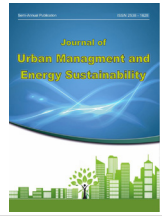


Journal of Urban Management and Energy Sustainability (JUMES)

Homepage: <http://www.ijumes.com>



CASE STUDY RESEARCH PAPER

Evaluation of the effect of semi-open spaces on the ventilation of indoor spaces and the distribution of fine dust

Samaneh Foroughian^{1*}, Mahdi Zandieh², Hossein Medi³, Fariborz Karimi⁴, Mohammadjavad Mahdavinejad⁵

^{1*} Department of Architecture, Faculty of Architecture and Urbanism Planning, Imam Khomeini International University, Qazvin, Iran

² Professor Department of Architecture, Faculty of Architecture and Urbanism Planning, Imam Khomeini International University, Qazvin, Iran

³ Associate Professor Department of Architecture, Faculty of Architecture and Urbanism Planning, Imam Khomeini International University, Qazvin, Iran

⁴ Assistant Professor Department of Architecture, Faculty of Architecture and Urbanism Planning, Imam Khomeini International University, Qazvin, Iran

⁵ Professor of Department of Architecture, Faculty of Art and Architecture, Tarbiat Modares University, Tehran, Iran

ARTICLE INFO

Article History:

Received 2024-07-05

Revised 2024-09-29

Accepted 2024-11-21

Keywords:

Air flow, balcony, CFD, Field sampling, Fine dust, Natural ventilation, semi-open spaces.

ABSTRACT

Fine dust is one of the environmental challenges, which disturb human comfort. Wind is the main factor in the movement of fine dust, and the movement pattern of wind is affected by the architecture of cities. semi-open spaces such as balconies has an effect on the nature of wind and fine dust flow. The purpose of this research is to compare the distribution of wind flow and fine dust in the interior plan, with three variables: location, proportions of balconies and partitioning of interior. Study was done by CFD. K-Omega-SSD turbulence model is used. In order to the software data (the size and type of particles) and software validation, the field sampling method has been used. Research findings show that the design of balconies has a better performance against ventilation. On the other hand, shallow balconies with a wider opening are more suitable. Also, the presence of an internal partition has a positive effect on the ventilation of spaces. The results show that the design of the balconies at the entrance and exit of the wind flow increases the number of suspended particles. The design of these balconies with a shallower depth and a wider opening lowers particle with smaller sizes in the interior spaces with a higher percentage. Also, the design of closed spaces, compared to the design of open spaces, improves the design in dealing with the flow of fine dust.

DOI: [10.22034/ijumes.2024.2045510.1267](https://doi.org/10.22034/ijumes.2024.2045510.1267)

Running Title: Semi-open spaces on the ventilation of indoor spaces and the distribution of fine dust



NUMBER OF REFERENCES

17



NUMBER OF FIGURES

23



NUMBER OF TABLES

02

*Corresponding Author:

Email: samaneh_foroughian@yahoo.com

Phone: +98989379384541

ORCID: <https://orcid.org/0000-0003-2268-9219>

INTRODUCTION

The micro-dusts affect human life in three ways; environmental effects and their effects on human health, their effect on life quality and the effect on climate change. Most of the micro-dusts have natural origin, but the amount of dust emission with human origin, especially in urban areas, is significant. In natural micro-dusts the higher the wind speed, it is more capable of carrying more micro-dusts, and if the wind speeds are reduced, micro-dusts died away and will not move. The three properties; particle subsidence rates, size and chemical compounds of the micro-dusts, affect the risk rate of micro-dusts. The smaller the particles are capable of being carried up to longer distance, but the coarse particles subside faster and transported less (Ziayee, 2020). The wind, the air flow, is affected by the pressure difference, which has two characteristics; direction and speed. Landsberg considers the roughness caused by the winds in the wind path as the most important reason of the wind speed decline near the ground. Micro-dusts that enter the urban texture, due to diversity in building density, diversity of plant texture density, difference in the city size, the kind of urban network and the pathways direction, altitude and form of buildings, have different effects than desert and without building textures around the city (Managhebi Pour and Shahr Ayini, 2016). In addition, different factors in the interior design of the plans affect the wind speed and consequently on the micro dusts flow. These factors include partitions, shapes and dimensions of spaces, facade elements including facade openings, its dimensions and position. The majority of this category research is on the field, location and size of the openings and doors in the plans.

Background research

In the following, a set of articles on the relationship between the interior elements of the plan, with the space ventilations and the air flow, and consequently, the motion pattern of pollutants is discussed. In this study, in a study conducted in 2019, the effect of ventilation created by

opening and closing different windows from the buildings room and the effect of openings area on the air flow and the way of pollutants dispersion has been discussed. The results show that the concentration of internal pollutants is related to the location of the pollutant source and ventilation path, and in addition, with the reduction of the open surface up to half, the pollutant concentration increases in the index room, up to 4 times and in the receiver room, up to 2 times, indicating that inlet air flow plays an important role in the dispersion of pollutants (Liu et al., 2019). In another article, in 2017, six common types of window openings have been examined from the opening direction and form perspective to examine pollutants release rate. Generally, as the opening surface increases for any window type, the amount of pollutant transfer to the space increases, however, as the window's opening surface increases, the contaminant concentration decreases. In addition, window's behavior varies in different floors and its concentration in the upper floors is lower. Finally, the best window style in terms of the least pollutant transmission has been chosen the AW model (hinge from the top) (Wang et al., 2017). In 2020, three horizontal, vertical, and square opening models, with a constant area, were investigated in terms of effect on the pollutant's dispersion, and it is concluded that with increasing height to spans ratio, the pollutants' concentration increases (Bazdidi-Tehrani et al., 2020). In a study, in 2016, exterior wall openings were also examined in different sizes and positions, and it is concluded that the air flow rate is more dependent on the air inlet and outlet size than the location of the openings (Shen et al., 2016). In this regard, in another study using CFD, ventilation flow, for different dimensions and layouts of the openings and for different directions of the wind, have been investigated and the results showed that minor changes in the dimensions and location of the window increase the volumetric flux of the normal ventilation flow and in addition, when the wind direction exceeds

