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Investigating the Effect of Balcony Types on the Naturally-Ventilated Buildings

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Investigating the Effect of Balcony Types on the Naturally-Ventilated Buildings

Elahe Mirabi*, Nazanin Nasrollahi

University of Ilam, Faculty of Engineering, Architecture Department, Pajoohesh boulevard

Mehdi Dadkhah

University of Tehran, Faculty of Engineering, Mechanic Department, Hafez street

*Corresponding author: **goodness.41@gmail.com**

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Natural ventilation is application of natural drift power of wind. Wind can enter and exit buildings through the openings on facades. Hence, Form of facades can impact the air flow behaviour and consequently natural ventilation because they can change the pressure distribution on facades. Moreover, difference between wind-induced pressure on windward and leeward facades is the most important factor affecting natural ventilation. So, it is worthy to focus on facade details in order to enhance natural ventilation. Particularly, geometrical details of facades such as protrusions and indentations e.g. balconies can be considered effective elements on average pressure distribution on both windward and leeward facades, changing pressure difference between these facades. This difference can drive the air flow towards interior spaces significantly. Although this basic rule has been used by different researchers in order to increase natural ventilation buildings, the most research has been studied buildings with flat facades. Therefore, the goal of this research is investigating effects of balcony types on the naturally-ventilated buildings. Three types of balcony are simulated and changes in wind pressure caused on facades are analysed. All these simulations are carried out for normally (perpendicular) and obliquely incident wind. This study is performed with Ansys Fluent 18 for all simulations. The results showed that balcony types can affect the pressure distribution on the opposing facades of buildings, leading to the more or less pressure difference between these two facades. These results show that protrusion (protrusive balcony) can cause more complicated pattern of the wind pressure on facades than the others. Also, re-entrant balcony causes the more pressure difference between the opposing surfaces and enhances wind-driven ventilation in buildings more considerably than the protrusive one.

Keywords: Air flow, Balcony, Façade geometry, Natural ventilation.

Introduction

Natural ventilation is application of natural drift power wind. wind can enter and exit buildings through the openings on windward and leeward facades respectively (Khan et al. 2008). When wind flow is blocked by a building, high wind pressure is induced on the windward façade, while the leeward experiences the low pressure. This difference can drive the air flow towards interior spaces (Aflaki et al. 2015) The more pressure difference can drive more air flow across the buildings. This basic rule has been used by different researchers in order to enhance natural ventilation across buildings and comfort condition (Aynsley, 2014). Since the principles of ventilation shows how exterior and interior air flow are connected with each other and form of facades can impact the air flow behaviour (Catto Lucchino and Goia 2019), wind characteristics around facades play

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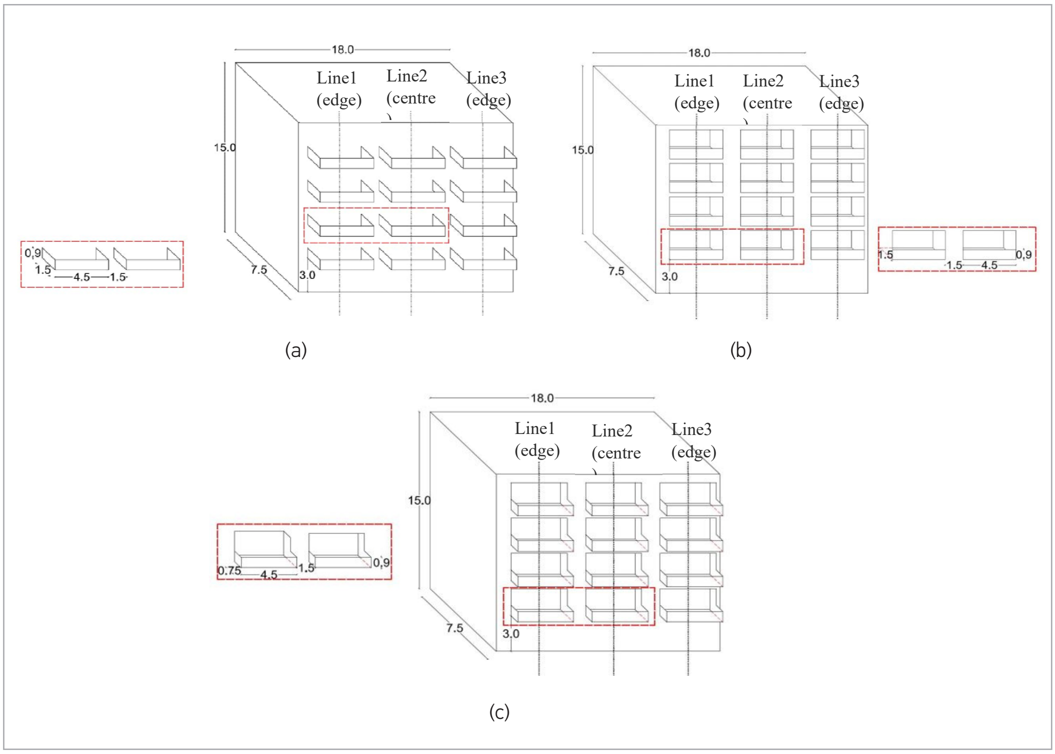
a part in assessing the wind-driven ventilation (Charisi et al. 2019). Wind loads on facades are affected by considerable number of conditions, including wind direction (Liu et al. 2019) building surrounding and geometry (Meng et al. 2018). Building geometry, in this vein, is a key factor in ventilation process across buildings (Aflaki et al. 2015). So, it would be worthwhile to focus on building geometry in order to enhance natural ventilation (Iousef et al. 2019). Particularly, building facades (Bedon et al. 2019) including protrusions and indentations such as balcony not only can be considered a favourite space (Kennedy and Buys, 2010) but also are the most effective elements on average pressure distribution on facades (Hui et al. 2019). Balcony is the most influential element to change wind velocity and pressure (Allard and Ghiaus, 2012). To predict how balconies on facades can affect the natural ventilation of buildings, various experiments or simulations related to air flow are needed. All this process requires data namely pressure coefficient to analyse natural ventilation (Costola et al. 2009). Pressure coefficient can play a vital role in ventilation determined through field measurement (Gough et al. 2018; Persily, 2016). Tunnel wind experiment (Richards et al. 2007). Numerical simulations by calculation fluid dynamics (CFD) (Cao, 2019; Daemei, 2019). Field measurement suggests real situation and complexity about studies, However, it can be done with limited control on the boundary conditions and in limited spots. On the other hand, tunnel wind experiment allows to control boundary layers. But some time, this way can be too expensive (Reinhold, 1982). CFD simulations allow to assess parameters and suggest studies (Blocken, 2018), including Natural ventilation of buildings (Tong et al. 2019), dispersion of pollution (Dhunny et al. 2018), heat transfer (Allegrini and Carmeliet, 2018) and so forth. One study showed that the results stem from Fluent software are reliable as well as wind tunnel experiment for balcony and air flow (Montazeri and Blocken, 2013). There is some research about balcony and its impact on the thermal comfort, natural ventilation, air flow, and energy usage. One study assessed the influence of combining door and balcony on the across air circulation in buildings (Prianto and Depecker, 2002). The results showed that direction between balcony and opening and the location of opening can change the interior natural ventilation rate and the lower height of balcony ceiling can decrease the ventilation rate (Ai et al. 2011). The study carried out on building appurtenances resulted that balconies can cause more complexity in the air flow behaviour surrounding buildings and decrease wind loads on facades (Stathopoulos and Zhu, 1988). According to another research, wind pressure distribution on windward façades is much more complicated than leeward facades and balcony can enhance natural ventilation (Chan and Chow, 2010). In simple terms, balcony can be considered as a scoop able to drive outdoor air flow towards interior spaces (Mohamed et al. 2008). Additionally, balcony can complicate and change air flow and turbulence characteristics, leading to decrease in natural ventilation in some situations (Mohamed et al. 2009). Through changing ventilation process, balcony can help habitants with providing better thermal comfort conditions (Omrani et al. 2015; Omrani et al. 2017). specially in high-rise buildings (Mohamed et al. 2011). Although balcony can be deemed as an important determining factor to change natural ventilation, most research has studied buildings with simple geometry and flat facades (Lukiantchuki et al. 2019). Therefore, this study aims to investigate effects of balcony types (protrusive, re-entrant and semi protrusive-semi reentrant balconies, presented as balconyp, balconyr and balconys respectively) on the natural ventilation.

