13th International Conference on Indoor Air Quality and Climate 2014

Hong Kong
7-12 July 2014

Volume 1 of 6

ISBN: 978-1-63439-731-5

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Proceedings of Indoor Air 2014, Hong Kong

Topics included in Volume I:

Indoor air chemistry
Indoor air physics
Indoor air microbiology
Indoor aerodynamics
Indoor transport phenomena
Health and indoor air epidemiology

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Erratum

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Hong Kong
7-12 July 2014

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ISBN: 978-1-63439-731-5

Proceedings of Indoor Air 2014, Hong Kong

Topics included in Volume II:

Thermal comfort

IAQ & perceived air quality

Indoor air acoustics and lighting

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13th International Conference on Indoor Air Quality and Climate 2014

Hong Kong
7-12 July 2014

Volume 3 of 6

ISBN: 978-1-63439-731-5

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13th International Conference on Indoor Air Quality and Climate 2014

Hong Kong
7-12 July 2014

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ISBN: 978-1-63439-731-5

Proceedings of Indoor Air 2014, Hong Kong

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13th International Conference on Indoor Air Quality and Climate 2014

Hong Kong
7-12 July 2014

Volume 5 of 6
Part 1 of 2

ISBN: 978-1-63439-731-5

Proceedings of Indoor Air 2014, Hong Kong

Topics included in Volume V:

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13th International Conference on Indoor Air Quality and Climate 2014

Hong Kong
7-12 July 2014

Volume 6 of 6

ISBN: 978-1-63439-731-5

Proceedings of Indoor Air 2014, Hong Kong

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New chemical substances in buildings

Nanoparticles in indoor environment

Climate change and indoor environment

Environmental impact of buildings

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Topic B4: Ventilation

NUMERICAL ANALYSIS OF THE THERMAL STRATIFICATION MODELLING EFFECT ON COMFORT FOR THE CASE OF A COMMERCIAL LOW-RISE BUILDING

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Keywords: Thermal stratification, Mixing and Displacement Ventilation, Low-rise building, Summer comfort

SUMMARY

Passive cooling solutions are almost never considered to ensure thermal comfort during summer of commercial low-rise buildings. The present study aims at evaluating the indoor temperature by using different approaches to account for thermal stratification and analysing the potential of natural ventilation to ensure thermal comfort in the occupied zone. Two building thermal configurations have been defined to model the indoor temperature profile: a single zone model and a vertical stratification one with different hypotheses regarding the airflow pattern. The results show that the single zone model is not accurate enough to predict thermal comfort in the occupied zone. Besides, mixing/displacement mechanical and natural ventilation models modify the temperature profile. The proposed modelling methodology improves the thermal comfort evaluation and shows the significant impact of natural ventilation on occupied areas.

INTRODUCTION

Most thermal transient simulation tools use the single zone approach in thermal balance problem solving (TRNSYS, EnergyPlus, ESP-r...) for reasons of simplicity and reasonable computational time. However, this method cannot account for building thermal stratification. The air temperature's vertical gradient is important for thermal comfort evaluation especially for large volume building and is one of the discomfort criteria (ISO 7730, 2006). Low–rise commercial building is characterized by high ratio of surface to volume hence the roof and ground floor design is often a crucial key-factor on heat transfer between the building and outdoors. The vertical temperature stratification of indoor air is affected by heat gains/losses by roof/floor, spatial distribution of internal heat gains and internal airflow. Various numerical and experimental researches on building thermal stratification showed that air temperature varies vertically up to 4 °C-11 °C depending on building height, geometry, envelope, internal heat gain, ventilation model and season (Dean et al., 1976; Saïd et al., 1996). The temperature stratification for a large space building is stronger during summer than other seasons. Regarding energy consumption, the thermal losses through the roof and by air renewal are predominant in terms of cooling and heating loads and can represent up to 42.1 % and 33.7 % of the total energy demand, respectively (Huang et al., 2007).

