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Computational Simulation of Heat Source Influence on Particulate Behavior and Deposition in Indoor Residential Room

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Abstract - The indoor air quality has recently been a major public concern. Several health effects are linked to this problem. The sub-Sharanian climate is characterized by violent winds causing the transport and deposition of sand particles and desert dust in buildings. The results of several studies have shown that the air conditioning (air heaters) and the radiator systems is the main contributor to the problem of indoor pollution and the health of the occupants. The objective of this work is to assess the indoor air quality of a building by studying the movement of particles in a living room driven by two different heating systems.

In this work, the flow of natural fluid-particles was simulated employing the Eulerian-Lagrangian CFD-DPM framework. The effect of the particle motion and deposition rate on the indoor air quality was explored considering two different heating systems and the particle size. The research demonstrated that particle behavior is fundamentally governed by two critical factors: instantaneous fluid velocity within heating systems and specific particle size.

Keywords**:** Particle movement; Simulation; Particle concentration; Indoor air quality; Hot and dry climate

1. Introduction

Indoor air quality (IAQ) has been a global concern for the general population, governments, and scientific community during the last decade [1, 2]. Indoor pollutants are primarily categorized into two categories: Gaseous contaminants and aerosol pollutants. Exposure to high levels of airborne particles is a public health issue [3, 4]. It is particularly important to consider personal exposure to particles indoors, as people spend a lot of time inside. The risk of developing chronic obstructive pulmonary disease can be heightened by the presence of solid particulate matter in the environment, as stated by epidemiologists [4]. PM10 particles, also known as inhalable particles, have the ability to penetrate the respiratory tract system of humans. Prolonged exposure to these air pollutants can lead to various diseases, including congenital heart disease, premature birth risk, and increased cancer risk [5, 6]. The particles, ranging in size from 5 to 10 μm, primarily remain in the upper respiratory tract, such as the nose and throat. They can be expelled through throat movement and have limited impact on health [6]. However, if these particles are ingested and enter the digestive system, some components can be absorbed by the body. Particles smaller than 2.5 μm can reach the bronchioles, alveolar sacs, and alveoli in the lungs. Approximately half of the particles with a size of 0.01–0.1 μm will settle in the alveolar cavity. Exposure to PM2.5 has been linked to various detrimental health effects, including metabolic syndrome, systemic inflammation, and respiratory diseases [7]. Particles with smaller sizes deposit at a slower rate and stay suspended in the air longer. This leads to deeper penetration into the respiratory tract and greater impact on the human body. PM10 concentrations in most cities exceed WHO standards, posing a threat to our health. Indoor air quality is now a significant public health concern, requiring research on indoor particulate matter [8, 9].

Sandstorms are a disastrous weather phenomenon common in arid, semi-arid, and desert regions. Recently and with climate change, sandstorms are increasing around the world [10] and the smallest particles are sometimes carried thousands of kilometers as happened in 2020 in Europe which experienced an opaque world with air loaded with yellow dust. This phenomenon has been reproduced in South and North America. They severely affect indoor air quality and disrupt people's lives. In southern Algeria sandstorms were very frequent in spring and summer, but with climate change and the drought that the region is experiencing, these wind storms occurred throughout the year, and thus constitute, in addition to the behavior of the occupants and their domestic activities, a source of dust in homes, which contributes to the deterioration of indoor air quality.

The type of heating, ventilation, and air conditioning (HVAC) system plays a significant role in the movement and dispersal of particulate matter within buildings. Various types of heating systems can be used to provide heat during the winter months. These include: radiator heating, underfloor heating, fan convector systems and split air conditioning heating. Indoor aerosol particle dispersion and deposition have been performed using both computational [11-13] and experimental approaches [14-17]. The literature contains several comparative studies of aerosol particle deposition and dispersion in various heating systems [18-22]. Weichenthal et al. [23] investigated the impact of several domestic heating systems on indoor ultrafine particle exposures, including electric baseboard heaters, wood stoves, and forced-air oil/natural gas furnaces. Their findings showed that home heating systems did not appear to be key factors of mean or baseline indoor ultrafine particle exposures, and that cooking and smoking are likely considerably more significant predictors of in-home ultrafine particle levels. Wang et al. [24] examined the effect of ventilation on particle diffusion in a residential kitchen. The researchers concluded that particle diffusion is influenced greatly by the rising thermal plume and that ventilation plays an important role in particle distribution.

