Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company’s public news and information website.

Elsevier hereby grants permission to make all its COVID-19-related research that is available on the COVID-19 resource centre - including this research content - immediately available in PubMed Central and other publicly funded repositories, such as the WHO COVID database with rights for unrestricted research re-use and analyses in any form or by any means with acknowledgement of the original source. These permissions are granted for free by Elsevier for as long as the COVID-19 resource centre remains active.
Characterisation and analysis of indoor tornado for contaminant removal and emergency ventilation

Yihuan Yan a, Xiangdong Li a, Jiyuan Tu a,b,⁎, Peijie Feng a, Jiaqiao Zhang a

a School of Engineering, RMIT University, PO Box 71, Bundoora, VIC, 3083, Australia
b Key Laboratory of Ministry of Education for Advanced Reactor Engineering and Safety, Institute of Nuclear and New Energy Technology, Tsinghua University, PO Box 1021, Beijing, 100086, China

ARTICLE INFO

Keywords:
Indoor tornado
Core region
CFD
Contaminants removal
Emergency ventilation

ABSTRACT

As an essential emergency management strategy, innovative emergency ventilation schemes that can quickly remove infectious and fatal contaminants without further spreading are highly demanded for public and commercial buildings. This study numerically investigated a vortex flow driven ventilation in a model room to explore the dynamic characteristics and 3D visualisation of vortex-driven indoor tornadoes. Four approaches to identify the core region of the indoor tornado were developed and compared against each other. By successfully capturing the continuously changing centre of the vortex and significant core region size variations at different heights, the swirl vector method was recommended as a quantifiable approach to identify the core region of indoor tornados. The numerical outcomes also revealed a strong connection between the lift angle, vortex intensity, overall size of indoor tornado and maximum size of core region. The best contaminants control and removal was achieved at lift angle of 20° in this study and an optimum lift angle ranging from 10° to 20° was recommended for future study.

1. Introduction

In all indoor environments, from a small residential compartment to a large airport terminal, the ventilation system has always been one of the most vital components and it vastly dominates the design index including indoor air quality, occupants’ thermal comfort and occupational health and safety (OHS) [1,2]. The performance of the ventilation system largely depends on its scheme, such as whether it is mixing or displacement ventilation [3]. Most of the existing and widely applied ventilation schemes are designed to create well-mixed air distribution inside the room so that the air can remain relatively refresh with effectively high air removal rate. However, everything is two-sided, while traditional ventilation systems create well-mixed and relatively low-momentum air flow distribution in indoor spaces, they also inevitably accelerate the transport and exposure of local indoor contaminants that can be generated or released from many sources (e.g. human, carpet, electronic devices, etc.) [4–6]. When contaminants are highly concentrated locally, these commonly used ventilation systems would be most likely promoting the transport of local contaminants rather than removing or isolating them away from further spreading. Costly lessons were learned through several past events. For instance, the Sarin chemical attack that happened in the Tokyo subway in 1995, caused over a dozen deaths and thousands of injuries, in which the ventilation system immediately accelerated the dispersion of the fatal gas [7]. Recently, nosocomial infections of the Middle East respiratory syndrome (MERS) took place in 16 hospitals of South Korea through the ventilation systems and eventually caused the national outbreak of MERS in 2015, which ended up quarantining 16,993 individuals for 14 days [8]. Under such circumstances when locally concentrated contaminants are highly infectious or fatal, innovative ventilation strategies or schemes are in urgent demand to minimise the damage caused by harmful contaminants in indoor spaces.