This paper aims to evaluate the indoor temperature stratification in commercial low-rise building by considering different mechanical/natural ventilation configurations. In a first part, the studied building is presented along with the description of its thermal model. A particular care has been taken to describe the internal airflow modelling. In a second part, after the evaluation of the vertical discretization influence on the thermal stratification, thermal comfort is evaluated and discussed for mixing and displacement ventilations. A last section is dedicated to the analysis of the natural ventilation potential for passive cooling.

METHODOLOGIES

Description of the studied commercial building

The studied commercial low-rise building is made of steel structure with a square floor surface of 36 m sides (Figure 1). The building height is 6 m. This building is located in a sub-urban area of a temperate climate region (Marseille, France). The vertical metallic walls (U-value = 0.122 W/m^2.K) have a total thickness of 30.5 cm (1.3 cm gypsum, 14 cm glass wool, 15 cm rock wool and an outer steel cladding of 2 mm) and include 30 m^2 of windows on the east, west and south façades. The roof is horizontal (U-value = 0.162 W/m^2.K) with a thickness of 24.2 cm (24 cm rock wool, 2 mm outer steel cladding), it is fitted with 31.36 m^2 skylight (2.42 % of total surface area). The floor is composed of 16 cm concrete slab without thermal insulation. The building is equipped with a heating system; no cooling system is installed. To ensure indoor air renewal, a mechanical ventilation system provides 6.9 l/s.person during the occupation period (07.00 AM–10.00 PM) every day except on Sundays. The occupation density of this commercial building is evaluated to 11.6 m^2/person (Deru et al., 2011). The thermal gain from human body is defined by ISO 7730 (ISO 7730, 2006). The height of the occupied zone is 1.8m. The air permeability level of the present building has not been measured, a value of 2 cm^2/m^2 has been considered for a common steel construction materials (Persily, 1998). The thermal gain of artificial lighting (suspended lamp) is 8 W/m^2 with 40 % of convective part (Rea, 1993).

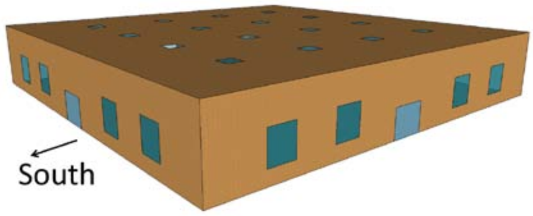


Figure 1. Geometry of studied commercial building.

Building thermal simulation model

The simulation of the commercial low-rise building has been performed using the transient system simulation tool TRNSYS. Several other programs, like EnergyPlus and Esp-r, may have suited for the present analysis but TRNSYS allows for example an easy way to integrate new models such as the air jet equations implemented in this study. The coupling between TRNSYS type 56 (building energy balance) and 97 (airflow network between zones) has been used here. As presented in Figure 2, Type 56 provides the air temperature of the building zones and Type 97 gives back the airflow rates between those zones and through the building envelope. As these infiltration and natural ventilation airflow rates are induced by wind and stack effects, wind pressure coefficients on the building envelope have to be provided. In this study, the Swami and Chandra correlations (Swami and Chandra, 1988) have been used. Moreover, heat transfer through the ground is modelled with the one-dimensional approach described in a previous paper (Lapisa et al., 2013a, 2013b). A first year of initialization has been performed to avoid initial condition influences.

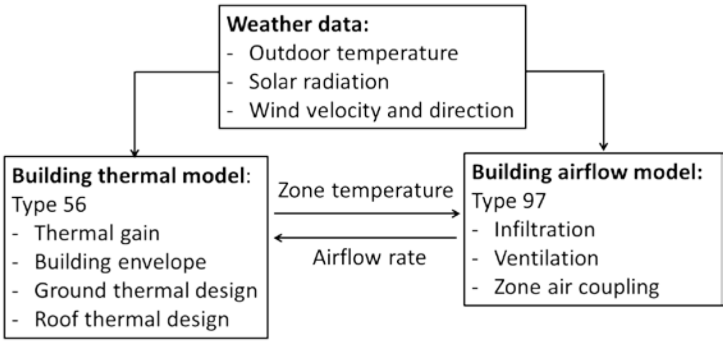


Figure 2. Coupled models.