A study conducted by Ghasemi et al. [17] investigated the dispersion of PM2.5 and PM10 airborne particles in a residential room. It was found that the floor heating system is a healthier heating system based on the deviation of PM2.5 and PM10 concentrations from their respective limits. Their results showed the sensitivity of PM2.5 concentration to variations in soil condition and air temperature. Dehghan and Abdolzadeh [21] examined particle distribution in a room across three distinct heating systems: underfloor, radiator, and skirt boarding heating. Their findings revealed that the skirt boarding system exhibited the lowest particle concentration. They attributed this to the presence of the heat source, which caused particles to adhere to the walls rather than dispersing into the environment. Chen et al. [25] examined the impact of the heat source-wall distance and temperature of the heat source on the deposition of particles of size varying from 2.5 lm to 10.0 lm. Their results demonstrated the positive influence of these two variants tested on particle deposition for the different particle sizes. Zhou et al. [19] investigated the impact of ventilation on floor heating systems through a combination of computational fluid dynamics (CFD) analysis and experimental validation. Their study focused on variations in ventilation type (inlet from below or above), inlet air velocity, and floor temperature. Their findings indicated that with up-supply ventilation, particles tend to accumulate in the middle of the room, and these concentration levels decrease as the floor temperature rises. Golkarfard and Talebizadeh [13] investigated the impact of radiator and floor heating systems on indoor particle dispersion and deposition. Their research revealed distinct patterns: the floor heating system predominantly deposited suspended particles on the ceiling, whereas the radiator heating system tended to deposit them on the floor. Notably, they found that the floor heating system was more effective at removing suspended particles compared to the radiator heating system. Ardkapan et al. [26] assessed the dispersion of ultrafine particles in a room containing a heat source. Their findings highlighted a correlation between particle concentration and the location of both the heat source and the particle emitter.

The literature review mentioned above suggests that different ventilation or heating systems have distinct effects on the dispersion of particles in indoor spaces. This is because the movement of particles is closely tied to the air flow and temperature distribution within the room.

The objective of this study is to numerically compare the impact of two types of heating systems, namely split air conditioning and radiators, on the deposition of particles of different sizes, representative of sand dust, on the surfaces (vertical walls, ceiling, and floor) of an unoccupied room.

2. Modeling Approach

2.1. Physical models

This section outlines the mathematical framework and computational methodology employed in our investigation, integrating turbulence mechanics with particulate transport phenomena in fluid dynamics. The Reynolds-Averaged Navier-

Stokes (RANS) equations, coupled with the k-ε turbulence model, were implemented to characterize turbulent airflow within a residential interior environment. COMSOL Multiphysics software was employed to simulate indoor atmospheric conditions containing suspended particulate matter, facilitating comprehensive examination of particle trajectory and deposition characteristics under two different heating systems.

The problem is to study particles flow in an air-conditioned room by using a commercial code COMSOL. Firstly, turbulence model, standard k-ε, was employed to simulate the airflow in steady-state conditions, then particles were injected under transient regime conditions. The studied domain geometry and dimensions are shown in figure 1. Two heating systems have been tested: a radiator system and a split AC. A radiator measuring 1.2 m in length and 0.55 m in height was positioned 0.01 m from the floor. The split AC is mounted on the window wall, with dimensions of 1.0 × 0.35 m, and is located 0.1 m from the window and 0.15 m from the ceiling. Both heating systems are positioned symmetrically relative to the center plane y = 1.2 m.

