

Computational study of wind-fire-structure interactions and their impact on bushfire resistance design of housing

K.C.S. Kwok ^a, Y. He ^b, M. Poty ^b

^a *Institute for Infrastructure Engineering, University of Western Sydney, Australia*

^b *School of Computing, Engineering and Mathematics, University of Western Sydney, Australia*

ABSTRACT

This current paper presents the results of computational fluids dynamics (CFD) simulations of external flow over a cubic building block. The focus is given to the investigation of the domain size dependence of such simulations. This parametric study used a systematic examination of the pressure coefficient distribution around the block with stepwise variation in domain extensions in 4 directions relative to the block. The results revealed differences between the different domain expansions in each direction and the trend of a convergence. Dimensionless parameters were introduced to link the optimum domain size to the building size. The study identified the dominant direction that influences the domain dependence the most.

KEYWORDS: Domain dependence, sensitivity, pressure coefficient.

Nomenclature

C_p pressure coefficient
 H characteristic building dimension (m)
 H_i building size in i -direction (m)
 P pressure (Pa)
 s distance around the perimeter of building (m)
 s^* non-dimensional distance $=s/H$
 R Pearson correlation coefficient
 T temperature (C, K)
 t time (s)
 U free stream velocity (m/s)
 x, y, z coordinates of the computational domain (m)

Greek

α constant in the power law for wind velocity profile
 Δ_i domain expansion in i -direction (m)
 δ_i grid size in i -direction (m)

ρ density (kg/m³)

Superscript

* non-dimensional parameter

1 INTRODUCTION

Bushfire is a natural phenomenon that occurs frequently in many places around the world, given favourable weather and fuel conditions, and ignition mechanisms naturally occurring, such as lightning, or man-made, such as fallen transmission lines. Most bushfires are dealt with and controlled by the various fire services at their early stages of development. However, bushfires which are difficult to control and with major fire runs, often in inaccessible areas, can develop into ragging catastrophic infernos causing widespread property damages and loss of lives, such as the recent Black Saturday Bushfire that claimed 173 lives and more than 2000 properties in Victoria, Australia on 7 February 2009 [1].

While considerable attention has been given to the principal agents of bushfire attack, including embers, radiant heat and flame contact [2], our knowledge about the characteristics of bushfire-enhanced winds and their impacts on buildings is relatively scarce. Early studies focused on the large scale, or meteorological scale interactions between wind and wild fires [3] and primarily on the effect of wind on fire spread [4]. Only recently, numerical investigations were conducted to study wind-bushfire-building interactions at the near ground level the scale comparable to building dimensions for different approach wind speeds and fire intensities [5-6]. The results demonstrated the exacerbation of wind conditions due to buoyancy effect created by a bushfire simulated as a line-like fire front. The fire-enhanced wind profile showed a significant increase in wind speed near the ground, and the speed-up effects were found to depend on the approach wind speed and the fire intensity. When the Silsoe 6 m cube was placed downstream from the fire front of a moderate intensity, the fire-enhanced wind caused a substantial increase in the positive windward wall pressures and a small decrease in the negative roof pressures, while the sidewall and leeward wall pressures remain relatively unchanged.

It is well known that the results of numerical simulations are grid dependent both in terms of grid cell size (or mesh resolution) and grid domain size [7-10]. Grid cell size sensitivity study using the particular numerical package, namely, the Fire Dynamics Simulator [11] has been investigated in a previous study [6]. Presented in the current paper is a continuous study on grid domain dependence.

1.1 Grid dependence studies

Murakami and Mochida [7] studied the behavior of an external flow over a cubic building. They focused on the influence of different mesh resolutions around the building, domain boundary conditions (free slip or non-slip conditions) and various wall functions (power or log law). Their investigations were carried out by comparing pressure coefficients, velocity vectors and solution or truncation errors between simulations and experiments. It was concluded that a mesh resolution in the order of $\delta x = H/24$ (or $\delta x = 0.042H$), where H is the height of the cubic model, is necessary in windward building corner to avoid errors and behind the building to study the wake. Moreover, according to their results, it would be better to set the pressure rather than the velocity at domain boundary and the log law for wall condition shows better agreement with experiment.

