the atmosphere. Results show that the particle concentrations decreased with increasing size, especially for smaller sizes. The findings of this study confirm Einberg and Holmberg's findings that particles between 0.3-0.5μm in diameter show significant differences of concentration in the breathing zone [22].

Figs. 12 to 15 show the indoor and outdoor particle concentration, and Indoor/Outdoor (I/O) ratio as a function of particle size, for the various systems. Fig. 12 shows that for the underfloor air distribution system, for particles with a diameter greater than 2.4 μm, indoor particle concentration is greater than outdoor particle concentration, with the I/O ratio reaching values greater than 1. Figs. 13 and 14 show that in the case of the system with ceiling supply and return near the floor, as well as the system with ceiling supply and return, indoor particle concentration always remained lower than outdoor particle concentration, and the I/O ratio remained below 1. Fig. 15 shows that for the split system, where no fresh air was drawn in the room, indoor particle concentration for particles with a diameter between 0.3-1.0 μm was similar to outdoor particle concentration, with an I/O ratio close to 1. For particles with a diameter >1.0 μm, indoor particle concentration was greater than outdoor particle concentration, with and I/O ratio reaching values greater than 1. Indoor concentration was nearly double outdoor concentration for particles between 3.0-5.0 μm.

Fig. 16 shows a comparison of the ratio between indoor particle concentration at the breathing zone and outdoor particle concentration, for each particle size range, for all systems. For particles between 0.3-1.0 μm in diameter, the underfloor distribution system showed the lowest I/O ratio, remaining below 1. For particles above 1.0 μm in diameter, the system with ceiling supply and return near the floor had the lowest I/O ratio. For all particle diameters, the system with ceiling supply and return had an I/O ratio between that of the underfloor distribution system and the system with ceiling supply and return near the floor. The split system had the highest I/O ratio for all diameters.

6. DISCUSSION AND CONCLUSIONS

The aims of this study were to analyse the impact of ventilation systems on particle size and concentration in the breathing zone of an individual at a workstation. The efficiency of the ventilation system in the removal of the particles in the breathing zone was analysed by measuring particle size and concentration, ventilation effectiveness and the ratio of I/O air. Four ventilation systems were used in a test chamber, designed to represent the typical size and characteristics of a typical office space. For each air distribution system, particle size and concentration were measured at the breathing zone, as well as in the supply and return air.

The results showed that particle concentration in the breathing zone varied according to particle size and the type of ventilation system. For example, the split system had the largest particle concentration in the breathing zone for all particle diameters analysed, even though this ventilation system displayed good ventilation effectiveness for small particles sizes. For particles between 0.3 and 1 μm, the underfloor air distribution system produced the smallest particle concentration in the breathing zone, despite having the lowest ventilation effectiveness for particles in that size range. In the same way, the underfloor air distribution system showed good ventilation effectiveness for large particles, however particle concentration in the breathing zone increased along with the increase of the particle diameter. Particle concentration for the underfloor air distribution system showed a strong correlation with I/O ratios, however these ratios showed no correlations when compared with ventilation effectiveness.

For the system with a ceiling supply and return near the floor, it was observed that particle concentration and ventilation effectiveness both decreased with a decrease in particle diameter and this ventilation system had a small I/O ratio for all particle sizes. However, for the system with a ceiling supply and return, particle concentration was observed to increase with an increase in particle diameter, whilst the ventilation effectiveness decreased when particle diameter increased from 0.3 to 3.0 µm and then began to increase when particle diameter increased beyond 3.0 µm.

It was found that, in general, the concentration of pollutants at the breathing zone varied significantly, depending on particle size and the air distribution patterns produced by each ventilation system. Overall, the underfloor system had the highest ventilation effectiveness for all particle sizes, while the split system resulted in the largest particle concentration at the breathing zone.

Although the ventilation effectiveness varied significantly for each system, particle concentration at the breathing zone was small when compared with measurements taken from the supply air and return vent for all ventilation systems with a ventilation effectiveness < 1. When analysing the particle removal efficiency at the breathing zone, no correlation was found between ventilation effectiveness and particle size or particle concentration. However, particle concentration did show a correlation with particle size, whereby particle concentration decreased with increasing particle size for all ventilation systems. The system with ceiling supply and return, and the system with ceiling supply and return near the floor, were the most efficient at removing all particle sizes.

The underfloor air distribution system showed the greatest capacity for creating better air quality in the breathing zone for small particles, because the heat produced in the office space moves the air, including contaminants, towards the ceiling, where it is exhausted. The results of this study show that the buoyant airflow into an upper zone principally favours the evacuation of small particles. On the other hand, this system was not efficient at removing large particles. The results showed that for particles with a diameter above 2.4 μm, indoor particle concentration was greater than outdoor particle concentration, with the I/O ratio reaching values greater than 1.

Although the split system showed satisfactory ventilation effectiveness, this system still resulted in a high particle concentration at the breathing zone. This is due to the fact that the split system only recirculates the indoor air, without a fresh supply outdoor air. Consequently, particle concentration at the breathing zone was so high that it was comparable with the particle concentration at the return vent. This phenomenon creates the illusion of satisfactory ventilation effectiveness at the breathing zone, when in fact, this is not the case.

