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The effect of the wind speed velocity on the stack pressure in medium-rise buildings in cold region of China

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Abstract

This paper presents the numerical simulation results of the stack effect in medium-rise buildings in Harbin, a typical city in the severe cold region of China. The simulation was carried out using the multizone ventilation model COMIS. The effect of the wind speed velocity and the temperature of the stairwell on the pressure difference curves shape have been investigated. The pressure difference between the stairwell and the outside shows a linear variation with the height. However, the wind speed velocity may have a strong effect on the pressure difference. The results of the simulation show that at high wind speed velocity the curve of the pressure difference is not linear in shape. It has been also shown that the air total change cannot be provided by only infiltration due to leakage particularly for such air-tight residential building in windy cold climate. Therefore, mechanical ventilation is required to compensate for the lack of it. A quantitative evaluation of IAQ based on the total volatile organic compounds (TVOCs) concentration has been done. The effect of the wind speed velocity and the temperature of the stairwell on the VOTCs concentration at each floor have been also presented.

Keywords: Stack effect; Stairwell temperature; Pressure difference; Air infiltration; TVOCs

1. Introduction

When it is cold outside, air tends to move upward within building shafts (e.g., stairwell, elevator shaft, dumb water shafts, mechanical shafts, mail chutes). This normal stack effect occurs because the air in the building is warmer and less dense than the outside air. Normal stack effect is large when outside temperatures are low, especially in tall building. When the outside air is warmer than the building air, there is a natural tendency for downward air flow, or reverse stack effect, in shaft [1]. The stack effect causes many problems which are: the energy loss caused by airflow; the sticky elevator door; the difficulty of opening the doors of room around the core; and loud noise [2].

Several works treating the aspect of stack effect in medium and high-rise buildings have been investigated by numerous authors. Recently, Yu et al. [2] have evaluated the stack effect according to the shape and the window area ratio of lobby in high-rise building. The investigation of the air quality in newly constructed high-rise multi-family houses and the improvement of the indoor air quality have been carried out by Yu et al. [3]. The influence of architectural elements on stack effect problems in tall residential buildings has been studied by Koo et al. [4]. Some problems about the stack effect have been studied but these are only partial solution [5,6]. For stack effect, mechanical ventilation systems were used to control pressure difference [7,8]. Nevertheless, this may lead to other problems with regard to the system efficiency [2].

The pressure difference between the stairwell and outside in term of indoor temperature, temperature in the stairwell on the *i*th floor and the outside temperature shows a linear variation with the height [1]. However, in windy cold climate the wind speed velocity may affect seriously the pressure difference.

The present paper consists of the investigation of the effect of the wind speed velocity on the stack effect in medium-rise building of seven floors in Harbin, a typical

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city in the severe cold region of China. The effect of the air-tightness on the total infiltration and the temperature of the stairwell on the stack effect have been also investigated. This paper is an extension of the previous one which dealt with the air infiltration performance for apartment buildings in winter of Harbin China focusing on the performance of air infiltration and the energy consumption [9].

In this paper, total volatile organic compounds (TVOCs) were selected to characterize the indoor air quality impact to residents. A quantitative evaluation of IAQ based on TVOCs concentration and the effect of the wind speed velocity and the temperature of the stairwell on this pollutant concentration at each floor have been also presented.

2. Description of the building and climate conditions

The building is an air-tight medium high-rise residential one of seven floors. It consists of three sections, and only the middle section was chosen for study [9] (Fig. 1). The chosen section consists of two 50 m^2 apartment per floor and one 12 m^2 internal stairwell, and all the floors have identical floor plans. The mean outdoor temperature of $-24.9\,^{\circ}$C is considered. The apartment temperature was assumed uniform at 20 °C. Fig. 2 shows the apartment layout per floor.

The effective leakage area of the interior doors between apartments and stairwell, the exterior door of the stairwell and the windows between the stairwell and outside are 0.00445 kg/s at 1 Pa, 0.01 kg/s at 1 Pa and 0.01192 kg/s at 1 Pa, respectively [9].