Indoor airflow models

For the first approach, a model with only one air node is considered and referred as monozone model hereafter. The indoor air properties are homogeneous within the whole building volume. For the other models, the building is split into 12, 7 or 3 vertical stacked cells (Figure 3) with homogenous air properties in subzones. The smallest cells (0.5 m high) are located near the roof and the floor where higher temperature gradients may occur. In this study, horizontal temperature variations are neglected. The internal heat gain distribution is calculated according to the air nodes positions relative to the heat sources (occupant and lighting).

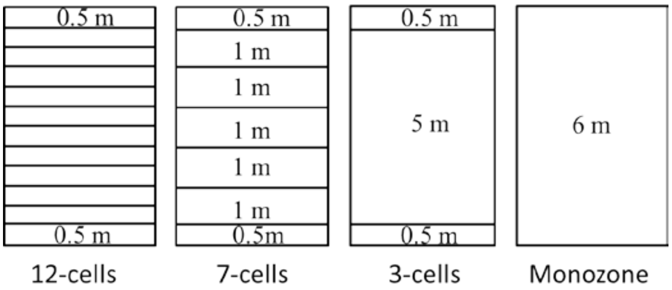


Figure 3. Mesh discretization of building air volume.

For the case of *mechanical mixing* ventilation, the air is introduced by 20 cm diameter diffusers located at the building ceiling providing a descending air jet all over the whole building height. The air mixes with the stratified zones and then is extracted by outlets placed at the building roof.

The vertical downward airflow rates for each interface are calculated by isothermal axisymmetric-wall jet equations (Abadie et al., 2012; Musy et al., 2001). The total (initial + entrainment) airflow crosses an interface n at a distance X_n (m) from the roof is expressed by following equation:

$$Q_{j,n} = Q_{j,o}\left(1 + \frac{4\,C_u^2\,K_v}{d_o\,\ln(2)}\,X_n\right) \tag{1}$$

where $Q_{j,n}$ is the jet airflow rate (kg/s) at a distance X_n (m) from the diffuser, $Q_{j,o}$ is the airflow rate at the inlet (kg/s), C_u and K_v are constant parameters depending on the jet type and are respectively equal to 0.097 and 6.3 and d_o is the diffuser diameter (m).

The temperature for each interface is evaluated by energy balance between the jet and the entrainment flow from the subzone. A general equation for the interface temperature is given by:

$$T_{j,n} = \frac{T_{j,n-1} + K_e \Delta \mathrm{X}_n\big((\mathrm{n}-1)T_{j,n-1} + T_n\big)}{1 + K_e \mathrm{X}_n} \qquad (2)$$

where $T_{j,n}$ is the temperature at the subzone lower interface (K), $T_{j,n-1}$ is the temperature of subzone upper interface (K), $T_{j,n-1}$ is the temperature of subzone (K), K_e is the entrainment air coefficient (1.71), X_n is the distance between the roof and the subzone lower interface (m), $\Delta\mathrm{X}_n$is the subzone height (m) and n is the subzone number starting from 1 at the roof.

Figure 4 illustrates the heat and mass balance of the building indoor air. The vertical downward jet flow induces the entrainment flow rate $Q_{e,n}$ for each subzone. Infiltration is accounted through the $Q_{inf,n}$ flow rate and interactions with the adjacent subzones are introduced with the $Q_{ac,n}$ and $Q_{ac,n+1}$ variables. In Type 97, the first one is calculated by the conventional airflow model through cracks and the second ones are evaluated using a horizontal large opening model.

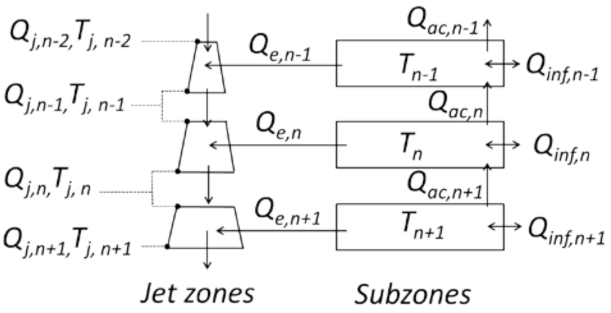


Figure 4. Heat and mass balance of the building indoor air.