This configuration of the room is analogous to the experimental cell reported in Oleson et al. [27]. The fresh air enters the room at -5 °C from an inlet and with volume flow rate of about 7 L/s. A pressure outlet condition is supposed at the outlet and no-slip conditions is applied for the other wall. A constant temperature boundary condition of 45°C and 22°C are imposed for the radiator split AC surfaces, respectively. For the window and front wall, the heat convective flux boundary condition is assumed with heat transfer coefficient of 2.3 $Wm^{-2}K^{-1}$ and 3 $Wm^{-2}K^{-1}$ respectively and a temperature of -5°C.

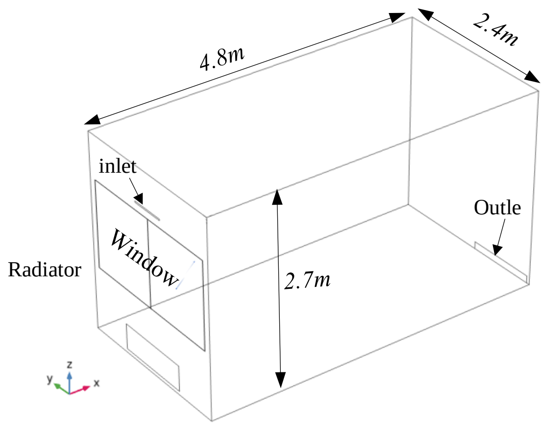

Fig. 1: Geometry of the studied domain

2.2. Mathematical modeling

This section outlines the mathematical framework and computational methodology employed in our investigation, integrating turbulence mechanics with particulate transport phenomena in fluid dynamics. The Reynolds-Averaged Navier-Stokes (RANS) equations, coupled with the k-ε turbulence model, were implemented to characterize turbulent airflow within a residential interior environment. COMSOL Multiphysics software was employed to simulate indoor atmospheric conditions containing suspended particulate matter, facilitating comprehensive examination of particle trajectory and deposition characteristics under two different heating systems.

a. Continuous phase

The fundamental equations describing incompressible fluid dynamics can be expressed in their generalized formulation as follows:

$$\frac{\partial \varphi}{\partial t} + \nabla \cdot (u\varphi) = \nabla \cdot \left(\Gamma_{\varphi} \nabla \varphi\right) + S_{\varphi} \tag{1}$$

Where u is the velocity vector; φ represents the components of velocity vector (u, v, w), the kinetic T, the kinetic energy of turbulence k and the dissipation rate of kinetic energy ε. Γ_{φ} is diffusion coefficient and S_{φ} the source terme.

b. Discrete phase

Particles in the continuous phase were tracked using a Lagrangian frame, integrating their motion based on Newton's Second Law to determine velocities and positions over time. The key governing equation is:

$$m_p \frac{dv}{dt} = \sum F_i \tag{2}$$

where m_p is the particle mass, F_i are the forces acting on the particles and v is the particle velocity.

To simplify the study a number of assumptions were considered. The modeling of the particles inside the building envelope is carried out by choosing the unidirectional coupling, this choice is justified by the fact that the mass fraction of the particles in the fluid is low. In addition, the interaction between the particles is neglected, so the distance between them can be less than the diameter of the particles.

The motion of each particle is then described by the following system:

$$m_p \frac{dv}{dt} = F_g + F_D + F_L + F_T \tag{3}$$

Where F_g, F_D, F_L and F_T are the gravitational, drag, lift and thermophoretic forces respectively.

To simulate the particles motion, solid particles were released at the inlet with an initial velocity equal to fluid flow velocity. Furthermore, particles used in these simulations are solid particles with various diameter $(0.1 - 12.5\mu m)$ and with density of $1400 kg/m^3$ [24] . The mass flow rate of particles released is set to $2.2 mg/h$.

2.3. Mesh resolution optimization

Numerical simulations were conducted using an unstructured tetrahedral mesh. To improve the accuracy and efficiency of the computations, a grid sensitivity analysis was performed to select the most appropriate mesh. Four grid sizes (2703178, 3214833, 476089 249134 elements for radiator and 301082, 455476 elements for split) were analyzed and compared. As a result, a computational mesh comprising approximately 301082 elements for the radiator heating system (and 3214833 elements for the split AC system) was found to provide sufficient accuracy for further analysis.