3. Multizone infiltration model and simulation procedure

In the present study the simulations have been carried out using the multizone model of COMIS. This code allows solving the non-linear system of equations representing the airflow distribution in multizone buildings [10]. In COMIS, the building is modeled as a system of interconnected zones, each at constants temperature and contaminant concentration. Some relevant parameters such us airflow paths between zones and outdoor weather must be specified in input file. Multizone buildings can be either single-room structure, single family houses or large building complexes. A number of infiltration programs have been developed to calculate air flows penetrating the building's envelope and traveling through the different zones of a multizone structure. Besides being able to simulate infiltration in large buildings theses models are able to calculate mass flow interactions between the different zones. In term of air-mass flow buildings represent complicated interlacing systems of flows paths. In this grid-system the join represent the rooms of the building and the connections between the joints simulate flow paths. These include the flow resistances caused by open or closed doors and windows and air leakage through the walls. The boundary conditions for the pressure can be described by grid points outside the building. Wind pressure distribution depends on the velocity and the direction of the wind, the surrounding terrain of the building and the shape of the building. If the physical interrelationship between flow resistance and the air flow is known for all flow paths the air flow distribution for the building can be calculated as long as there is no temperature difference between outside and inside air. Differences in density of the air, due to differences between outside and inside air temperatures, cause further vertical pressures while also influencing the air-mass flow.

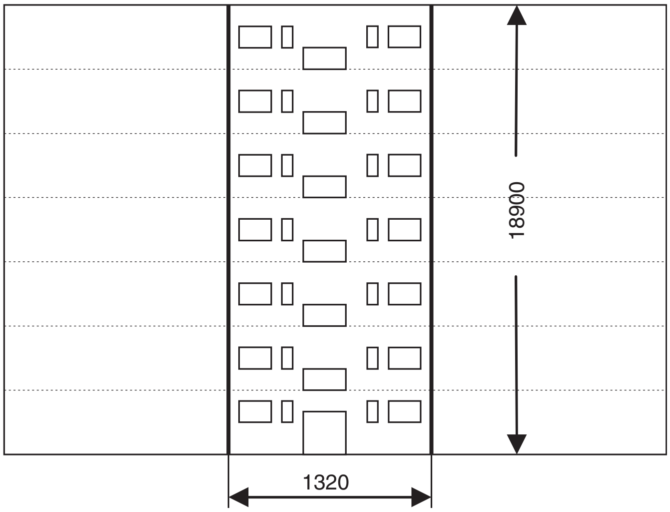


Fig. 1. Front façade of the building.

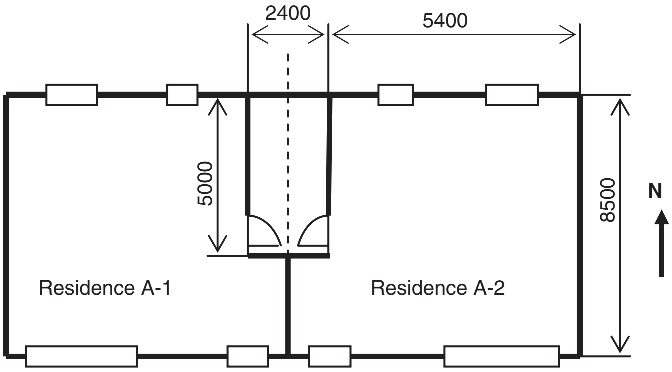


Fig. 2. Apartment layout per floor.

Mechanical ventilation can be included in this network, the duct system being treated like the other flow paths in the building. The advantage for calculating the air flow distribution effects of mechanical ventilation systems is that the duct pathways, as well as their connections with the building, are known. In the case of mechanical ventilation systems the fan can be described as the source of pressure differences, lifting the pressure level between two joints according to the characteristic curve of the fan [10].

Multizone infiltration network models deals with the complexity of flows in a building by recognizing the effects of internal flow restrictions. They require extensive information about flow characteristics and pressure distributions and, in many cases, are too complex to justify their use in predicting flow for simple structure such as single-family residences [10]. The COMIS model has been extensively validated using experimental data [11].

As for their single-zone counterparts these models are based on the mass balanced equation

$$0 = \sum_{l=0}^{m}\left\{\sum_{j=0}^{k}\left[\rho C_{j,l}|P_{0j,l} - P_{\mathrm{i}}|^{nj,l}\left[\frac{P_{0j,l} - P_{\mathrm{i}}}{|P_{0j,l} - P_{\mathrm{i}}|}\right]\right]\right\} \tag{1}$$

with ρ is the density of air, $C_{j,l}$ the flow coefficient for flow path j of zone 1, $P_{0j,l}$ the external pressure for flow path j of zone 1, P_{i} the internal pressure, $n_{j,l}$ the flow exponent for flow path j of zone 1.