45 degrees, the wind discharge operates independently of the span dimensions (Derakhshan and Shaker, 2016). In 2021, Mohammadi has specifically examined the effect of ventilation strategy on the transfer of open space pollutants aimed to identify pollutants transferred to interior spaces. The 5 different modes of windows openings in the facade wall in the street valley are compared and the movement behavior of the pollutants is analyzed in the interior spaces. The results show that, with a linear pollution source along the street, the interior spaces of the building upper floors have less pollution than the lower floors. Cross-ventilation (window faces each other) can minimize pollutant penetration into the interior space. In addition, the results show that unilateral ventilation from the valley results in the pollutants accumulation in the buildings and the accumulation rate in upstream buildings is 10-20 times higher than the downstream. For other ventilation modes, upstream buildings have little pollutants penetration. While downstream buildings have permanent penetration of particles. As a result, living in upstream buildings is a better option, and residents of upstream buildings should ensure that their spaces have cross-ventilation from the wind side, but residents of the downstream buildings, regardless of ventilation mode, are exposed to constant contamination (Mohammadi and Calautit, 2021). In the same line, Yang in 2015 and Cui in 2021 also conducted researches (Yang et al., 2015; Cui et al., 2021). In 2019, the airflow in a building model having 4 rooms with one window and one door with opening percentage of 5 and 10 % and the different condition open and closed of the room doors have been investigated. The results showed that the room under cross -ventilation has a much larger ventilation rate than one -way ventilation. The room also has a higher ventilation rate from the back room. In this study, the concentration of pollutants in the rooms is also measured (Liu et al., 2019). In a study, Liu compares three room plans with square forms, L-shaped and Z-shaped

with different ventilation states, from the window and door perspective in terms of particles sedimentation rate and mixing coefficient, and concludes the Z-shaped room has a higher mixing coefficient at the same ventilation rate. Also, the sediment speed increases as the air change rate increases, and the L-shaped room has the highest particles sedimentation rate (Liu et al., 2019). In a study, Kao examines the air flow and the particles transfer in the multi-room building for different natural ventilation patterns. A plan with 4 opening positions is compared to each other (indicating the output to input span size ratio). Particles of PM1, PM2.5 and PM10 have also been investigated. The results show that the model with the right output ventilation pattern has the lowest average speed, and in addition, the disturbance intensity for the completely open pattern is 50 % higher than other patterns. In addition, the PM10 particles removal is much easier than the smaller particles. The completely open pattern, which has the highest ratio of the output to input span size, is the most effective ventilation pattern for PM reduction, and the left output pattern, having the lowest output to input span ratio, has the worst efficiency of the particle's elimination suspend in the interior environment (Kao et al., 2009). In the following there are some studies on miscellaneous fields. In 2020, in a study the effect of urban density in three modes of low, medium and high density and wind direction for a building with fixed area and opening on both sides, was examined on the behavior of the building. The results show that by increasing urban density from 0.25 to 0.6, surface pressure difference coefficient decreases, and the rate of passing air flow decreases significantly (Shirzadi et al., 2020). The research background shows that the effect of designing the semi -open spaces, such as balconies in front of the windows, on the motion behavior of the wind flow and the subsidence of the micro-dusts, has not been taken into consideration, also the results for different climatic conditions, showing different results.

In addition, the majority of conducted research is about pollutants emission from vehicles and environmental pollution, while this study examines the status of micro-dusts of natural origin. Therefore, this study has an innovation and its results are reliable to benefit from the environmental design of architecture due to the achievement of appropriate aerial quality. In this research, it is attempted to answer the following question according to the existed gap in the subject literature: What is the role of semi-open spaces in the micro-dusts suction into the plan? The authors assume that the semi-open spaces (balconies) in micro-dusts suction rate into the plan are directly related to the structural characteristics of the plan (layout of the opposite surfaces openings and partitioning).

MATERIALS AND METHODS

The main means of evaluating are the architecture body, field measurement, full-scale laboratory measurement and reduced scale, and numerical similarity, including computational fluid dynamics (Yousefian et al., 2021). In this study, the modeling technique was used by applying computational fluid dynamics and the model validation was done by field sampling. Therefore, the type of used method is a quantitative method. In the field of architectural form modeling, some researchers used hypothetical geometry (Huang et al., 2019; Nosek et al., 2018), reality-based geometry (Gao et al., 2018; Shen et al., 2017) and a combination of both methods

(Tobón et al., 2020; Hadavi et al., 2020). Here the combination modeling of both methods is used in the Mashhad city's bed. The following research is in the applied research category and can be used in architectural design. In the modeling section of the ANSYS Design Modeler for geometry drawing, ICFM environment (ICFM) for the network production process, from fluent software from the ANSYS Fluent family to solve the current field and from single software Plot and fluent are used to display the results.

Research Index

Since the balconies are an inseparable part of the exterior form of buildings and, on the other hand, they are very effective on the interior spaces quality, in this study, the role of semi-open spaces (balconies), on the interior ventilation of the plans, and the motion pattern of micro-dusts are studied. In order to select the simulated form, by examining the internal plan of famous residential towers in Mashhad, their common plan type was identified and finally a form for modeling was selected. (Fig.1)

From the analysis of the plan was concluded that in the majority of them, the semi-open balcony space is directly related to the three spaces; kitchen, living rooms and bedrooms. Therefore, the final plan, as the base model, was designed with reality-based geometry, and other models were designed on the base model to examine the mentioned variables. (Fig.2)

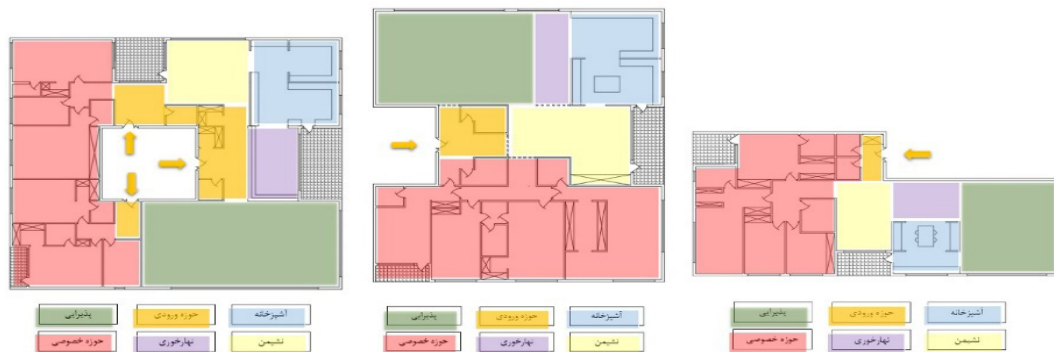


Figure 1: Internal plan of the prominent towers of Mashhad

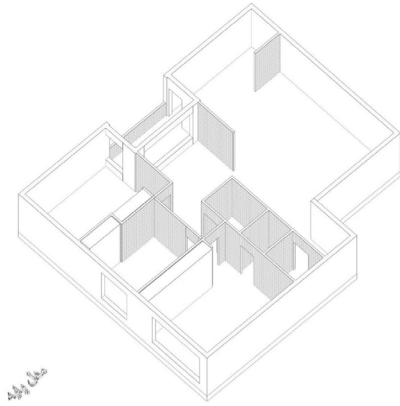


Figure 2: Basic model

In order to reach the plan form in the Mashhad climate Baran 1, Baran 2, Baran 3, towers, Residential Tower Sabz Kosar, Cheshmandaz

tower, and Ghasre Aseman tower have been investigated. Most of the investigated buildings have 4 units, three units, two units and single units in different floors, and the number of floors is 4 in the majority. In their best condition, these units have two sky-light fronts, where the wind flow enters from one front and exits from the other. In the following the internal forms of the three indicators studied include the balcony position, the dimensions and proportions of the balcony and the internal partition have been given. In all designed plans, unit area, layout of the interiors and dimensions of windows, separately the windows located in the positive pressure of the wind and windows located in the negative pressure of the wind, are considered the same. (Fig.3-5)