For the case of *displacement ventilation*, air is introduced and completely mixed in the lower subzone and extracted in the upper part of the building. *Natural ventilation* is modelled using the vertical large opening approach in Type 97 to calculated the airflow rates through the additional openings located in the lower (open window) and upper (open skylights) subzones.

RESULTS AND DISCUSSIONS

Volume discretization effect on thermal stratification

A comparative analysis has been performed to evaluate the mesh discretization influence on the building indoor air temperature stratification. This preliminary study was focused on the mechanical mixing air ventilation configuration. Figure 5 shows the vertical air maximal temperature profiles for the monozone, 3, 7 and 12 subzones cases. This maximal temperature is the mean of the daily-maximal temperature over the summer period. Firstly, the three stacked zones models give similar coherent results. The temperatures obtained by those models are found higher than the monozone model, especially at the roof level where the difference reaches about 7.1 °C (for maximal temperature) as a result of solar heat gain absorbed on the roof, lighting heat gains and thermal stack effect.

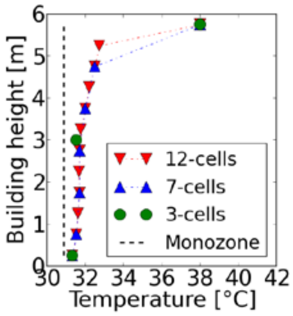
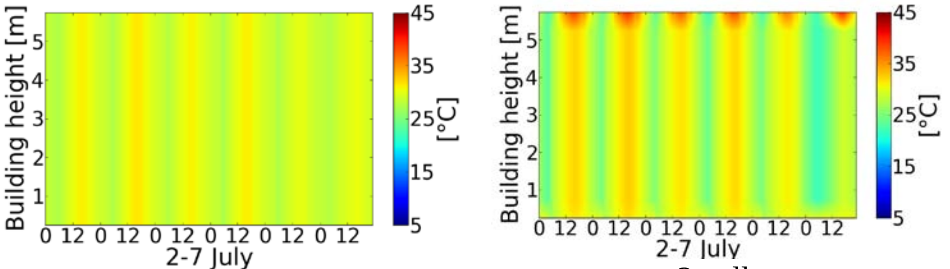


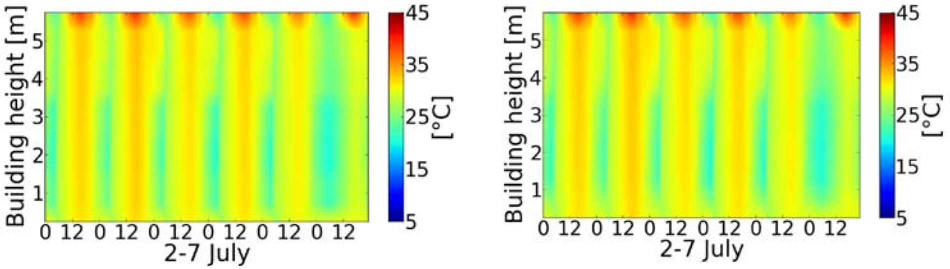
Figure 5. Maximal air temperature profile – Mechanical mixing ventilation.