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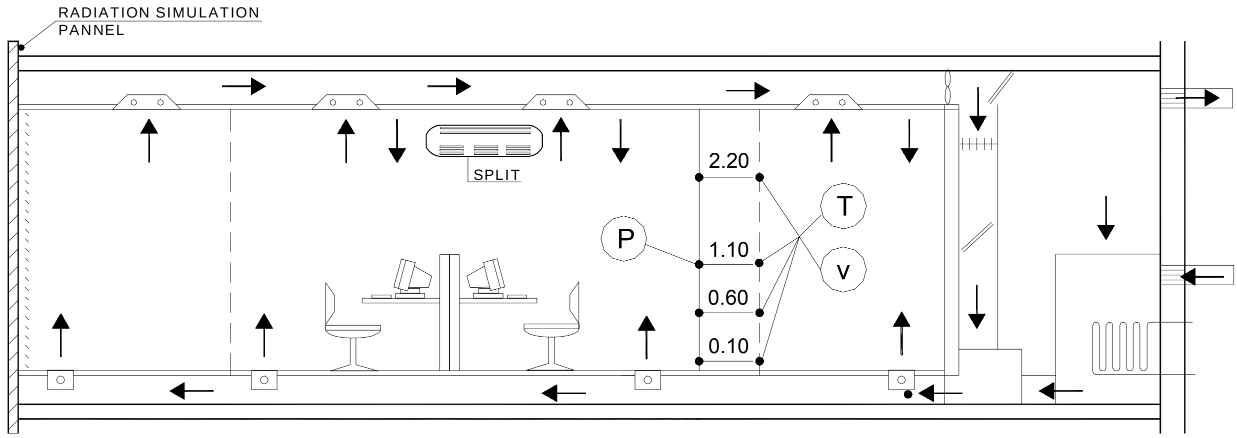
Figure Captions

Fig. 1. Side view of the test chamber, including air flow.
Fig. 2. A top-view of the test chamber (furnishings and floor diffusers).
Fig. 3. A top-view of the test chamber ceiling.
Fig. 4. Vertical temperature differentials for each system.
Fig. 5. Vertical velocity differentials for each system.
Fig. 6. Comparison of the removal effectiveness at the breathing zone for each system.
Fig. 7. Comparison of the particle concentration in the breathing zone for each system.
Fig. 8. Particle concentration as a function of particle size for underfloor system.
Fig. 9. Particle concentration as a function of particle size for the system with ceiling supply and return near the floor.
Fig. 10. Particle concentration as a function of particle size for the system with ceiling supply and return.
Fig. 11. Particle concentration as a function of particle size for the split system.
Fig. 12. Indoor and outdoor particle concentration and I/O ratio as a function of particle size for the underfloor air distribution system.
Fig. 13. Indoor and outdoor particle concentration and I/O ratio as a function of particle size for the system with ceiling supply and return near the floor.
Fig. 14. Indoor and outdoor particle concentration and I/O ratio as a function of particle size for the system with ceiling supply and return.
Fig. 15. Indoor and outdoor particle concentration and I/O ratio as a function of particle size for the split system.
Fig. 16. I/O particle concentration ratios for all systems.



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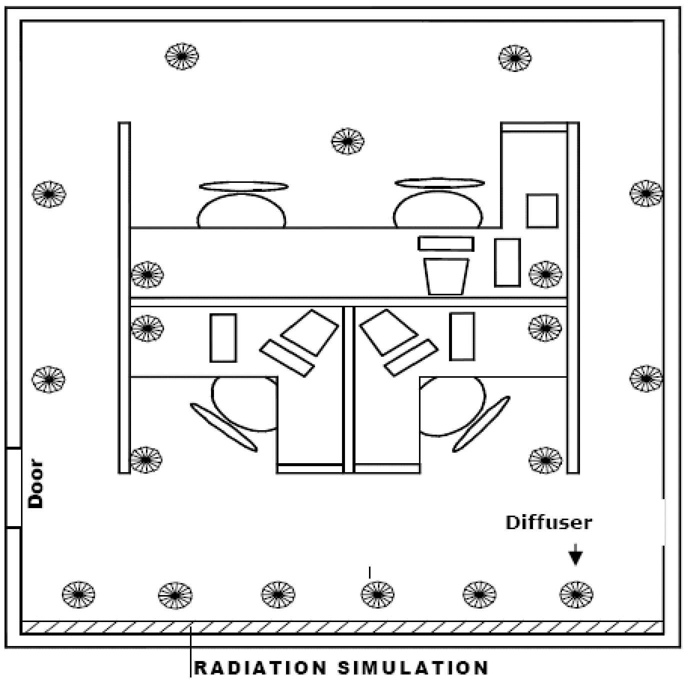

Fig. 2. A top-view of the test chamber (furnishings and floor diffusers).

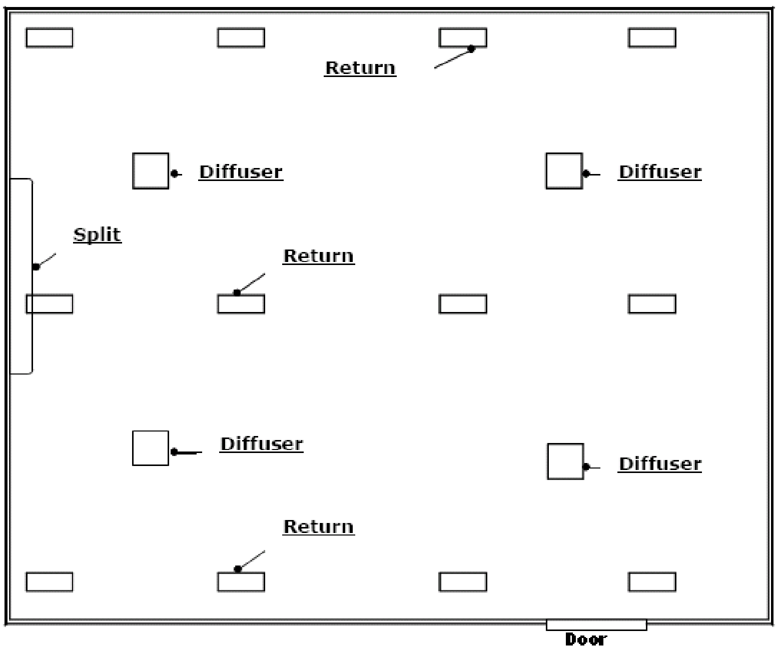

Fig. 3. A top-view of the test chamber ceiling.