Research method

This study uses CFD to investigate the natural ventilation rate impacted by three types of balcony in a model used in several articles. These articles compared mainly natural ventilation in buildings with and without balcony. So, the goal of this research is to go further and make comparison between the impact of balcony types, including protrusion (balconyp), reentrant (balconyr) and semi protrusion-semi reentrant (balconys) on natural ventilation. Each model is simulated with both perpendicular and oblique direction of wind. CFD is the commonly-applied method to evaluate air flow characteristics indoor and outdoor thanks to the considerable lower cost compared to experimental tests and its accuracy. Hence, CFD has been implemented as a valuable strategy to simulate natural ventilation of buildings in several studies. This study is performed with Ansys Fluent 18 for all simulations. Three dimensional models are generated within a computational domain using Workbench software. The building and domain size are in accordance with earlier research (Montazeri and Blocken, 2013). The building is modelled in width of 18m, depth of 7.5m and height of 15m. Three balconies with width 4.5m, depth 1.5m and height 0.9m are positioned at the first up to the fourth floors. Three vertical lines (1, 2, 3) are considered in the middle of balconies to measure average pressure on facades along them (Fig. 1). Windward and leeward facades are named opposing facades/ surfaces in this study.

Fig. 1

Base model and guidelines (a) $balcony_p$ (b) $balcony_r$ (c) $balcony_s$



The dimensions of the domain are modelled with 318 x 307.5 x 90 m^3., Velocity (U) as inlet, pressure as outlet, symmetry for top and side faces and wall for the ground are considered for boundary-conditions. RNG k- ε, the pressure-velocity coupling scheme, second order upwind, steady-state mode and gravity are chosen for solver settings. A maximum value of stretching ratio is entered 1.2 in the surroundings of the model. The buildings are modelled as a bulk in wide open surrounding. The settings remain unchanged over all simulations. Just as the reference article (Montazeri and Blocken, 2013) and for strong validation, this paper uses the general log wind profile for CFD simulations. This way makes the results practically comprehensive and useable with no regard to climates. This profile estimates confidently the wind gradient varying along with increase in height. The outputs are pressure coefficient (C_p) contours where different values of C_p for 3 types are compared to each other. The c_p is a non-dimensional quantity characterising the relative pressures caused by air flow on a surface (façade) and determining crucial areas in a model. To predict wind loads on these crucial areas, the pressure coefficient with confidence is applied. The maximum value for C_p is plus one, but the minimum value can be less than minus one.

