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Numerical modeling of particles deposition in domestic floor heating systems

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Abstract

Nowadays due to the variety of heating systems, efforts are being made to optimize each of these systems. Due to the fact that people spend most of their time in their home or indoors, providing cleaner and more comfortable air should also be of interest to researchers and developers of these systems. The floor heating system was initially introduced as the most ideal heating system and is used by many people. After the growth of floor heating systems, theories that this system, like other common heating systems such as radiator or heater systems, can move particles in the floor of living spaces and cause diseases such as allergies; has been raised. But some experts argue that radiation is the main mechanism of heat transfer in the floor heating system and that the system is unable to move and lift particles. A response to these two contradictory theories must be examined in order to further optimize these systems. In the present study, the effect of floor heating systems on the behavior of dust on the floor of the study area is investigated. The present work has been validated using the results of an experimental work in which the airflow within the desired geometry is investigated. In this study software (ANSYS-Fluent 19.1) and discrete phase model two-phase is used to simulate this model. By examining the results, it is found that the free displacement caused by the floor heating system and the inlet air from the window is capable of lifting and moving the particles on the floor at specified directions. Also, by examining the effective parameters on the displacement rate of these particles, including diameter, density and velocity of inlet air, it was observed that particles with less than 1 micrometer diameter and less than 750 kg/m3 density range can move in the geometry space studied.

Keywords: Floor heating systems, Numerical study, Two phase flow, Particle deposition, Allergies.

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1. Introduction

Recently, with the increasing growth of various types of home heating and air conditioning systems, efforts have been made to optimize each of these systems among researchers and manufacturers. During several studies, the issue of optimization of underfloor heating system compared to other systems in terms of economy, energy and proximity of the temperature of this system to the desired temperature of the human body, etc. has been proven [1]. However, studies have shown that the conditions of the air produced by these systems, the effects of these systems on the quality of air in the workplace or people's lives, as well as the production of the most pleasant air by these systems are less considered. Fine particles of any kind can damage a person's respiratory system and can lead to asthma, allergies, cancer, or even long-term death [2]. Research has shown that people who are constantly exposed to such particles suffer from acute illnesses, respiratory syndromes and even death [3]. Since people spend most of their time indoors, such as at home, in offices, and in other indoor environments, it is important to provide the cleanest and highest quality air in these environments. The importance of this issue from the beginning and with the most basic home heating systems after the industrial revolution such as coal or oil heaters and fireplaces to date in the most advanced and up-to-date home heating systems such as underfloor heating systems or panel radiators have attracted the attention of researchers. In 1996, Moriske et al. [4] compared the pollution caused by the production of carbon suspended particles, heavy metals, and dust in open and central heating systems with coal fuel. They clearly found that the pollution caused by the scattering of these particles in the open system was greater than in the central system. In 2010, Kong et al. [5] examined the effect of air temperature and the location of ventilated air on the room on rising and moving particles in the room and concluded that the lower the temperature of the air entering the room, the greater the concentration of suspended particles in the range. Golkarfard and Talebizadeh [6] modeled the floor heating system and the radiator while examining the effect of free convection on pre-suspended particles in the air of a room, proving that the percentage of particle scattering in underfloor heating systems is higher than the heating system. It is with the radiator that it is shown that the stability and the percentage of suspension of these particles are higher in radiator heating systems and the particles in these systems are expelled later. They also looked for the percentage of particle accumulation on different surfaces and concluded that particles in floor heating systems are more scattered on floor and ceiling surfaces than radiators. In figure 1, the percentage of particle scattering in the floor heating and radiator heating systems can be compared. As mentioned, the percentage of movement and movement of particles in underfloor heating systems is less than the heating system with radiators.

They also looked for the percentage of particle accumulation on different surfaces and concluded that particles in floor heating systems are more scattered on floor and ceiling surfaces than radiator heating systems, and in radiator heating systems more particles are scattered in the middle of the room, that is more exposed to respiration, is dispersed. These results can be seen in Figure 2 and Figure 3.

Studies have shown that in such researches, the effects of underfloor heating systems on particles that have been suspended in the room air from the beginning and most parameters such as stability time and then subsidence or repulsion of these particles have been studied. Therefore, in the present article, by modeling the floor heating system in a room, the effect of this system on the lifting and movement of fine dust particles in the floor of the room is examined. This can be used to track the movement of these particles, and to find an answer to this challenging theory of whether this system or any other similar system can be allergenic. Is it possible to find a way to collect these particles or take them out of the desired environment if the particles rise from the bottom? The results of this