During the simulation process, four parameters have been considered. These parameters are as follows:

- air-tightness of the building,
- temperature of the stairwell,
- wind speed velocity,
- and the wind direction.

Table 1 summarizes the parameters used in simulation and their values. The wind pressure coefficients were obtained using parametrical model developed by Grosso [9]. We should mention that all the windows and doors of the apartments are kept close during the simulation process.

4. Results of the simulation

4.1. Air infiltration

4.1.1. Uniform heated stairwell

The flow pattern and the air flow rates are shown in Fig. 3. Figs. 3a–e and f are obtained with the air-tightness of 1.5 and 2.5 cm^2/m^2, respectively with uniform heating of the stairwell for different values of the wind speed velocity. We should mention that the airflow pattern and the airflow rates for apartments on the same floor are identical. The outdoor cold air tends to enter the heated apartments from the lower floors, goes to the stairwell through the doors and then moves up. Indoor air tends to exit the building from the upper floors.

4.1.2. Unheated stairwell

When the stairwell is not heated, its temperature varies with outdoor temperature. It has been shown that the temperature difference between the stairwell and indoor is reverse relationship with the level of the ith floor [12]. This relation is given by

$$\frac{T_{\mathrm{in}} - T_{i,\mathrm{stair}}}{T_{\mathrm{in}} - T_{\mathrm{out}}} = -0.1046i + 0.9793, \tag{2}$$

where T_{in} $T_{i,\mathrm{stair}}$ T_{out} and i are the indoor temperature, the temperature in the stairwell on the ith floor, the outdoor temperature and the number of the floor, respectively.

Fig. 4 shows the linear variation of stairwell temperature as function of the building height. It can be seen that the effect of the temperature stratification in the stairwell is significant.

The airflow pattern and rates in case of unheated stairwell is shown in Fig. 5. The rates of the airflow at each level of the floor are smaller compared with the results obtained when the stairwell is heated.

4.2. Total air infiltration and air change

The total air infiltration is shown in Fig. 6. Seven cases have been studied with regard to the four parameters described above. Table 2 describes each case. The total infiltration increases with the increase of the wind speed velocity. However, the maximum is obtained when the wind blows from the north. Increasing the air-tightness from 1.5 to 2.5 cm^2/m^2 means an increase of 100 cm^2 leakage area for one apartment and the total air infiltration increases by 16.7% ($V = 2$ m/s). Whatever, 2.5 cm^2/m^2 can be considered as a very low air-tightness level. When the stairwell is unheated the total air infiltration is reduced by 29.7% compared with heated stairwell with air-tightness = 1.5 cm^2/m^2 and $V = 2$ m/s.