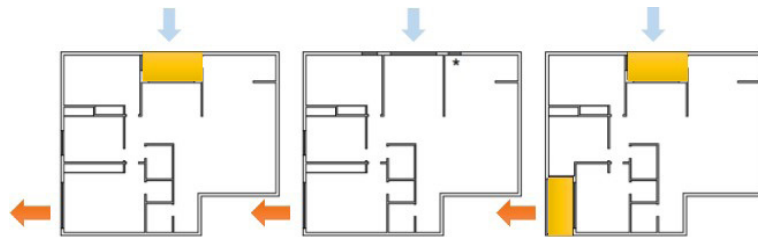


Figure 3: Plan of simulated models with balcony position index (author)



Figure 4: The plan of the simulated models with the index of dimensions and proportions of the balcony (author)

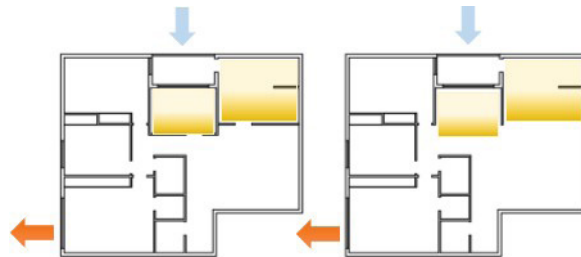


Figure 5: The plan of simulated models with the index of internal partitions (author)

Research field

The area investigated in this article is located in the residential part of Mashhad. In order to validate the results of the software, a building with a height of 92 meters with 3 floors for public use and 22 residential floors (Baran Tower 3) in Kohsangi area was selected to check the amount of particles settling In its different classes (reality-based geometry).The base model is based on the real geometry, one of the units of this tower and the other investigated models are selected based on the hypothetical geometry with the position and variable proportions of the terrace and internal partitions.

Model settings

Pollutant

The pollutants considered in this research include fine dust particles, clay (less than 2 microns) 7%, silt (2-50 microns) 69% and sand (more than 50 microns) 24%. (Tab.1)

Climate data

In this research, the data of Wind roses drawn at Iowa State University in 2022 have been used. According to the comprehensive report of environmental pollutants monitoring in Mashhad, the fine dust highest amount is related to the June and July months (Wind roses in July) that the highest wind speed is also recorded in this month. According to Wind roses in July 2022, two wind directions with an angle of 30 and 40 degrees, which have the highest frequency and the highest wind speed, have been considered. The average wind speed for these two directions is 12.96 miles per hour, equivalent to 5.8 meters per second. In addition, considering the frequency of winds in Wind roses of July, the wind angle of 34.7 degrees is considered as the wind flow average angle. (Fig.6)

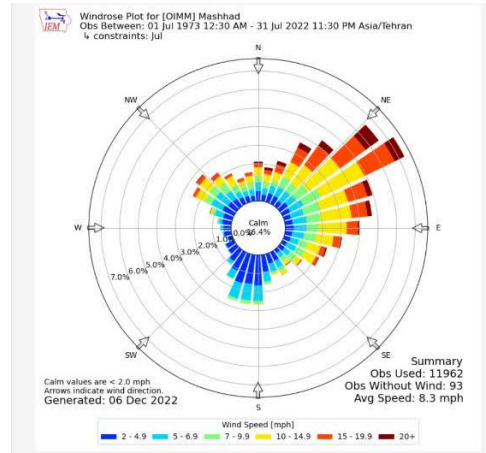


Figure 6: Wind roses plot for Mashhad in July 2022 (www.mesonet.agron.iastate.edu.com)

Boundary conditions, reticulation and equations solution type

The size of the computational domain used for CFD analysis by considering the minimums mentioned in the studies as well as the model building dimensions (28 * 54 m with a height of 92 m) on one hand and the acceptable convergence of the results on the other hand, was determined. The geometry distance to the entrance boundary and side borders is 150 meters, to the exit boundary is 420 meters, and the height of the domain is 200 meters. CFD solution is also done in a three-dimensional domain.

Due to the incompressible flow, the solver type the base pressure has been considered. The solution of the flow has been done in a steady and K-Omega-SST model has been used to model the flow.

The inlet fluid is air, with an inlet velocity of 5.8 m/s, a density of 1.225 kg/m³, and a viscosity of 1.7894*10⁻⁵, in the form of UDF, which represents the effects of Ultrafine Depth Filtration on the velocity profile is considered.

Table1: amount and size of particles in the study area (author)

Sand (more than 50 microns)					Silt (2-50 microns)			clay
small	very small	very large	large	medium	small	very small	Less than 2 microns	
19%	5%	36%	17/5%	5/8%	4%	3%	7%	

The formula of wind speed vertical input profile $u(z)$, turbulent kinetic energy $k(z)$ and turbulence loss rate $\epsilon(z)$ is specified as follows.

$$u(z) = \frac{u^*}{K} \cdot \ln\left(\frac{z+z_0}{z_0}\right)$$

$$u^* = K \cdot \frac{u_{ref}}{\ln\left(\frac{H_{ref} + z_0}{z_0}\right)}$$

$$k(z) = \frac{u^{*2}}{\sqrt{c_\mu}}$$

$$\epsilon(z) = \frac{u^{*3}}{K(z+z_0)}$$

The boundary of the surrounding walls mummy has a no-slip condition and includes the ground surface and all walls of the building. In order to connect velocity and pressure, a simple model has been used, and to discretize the equations of pressure, momentum, turbulent kinetic energy and specific loss rate, the second order upwind direction has been used. The Under-relaxation have been used for pressure 0.3, for density 1, for momentum 0.7, for turbulent kinetic energy and specific loss rate 0.8, and for turbulent viscosity, a coefficient of 1 has been used. It should be noted that the convergence absolute criterion is considered 10^{-5} for all equations.