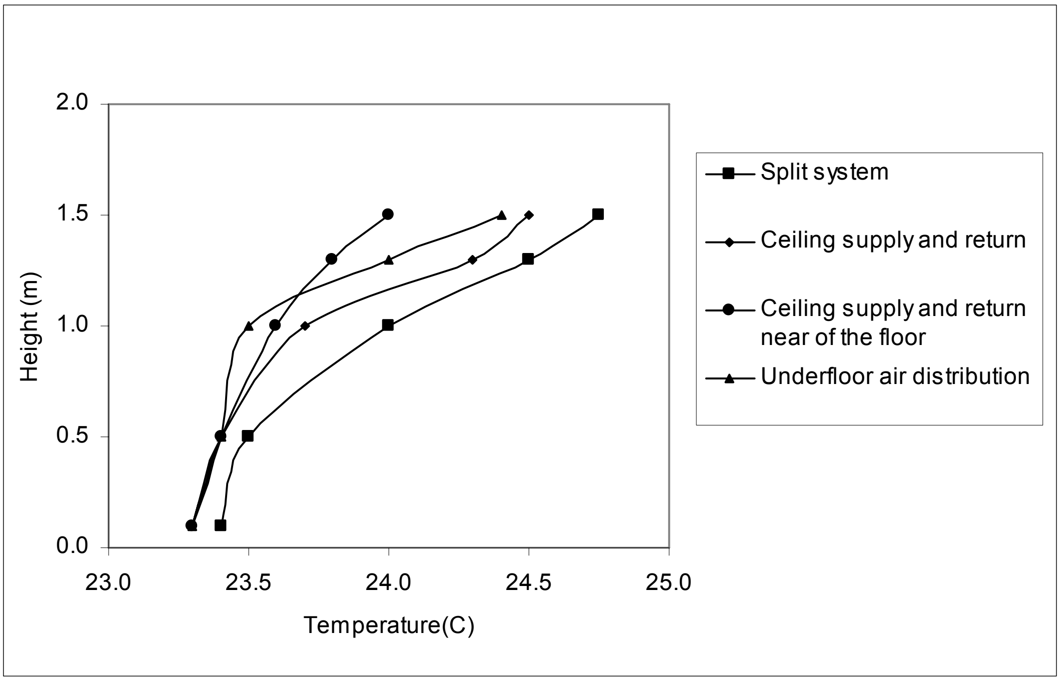

Fig. 4. Vertical temperature differentials for each system.

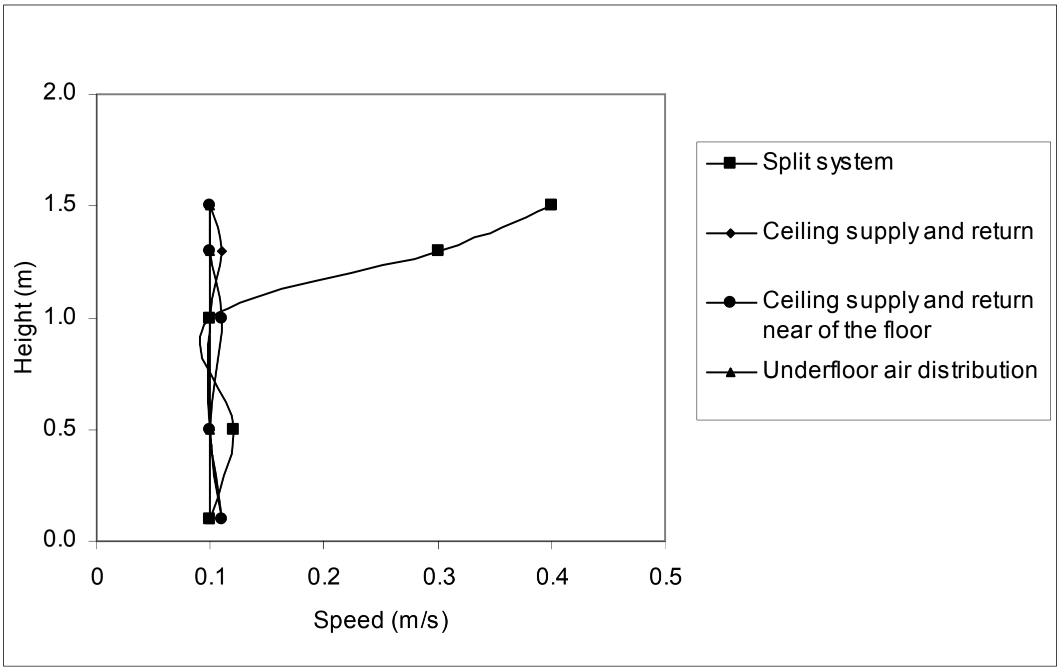

Fig. 5. Vertical velocity differentials for each system.