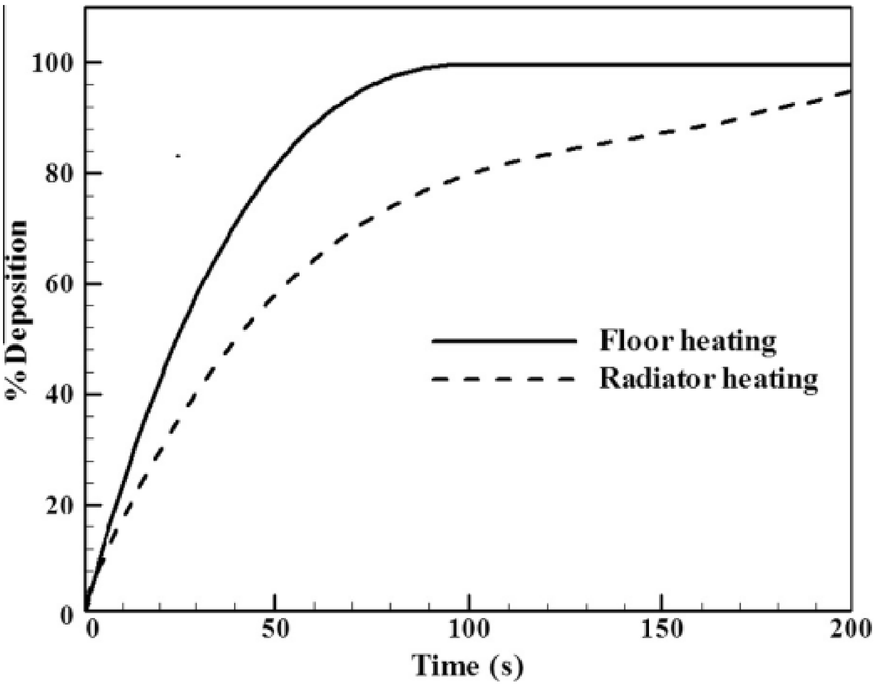


Figure 1: Comparison of particle scattering percentage in underfloor heating systems with radiator heating system [6]

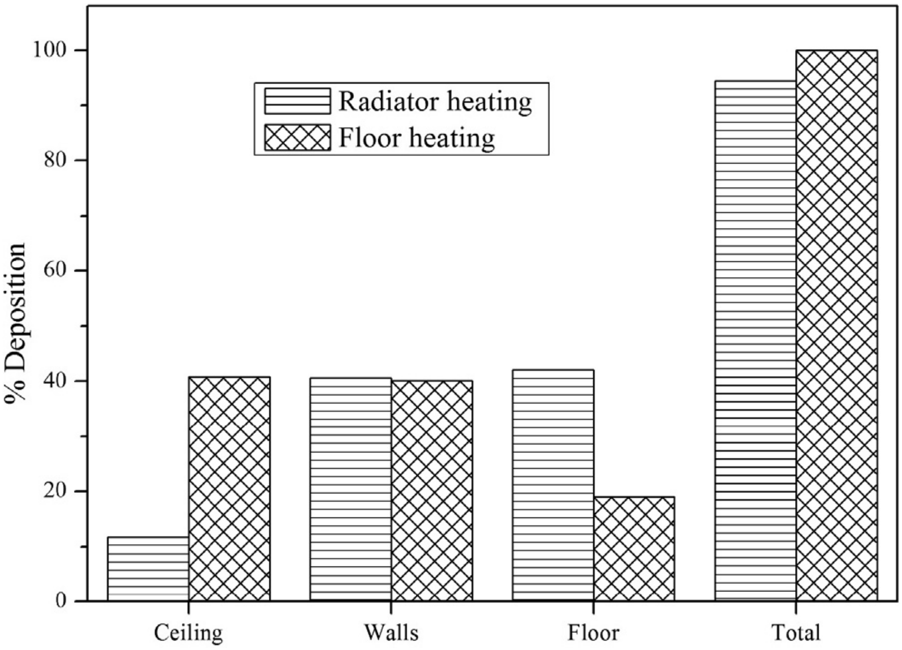
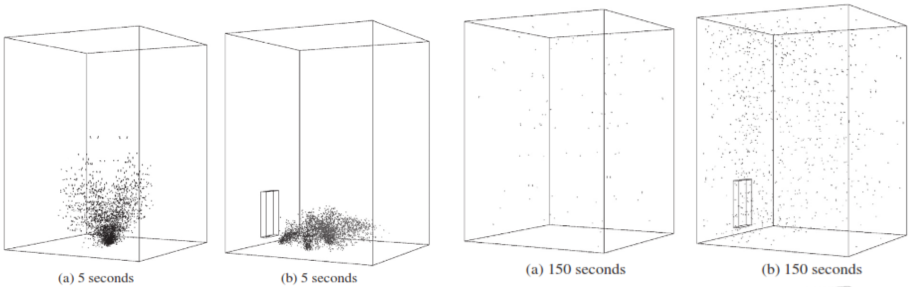
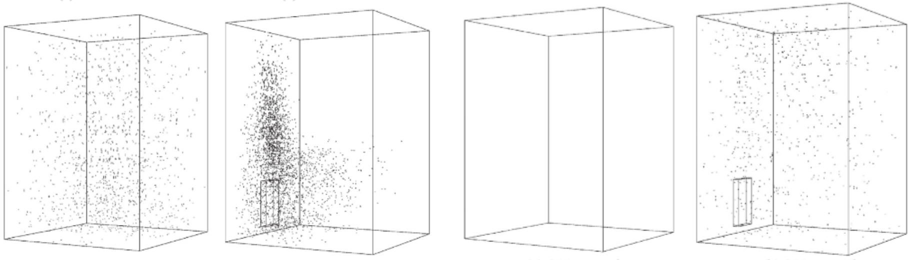


Figure 2: Comparison of particle scattering percentage on room surfaces in underfloor heating systems and radiator heating systems [6]

research can be used in the best possible design of these systems, especially ventilation systems, as well as in the architecture and optimal design of houses.