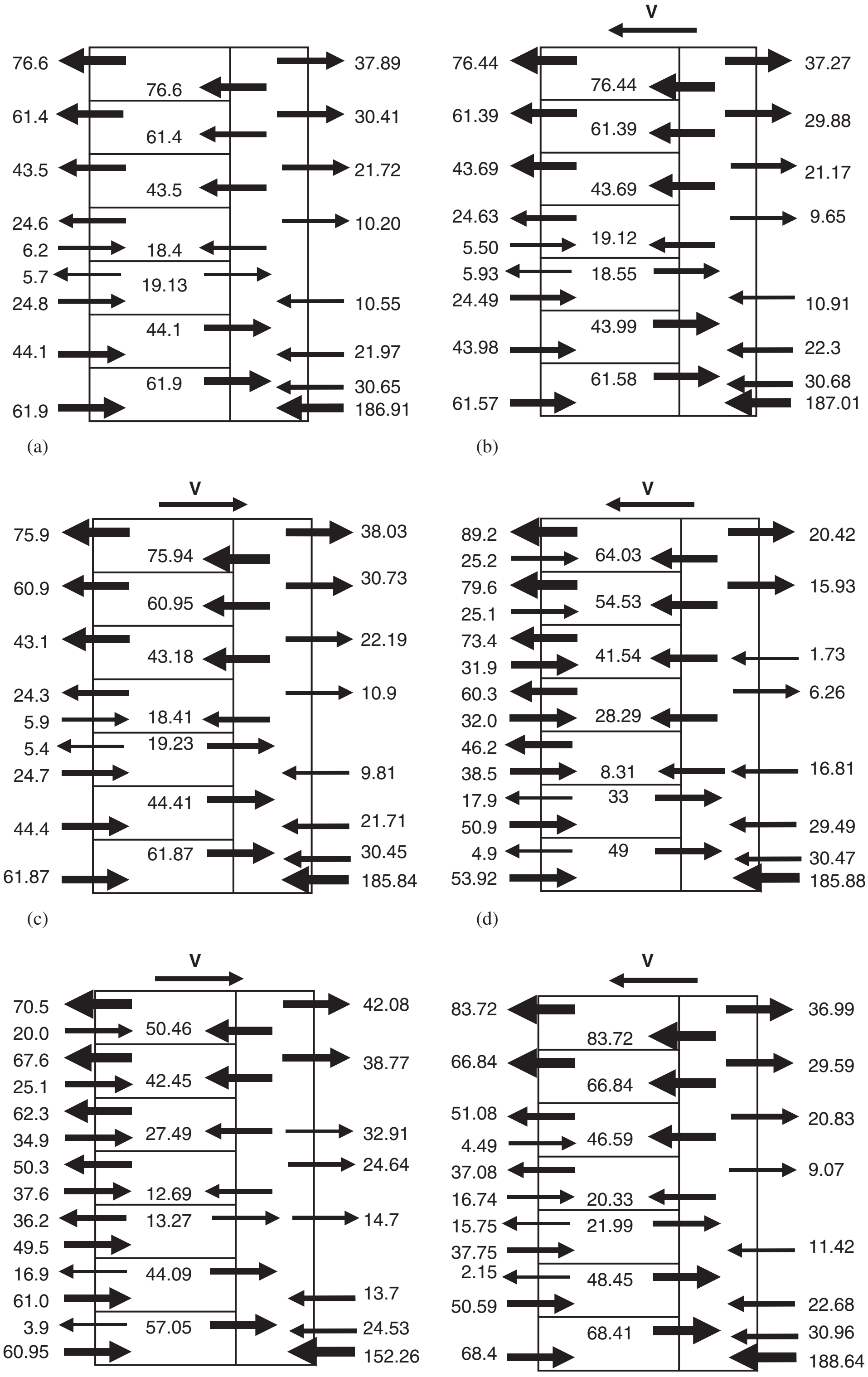
Fig. 7 shows the total air change rates. It can be seen that for all cases the total air change rates are low compared with the standard rate (0.5[ach]). This can results in the risk of indoor contaminants. Therefore, mechanical ventilation may be needed to overcome this problem.

4.3. Pressure difference

Fig. 8 shows the pressure difference between the stairwell and outside. Fig. 8a represents the pressure difference in case of $V = 0$ m/s. A positive pressure difference indicates

Table 1
Parameters used in simulation and their values

Air-tightness	$\alpha A' = 1.5$ cm^2/m^2								2.5 cm^2/m^2
Temperature of the stairwell	Heated uniformly (20 °C)							Unheated	Heated uniformly (20 °C)
Wind speed velocity	0	2 m/s		5 m/s		10 m/s		2 m/s	2 m/s
Wind direction		North	South	North	South	North	South	North	North



(a) (b) (c) (d) (e) (f)

Fig. 3. Air flow pattern and air flow rates [m^3/h] with uniform stairwell heating $T_{\mathrm{stair}} = 20\,^\circ\mathrm{C}$. (a) $V = 0$, $\alpha A' = 1.5\,\mathrm{cm}^2/\mathrm{m}^2$, (b) $V = 2\,\mathrm{m/s}$ (north), $\alpha A' = 1.5\,\mathrm{cm}^2/\mathrm{m}^2$, (c) $V = 2\,\mathrm{m/s}$(south), $\alpha A' = 1.5\,\mathrm{cm}^2/\mathrm{m}^2$, (d) $V = 10\,\mathrm{m/s}$ (north), $\alpha A' = 1.5\,\mathrm{cm}^2/\mathrm{m}^2$, (e) $V = 10\,\mathrm{m/s}$ (south), $\alpha A' = 1.5\,\mathrm{cm}^2/\mathrm{m}^2$, (f) $V = 2\,\mathrm{m/s}$ (north), $\alpha A' = 2.5\,\mathrm{cm}^2/\mathrm{m}^2$.