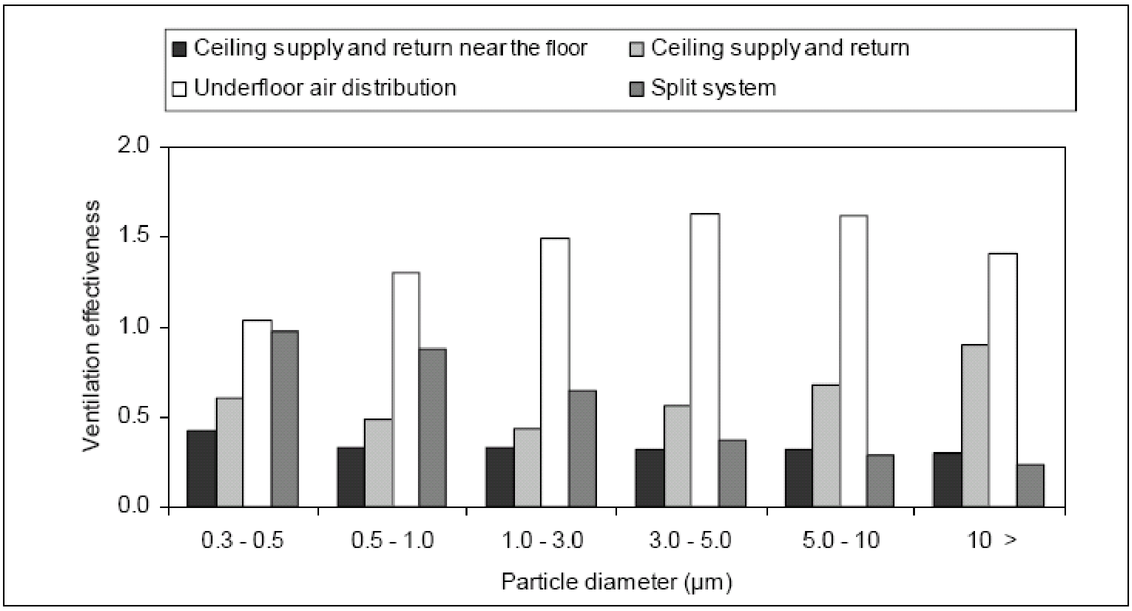

Fig. 6. Comparison of the removal effectiveness at the breathing zone for each system.

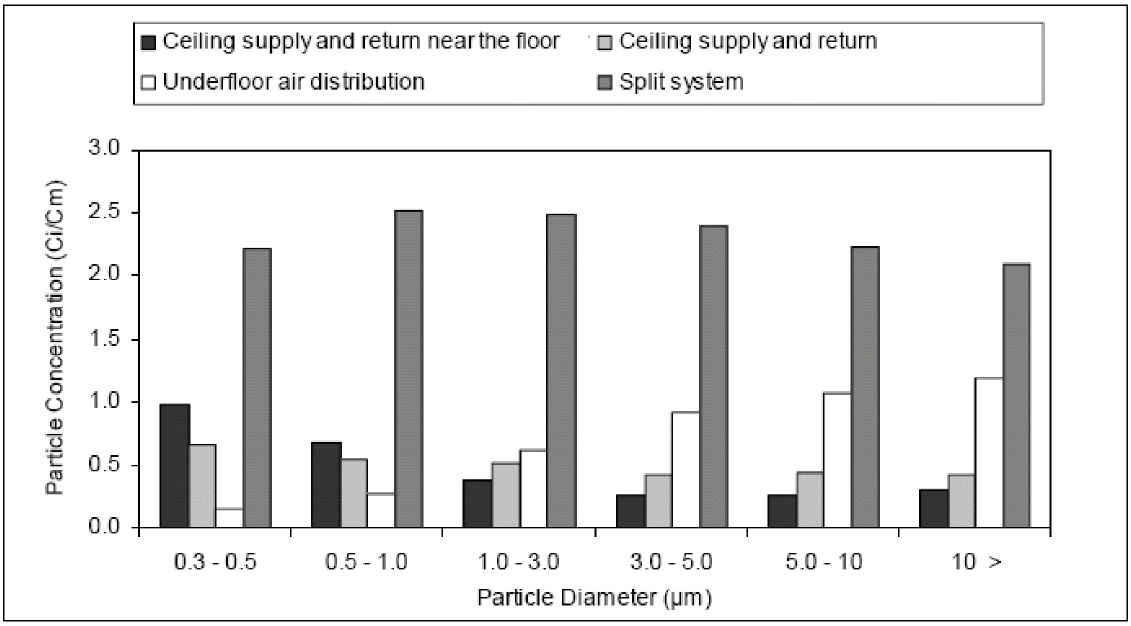

Fig. 7. Comparison of the particle concentration in the breathing zone for each system (Ci – indoor particle concentration, Cm – average particle concentration).