With the large fraction of studies focused on investigating and optimising the existing ventilation systems [9–11], the limitations of these ventilation systems for contaminant removal were also revealed more clearly. Since the traditional ventilation systems mainly rely on dilution and displacement to remove the contaminants [11], the effectiveness of contaminants removal could be very sensitive to the size of the room and become ineffective in large buildings or densely occupied indoor environments [12]. Also, the dilution method would inevitably increase the chance of further spreading the contaminants. To seek possible solutions, a few studies aimed to develop new ventilation systems [13–15]. Cao et al. [12] proposed a so-called vortex flow ventilation system, which uses a number of inlets near the ground level to form...
strong ascending vortices inside an enclosed chamber. They further tested their proposed vortex flow ventilation in an indoor space and provided a much better contaminants removal rate when compared with other traditional ventilation systems [16]. This idea of generating indoor ascending tornado was effective since it could directly remove the contaminants from the source to the exiting vent without further spreading. However, the behaviour of the indoor tornado could be very sensitive to a wide variety of factors such as swirl ratio, core region and vortex intensity [17,18]. These factors would significantly change the size, pattern and even formation of the tornado, which would essentially affect the transport and dispersion of the contaminants. It is of great importance to understand the dynamic behaviour of the indoor tornado prior to integrating it into an applicable indoor environment. Also, since physical boundaries do not exist in tornados, most existing studies referred to the geometrical positions of the tornado centre and used its relevant distance to the platform or the inlets to estimate the core region of the vortex [13]. This geometric-based estimation assumes that the size of the core region was uniform along the vertical direction. This assumption could be reasonable for outdoor tornados, in which the space has no restriction and the thereby the size variation on the core region compared to the overall size of the tornado is not significant. However, the formation of tornado in indoor spaces is seriously restricted by many factors, such as the height limit of the room and the size of the exhaust. All these factors would cause the core region of the indoor tornado to be significantly different at various heights and thereby the assumption of uniform core region is not realistic in indoor spaces. New criteria or approaches on identifying reasonable boundaries of indoor tornados could be of great significance in vortex flow ventilation systems.

Therefore, this study focused on a vortex flow driven ventilation and carefully investigated the major indoor tornado factors (lift angles, core region and vortex intensity, etc.) using numerical approaches. A room was modelled matching an existing experimental measurement chamber [13] to validate the reliability of the simulation and further explore the dynamic characteristics and 3D visualisation of indoor tornado and the corresponding vortex flow ventilation system. A novel approach (swirling vector method) to effectively identify the core regions and vortex intensity of the indoor tornado was proposed after in-depth comparison among four developed approaches. The 3D visualisation on the real pattern of the indoor tornado were thereby achieved based on the swirling vector approach. The ability of the vortex-driven ventilation to trap contaminants inside the tornado under various conditions were further tested. The outcomes of this study revealed a strong and coupled relationship among the key factors (lift angle, vortex intensity, core region, etc.) and summarised an optimum configuration on the lift angle for contaminant removal.

**Table 1**

| Case No. | Lift angle θ(°) | Offset angle α(°) | Horizontal angle β(°) | Swirl ratio |
|----------|----------------|-----------------|----------------------|------------|
| 1–1      | 0              | 16.7            | 4.8                  | 0.12       |
| 1–2      | 0              | 16.7            | 8.7                  | 0.22       |
| 1–3      | 0              | 16.7            | 13.8                 | 0.35       |
| 2–1      | 10             | 16.7            | 4.8                  | 0.12       |
| 2–2      | 10             | 16.7            | 8.7                  | 0.22       |
| 2–3      | 10             | 16.7            | 13.8                 | 0.35       |
| 3–1      | 20             | 16.7            | 4.8                  | 0.12       |
| 3–2      | 20             | 16.7            | 8.7                  | 0.22       |
| 3–3      | 20             | 16.7            | 13.8                 | 0.35       |
| 4–1      | 30             | 16.7            | 4.8                  | 0.12       |
| 4–2      | 30             | 16.7            | 8.7                  | 0.22       |
| 4–3      | 30             | 16.7            | 13.8                 | 0.35       |

**Fig. 1.** Computational domain.

**Fig. 2.** Lift angle θ, offset angle α and horizontal angle β.
2. Methodology

2.1. Computational models and boundary conditions

An enclosed chamber with dimensions of 3 m × 3 m × 3.5 m (L × W × H), as illustrated in Fig. 1, was used as a test model of this study to investigate the developing pattern and affecting parameters of the indoor vortex. The local airflow is driven by 4 jet inlets with diameter of 0.2 m near the ground level and one exhaust with double the diameter of the inlet vents at the ceiling. According to the experimental measurements by Cao et al. [13], such ventilation scheme would promote the formation of a locally concentrated indoor vortex. All side walls of the computational domain were set as free-flow opening with zero-gauge pressure to allow the air flow entering and existing the domain freely depending on the interior conditions. Computations were conducted with a room temperature of 20 °C.