that the stairwell pressure is higher than the outside pressure. The neutral plane is near the mid-height of the building since the leakage paths are uniform with height. At standard atmospheric pressure, the pressure difference due to the stack effect is expressed by

$$\Delta p = 3460\left[\frac{1}{T_{\mathrm{o}}} - \frac{1}{T_{\mathrm{i}}}\right]h, \tag{3}$$

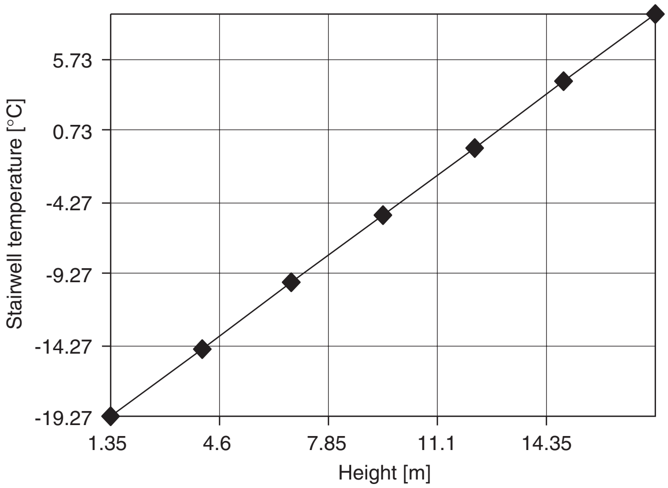


Fig. 4. Variation of the temperature of the stairwell vs. height.

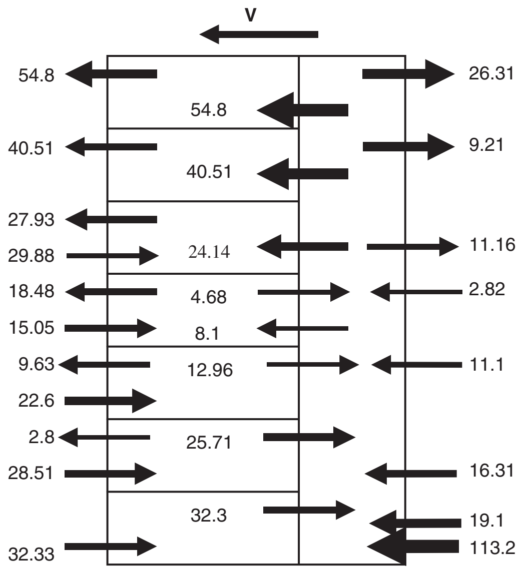


Fig. 5. Air flow pattern and air flow rates (m^3/h) with stairwell unheated $V = 2\,m/s$ (north), $\alpha A' = 1.5\,cm^2/m^2$.

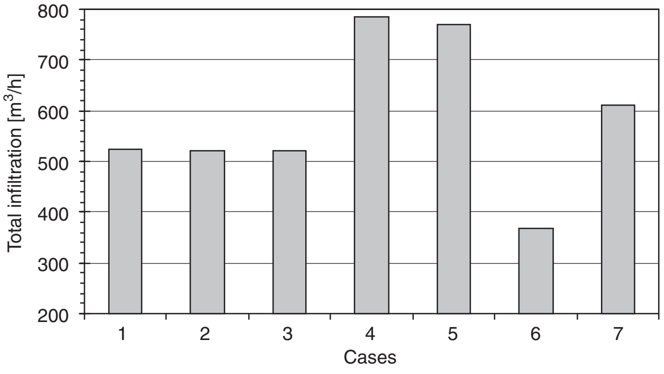


Fig. 6. Total air infiltration for each case (m^3/h).