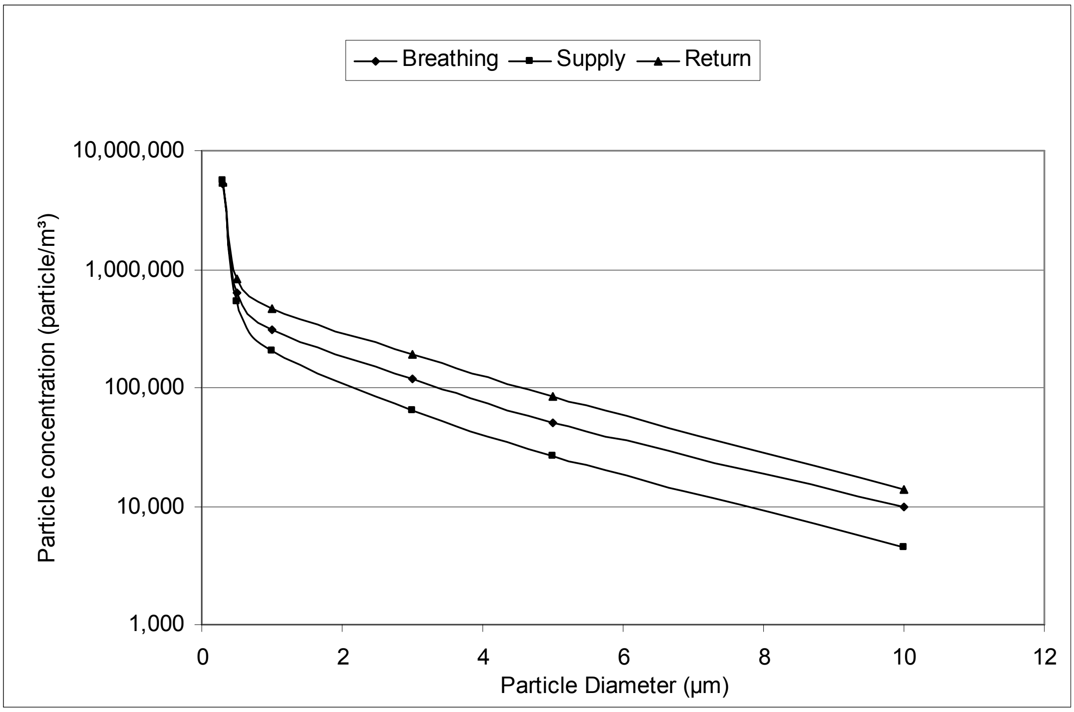

Fig. 8. Particle concentration as a function of particle size for underfloor system.

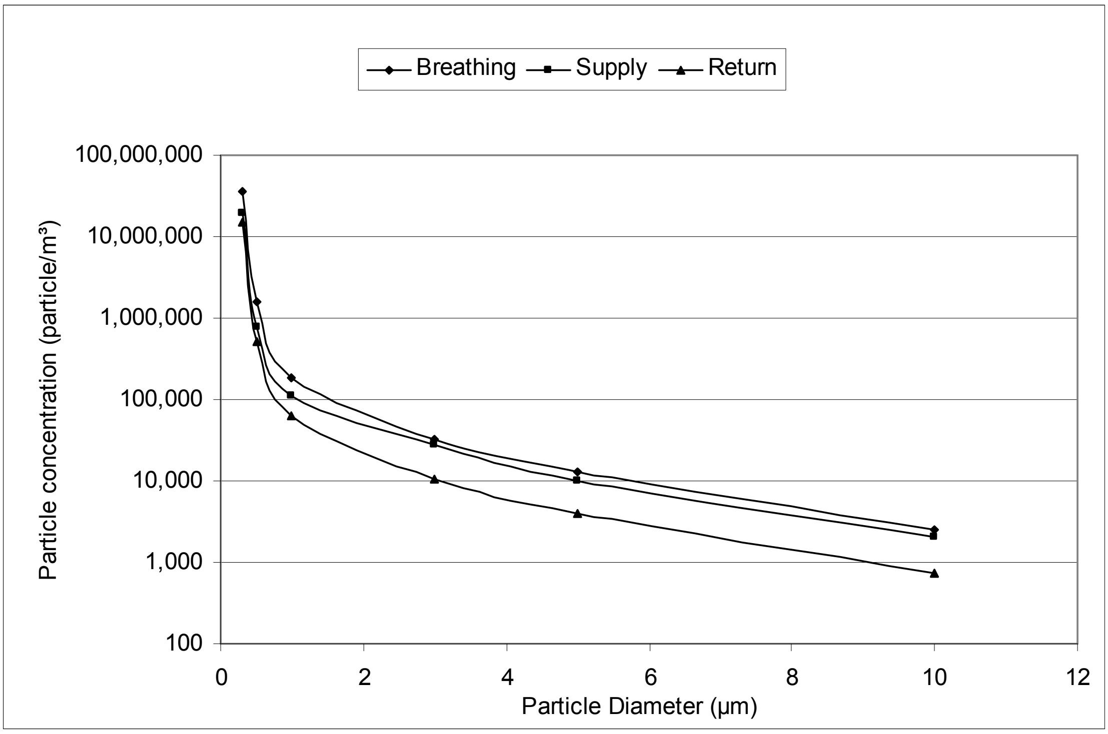

Fig. 9. Particle concentration as a function of particle size for the system with ceiling supply and return near the floor.