The computational domain was discretised using the unstructured tetrahedron mesh in ICEM 17.2 [19]. To capture detailed velocity and pressure gradient change at the near wall regions, 10 inflation layers with growth ratio of 1.1 were generated near all inlets, exhaust and the source surface of contaminants. Mesh independence was achieved at 2.57 million elements with 95% elements below skewness number of 0.3 and maximum surface y + below 5. Further refining the mesh did not contribute significant differences of the air velocity profiles, pressure or contaminants distributions. The airflow field was solved using the incompressible Navier-Stoke (N–S) equations and the SIMPLEC algorithm was employed for the velocity-pressure coupling. The airflow and contaminant fields were solved using high-resolution advection scheme to achieve better robustness and accuracy of the advection terms. RNG k-ε model was applied for the air turbulence due to its successful application in modelling airflow and contaminants transport in indoor and enclosed environments [20,21]. Gaseous contaminants were released from a small circular surface at the coordinate origin of the domain. Contaminant transport was solved using a transportable scalar [19],

\[
S = \frac{1}{2a} \frac{V_{\text{ref}}}{V_{\text{ref}}_i} = \frac{1}{2a} \tan \alpha
\]  

(1)
**Fig. 4.** Radial profiles of the tangential velocity normalised with the axial velocity.

**Fig. 5.** Velocity magnitude refinement for case 2–1 at Z = 1.0 m, a. sub-grid velocity contour and histogram velocity distribution; b. velocity vector; c. core region defined by velocity magnitude.

**Fig. 6.** Velocity magnitude & tangential direction refinement for case 2–1 at Z = 1.0 m, a. schematic discrepancy angle; b. core region defined by magnitude only; c. core region defined by magnitude & tangential direction.
The dimensionless number swirl ratio has been widely used to describe the flow characteristics of the indoor tornado caused by the horizontal angle change of the inlet jet flow. The swirl ratio can be defined as the ratio of the tangential velocity to the radial velocity at the inflow region, which can be calculated as below:

\[
\frac{\partial}{\partial t}(\rho C) + \nabla \cdot (\rho \mathbf{v} C) - (\mathbf{r} + D)\nabla C = S_C
\]  

(2)

where, \( a \) is the geometric aspect ratio, which is defined as the ratio of inflow height (H) and the updraft radius (r_u). The aspect ratio was calculated as 0.35 in this study, which is inside the typical atmospheric range for the aspect ratio (0.2–1) [22]. \( V_{tan,i} \) and \( V_{rad,i} \) is the tangential velocity and the radial velocity, respectively. \( V_{tan,i}/V_{rad,i} \) equals \( \tan(\alpha) \), in which \( \alpha \) is the horizontal angle with respect to the radial direction. Three sets of the horizontal angle were applied in this study to achieve the swirl ratio of 0.12, 0.22 and 0.35, respectively.

The swirling strength method [23] was first applied to identify the vortex intensity. The velocity gradient tensor in cartesian coordinate can be decomposed:

\[
\mathbf{V}_{\alpha} = [d_j] = [\nabla \mathbf{v}_\alpha, \mathbf{v}_\alpha] = \begin{bmatrix} \lambda_\alpha & 0 & 0 \\ 0 & \lambda_{\alpha i} & \lambda_{\alpha j} \\ 0 & -\lambda_{\alpha i} & \lambda_{\alpha j} \end{bmatrix} [\nabla \mathbf{v}_\alpha, \mathbf{v}_\alpha]^T
\]

(3)

where, \( \lambda_\alpha \) is the real eigenvalue with corresponding eigenvector \( \mathbf{v}_\alpha \) and the complex conjugate pair of complex eigenvalues is \( \lambda_{\alpha i} \pm i\lambda_{\alpha j} \) with corresponding eigenvectors \( \mathbf{v}_{\alpha i} \pm i\mathbf{v}_{\alpha j} \). The strength of the swirling motion can be quantified by \( \lambda_{\alpha i} \), which can be defined as the vortex swirling intensity.

To holistically study the parameters that would have significant impacts on the indoor tornado formation and transport characteristics, parametric studies were conducted in this study with the aforementioned parameters. The case conditions are summarised in Table 1.

2.3. Model validation

In order to achieve accurate prediction of the indoor tornado 3D pattern and its dynamic characteristics, the modelling of the indoor tornado was pretested and compared to the experimental data reported in the literature [13,17] before further investigating the other parameters.