Validation

In this section, we make a comparison between the CFD output resulted from the base model simulation and that of the reference article (Montazeri and Blocken, 2013) with similar settings. The pressure coefficients (C_P) are compared where P is the pressure at the facades. Fig. 2. compares the current results in this study with the results of the reference article, showing the C_P along the mentioned lines. On the windward surface, the mean discrepancy between present outputs and those of reference for the centre line is more than edge lines (Fig. 2 a and b). It is worthy to say that there are some discrepancies in the current simulations: C_P at lines 1,3 on the first and second rows of balconies is overestimated, while at centre line this simulation underestimates, and on the third and fourth rows of balconies for all lines, current simulations mainly provide underestimations.

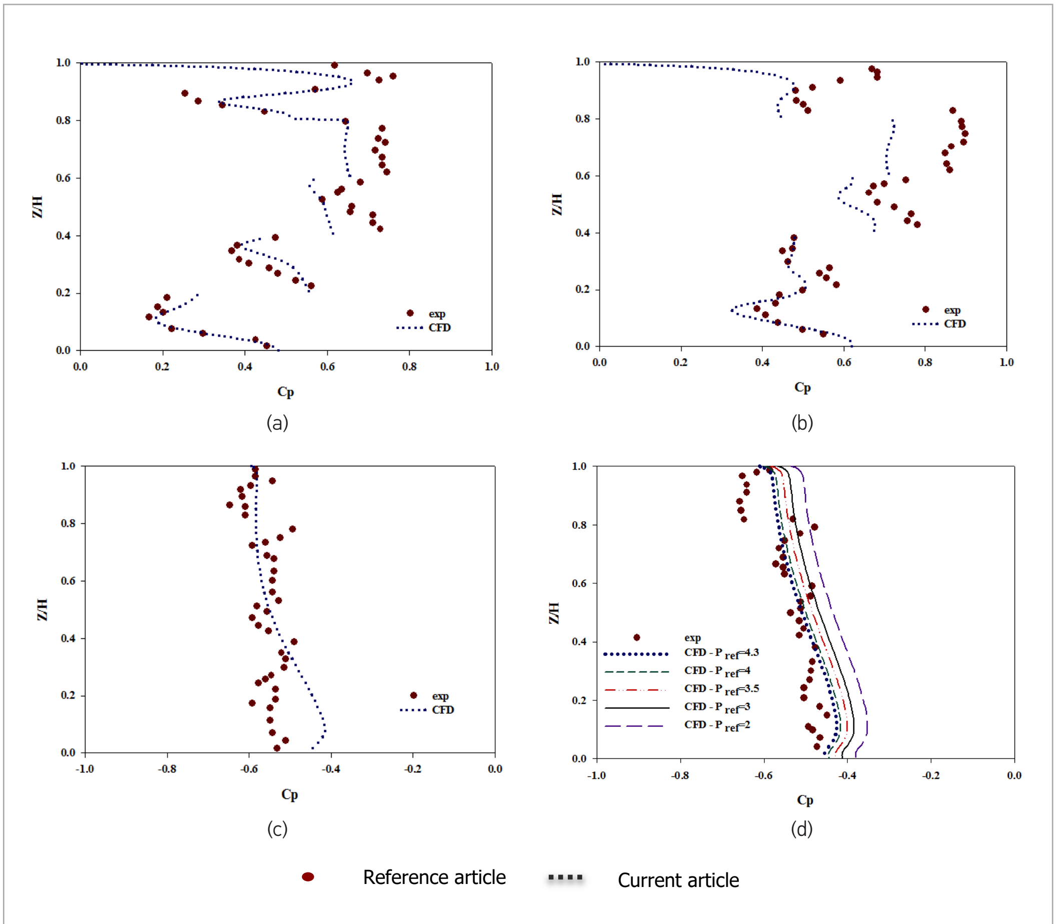


Fig. 2

C_P resulted by CFD simulations in the current study compared to the reference article on windward surface on (a) line 1(3); (b) line 2; and on leeward surface on (c) line 1(3); (d) line 2

Overall, the agreement between current simulations and the reference simulations is regarded to be acceptable. Also the results for the leeward facade, agree well with reference results (Fig. 2 c and d). The mean discrepancy for three lines is negligible. Generally, the comparisons presented in this stage confirm the reliability of the current simulations and study to accurately predict the airflow field at the facades. Therefore, these solver settings can be used for other simulations with confidence.

Discussion

The impact of balcony types on the natural ventilation in perpendicular wind direction

In this section the impact of three types of balconies on C_p for perpendicular approach wind, is compared to each other. These results are shown in Figs. 3 to 8 and the succeeding points are taken:

Fig. 3 shows the C_p assessed on the guidelines for both windward and leeward facades in three models. According to these results, the most amount of C_p belongs to the third floor in all models and generally, based on the contours in Fig. 1, balcony$_r$ (b), balcony$_s$ (c) and balcony$_p$ (a) have the most, the second most and the least amount of distributed C_p across the facades respectively. The balconies located along lines 1 and 3, balcony$_p$ mainly causes the less C_p value (C_p=0.63, 0.55, 0.38 for line 1) compared to C_p=0.72, 0.63, 0.46 for line 2 on the fourth to the second floors (Fig.1a). Similarly, C_p values produced by balcony$_{r \text{ and } s}$, are more for lines 1 and 3 than those on line 2. however, C_p distribution on the model with balcony$_p$ is more complex rather than the others.