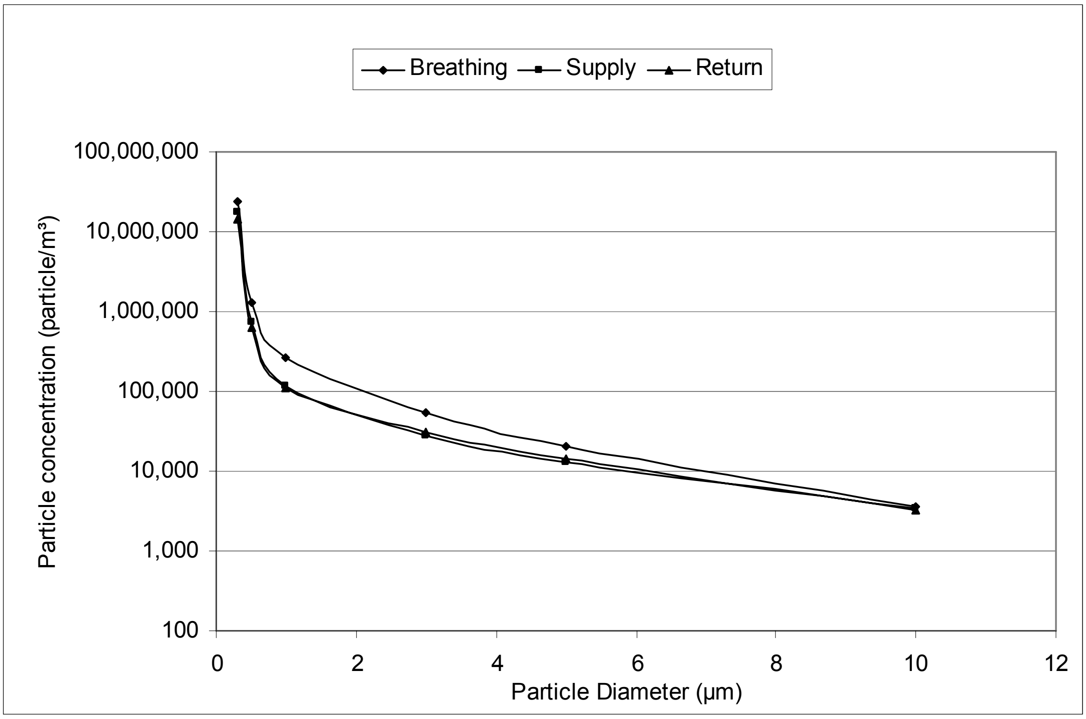

Fig. 10. Particle concentration as a function of particle size for the system with ceiling supply and return.

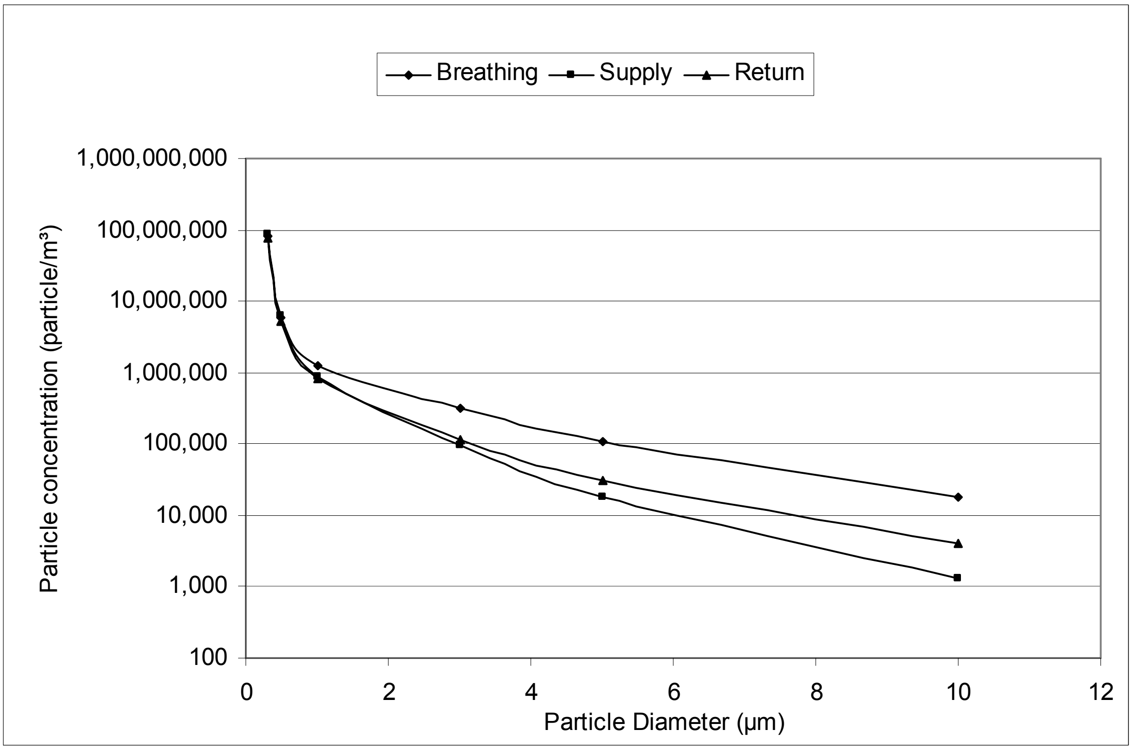

Fig. 11. Particle concentration as a function of particle size for the split system.