(a) 5 seconds (b) 5 seconds (a) 150 seconds (b) 150 seconds



(a) 50 seconds (b) 50 seconds (a) 200 seconds (b) 200 seconds

Figure 3: Comparison of the distribution of airborne particles in underfloor heating systems and heating systems with radiators [6]

2. MATERIALS AND METHOD

Reference articles have been used to validate the analysis and modeling. In 1992, Blay et al. [7] examined the effect of free and forced displacement caused by underfloor heating system on room temperature during an experimental work. In 2018, Yuce and Pulat [8] simulated the numerical simulation of Blay et al. and validated their work results with it. According to Figure 4, the geometry used in the present simulation is taken from the article by Yuce and Pulat.

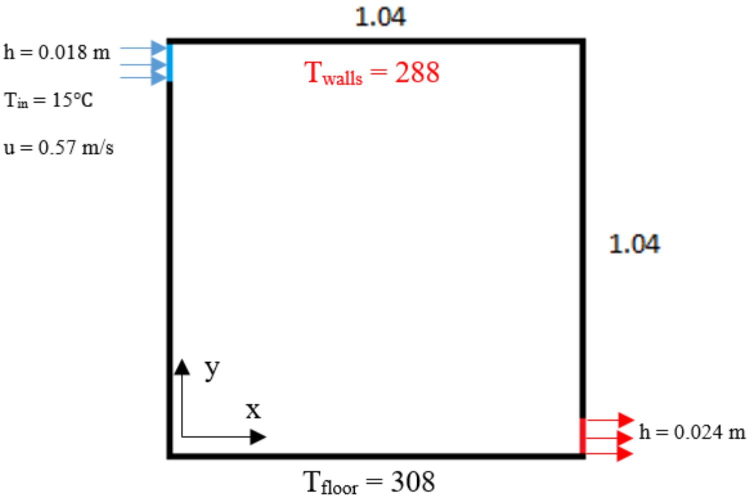


Figure 4: Geometry used in numerical simulation

As shown in Figure 4, a geometry measuring $1.04 \times 1.04 m^2$ with an input of 0.018 meters, an inlet air with a velocity of 0.57 m/s and a temperature of 288 Kelvin and an output of 0.024 meters is considered. The floor temperature is 308 Kelvin, the wall temperature is 288 Kelvin and the ceiling is isolated.

3. SINGLE PHASE EQUATIONS

The equations of continuity, momentum, and energy for continuous incompressible fluid and for the steady states are written as follows:

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0 \qquad \text{Continuity equation} \tag{3.1}$$

$$\frac{\partial}{\partial x_i}(\bar{u}_i \bar{u}_j) = -\frac{1}{\rho}\frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\left[(\upsilon + \upsilon_t)\frac{\partial \bar{u}_i}{\partial x_i}\right] + g_i \beta(\bar{T} - T_0) \qquad \text{Momentum equation} \tag{3.2}$$

$$\frac{\partial}{\partial x_i}(\bar{u}_i \bar{u}_j) = \frac{\partial}{\partial x_i}\left[(\alpha + \alpha_t)\frac{\partial \bar{T}}{\partial x_j}\right] \qquad \text{Energy equation} \tag{3.3}$$

In these equations, α_t is the turbulence thermal diffusivity and υ_t is the turbulent kinematic viscosity and according to the work of Zhou et al. [9], the relations (3.4) and (3.5) are calculated.

$$\alpha_t = \upsilon_t / Pr_t \tag{3.4}$$

$$\upsilon_t = \frac{C\mu k^2}{\epsilon} \tag{3.5}$$

These equations must be solved simultaneously using boundary conditions. Given the non-slip condition, the velocity on the walls of the room is zero. Also, the gradient of pressure on the walls of the room is zero and the temperature of the walls of the room is one of the known boundary conditions of the problem.

4. TWO PHASE EQUATIONS

Particle motion equations are rewritten and solved by considering the average velocity of the discrete and continuous phase [6].

$$\frac{d\bar{u}_p}{dt} = \frac{18\mu C_D}{24\rho_p d_p^2} Re_p(\overrightarrow{u} - \overrightarrow{u}_p) + \left(\frac{\rho}{\rho_p} - 1\right)\overrightarrow{g} + \overrightarrow{F}_a \tag{4.1}$$

$$\frac{dx_p}{dt} = u_p \tag{4.2}$$

The particle Reynolds number is calculated based on the relation (4.3) [6].

$$Re_p = \frac{D|u - u_p|}{\upsilon} \tag{4.3}$$

Also, the drag coefficient C_D is calculated according to the particle Reynolds number of relations (4.4) or (4.5) [6].

$$if: \ Re_p > 1000 \longrightarrow C_D = 0.44 \tag{4.4}$$

$$if: \ Re_p \leq 1000 \longrightarrow C_D = \frac{24}{Re_p}(1 + 0.15 Re_p^{0.687}) \tag{4.5}$$