2.4. Validation

To validate the computational model to estimate indoor particle spatial distribution, we used experimental measurements by Chen et al. [24] made in a scaled room configuration. These results data have been widely used in many similar studies as validation benchmarks for computational models. As indicated in Figure 2, the comparison study demonstrates significant accordance between our predicted velocity profiles and normalized concentration distributions and experimental measurements.

3. Results and discussions

a. Air temperature and velocity distribution

Since accurate prediction of fluid flow patterns is critical for understanding particle transport, precise simulation of the flow field is essential. This section presents a comprehensive analysis of the key characteristics of fluid flow, serving as a foundational reference for exploring the behavior of particles within the fluid medium.

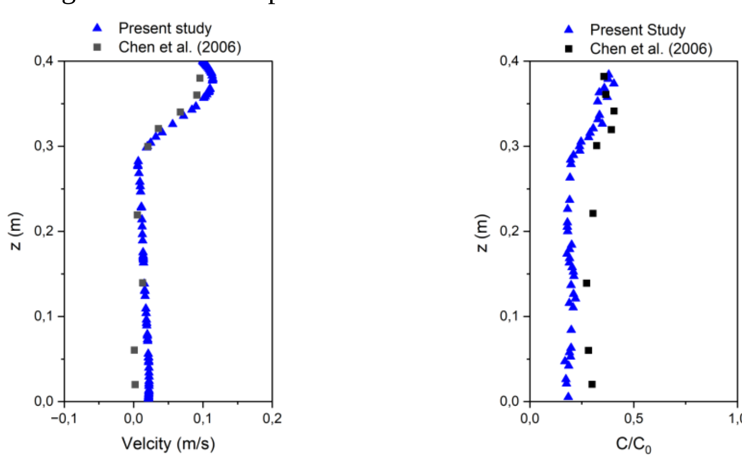

Fig. 2: Comparison of measured and predicted velocity and normalised particle concentration at x = 0.4m

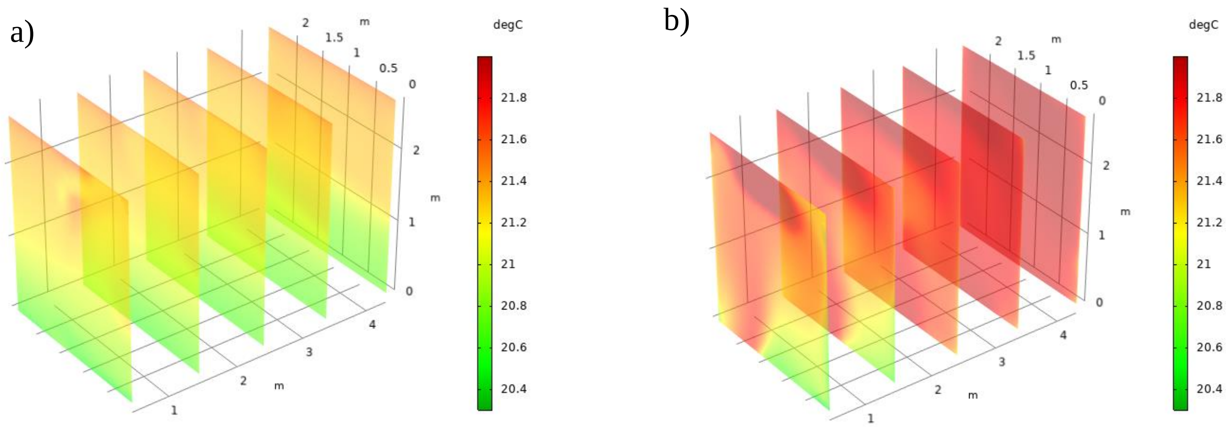

Fig. 3: Temperature Distribution and along the vertical planes for a) radiator and b) split heating system