In 1990, Baetke and Werner [12] studied external flow over a cubic building or over a square mounted rib respectively using a Reynolds averaged simulation scheme and a LES (Large Eddy

Simulation) simulation scheme. It was suggested that a mesh division of $\delta x = 19H/160$ (or $\delta x = 0.12H$), where H is the height of the rib, is necessary to obtain reasonable results.

More recently, He et al. [6] carried out a numerical study of wind-fire-building interactions. In their study a 6 meter cubic block was located downstream a fire bed and an external wind flow defined by $U_0(z) = U_r(z/z_r)^\alpha$ (where $\alpha = 0.16$, $U_r = 9.52$ m/s and $z_r = 6$ m). During this work, they began to simulate without fire and focused their study on grid dependence to find the mesh division which yields reasonably good agreement with experiments and is computationally economical. It was concluded that the optimum grid size was not necessarily the finest and the optimized grid size was $\delta x = 0.04H$, similar to that found by Murakami and Mochida [7].

Yet, the domain dependence problem was often neglected. The computational domain was often set arbitrarily. It could cause serious errors because a non-appropriate domain size may overestimate or underestimate key parameters as pressure coefficient or flow velocity. He et al. [8] and Zhang et al. [9] studied particularly the domain dependence in building enclosure fire simulations. They carried out systematic investigations into the relationship between domain extension, vent opening size and the heat release rate of compartment fires. It was found that the necessary domain extension beyond the compartment boundary could be proportionally linked to the vent opening size and the heat release rate. Moreover the coefficient of proportionality depends on whether the fire is fuel controlled or ventilation controlled and the domain extension is more efficacious in the direction perpendicular to the vent opening.

Domain dependence study can be as dramatic as comparing between 2D and 3D simulations. Hostikka et al. [13] studied an external flow and fire behavior around a building block. Their primary interest is to examine the sensitivity of heat transfer (particularly radiant heat transfer) evaluation on grid dimension and grid density. They concluded that 3D domain is necessary for accurate evaluation of radiant heat transfer with grid size in the range of $0.02H < \delta x < 0.04H$.

The objective of the current study is to investigate the domain dependence problem in computational fluid dynamics studies of external flows using Fire Dynamic Simulator. The parameter of interest is the aerodynamic characteristics, or pressure coefficient distribution around a 6 m cube building block. This paper reports the first part of the study where no fire was involved.

2 METHODOLOGY

For carrying out this study, reference case was taken from He et al.'s simulation [6] using the Fire Dynamics Simulation 5 (FDS5) software. FDS5 solves numerically a form of the Navier-Stokes equations by employing Large Eddy Simulation (LES) scheme. This scheme uses a type of Smagorinsky $k-\varepsilon$ model described in [11] to model the turbulence effect at the sub grid level and the core algorithm is a predictor-corrector scheme with second order accuracy in space and time [14].

He et al [6] have carried out a study to find the optimum grid size for a specified fire scenario. The same grid size was retained for the current study. Thus, during this investigation, multiple series of simulations with domain size extensions or contractions respectively in x , y and z directions were executed while keeping the same grid size. Each simulation has a domain size variation in only one direction to study the domain size dependence specifically in each direction. It was particularly important to take care of y direction, where the grid size is non-uniform, and keep the same mesh division around the building. So this parametric study uses a systematic examination of the results with stepwise variation in domain extension parameters. However this

stepwise variation, keeping the grid size constant, had to respect the restriction on cell numbers defined by the FDS User's Guide [10]. Thus the steps of domain size variation could not be maintained constant (Table 1). Moreover these domain extensions and contractions were described by non-dimensional parameters to allow future researchers to use the results for study with different building sizes.

The conclusion was obtained by comparing the predicted mean pressure coefficients in different cases and by identifying the parameters at which no significant difference occurs. The averaging was achieved by taking the predicted pressure during the quasi-steady period of simulation.

This domain dependence investigation was carried out firstly without involvement of fires. After finding the appropriate domain size, one more step was achieved. In order to observe the wind speed influence on the results, a simulation with variation in reference wind velocity was run. The criteria for determining the optimum domain size is that convergence is achieved in the predicted key parameter distributions, i.e. pressure coefficient distributions, within a prescribed relative error band and reasonable CPU time. The convergence is measured with two methods. On the one hand the Pearson correlation coefficient is calculated between the results of successive domain sizes simulations. On the other hand, the mean absolute pressure coefficient difference between results is also calculated.