According to Equation (4.1), $\overrightarrow{F}_a$ is effective on the motion of the particle in the continuous phase, which in this model includes Thermophoretic force, Saffman Lift Force, virtual mass force, pressure gradient force, erosion/accretion. Thermophoretic force due to the presence of temperature difference within the continuous phase, Saffman force due to the presence of shear stress during particle motion, erosion/accretion due to the possibility of particles colliding with the walls and continuous phase and also the accumulation of particles in the corners, are selected. All of these forces, except for the virtual mass force caused by the acceleration difference between the continuous and discrete phases for particles smaller than one micron, and the pressure difference force because they had no effect on the results, are used in this simulation

5. Modeling and Solution

As mentioned earlier, the equations of continuity, momentum, and energy must be solved simultaneously. On the other hand, in this paper, the effect of free and forced convection caused by underfloor heating systems in a geometry is investigated. In this case, the buoyancy and momentum forces will both have an effect. For this purpose, geometry has been drawn and meshed using Gambit software and then the model has been simulated and analyzed using Fluent 19.1 software.

Yuce and Pulat [8] examined the mesh independency of the model in four modes, which include 120 × 120, 160 × 160, 200 × 200 and 300 × 300 mesh sizes, and after analyzing the model, according to Figure 5, 160 × 160 grid size was selected as an optimal. In the present study, using the results of their work, according to Figure 6, 160 × 160 grid size has been used also.

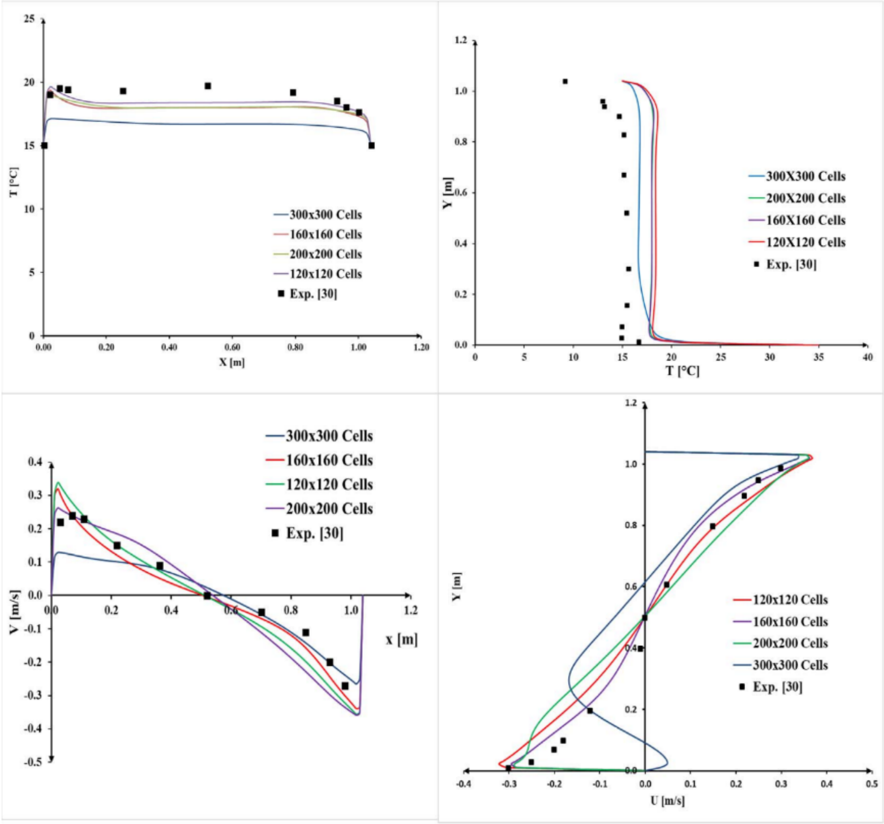


Figure 5: Investigating the mesh independency of the model in the work of Yuce and Pulat

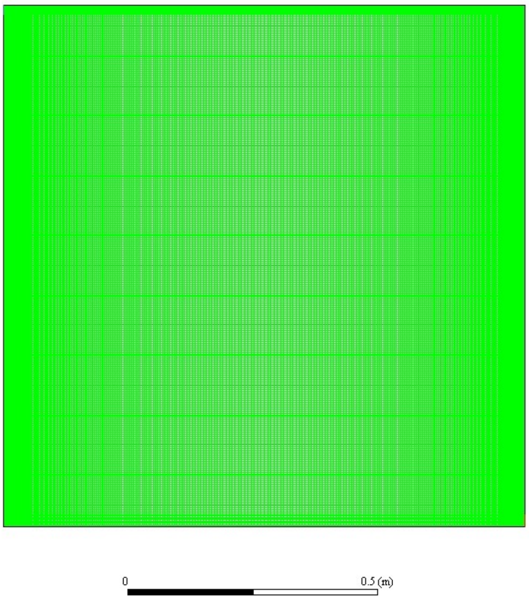


Figure 6: The mesh used in the present article

Air density is estimated using Boussinesq approximation and other physical properties of the air are considered as constant. The gravity force is taken into consideration. The material of the floor of the room is wooden and the walls are gypsum. The SIMPLE algorithm is applied to solve the pressure-velocity coupling. The second order upwind discretization is used for momentum, turbulent kinetic energy and turbulent dissipation rate. The values of convergence for all equations is set as 10^{-6} respectively. For all considered cases $k-\omega$ SST turbulence model is used.