Table 2
Cases used in simulation

Case	$\alpha A'$ (cm^2/m^2)	T_{stair}	Wind speed velocity (m/s) and its direction
1	1.5	Heated	0
2			2, North
3			2, South
4			10, North
5			10, South
6		Unheated	2, North
7	2.5	Heated	2, North

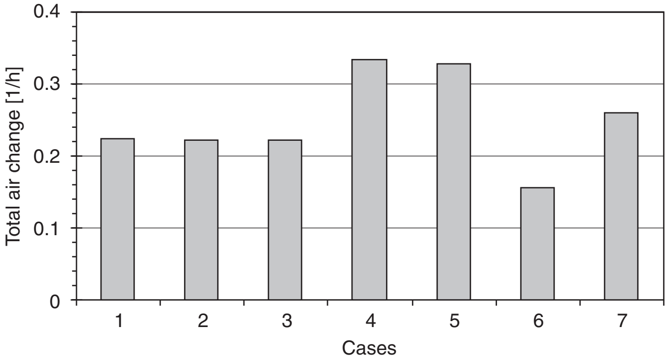


Fig. 7. Total air change rates.

where Δp is the pressure difference, Pa; T_o the absolute temperature of outside air, K; T_i the absolute temperature of air inside shaft, K; h the distance above neutral plane, m.

Therefore, the pressure difference due to stack effect varies linearly with the height of the shaft. Fig. 8b shows the pressure difference due to the stack effect for $V = 2\,m/s$ for both north (0°) and south (180°) direction of the wind speed. The graph shows that the curves are almost indistinguishable.

Increasing the wind speed velocity, the shape of the curves of the pressure difference presents some disturbances. Figs. 8c and d represent the variation of the pressure difference for 5, 7.5, 10 and 15 m/s for both north and south directions, respectively. The shapes of the pressure difference curves are significantly influenced by the value of the wind speed velocity. However, the disturbances are less when the wind blows from the south.

Eq. (3) represents the pressure difference between the shaft and outside. However, this relation does not consider the effect of the wind speed velocity. Therefore, when the wind velocity is small ($<5\,m/s$), its effect on the shape of the pressure difference curve is almost insignificant (see Figs. 8a–c). In case of $V = 15\,m/s$ (north direction), the pressure difference is negative along the stairwell height (see Fig. 8c). This means that the outside pressure is higher than the stairwell pressure.