2.1 *Domain description of the reference case*

As mentioned previously, reference case was taken from He et al.'s study [6]. The computational domain in reference case was a 40×30×18m rectangular space. A 6 meter cubic building block was located 25 meters downstream of the domain boundary. The origin of the x - y - z coordinate of the domain is set at the centre of the front base line of the building block as illustrate in Figure 1. Wind is blowing from left to right, along the positive x direction. The fire front of the bushfire, which is not involved during the first study step, is 3 m in width and runs in the entire domain in y -direction at the ground level. The trailing edge of this fire bed is located 20 meter upstream the left face of the building and the fire front is assumed stationary. The two domain boundaries in y -direction are closed and assumed slip conditions. The right and top boundaries are specified as "OPEN". All solid surfaces are specified smooth. The grid size in the reference case is 0.17, 0.24/0.42 and 0.15 m in x , y and z directions respectively. The grid size in y direction is non-uniform. A piecewise transformation was applied to achieve finer grid close to the building and relatively coarser grid further away from the building.

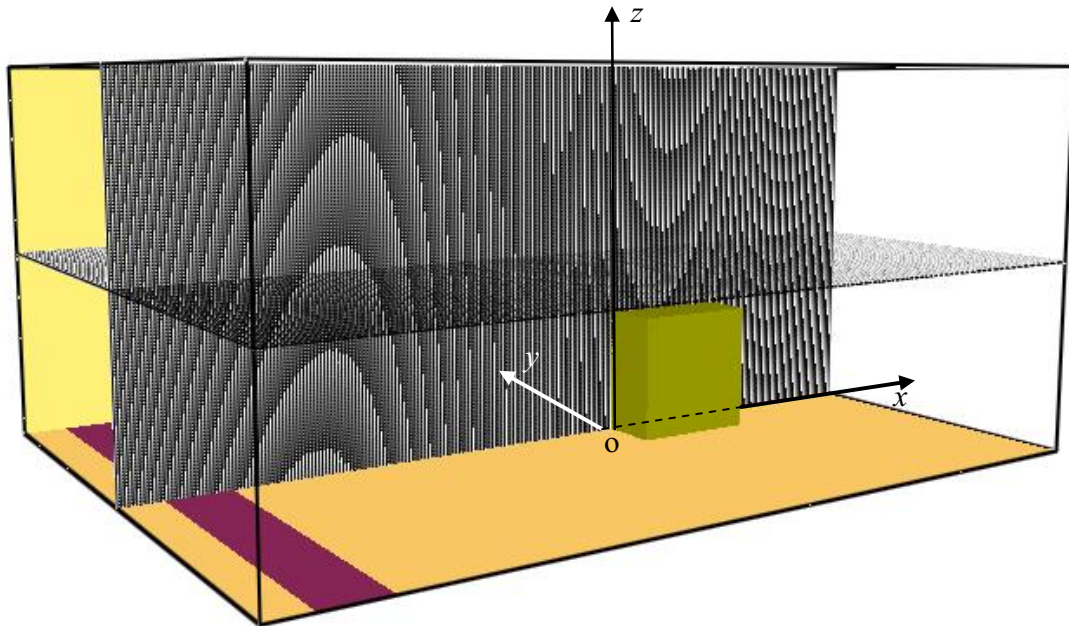
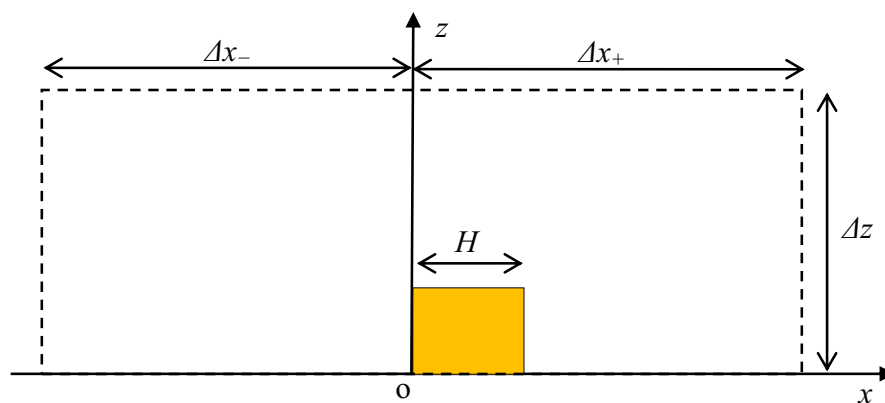