6. RESULTS

After analyzing the single-phase model with the proposed boundary conditions, it is observed that according to Figure 8 in underfloor heating systems after air is heated in the lower levels of the room, due to low density moves toward the upper part of the room. It moves and returns to a low level after cooling and density increase. In Figure 9 (A to D) the results of the present work are compared and validated with experimental results [7].

For numerical analysis of the two-phase model, particles of cotton fibers with non-spherical geometry and 0.3 shape factor, and 10^{-6} meters diameter, $100 kg/m^3$ density, with a temperature of 300 K, stagnant on floor level of the room and in the vicinity of the room air are considered with the pressure and temperature of the environment. After numerical analysis with the discrete phase model and reviewing the results, it was observed that according to Figure 9, these particles rose from the floor of the room and were in the air path caused by the free convection of the floor heating system. These particles pass through the room to the exit and a large number of them exit the outlet.

In the following, the effect of particle density on their displacement is discussed. As shown in Figure 10, as the density increases, the concentration of the particles on the line y=0.9 gradually decreases, and at densities above $750 kg/m^3$, the parameter reaches zero, indicating that none of these particles are able to pass beyond the line.

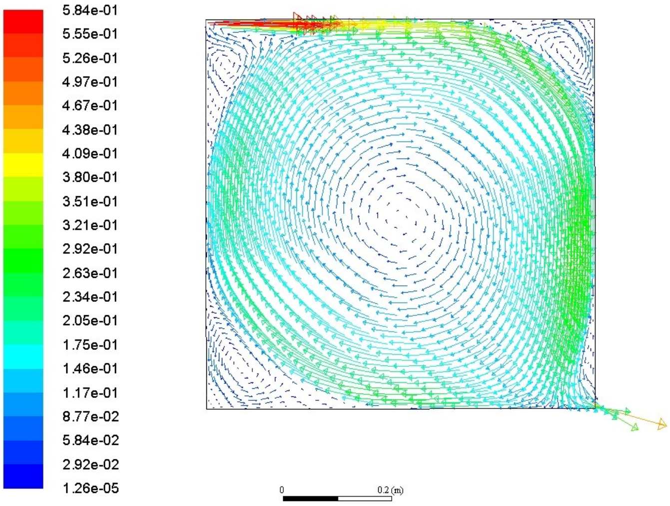
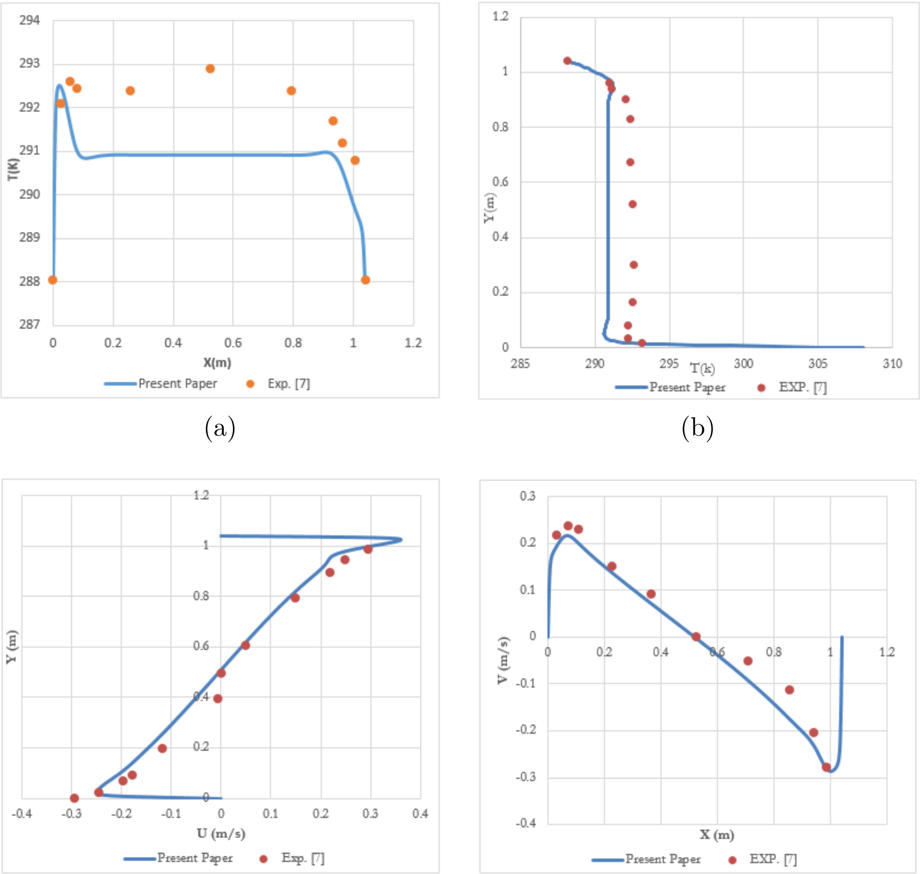