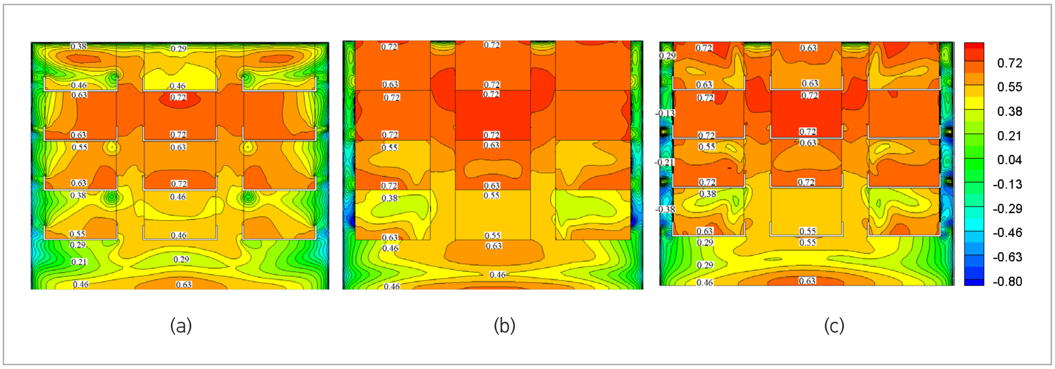


Fig. 3

C_p distributed by balconies on windward facades with (a) balcony$_p$, (b) balcony$_r$, (c) balcony$_s$ in perpendicular approach wind

Fig. 4 shows the mean C_p around all balconies separately. Each balcony is allocated an area owning the width of 4.5m and the height of 3m. The surface-averaged C_p values are presented for three cases: balcony$_p$ (Fig. 4 a), balcony$_r$ (Fig. 4 b) and balcony$_s$ (Fig. 4 c). These results indicate that the fourth row of balcony$_p$ causes a more significant reduction in the surface-averaged c_p than the others. Also, in the third floors, the differences between three types of balconies decline and in the first and second floors, presence of three types of balconies has a very small effect on surface-averaged c_p.

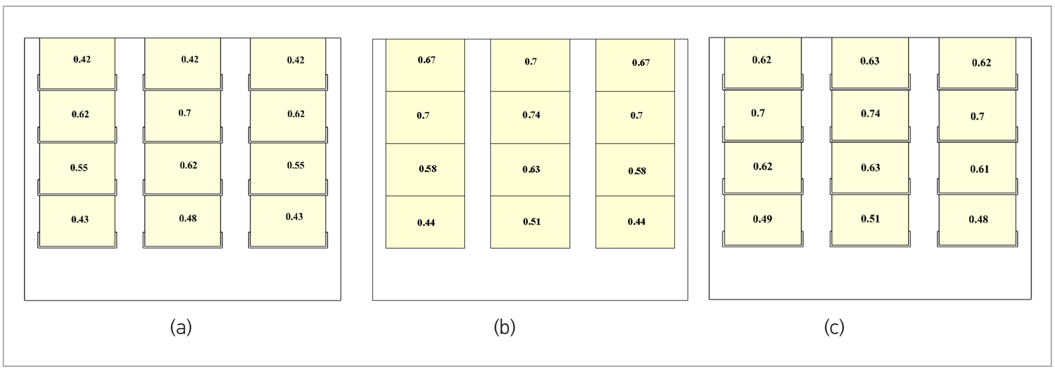


Fig. 4

Average C_p resulted in each balcony-related area for (a) balcony$_p$, (b) balcony$_r$, (c) balcony$_s$ in perpendicular approach wind

Fig. 5 shows the surface-averaged C_p -induced by balcony types on leeward facades of three models. The C_p values for balcony$_p$ (Fig. 5 a), balcony$_r$ (Fig. 5 b) and balcony$_s$ (Fig. 5 c) show that leeward facades in balcony$_{p \text{ and } s}$-models experience more variations in pressure difference. Fig. 5 shows that pressure coefficients generally decrease from the first to the fourth floor across leeward facades. In the model with balcony$_r$, more area over the leeward façade has the lower pressure coefficient. Also, in the other models, in the first floor, the area below the balconies experiences the more pressure coefficients than the upper area.

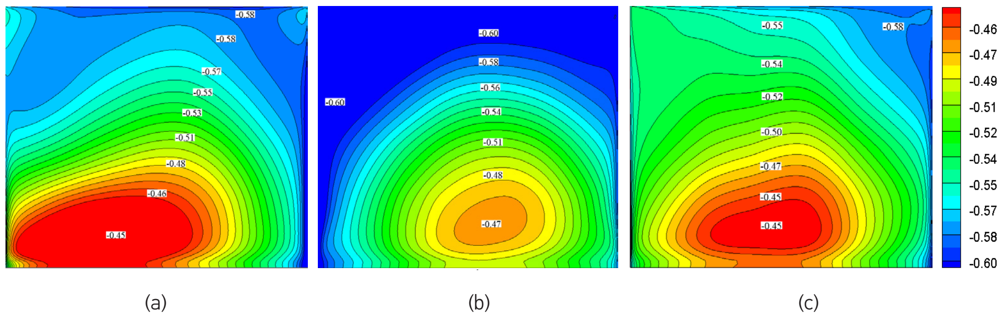


Fig. 5

C_p distributed by balconies on leeward facades with (a) balcony$_p$, (b) balcony$_r$, (c) balcony$_s$ in perpendicular approach wind

Fig. 6 shows the different pressure distribution on windward and leeward surfaces for three simulated models align with three line 1,2 and 3. Respecting these graphs, in model with balcony$_p$ (Fig. 6 a), line 1 generally witnesses a more pressure difference rather than that in line 2. In the model with balcony$_r$ (Fig. 6 b), the pressure difference between the line 1 and 2 is insignificant and in the first floors, it is somehow similar to balcony$_p$ model. This difference has moderate value in model with balcony$_s$. Regarding natural ventilation, in buildings with balcony$_r$, nearly all units are in a harmony.