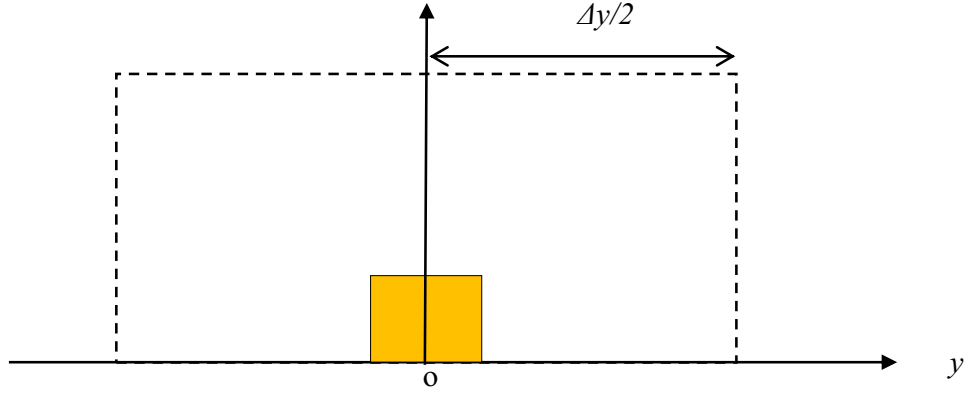
Figure 1. Computational domain and grid setup.

2.2 Normalized parameters

A group of normalized parameters are introduced to describe the dimension of the computation domain. The building block dimensions are defined as $H_x \times H_y \times H_z$. For the particular case investigated in the current study $H_x = H_y = H_z = H = 6$ m. The domain expansion from the origin is denoted by Δx_+ , Δx_- , Δy and Δz respectively in x_+ , x_- , y and z directions. The domain expansion in y direction is symmetrical and in z is always positive. See Figure 2.



(a) Domain expansion in x - z plan



(b) Domain expansion in y-z plan

Figure 2. Illustration of computation domain and coordinate setup.

For ease in generalisation, the following non-dimensional parameters are introduced:

$$\Delta x_+^* = \Delta x_+/H; \quad \Delta x_-^* = \Delta x_-/H; \quad \Delta y^* = \Delta y/H; \quad \Delta z^* = \Delta z/H \quad (1)$$

In addition, for the data presenting purpose, the non-dimensional parameter s^* is defined as $s^* = s/H$, where s is the distance measure from a reference point around the perimeter of the building block.

2.3 Summary of simulation scenarios

The domain expansion was undertaken in a stepwise manner in a series of simulations. From the reference case, domain expansion simulations are run. The major difficulty is to keep exactly the same grid size around the building. Moreover the number of cells in each direction has to be of the form $2^l 3^m 5^n$ where l , m and n are integers. So it is not possible to expand the domain arbitrarily whilst maintaining constant grid size. It is necessary to choose the domain size in function of the cell numbers permitted [10] to keep the same grid size. That explains why each domain extension in this study does not always use the same step. As regard y-direction and its non-uniform mesh division, it is not possible to keep the same grid size in the whole domain due to the piecewise linear transformation. Thus it was decided to keep the grid size unchanged close to the building. A summary of all the simulation scenarios are presented in Table 1.

Table 1. A Summary of simulation scenarios.

Simulation ID	Extensions	Domain size (m)			Grid size (m)		
		X	Y	Z	Δx	δy	δz
A	— ^a	40	30	18	0.17	0.24/0.42	0.15
B	$\Delta x_+^* \approx 1.8$	36	30	18	0.17	0.24/0.42	0.15
C	$\Delta x_+^* \approx 3.3$	45	30	18	0.17	0.24/0.42	0.15
D	$\Delta x_+^* \approx 4.17$	50	30	18	0.17	0.24/0.42	0.15
E	$\Delta x_+^* \approx 5$	54	30	18	0.17	0.24/0.42	0.15
F	$\Delta x_-^* = 5$	45	30	18	0.17	0.24/0.42	0.15
G	$\Delta x_-^* = 3.5$	36	30	18	0.17	0.24/0.42	0.15
H	$\Delta y^* = 4$	40	24	18	0.17	0.24/0.6	0.15
I	$\Delta y^* = 6$	40	36	18	0.17	0.24/0.375	0.15
J	$\Delta y^* = 8$	40	48	18	0.17	0.24/0.34	0.15
K	$\Delta z^* = 3.6$	40	30	21.6	0.17	0.24/0.42	0.15
L	$\Delta z^* = 4$	40	30	24	0.17	0.24/0.42	0.15
M	$\Delta z^* = 3.375$	40	30	20.25	0.17	0.24/0.42	0.15
N	$\Delta z^* = 3.2$	40	30	19.2	0.17	0.24/0.42	0.15
O	$\Delta z^* = 2.5$	40	30	15	0.17	0.24/0.42	0.15