Figure 7: Indicating the path of air flow inside the room with the underfloor heating system by velocity vectors



(a) (b)

(c) (d)

Figure 8: Comparison of the present paper simulation results with experiment of Blay et al. [7] including: (A) Chart (X-T) on line y / H=0.5 (B) Chart (T-Y) on line x/L=0.5 (C) Chart (U-Y) on line x / L=0.5 (D) Chart (X-V) on line y / H=0.5

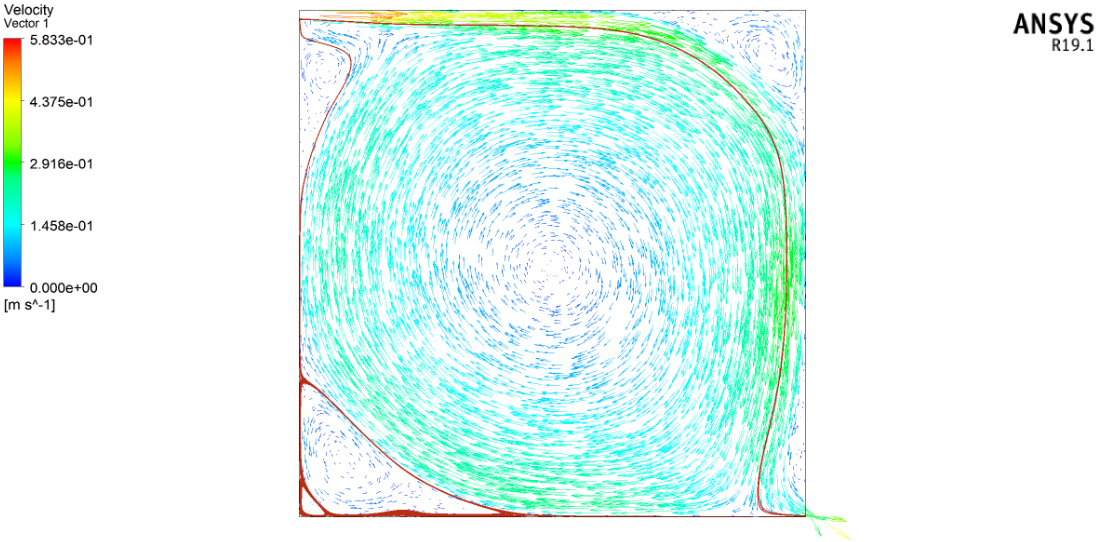


Figure 9: Investigating the direction of particle motion and the direction of air movement inside the room

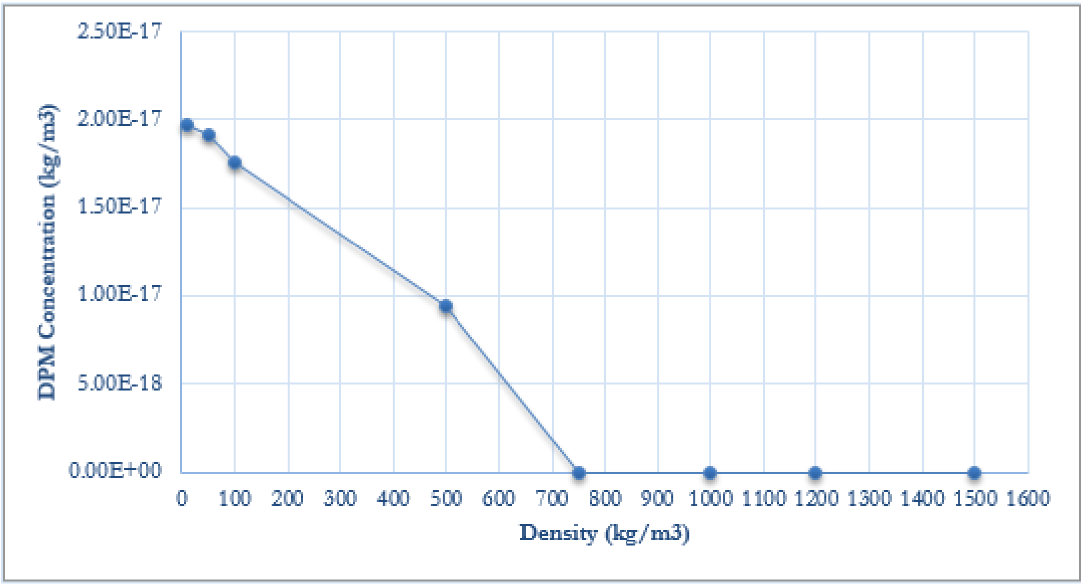


Figure 10: Investigating the effect of density on particle displacement on line y = 0.9

Among the studied densities, the density of $100 kg/m^3$, which is a reasonable and close to reality density for cotton fibers particles, is selected and the effect of particle size on its motion is investigated. For this purpose, diameters of 10^{-3}, 10^{-4}, 10^{-5}, 10^{-6} and 10^{-7} meters have been studied. After analysis, it is observed that among the selected diameters, only particles with a diameter of 10^{-6} meters and smaller are able to cross the middle level of the room. According to Figure 11 and Figure 12, diameters smaller than 1 micron are unable to rise and move at high levels.