Validation

In this study, in order to validate the results of the software field sampling method and laboratory analysis were used. For this purpose, marble sampling containers, in June, which have the highest amount of micro-dust particles, have been placed for a month on 5 floors of reality-based geometry (Baran Tower 3) including floors 4, 8, 12, 16 and 20. (Fig.7-8)



Figure 7: Baran Tower 3



Figure 8: Marble sampling vessels in the balcony of Baran Tower 3

At the end of the month, marble containers are collected and the marbles are washed with distilled water along with their container. Then the raw filter paper is weighted to determine the weight of each filter paper. After washing and separation of the soil from the marbles and container, the distilled water along with the washed micro-dusts from the container and the marbles, passed through 2 micrometer filter paper that its raw weight is specified, and after complete water passing from the paper, the micro-dust particles remain on the filter paper. In the following, a filter paper with the remaining micro-dusts on it is put in the oven to dry the paper and the micro-dusts. Finally, after they dry completely, the paper is again weighed along with the micro-dusts on it, and the weight obtained at this stage, deducted from the weight of the raw filter paper, to determine the precise weight of the remaining micro-dusts. (Fig. 9)

The results of samples weighting and software results are giving in the following table: (Tab. 2)

It is clear that in the simulation research method, due to the complexity of the calculations, some variables are considered consistent or they are ignored. So, the results that are extracted from the numerical simulation and field method are not fully compatible with each other, but with an error percentage, a clear relationship between their results can be found. (Fig. 10)



Figure 9: Weighing the studied sample (author)

Table 2: Comparison of the mass of deposited particles in two study methods (author)

Floor	Height m	particle mass g (extracted from the software)	particle mass g (field studies)
Fourth Floor	25/5	15/86	4/49
Eighth floor	39/5	14/8	2/12
12th floor	53/5	14/96	1/56
16th floor	67/5	13/66	0/9
20th floor	81/5	13/5	0/4

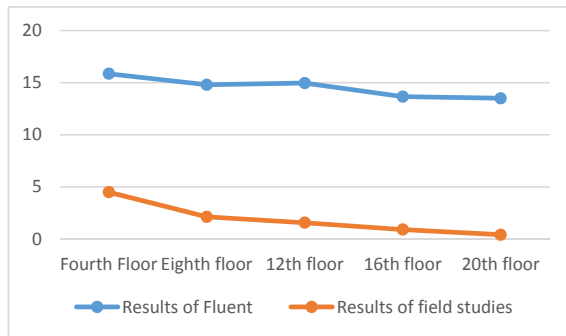


Figure 10: Comparison of the mass of settled particles extracted from software and field studies (author)

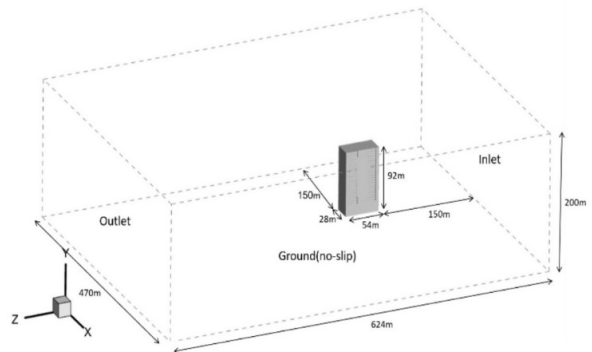


Figure 11: Software simulation of Baran tower (author)

According to Figure 11, the overall trend of reducing the number of micro-dusts with height increases in two methods of software and field studies, they greatly adapt to each other. The amount of subsidence of the micro-dusts decreases with the height of the building. (Fig. 11)

After validating the software results and finding out the software's accuracy and its settings, other models have been simulated and the results are extracted.

DISCUSSION AND FINDINGS

The variable of the place of the balcony position in the internal plans

According to the studies on the exterior form of high buildings, it has been concluded that the design of the balconies in the outer form reduces the wind speed at the balcony's inlet and thus the smaller number of micro-dusts enter the balcony space and, consequently, the interiors (Foroughian et al., 2024). For this reason, the

first investigated indicator related to internal ventilation and the behavior of micro-dusts in the interior spaces is the position of the balconies. In examining the balconies position index and its effect on internal ventilation and the micro-dusts flow, three forms are compared to each other: these three forms are:

Form 1: without balcony

Form 2 (Base Form): Balcony in the pressure area (windward)

Form 3: Two balconies in the pressure and suction area (a windward balcony and a leeward balcony)

The results are explained as follows in two branches:

Wind flow analysis

In general, from the comparison of the wind speed contours in the three studied forms, it can be concluded that among the interior spaces, the wind flow entering path from the windward balcony wall, to flow exiting from the window of bedroom 1 and 2, the air flow has a higher speed, and creating a break in the wind flow path, reduces the speed to a significant extent (the wind flow speed is higher in bedroom 1 than in room 2). Of course, the wind speed reduction rate due to the change in the movement direction has an inverse relationship with the wind speed, and the higher the inlet wind speed, the lower the effect of the wind direction change on the wind speed reduction.

The presence of a balcony in the wind flow span (area with positive wind pressure) reduces the flow speed in the interior spaces and the air

flow enters the interior spaces at a lower speed than the speed at the balcony inlet. In the comparison between the three openings designed in the balconies, the flow speed in the windward is higher than the window perpendicular to the wind flow. As a result, in the comparison between form 1 and the basic form, the presence of a balcony in the basic form, on one hand, reduces the wind speed at the entrance of the air flow to the interior space, and on the other hand, due to the presence of the balcony, it is possible to design perpendicular windows, and in this term the wind speed at the entrance of all three windows decreases (the decrease in wind speed is more noticeable for windows that are perpendicular to the wind flow). (Fig. 12)

In all three forms, the highest wind speed is related to the corridor space of the bedrooms, which is due to the reduction of the cross-sectional area of air passage in these spaces. The design of a semi-open space (balcony) in the suction area, unlike the balcony in the pressure area, increases the wind flow speed to some extent, and the design of the openings facing the suction area balcony has a direct relationship with the increase in the flow speed in the interior space.

Analysis of micro-dust flow

In the three forms examined in this field, the number of particles entering the environment is in the range of 250 to 290 thousand particles. As a result, these three forms do not differ much from each other in terms of the incoming particles amount. In form 1, the wind speed is at the

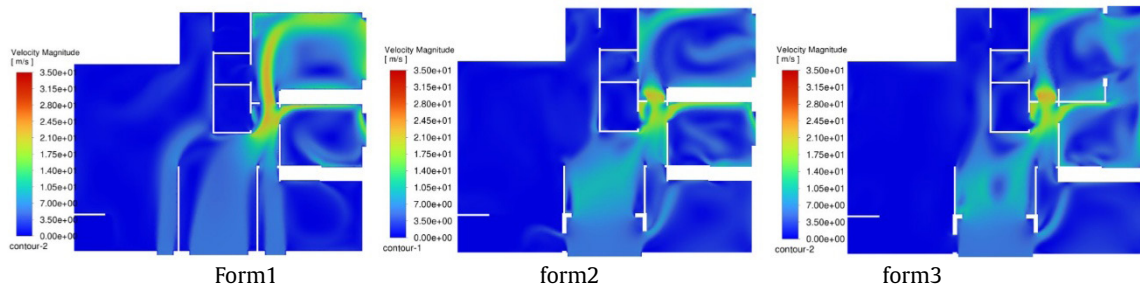


Figure 12: Wind speed at a height of 180 cm

highest amount and the movement of the flow occurs linearly, as a result, the majority of particles entering the environment move and leave in the same direction as the wind flow. Due to the linear movement of wind flow, the concentration of particles in other spaces is lower. In this form, about 35% of the particles subside, that the percentage of particles with larger sizes is less. (Fig. 13)