a. Simulation scenario A is the reference case of which the domain dimensions are $\Delta x_+^* = 2.5$, $\Delta y^* = 5$, $\Delta z^* = 3$ and $\Delta x_-^* \approx 4.2$.

3 RESULT AND DISCUSSION

3.1 Sensitivity to downstream (Δx_+) expansion

Presented in Figure 3 are the predicted pressure coefficient variations along the centerline and mid height of the cube. It can be observed from Figure 3 that a significant difference in pressure coefficient distribution if the x_+ domain size is varied. This phenomenon may be attributable to pressure boundary condition at the open boundary which was prescribed downstream of the domain. As such, the simulation of wake features and flow behavior behind the building block suffers a kind of truncation or discontinuity which resulted in higher pressure coefficient distribution above and behind the cube. When Δx_+^* is increased, the pressure coefficient distribution tends to settle asymptotically. Thus the domain has to be large enough in x_+ direction to allow the simulation to take the largest wake eddies into account.

It is also noticed from Figure 3 that the variation in domain expansion in x_+ direction hardly changes the shape of the distribution curve. Indeed, the Pearson correlation coefficients between successive simulations are all above 0.999 as shown in Table 2.

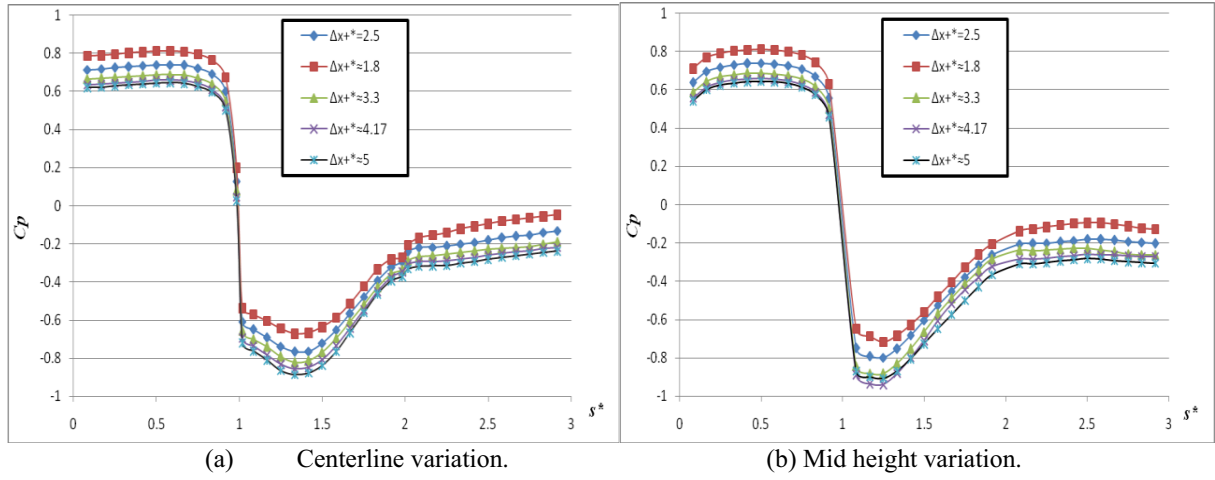


Figure 3. Mean pressure coefficient in simulations with domain variation in x_+ direction.

Table 2. Correlation coefficients between successive simulations with increasing Δx_+^* .