In the following, the effect of the incoming air velocity is examined. According to the results obtained in Figure 13 and Figure 14, it can be seen that as the inlet air velocity increases, particles displacement increases, and subsequently, according to Figure 14, the number of particles that exit the lower outlet after a certain path; increase.

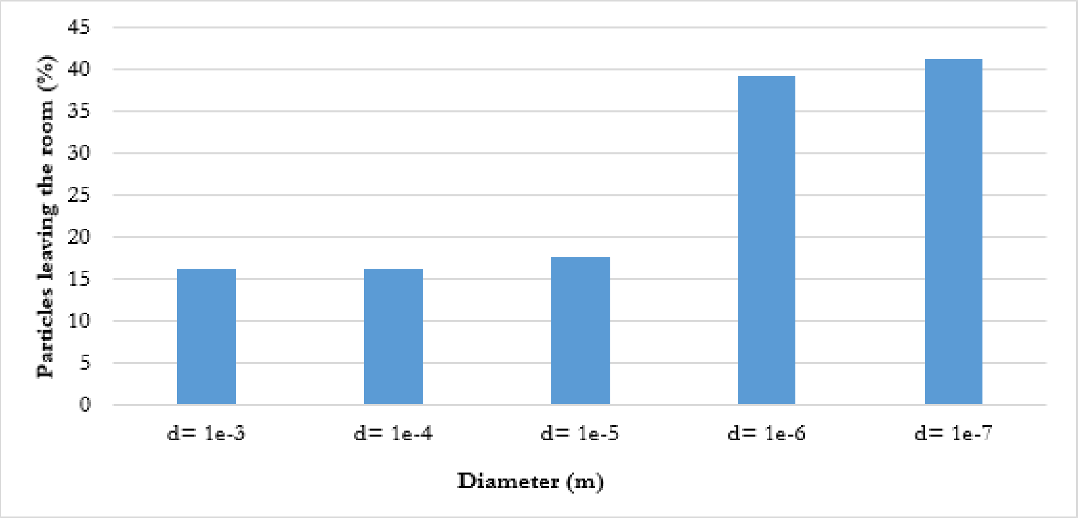


Figure 11: The effect of particle diameter on the rate of rising and exiting of particles through the outlet