In the basic form, the wind speed is reduced to some extent and the flow is more uniform than in form 1, and as a result, particles are present in a wider area of space. On the other hand, the created vortices increase the presence time and increase the concentration of particles. In this form, the amount of particle settling due to the higher concentration of particles in the environment is slightly higher than in form 1, but it does not have much different (38% of particles subside). (Fig. 14)

In form 3, also the concentration of particles in the inner space is similar to form 1, but the particles, especially those with a smaller diameter, subside more. (Fig. 15)

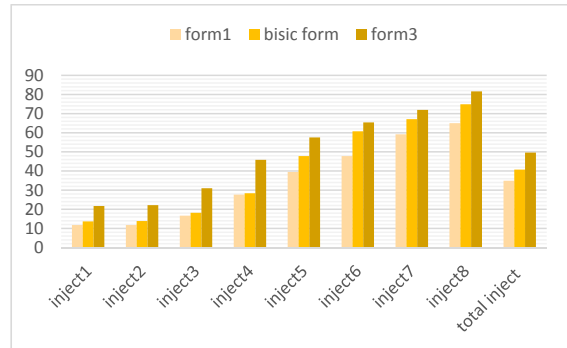


Figure 15: Comparison of the percentage of particles deposited on the floor in different diameters (information about the diameter of the particles is given in section 4-4) (author)

Balcony proportions variable in interior plans

Regarding the variable of balcony proportions, two forms are compared with the basic form, which are as follows:

Form 1: Balcony with more span length and less depth (5.4m *1.2 m)

Form 2 (basic form): balcony with proportions (3 m*1.5m)

Form 3: Balcony with shorter span length and greater depth (2.5m*1.8m)

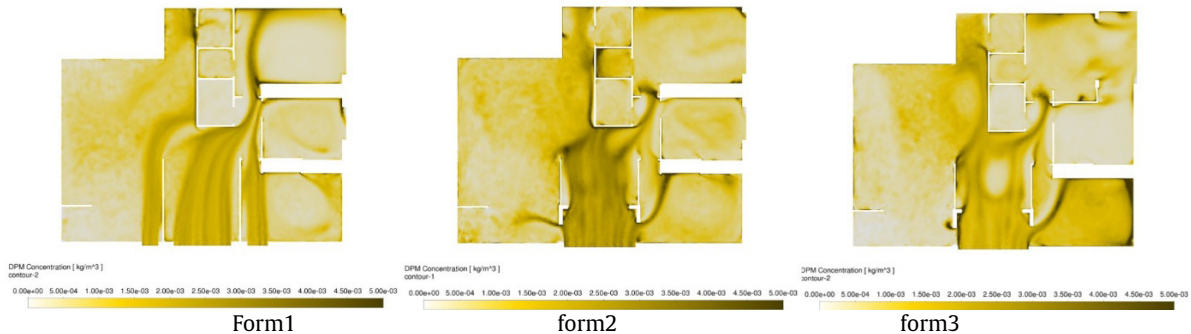


Figure 13: Concentration of particles at a height of 180 cm (the height of dust inhalation by the user)

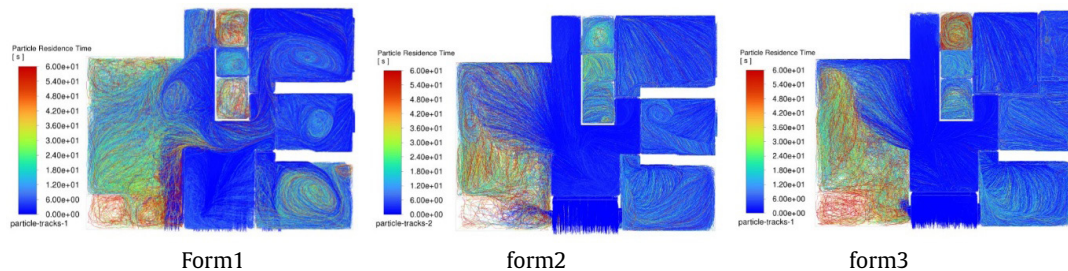


Figure 14: Time of presence of particles on the ground and before the particles settle (author)

In the following, the above three forms are compared with each other from two perspectives of wind flow and micro-dusts flow analysis.

Wind flow analysis

In form 1, due to the increase of the balcony span compared to the basic form, the cross section of the wind flow entering the balcony has increased and as a result the amount of flow entering the balcony increases. On the other hand, because the depth of the balcony is less, the wind speed is higher compared to the basic form. Due to the larger volume of the balcony and the higher speed of the air flow, the air entering the balcony also enters the space through two windows perpendicular to the wind flow, which causes the air flow to be dispersed over a wider area of the space and ultimately causes a uniform flow. (Fig. 16)

As mentioned earlier, the greater the depth of the balcony, the lower the flow speed. Increasing the speed in shallower and wider balconies enters the wind flow into the space at a higher speed, and of course, the wind speed in the corridors of the bedroom is also increased. This increases the speed of the wind flow inside the bedrooms (especially bedroom 1, which has an entrance without a rotation angle).

Analysis of micro-dusts flow

Form 1 has the highest wind speed among the three examined forms, as a result, the majority of particles entering the environment exit through the exit window, and the number of exited particles with smaller diameter is much more. On the other hand, in this form, better flow uniformity occurs, as a result, the wind shadow area is

also reduced and the presence of particles with a larger diameter is evident in this area. Also, due to the uniformity of the flow, the particles concentration in the entire space is almost uniform, and most of them include larger diameter particles, which, according to Figure 18, these particles also eventually settle. As a result, this form has the lowest concentration of particles in the environment (especially fine particles) and the highest rate of subsidence. (Fig. 17)

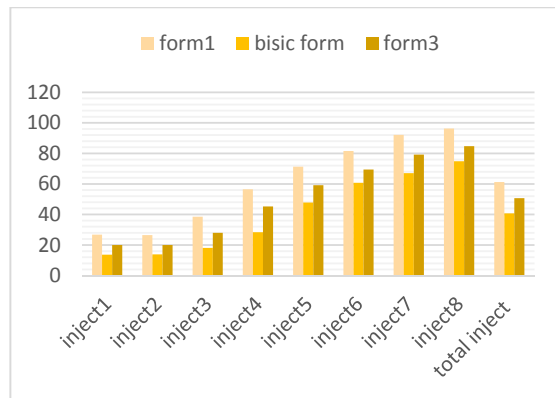


Figure 17: Comparison of the percentage of sedimentation of particles on the floor in different diameters (information about the diameter of the particles is given in section 4-4) (author)