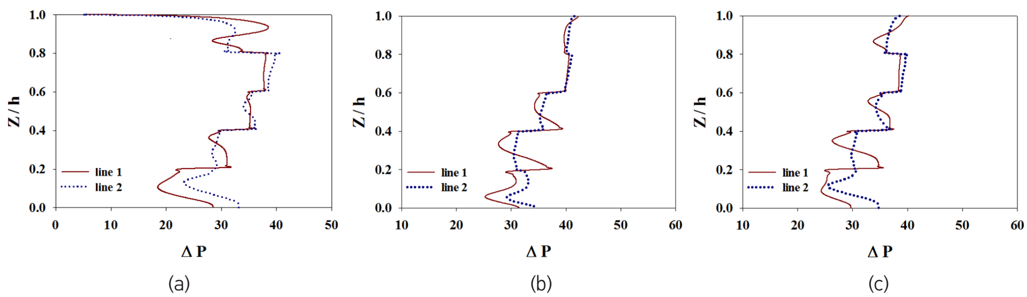


Fig. 6

The pressure difference distributed along the lines 1 (3) and 2 between windward and leeward facades for (a) balcony$_p$, (b) balcony$_r$, (c) balcony$_s$ in perpendicular-approach wind

Fig. 7 (a and b) shows wind-induced C_p on the windward and leeward surfaces for models with balcony$_p$, balcony$_r$ and balcony$_s$. The balcony$_p$ -model experiences the least amount of pressure difference on both facades and by contrast, the balcony$_r$ –model has the most value. Also, the pressure difference in the top and down parts of buildings is more than middle areas. As a result, in perpendicular-approach wind, balcony$_r$ would provide better natural ventilation.

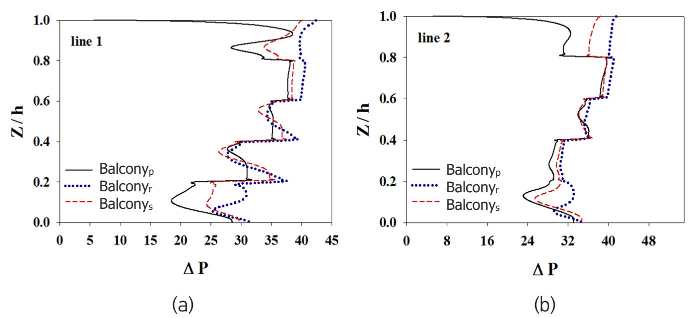


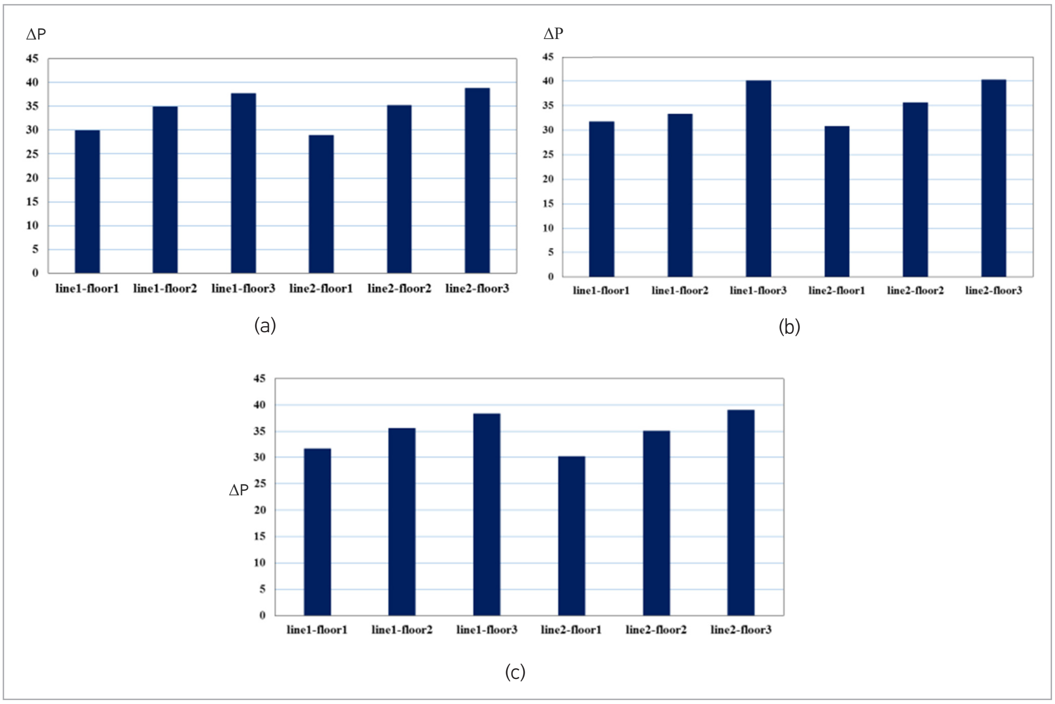
Fig. 7

The pressure difference distributed between windward and leeward for balconyp, balconyr and balconys on the (a) line 1 (3) and (b) line 2 in perpendicular-approach wind

Fig. 8 compares pressure differences for three balcony types on the lines 1 and 2 separately in perpendicular-approach wind. Accordingly, in all models, the higher levels experience the more difference between pressure distributed on the opposite faces. However, in models with balcony$_p$ and balcony$_s$, on the first and third floors, line 2 experiences less and more pressure differences respectively. By contrast, in balcony$_r$-model this value is fewer on line 1. Therefore, balcony types can change natural ventilation rate in different situations (vertical and horizontal).