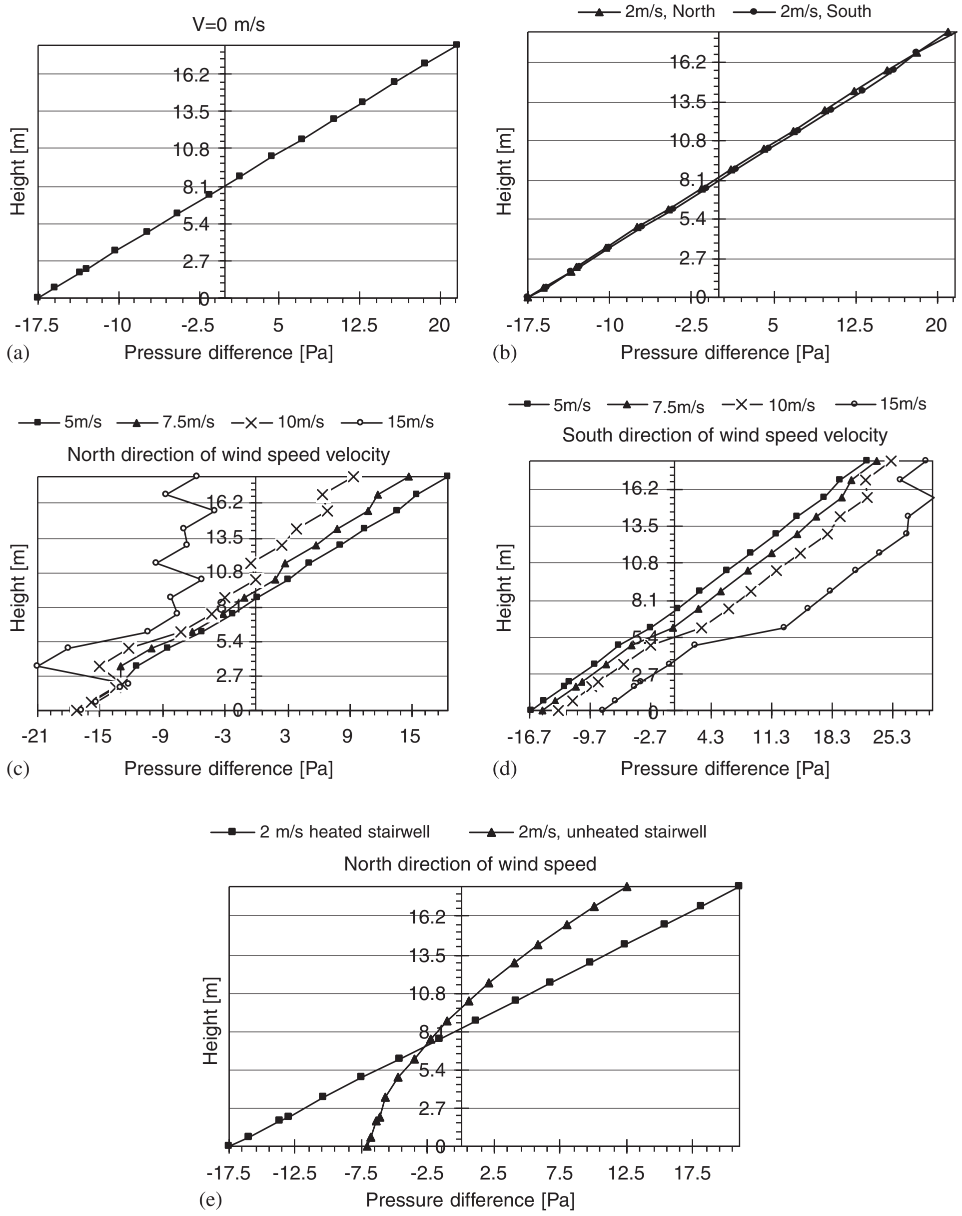


Fig. 8. Pressure difference between the stairwell and outside.

Fig. 8e shows the pressure difference between the stairwell and outside for $V = 2\,\mathrm{m/s}$ (north direction) for both heated and unheated stairwell. The gradient of the pressure between the stairwell and outside is smaller in case of unheated stairwell compared with heated one. This result was somewhat expected since the gradient of temperature is less. Moreover, the curve of the pressure difference in case of unheated stairwell in not linear in shape.

4.4. Indoor air quality

A quantitative evaluation of IAQ based on TVOCs concentration and the effect of the wind speed velocity and the temperatures of the stairwell on such contaminant concentration at each level have been investigated. The emission rate of TVOCs may change relatively with time and the kind of emitting sources [13,14]. However, in this paper, the source strength was assumed to have a constant value of $1\,\mathrm{mg/m^2/h}$. This value has been typically observed in field [15]. The outdoor level of TVOCs was assumed to be $0\,\mathrm{mg/m^2/h}$.

Fig. 9 shows the TVOCs concentration at each level of the building for different values of wind speed velocity from the north direction with air-tightness $= 1.5\,\mathrm{cm^2/m^2}$. As expected, the TVOCs concentration decreases with the increase of the wind speed. At high wind speed velocity ($V = 10$ and $15\,\mathrm{m/s}$) the shape of TVOCs concentration are more flat compared with those obtained with small wind speed velocities. The TVOCs concentration is maximal at the middle of the building height particularly at small value

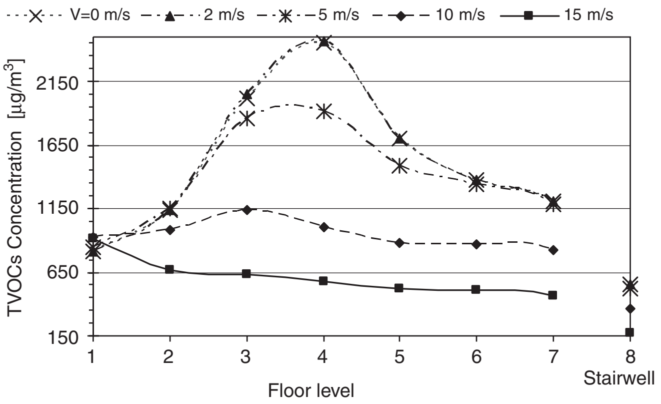


Fig. 9. TVOCs concentration at each floor for different values of wind speed (north), with uniform stairwell heating $T_{\text{stair}} = 20\,^{\circ}\text{C}$.