From Figure 18, in the basic form, it is concluded that, due to the lower speed and the creation of vortices, the entering particles remain in the space for a longer time and the concentration of the particles is higher. On the other hand, based on the results of Figure 18, particles with different diameters, especially fine particles, subside less and in the end, it is the most unsuitable form from the interaction with the phenomenon of fine dust point of view. (Fig. 18)

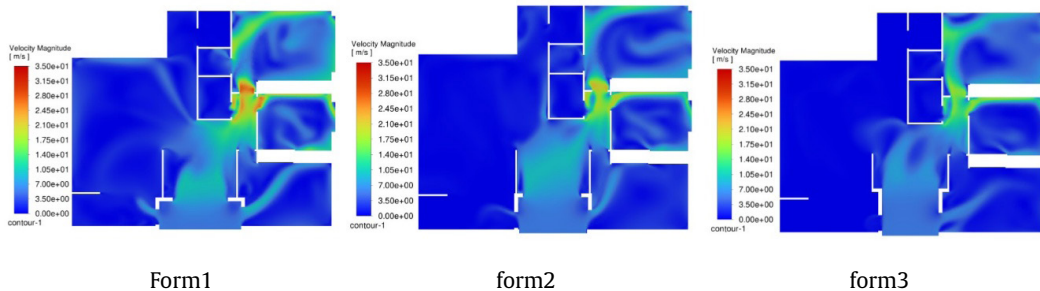


Figure 16: Wind speed at a height of 180 cm (author)

In form 3, due to the lower speed of the wind flow compared to the other two forms, fewer particles enter the space and the concentration of particles and the duration of their presence are less. In this form, about 50% of the particles subside, but the amount of subsidence is less than form 1, which is about 61%. Comparing forms 1 and 3, it can be concluded that more particles are entered in form 1 (about 331,000 particles), among which the smaller particles exit from the window with the air flow and the larger particles subside, and finally the concentration of particles in the environment is at the lowest possible state and the subsidence of particles is at the highest value. In Form 3, due to the lower speed of the wind flow, about 230,000 particles enters the environment, the majority of which are fine particles (due to the low speed, coarse particles enter the space less). Among the entered particles, which have a higher pathogenic power due to their smaller diameter, 50% of them subside. (Fig. 20)

Variable spatial partitioning in interior plans

In the basic plan designed for this research (basic form), which is the most frequent plan in Mash-

had city, the balcony has a direct relationship with three interior spaces. These three spaces include: bedroom, kitchen and living room, except the bedroom, which is considered a closed space, the other two spaces are designed as an open space. In the continuation of the research, the effect that internal partitioning (*form 1*) has on the distribution of wind flow and fine dust flow, because of spatial separation with walls and transform open spaces into closed ones, will be discussed.

Wind flow analysis

As shown in pervious figure, the presence of a balcony in the pressure area reduces the wind speed entering the interior spaces. But the presence or absence of internal partitions is effective on the balcony performance in reducing the wind flow speed. From Figure 20, it is understood that the conversion of internal open spaces into closed spaces increases the amount of speed reduction due to the placement of the balcony in the windward opening, and in the case of the openings perpendicular to the wind flow, the wind flow speed increases. Of course, this increase in speed is not only limited to enclosed spaces, and in

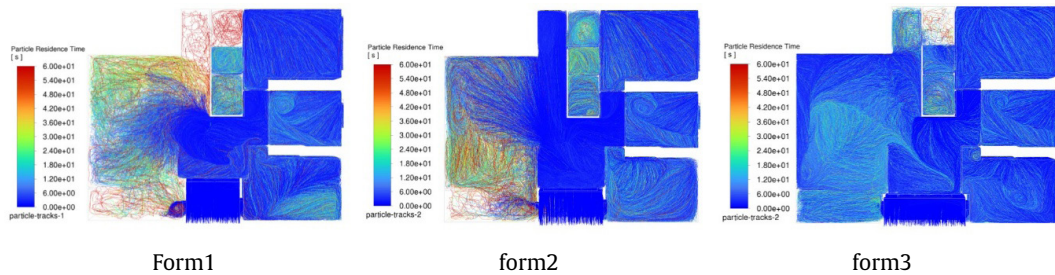


Figure 18: The time of presence of particles in the floor and before the sedimentation of the particles (author)

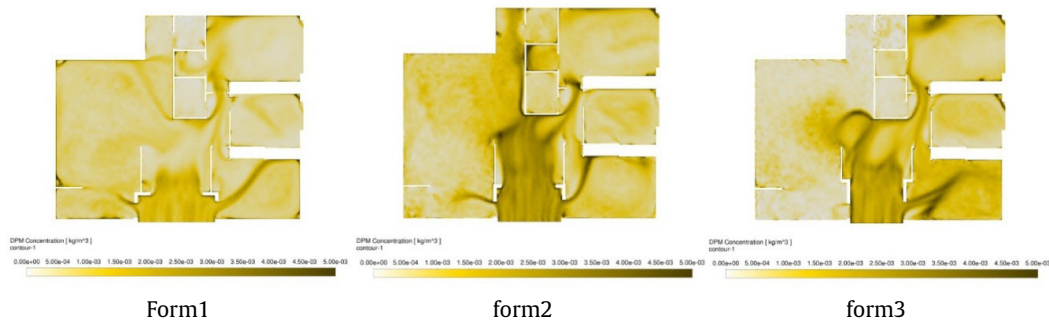


Figure 19: Concentration of particles at a height of 180 cm (the height of dust inhalation by the user) (author)

the case of designing partitions and converting open spaces into closed ones, the wind speed increases in all interior spaces, including corridors, bedrooms, and living rooms. (Fig. 20)

It is noteworthy that the conversion of the kitchen and living room open spaces into enclosed spaces has affected the function of the windows located in the balcony, and unlike the basic form, this time, the window is perpendicular to the wind flow, inside the balcony, it enters the wind into the space at a higher speed and the ventilation speed increases in the spaces behind them. In Form 1, due to the multiple entrances and exits against the wind flow, the flow is created in a wider area of the interior spaces and is more uniform.