Fig. 8

Comparison of average pressure difference (ΔP) on the line 1(3) and 2 on each floor for (a) balcony$_p$, (b) balcony$_r$, (c) balcony$_s$ in perpendicular-approach wind



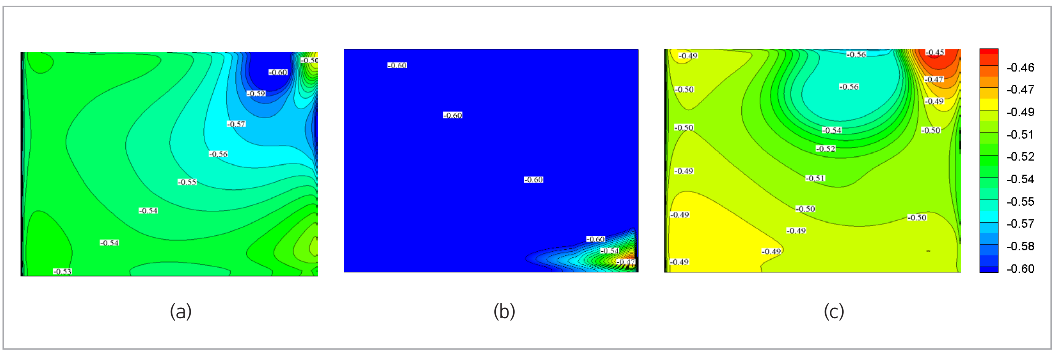
The impact of balcony types on the natural ventilation in oblique direction wind

The similar assessments were also taken for oblique direction of 45° (Figs 7-12). The succeeding points are taken:

- Fig. 9 and 10 show the pressure coefficient contours introduced across the windward and leeward surfaces for oblique direction wind respectively. According to Fig 7a-c and 8a-c, in three models, pressure coefficients on the windward facades decrease from left to right (wind flow direction). The most and least complexity of pressure coefficient belong to the model with balcony$_p$ and balcony$_r$ respectively. However, leeward facades witness other patterns. In this location, this complexity of balcony$_{p \text{ and } s}$-models is more than that with balcony$_r$. The model with balcony$_r$ experiences the least pressure coefficients across the leeward facades compared to balcony$_p$-model with the most value. In balcony$_r$ –model, pressure coefficients increase on the first floors, while this result occurs on the top floors in other models.

Fig. 9

C_p distributed by balconies on windward with (a) balcony$_p$, (b) balcony$_r$, (c) balcony$_s$ in oblique-approach wind



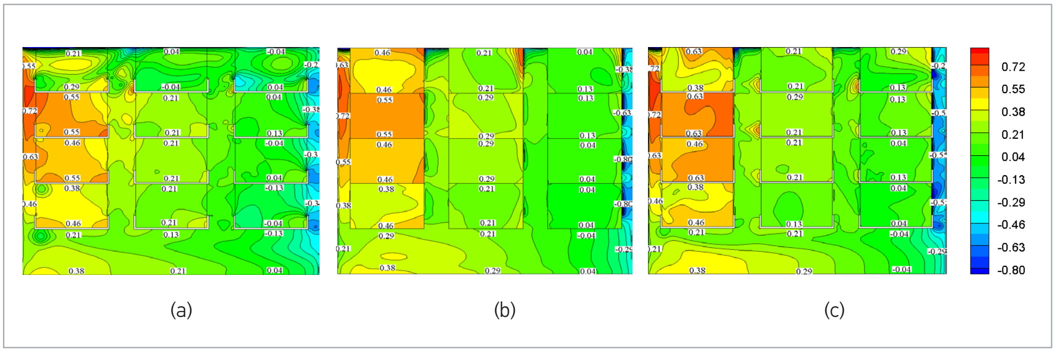


Fig. 10

C_p distributed by balconies on leeward facades of three models. The C_p for (a) balcony$_p$, (b) balcony$_r$, (c) balcony$_s$ in oblique approach wind

_ Fig. 11 shows the average pressure across the windward facades in areas limited to balconies. As it can be seen, on the first to the third floors (except the eastern part) pressure differences in balcony areas have low values for all models. On the fourth floor, the least amount of average pressure in this area is allocated to the balcony$_p$-model, while in the other models, this value is more significant and is the same.

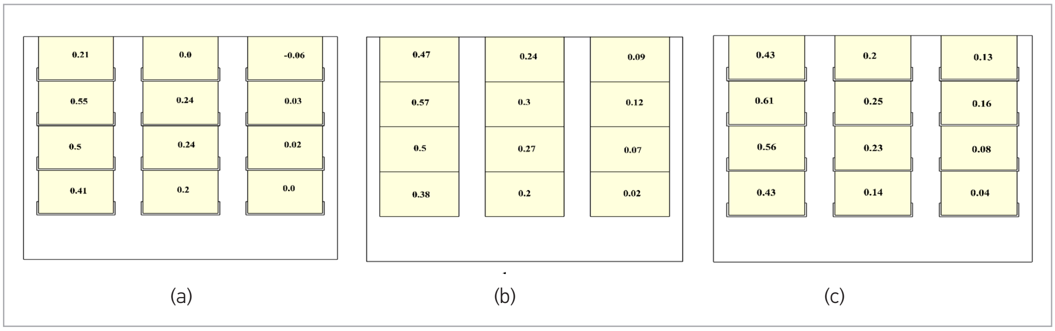


Fig. 11

Impact of balcony types on the surface-averaged pressure coefficients for (a) balcony$_p$, (b) balcony$_r$, (c) balcony$_s$ in oblique approach wind

_ Fig. 12 shows pressure difference measured on the lines 1,2 and 3 between windward and leeward surfaces for three models in oblique-approach wind. In all graphs, generally, from left to right, pressure differences decrease. Fluctuation of these values on windward and leeward facades on the line 1 or 3 are more than the line 2. Also, balcony$_p$-model on the top floor can cause the less pressure differences between the edge and centre lines. This difference is more significant on the windward and leeward facades in balcony$_r$-model. In balcony$_s$-model, line 3 on the first floor, line 2 and 3 on the top floors experience less pressure differences.