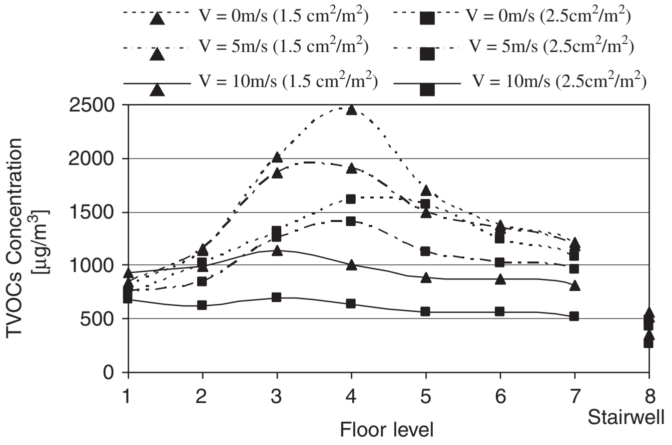


Fig. 10. Effect of the air-tightness on TVOCs concentration for different values of wind speed (north).

of V. In deed, the airflow rates, either infiltration or airflow from the stairwell are lower near the neutral level than other locations.

The effect of the air-tightness on TVOCs concentration for different values of wind speed velocity from the north direction is plotted in Fig. 10. The result shows that the concentration of TVOCs decreases with lower air-tightness levels for different wind speed velocities.

Fig. 11 shows the effect of the temperature of stairwell on TVOCs concentration with air-tightness $= 1.5\,\text{cm}^2/\text{m}^2$ and $V = 5\,\text{m/s}$ from north direction. As shown in Fig. 5, the rates of airflow at each floor are smaller in case of unheated stairwell compared with heated one. Therefore, the TVOCs concentration is higher at each floor in case of unheated stairwell space.

5. Conclusions

Numerical simulation has been carried out to evaluate the total infiltration and the effect of the wind speed velocity on the stack effect in medium-rise building located in Harbin.

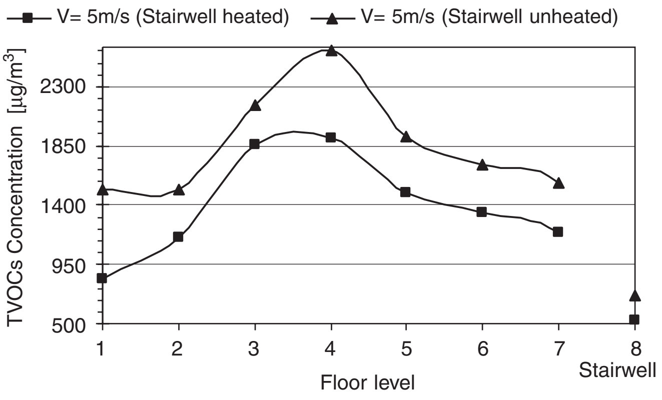


Fig. 11. Effect of the temperature of stairwell on the TVOCs concentration at different levels of the building ($\alpha A' = 1.5\,\text{cm}^2/\text{m}^2$, $V = 5\,\text{m/s}$, north).

The conclusions of this study are as follows:

- The total infiltration increases with the increase of the wind speed and the air-tightness. Increasing the air-tightness from 1.5 to $2.5\,\text{cm}^2/\text{m}^2$ would increase the total infiltration by 16.7% for a uniform heated stairwell with $V = 2\,\text{m/s}$.
- When the stairwell is unheated, the total infiltration is reduced by 29.7% with air-tightness $= 1.5\,\text{cm}^2/\text{m}^2$ and $V = 2\,\text{m/s}$.
- The effect of the wind speed velocity on the pressure difference between the stairwell and outside is insignificant for small value of the wind speed velocity ($<5\,\text{m/s}$).
- At high wind speed velocity, the effect is very strong. Therefore, the pressure difference curves are not linear in shape and strong disturbances on the curve occur.
- The gradient of the pressure between the stairwell and outside is small in case of unheated stairwell compared with heated one.
- The required air total change cannot be provided by only infiltration particularly for such air-tight residential building in windy cold climate. Therefore, mechanical ventilation is required to compensate for the lack of it.
- The TVOCs concentration decreases with the increase of the wind speed and is maximal at the middle of the building height particularly at small value of the wind speed. In deed, the airflow rates, either infiltration or airflow from the stairwell are lower near the neutral level than other location. The concentration of TVOCs also decreases with lower air-tightness levels for different wind speed velocities and is higher at each floor in case of unheated stairwell space.

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