The axial velocity and pressure profiles predicted at various lift angles were first compared to the experimental measurements by Cao et al. [13]. As illustrated in Fig. 3, the numerical predictions of this study were in very good agreement with the velocity and pressure profiles at four different lift angles with 10-degree increments, despite the slightly smoother transition of the profiles yielded by simulations against the height change. Then, the radial profiles of the tangential velocity normalised with the validated axial velocity at various swirl ratios were further compared to the experimental measurements by Refan and Hangan [17], as illustrated in Fig. 4. The plots compared in Fig. 4 show very similar radial profiles of the tangential velocity over the axial velocity at swirl ratio of 0.22 and 0.35, which reveal reliable 3D radial development of the indoor tornado and the corresponding core regions of the vortex.

3. Definition of core region

Accurate 2D core region size prediction is the key leading to reliable 3D pattern and the dynamic characteristics of the indoor tornados. To find an effective method that is capable of capturing the size variation of the 2D core region for indoor tornados, four different core region identification approaches were developed and compared in this study.

3.1. Velocity magnitude refinement (approach 1)

Since the core region of the vortex contains higher velocity in
comparison to the far field, the magnitude of the velocity could be considered as an important factor in core region definition. The airflow field on an arbitrary 2D plane was firstly divided into $N \times N$ sub-grids followed by a histogram velocity distributions of the space weighted average velocity, as illustrated in Fig. 5. The original velocity vectors (Fig. 5b) was refined according to the accumulative high velocity from the histogram distribution. The core region radius $R_{\text{core}}$ was then defined as containing 90% of refined velocity vectors as demonstrated in Fig. 5.

3.2. Velocity magnitude and tangential direction refinement (approach 2)

Although the above velocity magnitude refinement method was able to identify the core region by filtering out the low velocity region from far field, it was very difficult to accurately exclude the high velocity generated by the inlet jet flow. Therefore, the combined velocity magnitude and tangential direction refinement method was developed to eliminate the strong interruption from the inlet jet flow. As illustrated in Fig. 6, this method first defines the discrepancy angle between the velocity vector and its perfect tangential direction. The effective boundary of the vortex was then identified with the discrepancy angle smaller than 20° (Fig. 6a). The velocity magnitude refinement was applied after defining the discrepancy angle (Fig. 6c). This method was developed based on the assumption that the centre of the vortex core regions at various 2D plane were in the same vertical line.

3.3. Maximum tangential velocity refinement (approach 3)

Existing literature also recommended using maximum tangential velocity to identify tornado rotating columns [24]. It is assumed that the maximum tangential velocity occurs at the boundary of the core region and then decreases asymptotically to zero at an infinitely far distance from the centre. This recommendation was taken here to develop the third approach, the maximum tangential velocity method, as illustrated in Fig. 7. Since the vortex beyond the maximum tangential velocity still has considerable high vortex intensity, the maximum tangential velocity may lead to an under estimation of the core region size. A double maximum tangential velocity refinement was applied to compensate for the under-estimation of the tangential velocity method.

3.4. Swirling vector refinement (approach 4)

Although the above methods were able to refine the vortex region into a reasonable scope, they were all based on a very restrictive assumption that the centre of the vortex on any arbitrary 2D plane was the geometric centre and it was fixed. However, due to the strong swirling characteristics of the vortex, the centre of the vortex was continuously changing when the indoor tornado was travelling vertically. In order to capture this dynamic characteristic, a swirling vector refinement method was developed. This method was able to find the centre of the vortex at the selected plane in prior to identifying the core region boundaries. The centre of the vortex was found by refining the high swirling vectors meeting the criterion of $F_{\text{high}} \geq F_{\text{max}}$ (F close to 1), followed by averaging the positions into cartesian coordinates $(X_{\text{high}}, Y_{\text{high}}, Z_{\text{high}})$.

To identify the core region, the 2D velocity field was first divided into numerous numbers of concentric hoops with various sizes at each selected plane, followed by averaging the swirling vectors in each hoop. Through averaging the hoops, the characteristic mean swirling vectors in each hoop were obtained and globally normalised. The boundary of the core region was thereby identified where the swirling vectors significantly dropped to a small magnitude close to zero, as illustrated in Fig. 8a. The corresponding core region at arbitrary 2D plane can be captured as demonstrated in Fig. 8b.
4. Results and discussions

While indoor tornado carrying smoky contaminants can be easily visualised through experiments, the observations were only reflecting the high concentrated smoke region near the centre of the vortex. However, the actual size of the effective vortex could be much wider than the highly concentrated centre. It is extremely difficult to visualise or measure the effective vortex boundary through experimental measurements. Simulations, on the other hand, would have full potential to identify and visualise the effective boundary of the vortex, which would be the key leading to a better and deeper understanding of the indoor tornado. Therefore, the vortex identification criteria (e.g. vortex intensity and core region) were firstly studied and discussed in conjunction with the aforementioned factors to investigate the impacts of these factors on the development of the vortex and to provide accurate 3D visualisation of the indoor tornado.