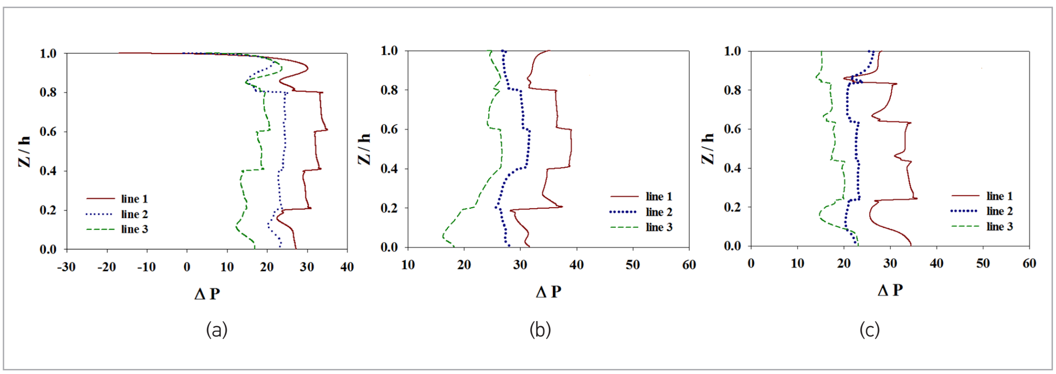


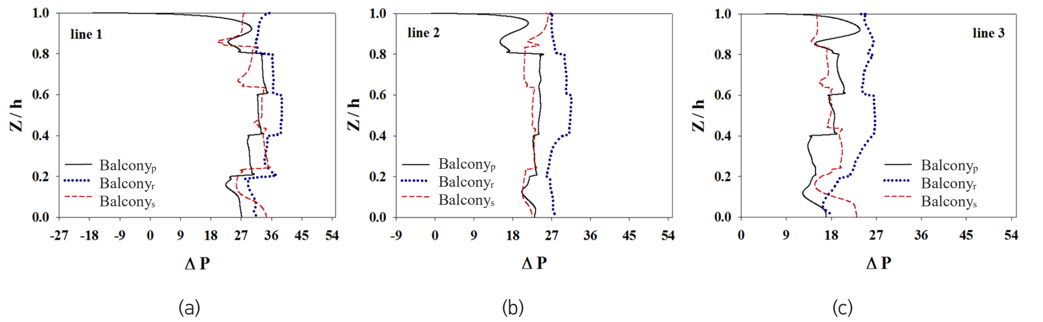
Fig. 12

The pressure difference between opposing surfaces on the line 1 (3) and 2 for (a) balcony$_p$, (b) balcony$_r$, (c) balcony$_s$ in oblique-approach wind

_ Fig. 13 shows the pressure differences induced between the opposing surfaces on the three lines for the balcony types. In general, balcony$_r$-model has more difference on the line 1 and 3 between these two facades. Then balcony$_s$-model on the first floors and balcony$_p$-model on the top floors experience the higher values respectively. Furthermore, on the line 3 in balcony$_r$-model, this pressure difference increases significantly. Balcony$_{p\ and\ s}$ on the first floors can cause negligible pressure difference between the opposing surfaces, while this value is higher for balcony$_r$.

Fig. 13

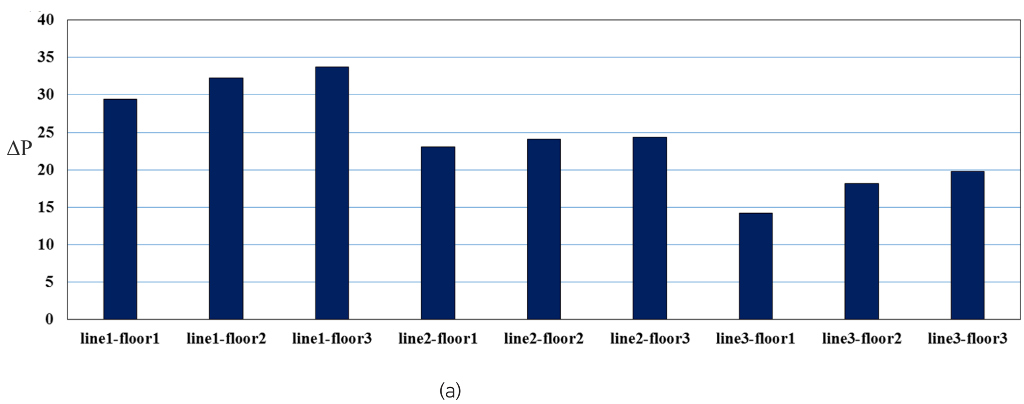
The pressure difference produced by balcony types between windward and leeward facades on the all three lines in oblique-approach wind