Correlation between scenarios	R	
	Centerline	Mid height
A–B	0.99956	0.99965
A–C	0.99994	0.99961
C–D	0.99993	0.99981
D–E	0.99998	0.99929

3.2 Sensitivity to upstream (Δx_-) expansion

For the Δx_- study only two additional simulations were run and the results are presented in Figure 4. These simulations do not reveal any significant change in comparison with simulation scenarios involving domain variations downstream of the building block. Again the correlation coefficients between successive simulations are very high, as shown in Table 3.

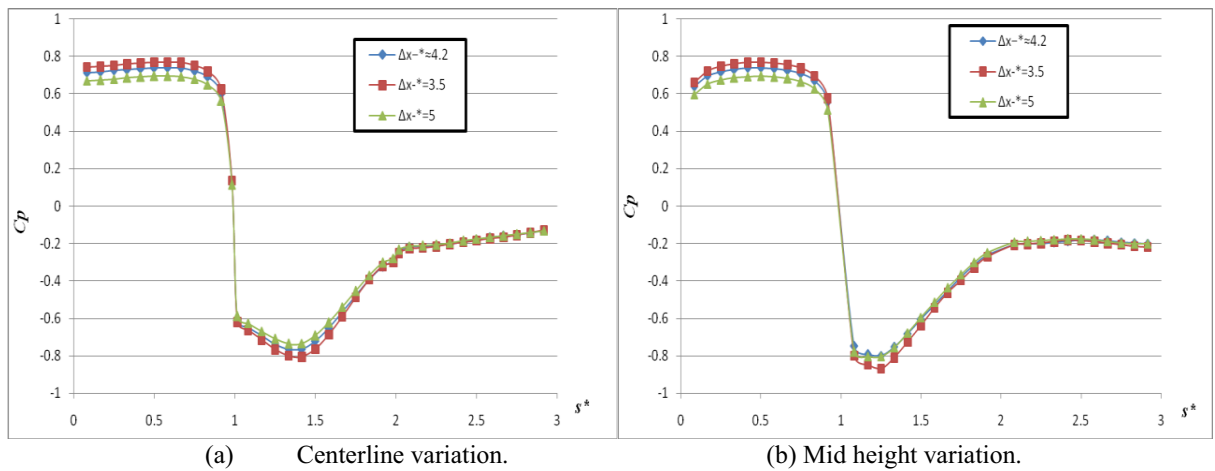


Figure 4. Mean pressure coefficient in simulations with domain variation in x_- direction.

Table 3. Correlation coefficients between successive simulations with increasing Δx_* .

Correlation between scenarios	R	
	Centerline	Mid height
A–G	0.99994	0.99986
A–F	0.99998	0.99961

3.3 Sensitivity to lateral (Δy) expansion

In Δy variation simulation, the centerline pressure coefficient distribution does not show significant change, as revealed in Figure 5. However, in the side face, the pressure coefficient appears slightly lower when Δy^* is reduced. This is due to the Venturi effect between the building block and the non-slip closed boundary. Thus the domain has to be large enough to avoid this effect. It is seen from Figure 5 that the lateral dimension of $\Delta y^*=5$ (Case A) yielded reasonable results and any further expansion in y direction did not necessarily yield anything much different. Once more, it can be noted that the Pearson coefficient values are all higher than 0.999 and make the results reliable, as shown in Table 4.