4.1. Vortex intensity

The predicted vortex intensity at various lift angles ranged from 0° to 30° were plotted in Fig. 9. The vortex immediately contained the maximum intensity at the ground level when the lift angle was set as 0°, which was indicating a strong formation of tornado near the ground level. On the other hand, when the lift angle was increase to 30°, the...
vortex intensity remained zero at lower height (up to 1.2 m), followed by a continuous growth of the intensity with the height increase. No indoor tornado was formed when the intensity of vortex was close to zero and thereby the formation of indoor tornado was significantly delayed and only occurred above 1.2 m when the lift angle was 30°. The other two methods, on the other hand, all predicted larger radius of the core region compared to the swirling vector and maximum tangential velocity methods. It is worth noting at lift angle of 30° that the swirling vector method predicted completely different profiles of the core region radius to the rest of the methods. At the heights below approximately 1.2 m, the radius of core region predicted by the swirling vector method was extremely small (close to zero), which indicates that there was no formation of the tornado until approximately 1.2 m. On the other hand, the rest of the methods yielded extremely large radii of the core region. The maximum tangential velocity method clearly over-predicted the radius of the core region (outside the boundary of the domain), which indicated that this method did not filter out the low velocity region at lower height and failed to distinguish the tornado to the surrounding flow. Since the vortex intensity at lower height was extreme small at 30° lift angle based on the above Fig. 9, the core region profiles from the swirling vector method (red lines) were better matching the vortex intensity pattern and better reflecting the real condition of the indoor tornado (i.e. no formation of indoor tornado until 1.2 m).

Since the boundary of the indoor tornado contains strong swirling characteristic and high momentum, the velocity vector plots indicating the velocity direction and magnitude changes were then used to further compare the predicted sizes of core regions at six different heights. It can be noticed from Fig. 11 that the double maximum tangential velocity method significantly over-predicted the size of the core region, especially at the lower heights (e.g. Z = 0.9 m) due to the interruptions from the inlet jet flow. Conversely, the size of core regions predicted by the single maximum tangential velocity method were too small at higher heights. Therefore, the maximum tangential velocity-based method is not ideal to identify the dynamic core region of indoor tornado since it can be easily affected by the surrounding flows. The velocity magnitude method showed very similar limitations as the maximum tangential velocity approach. In terms of the velocity magnitude and tangential direction combined method, it managed to minimise the interruption from the inlet jet flow and yielded relatively reasonable sizes of the core region. However, the centre of the predicted core region through this method was fixed at the geometrical centre, which was untrue. The velocity vector plots clearly proved the hypothesis that the centre of the vortex is not at the geometrical centre (e.g. at Z = 0.7 m and 1.3 m). Through comparing the core region sizes in conjunction with the velocity vector plots, the swirl vector method identified the most reasonable sizes of core regions at all height levels among the compared approaches. Most importantly, the swirl vector approach is the only approach that successfully captured the dynamic centre changes of the core regions. Therefore, the swirl vector method was the reliable and recommended approach to capture the dynamic centre and the boundary of indoor tornados. With the robustness of the swirl vector method being proved, the 2D swirling vector plots inside the core regions yielded from this method were applied to further study the characteristics of the indoor tornado.