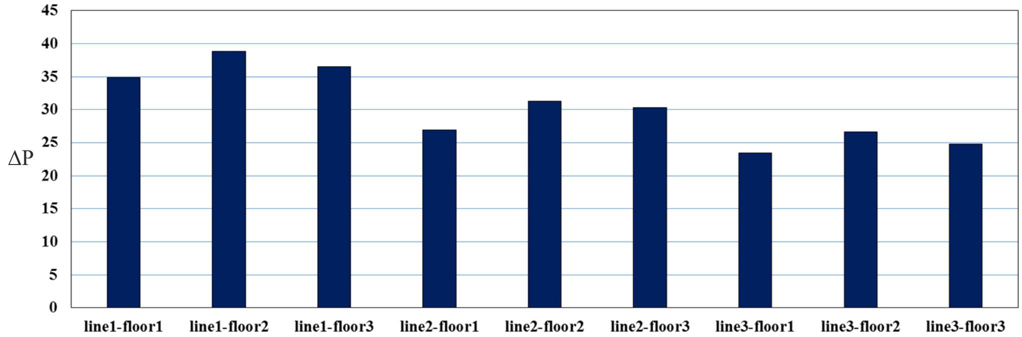


_ Fig. 14 compares the pressure difference on three guidelines 1,2 and 3 separately, for three balcony types. According to the Fig. 14 a, in the balcony$_p$-model, the higher levels produce the more pressure difference between two facades, moving from left to right. In this model the value in less between edge and centre lines. Moreover, in the balcony$_r$-model (Fig. 14 b) there is higher pressure difference between these facades on the median floors. On the first and top floors this difference is less. Based on the Fig. 14 c, increasing height in balcony$_s$-model can increase the difference between pressure introduced on the opposing faces (edge lines). However, this difference increases from the second floor to the third and falls back on the fourth floor.

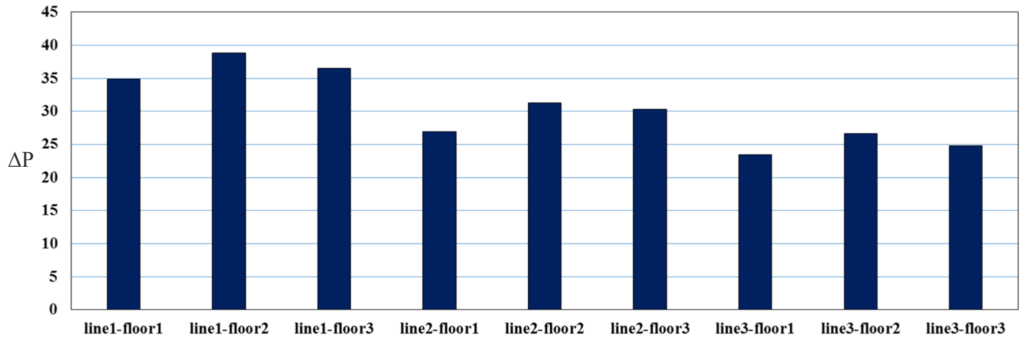
Fig. 14

Comparison of average pressure difference (ΔP) on the line 1 (3) and 2 on each floor for (a) balconyp (b) balconyr, (c) balconys in oblique-approach wind





(b)



(c)

Conclusions

Effects of balcony types on the natural ventilation were discussed in this paper. For this reason, three types of balcony in a model were simulated and the pressure distribution of wind on the windward and leeward surfaces were analysed. All these simulations were carried out for normally (perpendicular) and obliquely incident wind. Log wind profile was used for simulations and the results are reliable for all climates. This study includes protrusive, re-entrant and semi protrusive-semi reentrant balconies, presented as $balcony_p$, $balcony_r$ and $balcony_s$ respectively. The results showed that balcony types can affect the pressure distribution over the opposite faces of buildings, leading to the pressure difference between these two facades. Through this way balcony types can increase or decrease natural ventilation. The most significant outcomes are listed below:

- $Balcony_r$, $balcony_s$ and $balcony_p$ had the most, the second most and the least amount of distributed C_p across the facades respectively.
- Protrusive balcony could make C_p distribution more complex rather than the others.
- In model with $balcony_r$, more area on the leeward façade had the lower C_p.
- Respecting the average pressure on the facades, nearly all parts of the building with re-entrant balcony experienced to large extent similar wind pressure value.
- The $balcony_{p \text{ and } r}$ –model experienced the least and most amount of pressure difference distributed on the windward and leeward surfaces respectively.
- The top floors could experience the more different pressure distribution between the windward and leeward surfaces generally.

These results show that protrusion (protrusive balcony) can cause more complicated the pressure wind on facades, however, indentation (re-entrant balcony) can result in more similar distributed pressure coefficients. What's more, re-entrant balcony causes the greater values for pressure difference measured on the building facades, key factor for non-air-conditioned buildings. The more pressure difference distributed on the opposing facades, the better interior natural ventilation. As a result, re-entrant balcony type can enhance natural ventilation of buildings more considerably compared to the other types. It is worthy to note that in modern constructions such as towers or high-rise buildings, semi-open spaces or balconies can provide users with more pleasant environment. Building appurtenances can change the air flow pattern surrounding buildings and balconies are the most effective elements, changing the entering wind/air flow pattern and consequently natural ventilation. Although nearly all people are living in mechanically-ventilated buildings, designing buildings with regarding sustainable architecture and effective natural ventilation definitely reduces using the mechanical systems, leading to energy consumption reduction.

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About the Authors

ELAHE MIRABI

Main research area

Natural ventilation, low-energy buildings.

Address

University of Ilam, Faculty of Engineering, Architecture Department, Pajoohesh boulevard.
Tel. 0098-3476758
E-mail: goodness.41@gmail .com

NAZANIN NASROLLAHI

Address

University of Ilam, Faculty of Engineering, Architecture Department, Pajoohesh boulevard

MEHDI DADKHAH

Address

University of Tehran, Faculty of Engineering, Mechanic Department, Hafez street