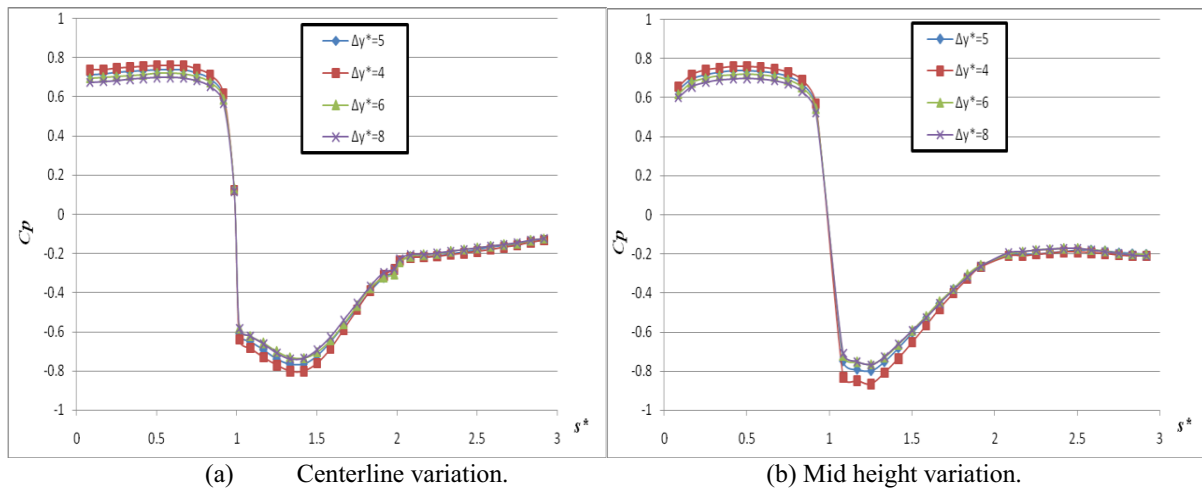


Figure 5. Mean pressure coefficient in simulation of domain size variation in y direction.

Table 4. Correlation coefficients between successive simulations with increasing Δy^* .

Correlation between scenarios	R	
	Centerline	Mid height
A–H	0.99987	0.99980
A–I	0.99991	0.99992
I–J	0.99985	0.99996

3.4 Sensitivity to vertical (Δz) expansion

Finally, the sensitivity to vertical domain size was studied in the last 5 scenarios in which Δz^* was varied from 2.5 to 4. The results are shown in Figure 6. Initially for relatively small vertical size $\Delta z^*=2.5 \sim 3.2$, the predicted pressure coefficient was almost invariant. However, when Δz^* was increased from 3.2 to 3.375, the pressure coefficient distributions exhibited on the windward face noticeable increases whilst on the roof and the side walls noticeable drops, and then remained almost invariant for $\Delta z^*>3.375$. Such a trend of variation was also revealed in the correlation analysis as shown in Table 5 where the correlation coefficient between the predicted pressure coefficient distributions of Case M and Case N attains the lowest values for both the centreline and mid height measurements.

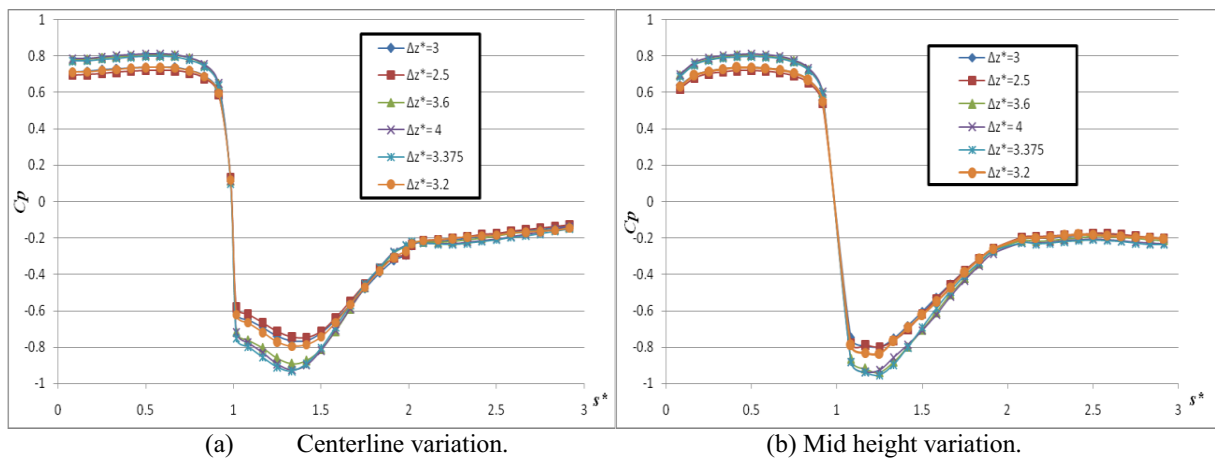


Figure 6. Mean pressure coefficient in simulation of domain size variation in z direction.

Table 5. Correlation coefficients between successive simulations with increasing Δz^* .