The temperature and the air velocity distribution on five vertical planes is given in Figures 3 and 4 for the two heating systems. According to the figure 3, the radiator generates a fairly uniform temperature compared to a split AC. The temperature contours reveal vertical stratification from floor to ceiling caused by buoyancy effects. Near the wall containing the split air conditioner, the temperature distribution appears irregular due to warm air discharge from the unit. In contrast, the vertical plane furthest from the split AC shows a more uniform temperature pattern, with readings between 21.5°C and 22°C. Because thermal comfort strongly depends on temperature gradients inside the room, radiator heating system gave thermal comfort better than that generated by split AC.

Looking at the velocity field plotted in Figure 4 and 5, two main recirculation zones are formed for radiator heating system. These two cells occupied almost the entire width of the room from the top to the floor. The split AC system generates a thermal plume within the room which creating a dominant vortex that circulates throughout the entire enclosed space. Concurrently, a smaller localized eddy formation is observed in proximity to the anterior wall.

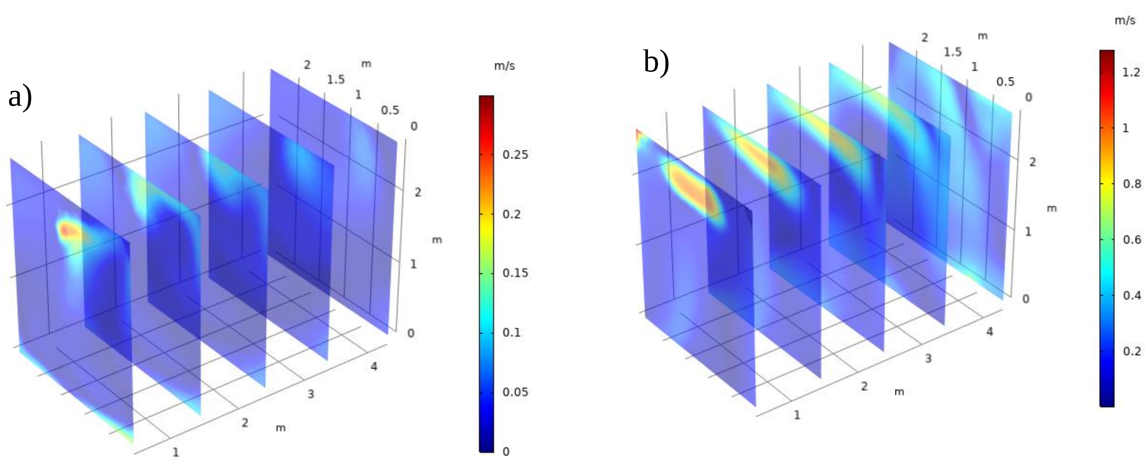

Fig. 4: Velocity Distribution along the vertical planes for a) radiator and b) split heating system