Analysis of micro-dusts flow

In general, the existence of internal partitions increases the wind flow speed, reduces vortices, and reduces the presence time of particles and uniformity of wind flow. The vortices created at low speed are effective on suspending the particles at the height of the user, in the basic form, and this causes an increase in the particle's concentration in the interior spaces. Because the particles entered into the environment are not able to be carried by the wind and remain suspended due to the existence of vortices. According to Figure 21, the particles in the basic form in all diameters, although their concentration in the environment is higher, subside less compared to form 1 (according to the diagram, the highest number of suspended particles in the environment is related to finer particles and par-

ticles with a larger diameter subside). (Fig. 21)

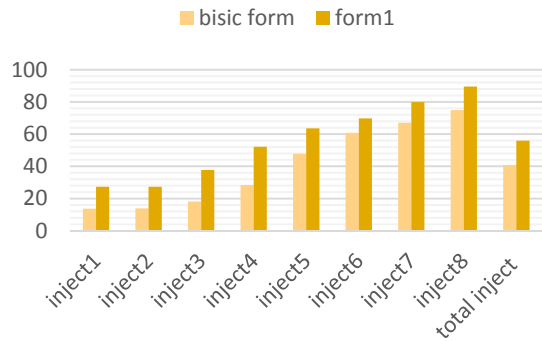


Figure 21: Comparison of the percentage of sedimentation of particles on the floor in different diameters (information about the diameter of the particles is given in section 4-4) (author)

According to Figure 22, the duration of the presence of particles in form 1 is less and the wind speed is higher, as a result, it has the ability to carry more particles outside the environment and the particles concentration inside the space decreases. On the other hand, according to the diagram, a higher percentage of particles entered into the environment subside. (Fig. 22-23)

RESULT AND CONCLUSION

There are two challenges related to micro-dusts flow and construction: disposal of micro-dusts or their subsidence. The answer to the question of whether it is more appropriate to dispose of micro dusts or their subsidence is not the same in all indicators and in the external and internal form of the plans. But in general, micro dusts are more harmful to humans when they remain suspended in the air. Therefore, if they somehow

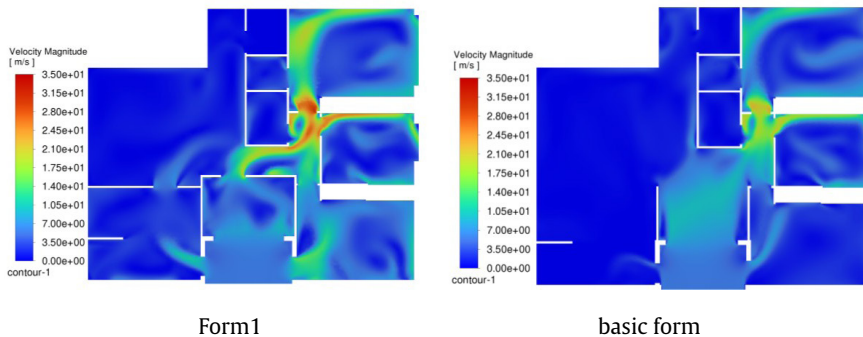


Figure 20: Wind speed at a height of 180 cm (author)

move away from the human presence space and the height of his/her inhalation, or enter the space but subside and do not remain suspended, they have the highest efficiency in terms of human health. As mentioned in the previous paragraph, the analyses of this treatise can be used in two general parts.

a) Motion pattern of wind flow and natural ventilation

b) Motion pattern of micro-dusts

The results of this treatise in part (a) are used even for other areas that are not involved with the micro-dusts phenomenon, in terms of the results that improve ventilation in interior spaces.

Wind flow analysis results and findings

This part of the research investigates the ventilation in interior spaces, due to the design of semi-open spaces such as balconies, for three indicators; the balcony location, the proportions of the balcony and the interior partitions design. From the analysis of the obtained results from the software, the following results are concluded:

1. In general, the design of the balconies, in the positive wind pressure front, reduces the wind flow entering the building, but makes the distribution of the wind flow more uniform. Now, if the interior plan, in addition to the windward balcony, also has a balcony on the negative pressure front of the wind flow (flow outlet), on the one hand, the flow will be created in a wider area of the interior spaces, and on the other hand, the ventilation will be done at a higher rate. Therefore, the design of semi-open spaces in the inlet and outlet of the wind flow simultaneously improves the ventilation of the interior spaces.
2. The wider and shallower the balconies located at the entrance of the wind flow, the higher the wind flow speed in the interior spaces, and in addition, the area in the shadow of the wind decreases and the ventilation occurs on a wider level from the internal plan, at a higher speed.
3. The design of internal partitions, in the spaces behind the balcony, improves the per-

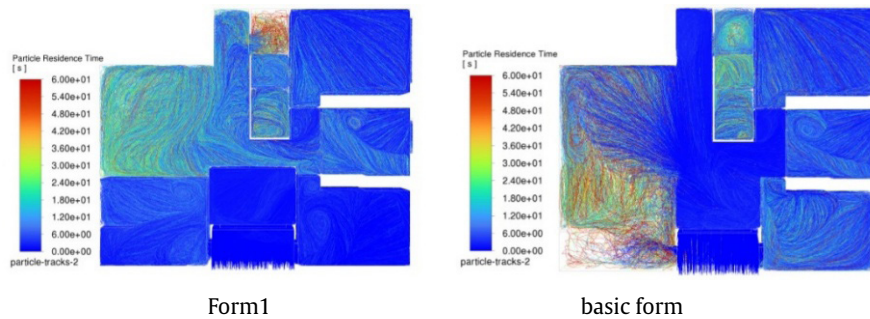


Figure 22: The time of presence of particles on the floor and before the particles settle

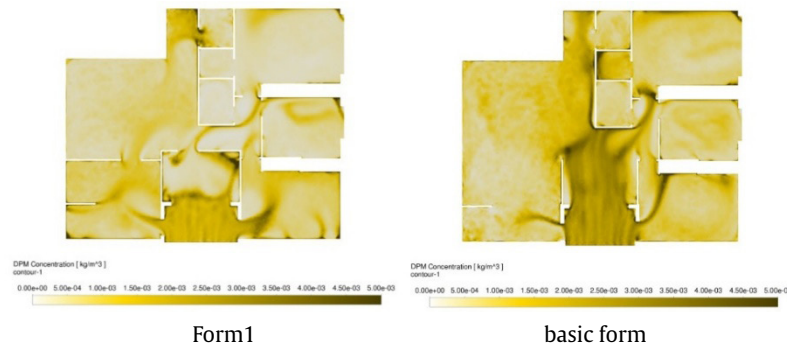


Figure 23: Concentration of particles at a height of 180 cm (the height of dust inhalation by the user)

formance of the windows perpendicular to the wind flow and the flow is become more uniformly and has a higher speed.

The results and findings of the micro-dusts flow analysis

There is a direct relationship between the wind flow speed and the particles concentration in interior spaces, so that the higher the wind speed, the more the particles are transported outside the environment and the concentration of the particles in the interior spaces decreases. But sometimes, due to the arrangement type and dimensions of the spaces in the plan, at the wind flow medium speeds, vortices are created that prevent the transfer of particles outside the internal spaces, and the particles remain in the environment and gradually, their concentration increases. Now, if the vortices have the ability to carry particles, they will remain suspended in space, otherwise, the particles will subside. The most appropriate way to deal with the micro-dusts phenomenon is to prevent them from entering human living spaces, but due to the need for ventilation in interior spaces, part of the particles inevitably enter the space. In this situation, removing micro dusts from the environment or their subsidence, both are suitable. On the other hand, their suspension in the air, especially particles with a smaller diameter, causes the particles to enter the respiratory tract and are harmful to humans.