Correlation between scenarios	R	
	Centerline	Mid height
A–O	0.99996	0.99982
A–N	0.99978	0.99982
N–M	0.99832	0.99967
M–K	0.99963	0.99980
K–L	0.99990	0.99984

4 CONCLUSION

A systematic examination of the mean pressure coefficient distribution in simulations with stepwise variation in each domain size has been carried out to examine the sensitivity of simulation outcome to computation domain size. As expected, the numerical simulation result of Fire Dynamics Simulator is domain dependent. In order of capture the effect of large eddies in the wake of a bluff body, sufficient domain space should be established around the bluff body. Based

on the result of the current study, a minimum domain size of 4 body length is recommended for both upstream and downstream of the body. Likewise, to avoid the “Venturi” effect, the total domain width in the lateral direction should be no less than 5 times of the body width, if the body is placed in the center location of the lateral direction. As for the vertical direction, the recommended domain height is greater than 3.5 times of the body height. The lateral and vertical domain requirement is consistent with the general requirement in wind tunnel model studies to keep the blockage ratio to be less than about 10%.

Finally, as the current study was undertaken for predominantly enclosure fire simulations, the optimum domain size is expected to be closely linked to the heat release rate or fire intensity when fires are involved. This aspect of the simulation is the subject of further studies.

5 REFERENCES

1. BCRC, *Victorian 2009 Bushfires Research Response: Final Report*. 2009, Bushfire Cooperative Research Centre: Melbourne.
2. Douglas, G., Tan, Z., Midgley, S., Short, L., *Bushfire building damage - A NSW perspective*. Proceedings of Royal Society of Queensland, 2009. **115**: p. 161-169.
3. Clark, T.L., Jenkins, M. A., Coen, J., Jackham, D., *A coupled atmospheric-fire model: convective feedback on fire line dynamics*. Journal of Applied Meteorology, 1996. **35**: p. 875-901.
4. Meroney, R.N. *Numerical Prediction of Fire Propagation in Idealized Wildland and Urban Canopies*. in *Proceedings of 12th International Conference on Wind Engineering (ICWE12)*. 2007. Cairns.
5. Kwok, K.C.S., He, Y., Douglas, G. B. *Wind impacts on fire spread and structural failure during bushfire in complex terrain*. in *Proceedings of 9th United Kingdom Conference on Wind Engineering*. 2010. Bristol, UK.
6. He, Y., Kwok, K. C. S., Douglas, G. B., Razali, I. M., *Numerical Investigation of Bushfire-Wind Interaction and Its Impact on Building Structure*, in *The 10th International Symposium on Fire Safety Science*. 2011, International Association for Fire Safety Science: Maryland, USA. p. 1449-1462.
7. Murakami, S., Mochida, A, *3-D Numerical simulation of airflow around a cubic model by means of the k- ϵ model*. Journal of Wind Engineering and Industrial Aerodynamics, 1988. **31**: p. 283-303.
8. He, Y., Jamieson, C., Jeary, A., Wang, J., *Effect of Computation Domain on Simulation of Small Compartment Fires*, in *Proceedings of the 9th International Symposium on Fire Safety Science*, B. Karlsson, Editor. 2008, International Association of Fire Safety Science: University of Karlsruhe, GERMANY. p. 1365-1376.
9. Zhang, X., Yang, M., Wang, J., He, Y., *Effects of Computational Domain on Numerical Simulation of Building Fires*. Journal of Fire Protection Engineering, 2010. **20**: p. 225-251.
10. Blocken, B., Stathopoulos, T., Carmeliet, J., *CFD simulation of the atmospheric boundary layer - wall function problems*. Atmospheric Environment, 2007. **41**: p. 238-252.

11. McGrattan, K., McDermott, R., Hostikka, S., Floyd, J., *Fire Dynamics Simulator (Version 5) User's Guide*. 2010, NIST Special Publication 1019-5, National Institute of Standards and Technology.
12. Baetke, F., Werner, H. , *Numerical simulation of turbulent flow over surface-mounted obstacles with sharp edges and corners*. Journal of Wind Engineering and Industrial Aerodynamics, 1990. **35**: p. 129-147.
13. Hostikka, S., Mangs, J., Mikkola, E., *Comparison of Two and Three Dimensional Simulations of Fires at Wildland Urban Interface*, in *Fire Safety Science – Proceedings of the 9th International Symposium on Fire Safety Science*. 2008, International Association for Fire Safety Science. p. 1353-1364.
14. McGrattan, K., Baum, H., Rehm, R., Mell, W., McDermott, R., *Fire Dynamic Simulator (Version 5) Technical Reference Guide*. 2010, NIST Special Publication 1018-5, National Institute of Standards and Technology.