4.3. 3D visualisation of indoor tornado

The 3D visualisation of the indoor tornado was achieved by plotting multiple layers of swirling vectors inside the core regions, as illustrated in Fig. 12. The 3D indoor tornado pattern demonstrated very strong uneven distribution of the vortex centre, especially at low lift angles.
Fig. 13. Maximum core region at different lift angle.
It can be clearly observed from the figure that the overall size of the indoor tornado became smaller when the lift angle went beyond 10°. The vortex was not even strong enough to form the tornado pattern at lower height when the lift angle was too high (30°). When controlling the indoor tornado size is necessary (e.g. minimising the size of the tornado to eliminate further spread of contaminants), the optimum lift angle is between 10° and 20°. Further lifting the angle could have a negative effect on the formation of indoor tornado. To further compare the size and location of the maximum size of the indoor tornado, the maximum core regions are compared in Fig. 13. The results reveal a clear pattern that the maximum core region size gradually reduces with the increase of lift angle (from over 0.5 m at 0° lift angle to almost half of the size at 30° lift angle). On the other hand, the height where the maximum core region occurred is lower, when the lift angle is increased. To carry as much contaminant as possible away from the source, a lower lift angle is preferred, while a higher lift angle could avoid further spreading of the contaminants at higher level. Therefore, to achieve optimum design, it is essential to investigate the contaminants transport under this indoor condition.

4.4. Contaminant distribution

Gaseous contaminants were assumed to be released on the surface of the platform. The predicted distributions of the released contaminants are shown on Fig. 14. The results clearly reveal the dominating control of the indoor tornado on the transport and distribution of the contaminants, while the unstable vortex pattern also strongly affected the pattern of the contaminants, especially the relatively low concentrated contaminants that were distributed close to the boundary of the indoor tornado. Through comparison, it is worth noting that the optimum control on the contaminants transport and distribution is achieved at a lift angle of 20°, in which the entire gaseous contaminants were successfully captured inside the tornado and were directly exhausted from the exit without further spreading inside the room. The optimum settings could be limited to this tested room, scale-up of the proposed system would be needed for real indoor application. In this study, the gaseous contaminants were employed as an example to demonstrate the effectiveness of the proposed system. The outcomes showed that the proposed system is very effective of capturing the contaminants inside the tornado and removing airflow-driven contaminants, which means it could also applicable to most of the particulate contaminants. However, particulate contaminants with extremely small size (nano size particles) or particles with strong inertia (i.e. very large particles) could have very different distributions and need to be further studied. Although the presented outcomes could be limited to the studied conditions and parameters. The methods of identifying the indoor tornado and the capabilities of the indoor tornado on contaminant control is promising, especially for large spaces and densely occupied indoor environments where the traditional ventilation schemes have very limited control (airport, train station, etc.)

Fig. 14. Contaminants distribution at different lift angle.
5. Conclusion

This study numerically studied the vortex flow ventilation in an indoor chamber and focused on investigating a number of major affecting factors (lift angle, core region, etc.). Four different methods were developed to identify the core region of the indoor tornado and were carefully compared, followed by 3D visualising of the indoor tornado patterns, as well as contaminant transport and distributions under various conditions. The conclusion arising from this study are as follows:

1. The swirling vector method was developed and is recommended to identify the cross-sectional core region of the indoor tornado. This approach successfully captured the continuously changing centre of the vortex and significant core region size variations at different heights, which are critical characteristics of indoor tornados due to the indoor limitations on room height, exhaust size and position, etc. With the boundary of the vortex at arbitrary 2D planes being accurately defined, the strong visualisation capabilities of computations were used to study indoor vortex flow ventilation. 3D visualisation of the indoor tornado profiles was easily achieved with high accuracy by applying the proposed swirling vector method.

2. The lift angle of the inlet jet was found to have a strong connection to the vortex intensity, the overall size of indoor tornado and the contaminants distributions. Increasing the lift angle would reduce the size of the tornado and thereby have positive impacts on controlling the contaminants transport. However, it was worth noting that the indoor tornado could fail to form at lower heights if the inlet jet angle was over lifted. The ideal lift angle found in this study was 20°, in which the released contaminants were successfully trapped inside the indoor tornado with minimised size and were directly exhausted through the exist without further spreading inside the room. Based on the outcomes from this study, optimum lift angles ranging between 10° and 20° are recommended.

Acknowledgements

The financial supports provided by the Natural Science Foundation of China (Grant No. 91643102), Australian Research Council (Project ID: DP160101953) and Railway Manufacturing CRC of Australia (Project ID: R3.6.1) are gratefully acknowledged.