Figure 6 presents the evolution with time (from the 2nd to the 7th of July) of the temperature vertical profile for the four cases. Firstly, as previously observed with the maximal values, hotter air during the daytime is noticed near the roof for the stacked models with a temperature gradient between the floor and the roof of about 6.7 °C. Yet, at night-time, the temperature near the floor is the higher one with temperature difference about 4.3 °C compared to upper level. This is due to the heat release from the ground during night; this phenomenon cannot be observed with the monozone approach. Secondly, higher temperature reduction is observed during night in the rest of the volume. This behaviour is better seen during Saturday (last day of the chart) when the building is unoccupied and the ventilation is turned off, like during night-time. Cooling is only due to heat conduction through the building envelope and air infiltration. As heat conduction is similarly treated in the monozone and stacked approaches, we investigate the infiltration flow rates calculated during night. Figure 7 presents the mean of the air renewal by infiltration over nights obtained with the monozone and the 12 stacked cells models. On the whole, the stratified model predicts an averaged value of 0.009 volume/h that is 15 % lower than the one calculated with the monozone approach (0.065 volume/h). This slightly lower rate of outdoor air (combined with the ascending piston effect that extracts the hotter air from the building) explains the lower cooling effect obtained with the stacked model (see the degree hours of discomfort temperature in the last section).



Monozone

3-cells



7-cells

12-Cells

Figure 6. Vertical air temperature of stratified models for different mesh.

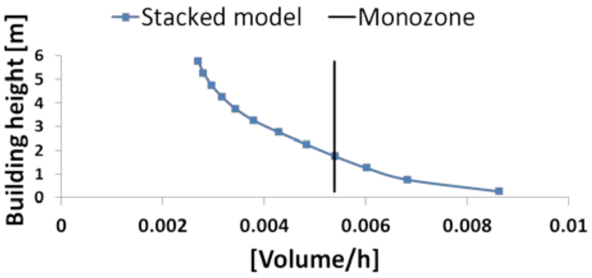
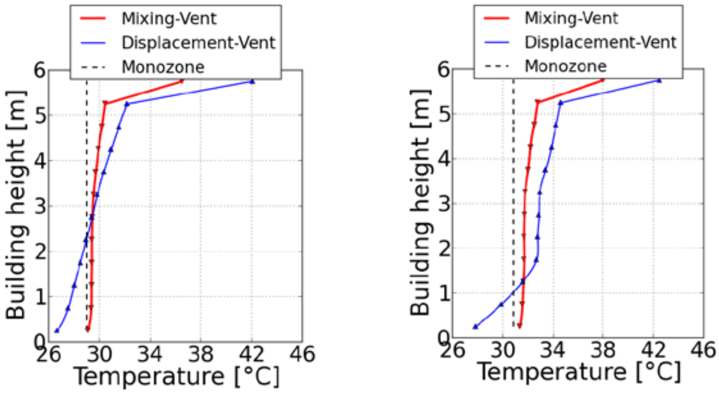


Figure 7. Air renewal by infiltration during night.

Considering the better representation of the thermal stratification and the small additional computational cost for the present problem, the 12 stacked cells model will be used in the rest of the analysis. Note that no validation of the proposed models has been done yet but comparisons with experimental results are planned for the coming year.

Mechanical air distribution model

Two air distribution configurations by mechanical ventilation have been defined: the first one is the vertical mixing air ventilation and the other one is the displacement ventilation. Both ventilation modes introduce the same amount of fresh air. In the first one, the air is supplied downward close to the roof, entrained air from the stacked zones, reached the lower zone and then goes back to the roof to be extracted. In the displacement ventilation mode, fresh air is supplied in the lower zone and is extracted at the roof as the first mode. Figure 8 presents the vertical maximal temperature profile for the empty (a) and the occupied building (b) for the two ventilation modes. Note that the monozone model gives the same results as it cannot take the differences between the two modes into account. Thermal stratification is clearly observed in both ventilation modes. Displacement ventilation exhibits lower and higher temperatures at the floor and roof, respectively. As a result, this ventilation mode provides better thermal conditions in the occupied zone than the mixing ventilation. However, this mode induces also a higher gradient of temperature between the locations of ankle and human head with temperature difference of about 4.8 °C (Figure 8.b) and thus can provoke local discomfort.