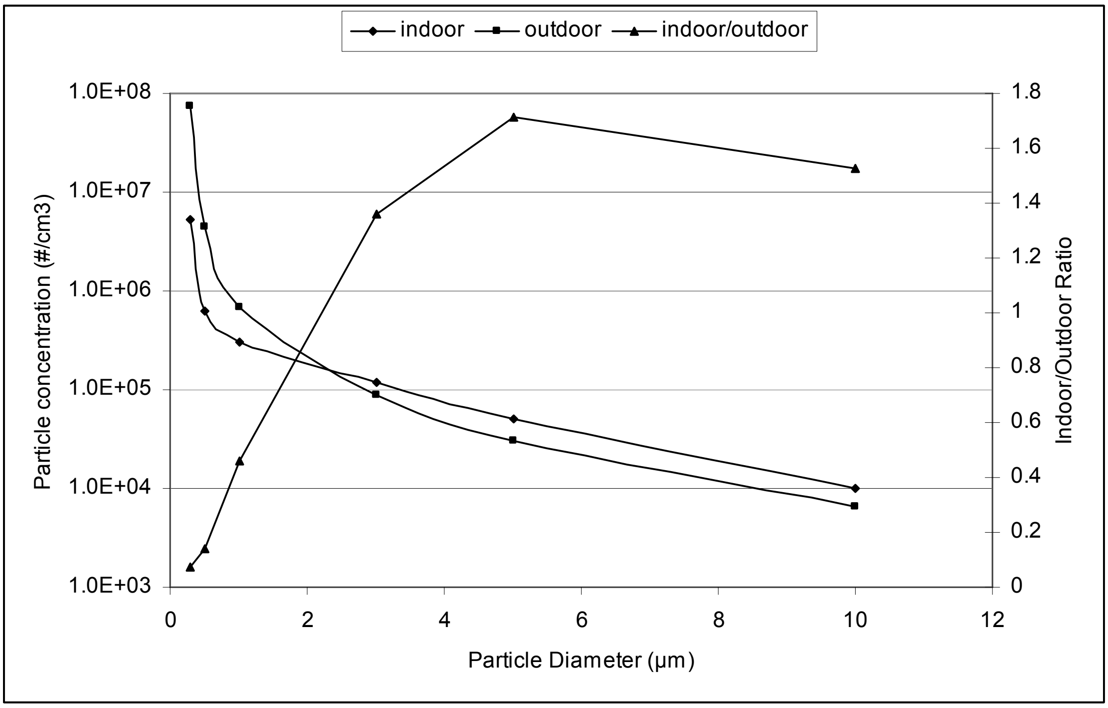

Fig. 12. Indoor and outdoor particle concentration and I/O ratio as a function of particle size for the underfloor air distribution system.

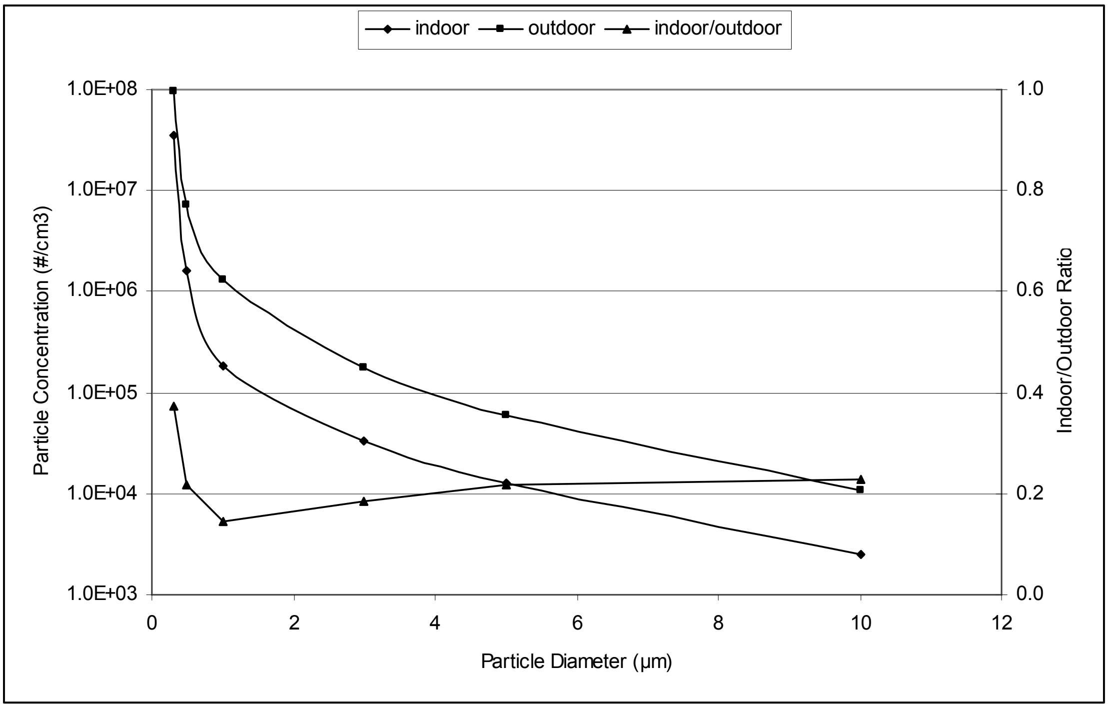

Fig. 13. Indoor and outdoor particle concentration and I/O ratio as a function of particle size for the system with ceiling supply and return near the floor.