References

[1] M. Sandberg, What is ventilation efficiency? Build. Environ. 16 (2) (1981) 123–135.
[2] P.V. Nielsen, Fifty years of CFD for room air distribution, Build. Environ. 91 (2015) 78–90.
[3] Y. Yan, X. Li, J. Tu, Numerical investigations of the effects of manikin simplifications on the thermal flow field in indoor spaces, Build. Simul. 10 (2) (2016) 219–227.
[4] X. Gu, J. Wen, M. Wang, G. Jian, G. Zheng, S. Wang, Numerical investigation of unsteady particle deposition in a realistic human nasal cavity during inhalation, Exp. Comput. Multiph. Flow 1 (1) (2019) 39–50.
[5] Y. Yan, X. Li, J. Tu, Thermal effect of human body on cough droplets evaporation and dispersion in an enclosed space, Build. Environ. 148 (2019) 96–106.
[6] J. Dong, L. Tian, G. Ahmad, Numerical assessment of respiratory airflow exposure risks to diesel exhaust particles, Exp. Comput. Multiph. Flow 1 (1) (2019) 51–59.
[7] P. Robyn, Consequence Management in the 1995 Sarin Attacks on the Japanese Subway System, John F. Kennedy School of Government, Harvard University, 2002 BCSIA Discussion Paper 2002.4.
[8] M.D. Oh, W.B. Park, S.W. Park, P.G. Choe, J.H. Bang, K.H. Song, E.S. Kim, H.B. Kim, N.J. Kim, Middle respiratory syndrome: what we learned from the 2015 outbreak in the Republic of Korea, Korean J. Intern. Med. 33 (2) (2018) 233–246.
[9] X. Peng, S.-W. Hong, L. Zhao, Using CFD simulations to develop an upward airflow displacement ventilation system for manure-belt layer houses to improve the indoor environment, Biosyst. Eng. 178 (2019) 294–308.
[10] Y. Wang, F.-Y. Zhao, J. Kuckelkorn, D. Liu, J. Liu, J.-L. Zhang, Classroom energy efficiency and air environment with displacement natural ventilation in a passive public school building, Energy Build. 70 (2014) 258–270.
[11] H. Lee, H.B. Awbi, Effect of internal partitioning on indoor air quality of rooms with mixing ventilation—basic study, Build. Environ. 39 (2) (2004) 127–141.
[12] H.-Y. Deng, Z. Peng, S.-J. Cao, Influence of air change rates on indoor CO2 stratification in terms of Richardson number and vorticity, Build. Environ. 129 (2018) 74–84.
[13] Z. Cao, Y. Wang, M. Duan, H. Zhu, Study of the vortex principle for improving the efficiency of an exhaust ventilation system, Energy Build. 142 (2017) 39–48.
[14] J. Fan, C.A. Hviid, H. Yang, Performance analysis of a new design of office diffuse ceiling ventilation system, Energy Build. 59 (2013) 73–81.
[15] I. Torres, New technique for treating rising damp in historical buildings: wall base ventilation, J. Cult. Herit. 31 (2018) 560–570.
[16] Z. Cao, Y. Wang, C. Zhai, M. Wang, Performance evaluation of different air distribution systems for removal of concentrated emission contaminants by using vortex flow ventilation system, Build. Environ. 142 (2018) 211–220.
[17] M. Refan, H. Hangan, Characterization of tornado-like flow fields in a new model scale wind testing chamber, J. Wind Eng. Ind. Aerodyn. 151 (2016) 107–121.
[18] N.B. Ward, The exploration of certain features of tornado dynamics using a laboratory model, J. Atmos. Sci. 29 (1972).
[19] ANSYS®, Academic Research Release 17.2, Help System, Coupled Field Analysis Guide, ANSYS, Inc., 2017.
[20] Q. Chen, Comparison of different k-ε models for indoor air flow computations, Numer. Heat Transf. B Fundam. 28 (3) (1995) 353–369.
[21] F. Chen, S.C.M. Yu, A.C.K. Lai, Modeling particle distribution and deposition in indoor environments with a new drift-flux model, Atmos. Environ. 40 (2) (2006) 357–367.
[22] C.R. Church, J.T. Snow, G.L. Baker, E.M. Agee, Characteristics of tornado-like vortices as a function of swirl ratio: a laboratory investigation, J. Atmos. Sci. 36 (1979) 1155–1176.
[23] V. Holmen, Methods for Vortex Identification, Mathematics, LUND UNIVERSITY, Sweden, 2012.
[24] Y.C. Kim, M. Matsui, Analytical and empirical models of tornado vortices: a comparative study, J. Wind Eng. Ind. Aerodyn. 171 (2017) 230–247.