According to the above explanations, it can be concluded from this research that:

1. The balconies design simultaneously at the entrance and exit of the wind flow increases the subsidence number of suspended particles and the concentration of particles decreases. On the other hand, the plan design with only one balcony at the entrance of the wind flow has the most inappropriate function in interaction with micro dusts.
2. The balconies design with less depth and wider span is subsided smaller particles in interior spaces with a higher percentage and is more suitable for areas with the micro dusts blowing risk.
3. The design of closed spaces behind the balconies, compared to the design of open spaces such as the kitchen, reception and living room, improves the design in dealing with the micro-dusts flow.

REFERENCES

- Bazdidi-Tehrani, F. Masoumi-Verki, S & Gholamali-pour, P. (2020), "Impact of opening shape on airflow and pollutant dispersion in a wind-driven cross-ventilated model building: Large eddy simulation", *Journal Pre-proof*, SCS 102196, Doi:10.1016/j.scs.2020.102196
- Ciu, P. Zhang, Y. Chen, W. Zhang, J. Luo, Y & Huang, Y. (2021), "Wind-tunnel studies on the characteristics of indoor/outdoor airflow and pollutant exchange in a building cluster", *Journal of Wind Engineering & Industrial Aerodynamics*, 241. 104645, Doi: 10.1016/j.jweia.2021.104645
- Derakhshan, S & Shaker, A. (2016), "Numerical study of the cross-ventilation of an isolated building with different opening aspect ratios and locations for various wind directions", *International Journal of Ventilation*, ISSN: 1473-3315, Doi:10.1080/14733315.2016.1252146
- Foroughian, S. Zandieh, M. Medi, H & Karimi, F. (2024), "Evaluation of the effect of horizontal holes in the tall buildings on the distribution of fine dust", *Naqshejahan - Basic studies and New Technologies of Architecture and Planning*, 13(4): 73 - 92. <http://bsnt.modares.ac.ir/article-2-72988-fa.html>
- Huang, YD. Hou, RW. Liu, ZY. Song, Y. Cui, PY & Kim, CN. (2019), "Effects of wind direction on the airflow and pollutant dispersion inside a long street canyon", *Aerosol Air Qual Res*, 19(5). Doi:10.4209/aaqr.2018.09.0344
- Kao, H.M. Chang, T.J. Hsieh, Y.F. Wang, C.H & Hsieh, C.I. (2009), "Comparison of airflow and particulate matter transport in multi-room buildings for different natural ventilation patterns", *Energy and Buildings*, 41. 966-974, Doi:10.1016/j.enbuild.2009.04.005
- Liu, X. Li, F. Cai, H. Zhou, B. Shi, S & Liu, J. (2019), "A numerical investigation on the mixing factor and particle deposition velocity for enclosed spaces under natural ventilation", *Building Simulation*. Doi:10.1007/s12273-018-0497-x

- Liu, X. Lv, X. Peng, Z & Shi, C. (2019), "Experimental study of airflow and pollutant dispersion in cross-ventilated multi-room buildings: Effects of source location and ventilation path", *Journal Pre-proof*, SCS 101822, Doi:10.1016/j.scs.2019.101822
- Liu, X. Peng, Z. Liu, X & Zhou, R. (2019), "Dispersion Characteristics of Hazardous Gas and Exposure Risk Assessment in a Multiroom Building Environment", *International Journal of Environmental Research and Public Health*, P. 17.199, Doi:10.3390/ijerph17010199
- Managhebi Pour, F. Shahr Ayini, M. (2019), "Evaluation of air flow in urban open space", *The first national building and city energy conference*. <https://civilica.com/doc/494259/>
- Mohammadi, M & Calautit, J. (2021), "Impact of Ventilation Strategy on the Transmission of Outdoor Pollutants into Indoor Environment Using CFD", *Sustainability Journal*, 13. 10343, doi:10.3390/su131810343
- Shirzadi, M.R. Tominaga, Y & Mirzaei, P.A. (2020), "Experimental study on cross-ventilation of a generic building in highly-dense urban areas: Impact of planar area density and wind direction", *Journal of Wind Engineering and Industrial Aerodynamics*, 196. 104030, Doi: 10.1016/j.jweia.2019.104030
- Tobón, AM. Moncho-Esteve, IJ. Martínez-Corral, J & Palau-Salvador, G. (2020), "Dispersion of CO using computational fluid dynamics in a real urban canyon in the city center of Valencia (Spain)", *Atmosphere (Basel)*, 11(7), Doi:10.3390/atmos11070693 <http://dx.doi.org/10.3390/atmos11070693>
- Wang, J. Zhang, T. Wang, S & Battaglia, F. (2017), "Gaseous pollutant transmission through windows between vertical floors in a multistory building with natural ventilation", *Accepted Manuscript*, ENB 7854, Doi:10.1016/j.enbuild.2017.08.025
- Yang, F. Kang, Y. Gao, Y & Zhong, K. (2015), "Numerical simulations of the effect of outdoor pollutants on indoor air quality of buildings next to a street canyon", *Building and Environment*, 87. 10-22, Doi:10.1016/j.buildenv.2015.01.008
- Yousefian, S. Pourjafar, M. Moshfeghi, M & Mahdavi-nejad, M. (2021), "Assessing the effects of urban canyon's direction on air flow pattern and CO dispersion using CFD (A case study of Tehran)", *Italian Journal of Planning Practice*, 11;1:P101-121. <http://www.ijpp.it/index.php/it/article/view/97/88>
- Ziayee, A. (2020), *Spatial and temporal distribution of geochemical characteristics, mineralogy of fine dust in Razavi Khorasan province*. Ph.D. Thesis. Mashhad Ferdowsi University.

COPYRIGHTS

©2023 The author(s). This is an open access article distributed under the terms of the Creative Commons Attribution (CC BY 4.0), which permits unrestricted use, distribution, and reproduction in any medium, as long as the original authors and source are cited. No permission is required from the authors or the publishers.



HOW TO CITE THIS ARTICLE

Foroughian, S., Zandieh, M., Medi, H., Karimi, F., & Mahdavi-nejad, M. (2024). Evaluation of the effect of semi-open spaces on the ventilation of indoor spaces and the distribution of fine dust. *International Journal of Urban Management and Energy Sustainability*, (), -. DOI: [10.22034/ijumes.2024.2045510.1267](https://doi.org/10.22034/ijumes.2024.2045510.1267)