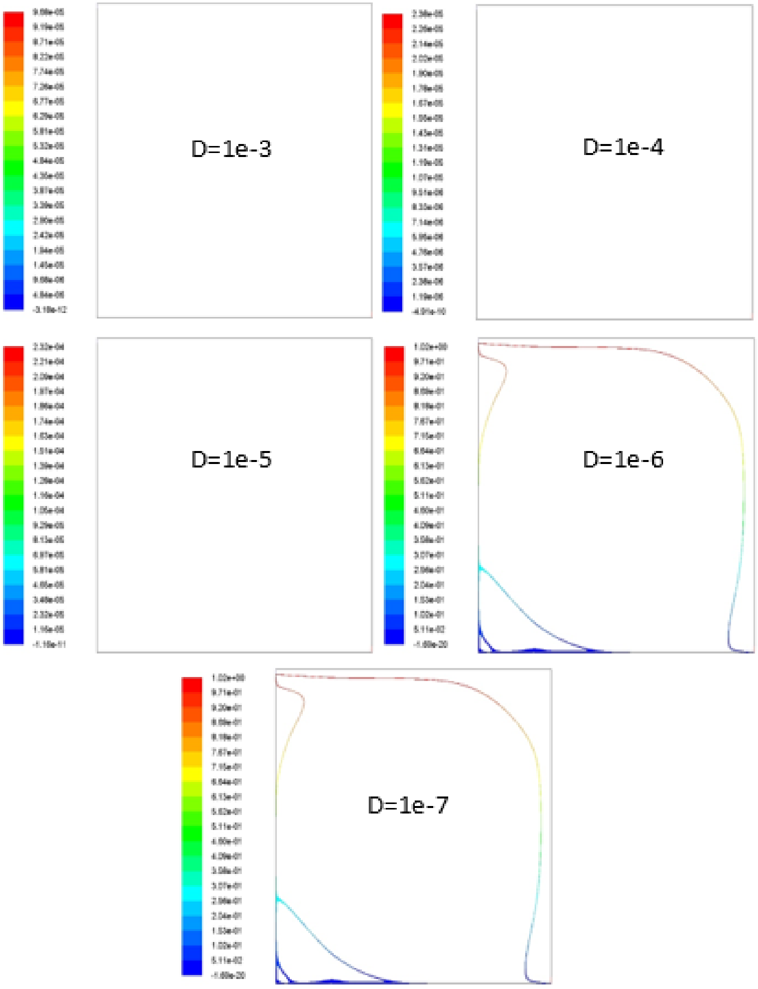


Figure 12: Investigating the effect of particle diameter on their displacement

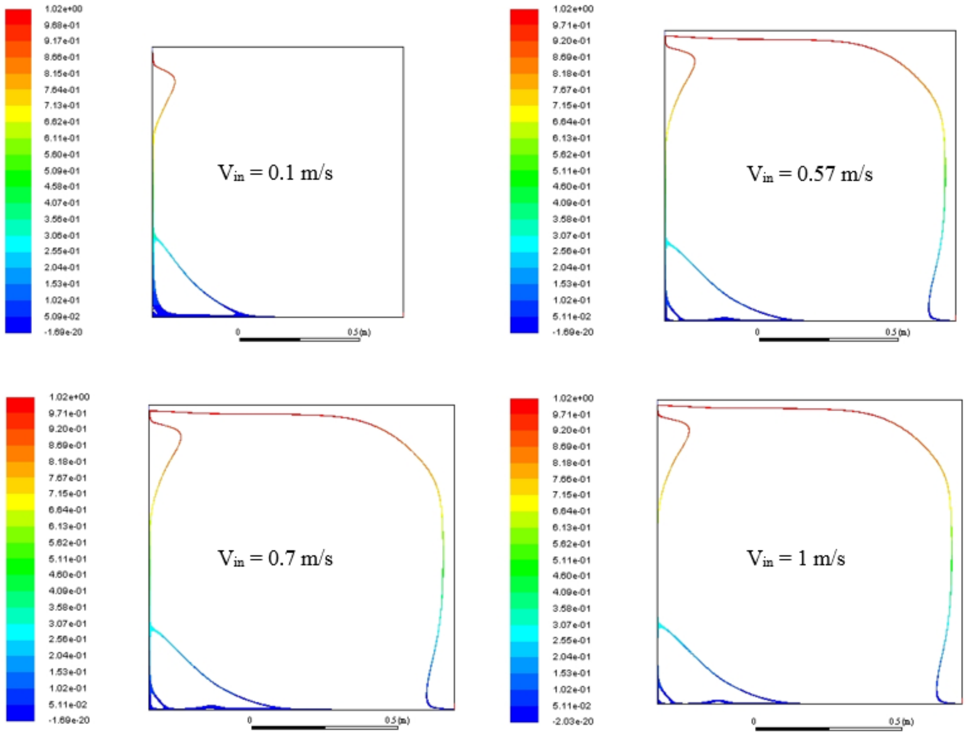


Figure 13: Investigating the effect of incoming air velocity on the rise rate and particle moving path

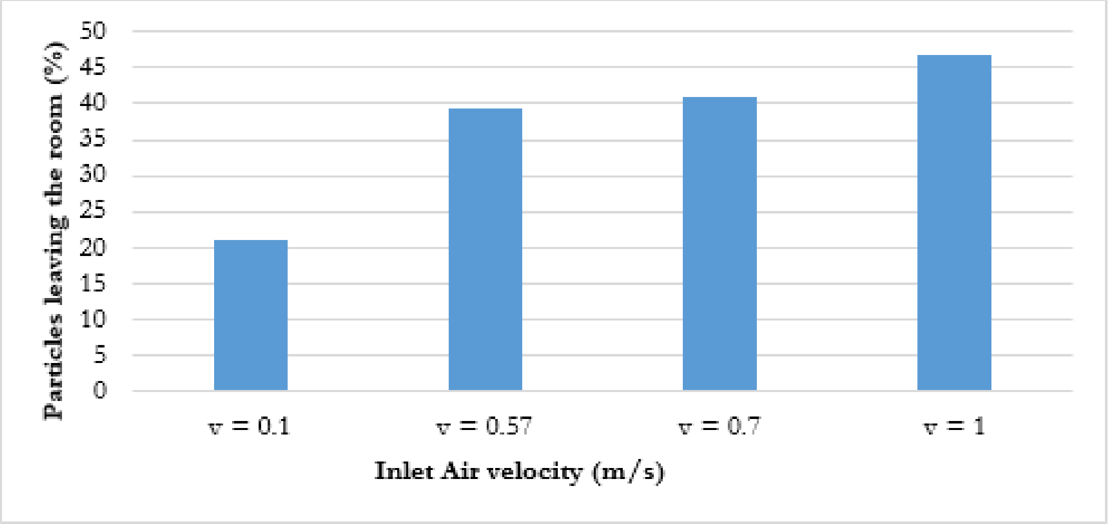


Figure 14: The effect of the inlet air velocity on the number of particles exiting the outlet

7. CONCLUSIONS

The air quality produced in heating systems is always of interest to the manufacturers and buyers of these systems. The main factor in the air conditioning of buildings is the lack of movement or, in case of movement, the rapid exit of dust particles. The presence of these particles in the air of homes has always caused dissatisfaction among people. With the advent of underfloor heating systems and the remarkable success of these systems in providing the most pleasant air temperature for homeowners, the theory of the effect of this system on the rise of fine particles in the floor has been proposed. Therefore, according to the results of this paper, despite the fact that the air flow is not noticeable in underfloor heating systems, the effect of this very slow flow on the movement of particles in the air and room surfaces cannot be ignored. The results showed that the free and forced convection flow in the studied geometry can lift small particles in the floor of the room with a size of less than 1 micrometer and a density of less than $750kg/m^3$ and move them in certain directions. The space of the room makes this range of particle size, despite their very small size, can be harmful to human health.

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