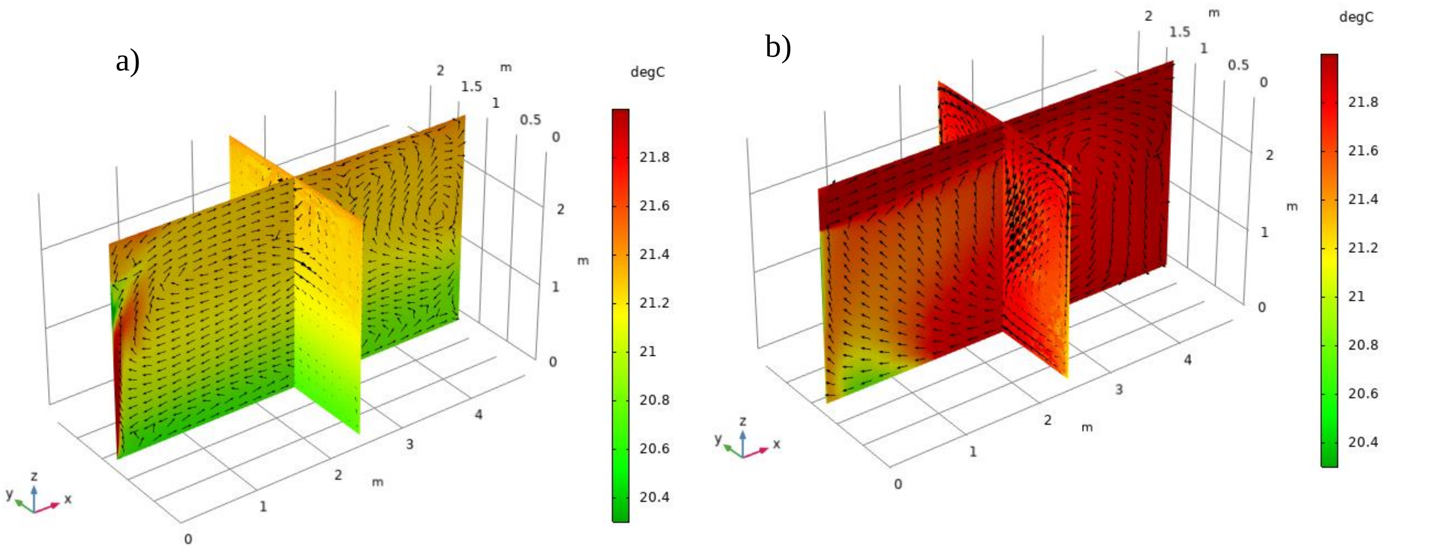

Fig. 5: Temperature Distribution and air velocity field on vertical plane and horizontal plane for a) radiator and b) split heating systems

In this study, the effect of the heating system on the motion and deposition of particles is investigated by computing the fraction of deposited particles which ratio of the amount of settled particles by the total number injected particles.

Fraction of deposited particles on room surfaces for various particles sizes is shown in Figure 6. The figure shows the existence of a significant difference in the deposition of particles on the room surfaces for the different particle sizes and depending on the type of heating.

As depicted in the graph, there is a substantial variation of the particle deposition on the floor and others walls. In the split AC heating system, the fraction of particles deposited on the front and side walls is minimal, while in the radiator system, it is almost nil. Larger particles are mostly deposited on the floor, while smaller ones typically end up on the back wall. This is supported by the fact that gravity force dominates the drag one for larger particles. It is evident from the figure that the rate of the particle adhering to the back wall has the highest proportion in split system, which can be attributed to the direction of airflow emitted from the split unit. The findings verified a direct correlation, more obvious in the case of the radiator system, between the size o f the particles and their floor deposition.

4. Conclusion

To gain a deeper understanding of human exposure and develop more targeted strategies to improve indoor air quality (IAQ), it is crucial to have knowledge about the removal and deposition of particles indoors. This study aimed to investigate the airflow and dispersion of particles in an unoccupied room with three heating systems: split air conditioning and radiator heating systems. A computational fluid dynamics (CFD) model, combining Eulerian and Lagrangian approaches, was utilized to predict the turbulent characteristics of the airflow and the trajectories of the particles. The focus of the analysis was primarily on the fraction of particles that were deposited on the surfaces of the room. By examining the air velocity fields, temperature fields, and particle deposition fraction, the following conclusions were drawn:

- Radiator heating system gave thermal comfort better than that generated by split AC.
- Notable distinction in particle deposition between the floor and walls in the radiator heating system is depicted.
- Fraction of particles deposited on the ceiling and side walls is minimal
- In the split AC system, no particles are deposited on the ceiling or side walls.
- Smaller particles have a tendency to be deposited on the back wall, while larger particles exhibit a strong affinity for the floor.
- Overall, the particles tend to be deposited on the floor and the wall in front

Our recommendation for future study is to study:
- the impact of dynamic boundary conditions on the behavior of particles for different heating systems,
- the impact of relative humidity on particle deposition