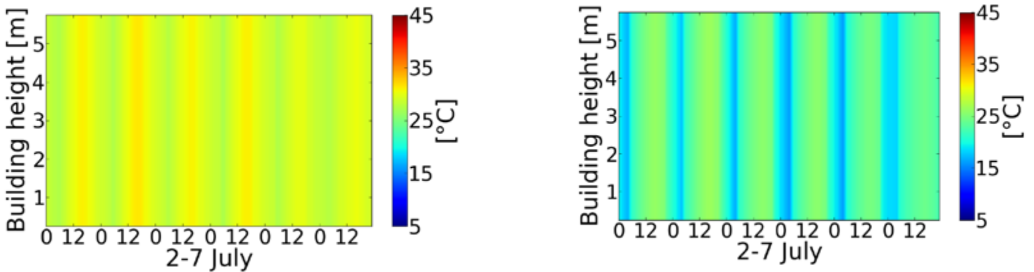
a. Empty building.

b. Occupied building.

Figure 8. Averages of maximal temperature of air nodes.

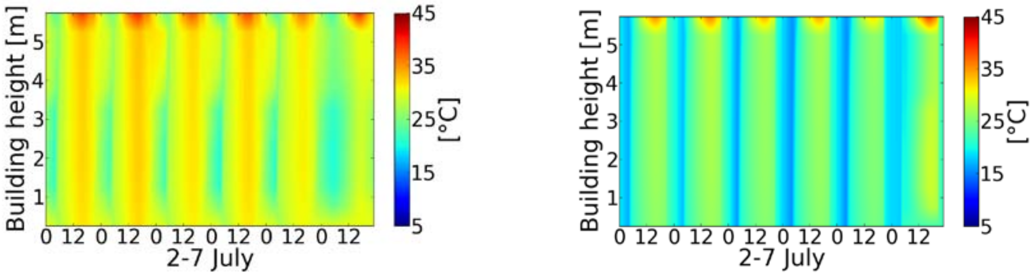
Natural ventilation effects

Night natural ventilation (NV) aims to mitigate the summer thermal discomfort by removing the heat through the opening. Figure 9 shows the indoor air temperature decrease induced by natural ventilation. For the stratified model, it can be observed that the natural ventilation effect not only reduces the temperature close to the roof level but also in the rest of the building volume. The heat extraction during the nights automatically reduces the average temperature for the next day. Results show that natural ventilation lowers the mean operative temperature in the occupied zone of about 6.2 °C, 5.9 °C and 5.3 °C for monozone, stratified model with mixing and displacement ventilation models, respectively.



a. Monozone without NV

b. Monozone with NV



c. Stratified model without NV

d. Stratified model with NV

Figure 9. Natural ventilation effect on temperature profile – Mixing air ventilation.

The building energy performance and the indoor overheating during summertime can be respectively evaluated by the degree-hours (°C.h) above the adaptive summer comfort temperature and the discomfort ratio (%) based on the occupancy hour's ratio, according to EN-ISO15251 standard. The degree hours of discomfort temperature calculated by the monozone approach is the lowest with 7232 °C.h. Stratification models with mixing air ventilation (9905 °C.h) and displacement ventilation (9143 °C.h) are found higher. The use of passive cooling by natural ventilation reduces those degree hours by 88.3 %, 74.4 % and 61.2 % for the monozone model, the stratification model with mixing air and displacement ventilation method, respectively. Moreover the natural ventilation lowers the temperature discomfort ratio from 94.9 % to 44 % and 90.2 % to 48.6 % for the stratification model cases with mixing and displacement ventilation. The monozone model predicts a higher cooling potential of natural ventilation showing a reduction of the ratio of temperature discomfort from the initial condition of 95.4 % to 31.3%.

CONCLUSION

The present numerical study demonstrates that the classical monozone representation is not accurate enough to predict the thermal comfort in a low-rise commercial building. Besides, this approach tends to amplify the building air response to outside air temperature fluctuations between day and night-time and overestimates the benefits of natural ventilation as a passive cooling technique. The use of a simple horizontal stacked zones model can overcome the limitations of the monozone approach by giving additional information on the thermal stratification allowing the comparison of different mechanical and natural ventilation strategies.

ACKNOWLEDGEMENTS

The authors wish to thank the Indonesian government for its financial support.

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