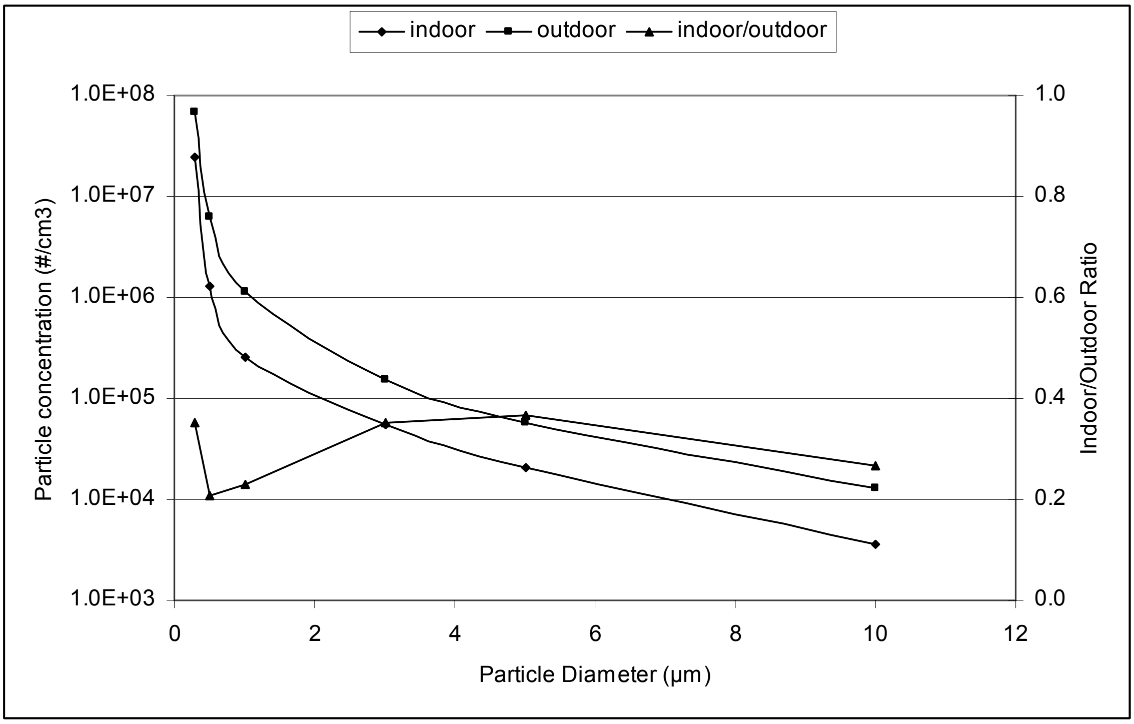

Fig. 14. Indoor and outdoor particle concentration and I/O ratio as a function of particle size for the system with ceiling supply and return.

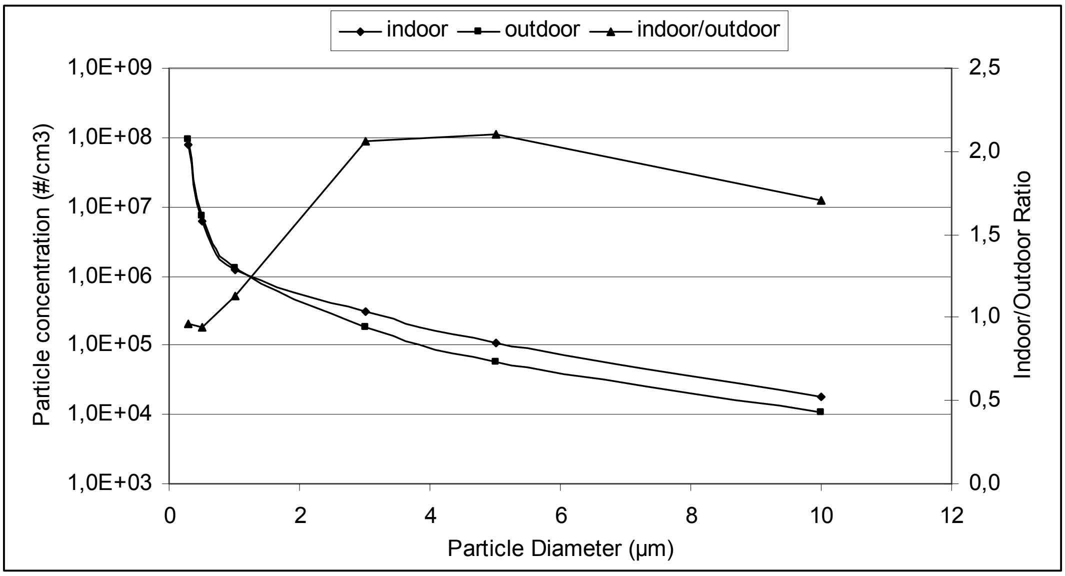

Fig. 15. Indoor and outdoor particle concentration and I/O ratio as a function of particle size for the split system.

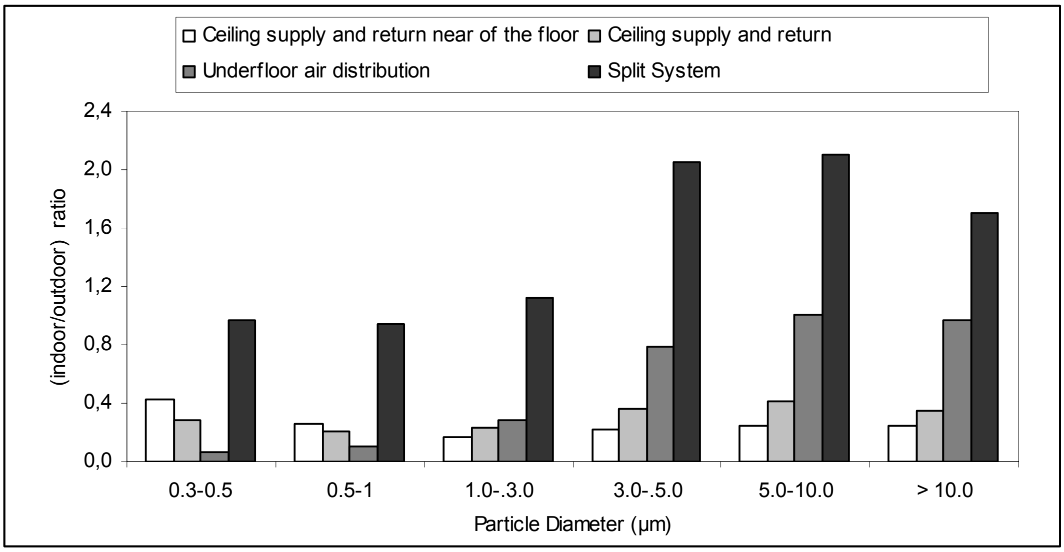

Fig. 16. I/O particle concentration ratios for all systems.