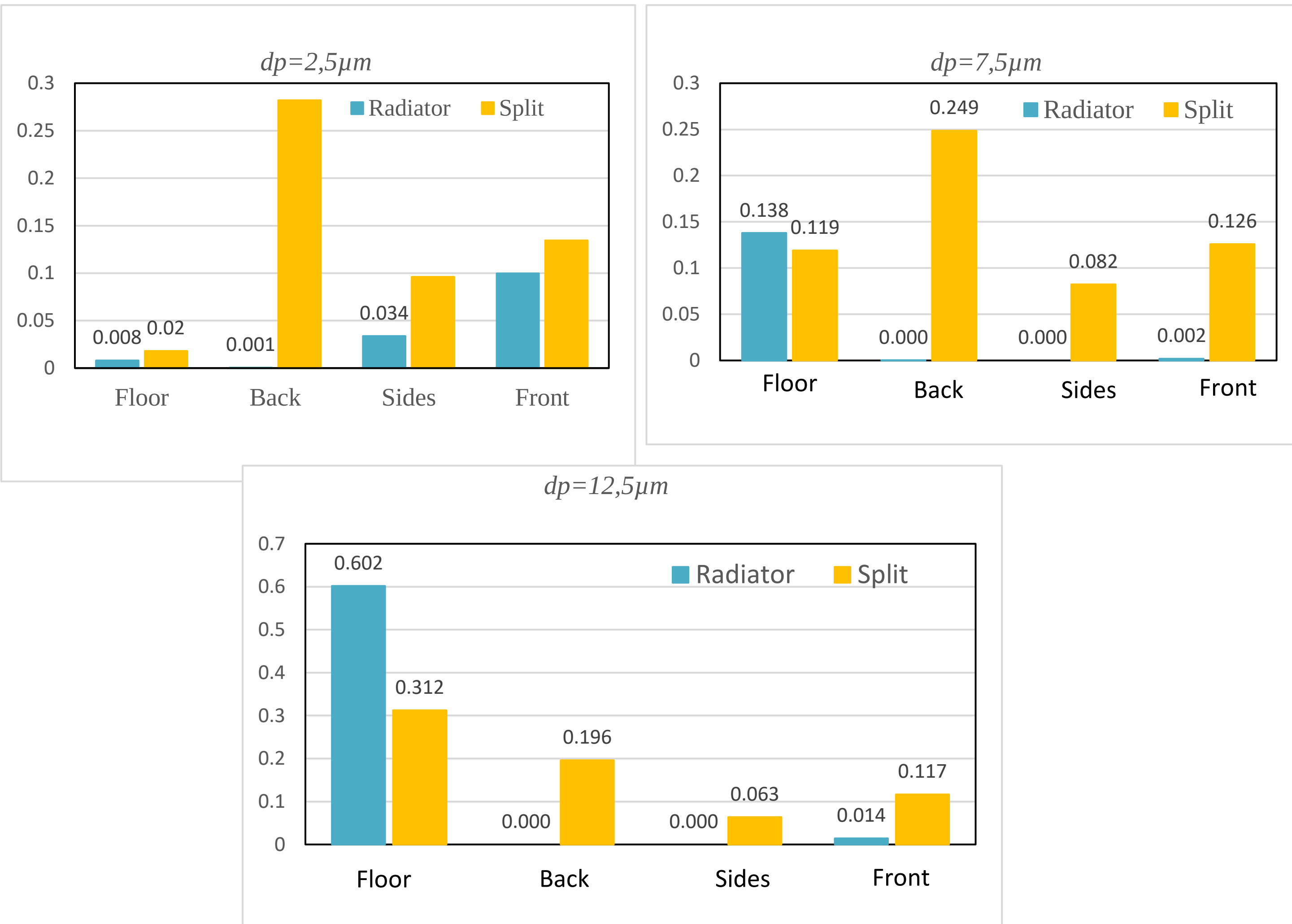

Fig. 6: Fraction of deposited particles on room surfaces for various particles sizes

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