Behavior of leakages exposed to dynamic wind loads. A numerical study using CDF on a single zone model

Dimitrios Kraniotis*, Thomas Kringlebotn Thiis, Tormod Aurlien

Department of Mathematical Sciences and Technology, Norwegian University of Life Sciences
Drøbakveien 31, P.O. box: 5003, IMT, N-1423, Ås, Norway
**Corresponding author: dimitrios.kraniotis@umb.no*

ABSTRACT

Wind is a potential dominant factor regarding the air infiltration through building envelopes. Due to its dynamic characteristics, quite complex aerodynamic phenomena arise around a structure or through cracks and openings. Energy perfomance is influenced by the climate conditions and thus it should be much more researched. Despite the fact that steady state measurements of infiltration rates offer a simple and easy way of estimating an enclosure's airtightness level, a supplement to those methods might be imposed. In this context, computational fluid dynamics could be a useful tool, generating interesting results and helping understand the role of flow mechanisms.

The current numerical study deals with the influence of wind gust on the infiltration rate of a bluff body ('box') on which cracks of varied size are located on different sides. Different internal volumes are also researched. On discussing the results, the dynamic leakage rates (infiltration and exfiltration) are under investigation, while the airflow patterns inside the 'box' are pointed out as well. Frequency characteristics of the wind gust and their correlation with the internal volume are also studied.

The results suggest that gust frequency is the dominant factor for air flows through cracks on the windward side, while the internal volume also plays an important role on the instantaneous leakage rates under unsteady wind conditions. The impact of the enclosure's volume seems to be of importance for relatively small cracks. In addition, there is a difference among the leakage rates through the studied cracks and openings depending on their location or switching from a small to a big volume. Comparisons with the respective behavior of the cracks-openings under steady state enclosure's pressurization at 50Pa are shown as well.

Since the studied enclosure represents a airtight single zone, where air flows only through the opening(s), a parallelism to the internal space of a high level airtight building arises. Taking into account the results of the current study, the influence of the frequency of the gust, the internal volume of a relatively airtight building and the location of the leakage area seem to be critical factors under climate conditions. Having ensured that leakages through the internal walls are very low, a further research should be proceed towards the importance of the location and airtightness of the internal walls. On the same mode internal volume's control and exterior local climate might be also considered.

KEYWORDS

Leakage rate, air flow, air infiltration, crack, dynamic wind load, wind gust, computational fluid dynamics, shear-stress-transport, single zone model

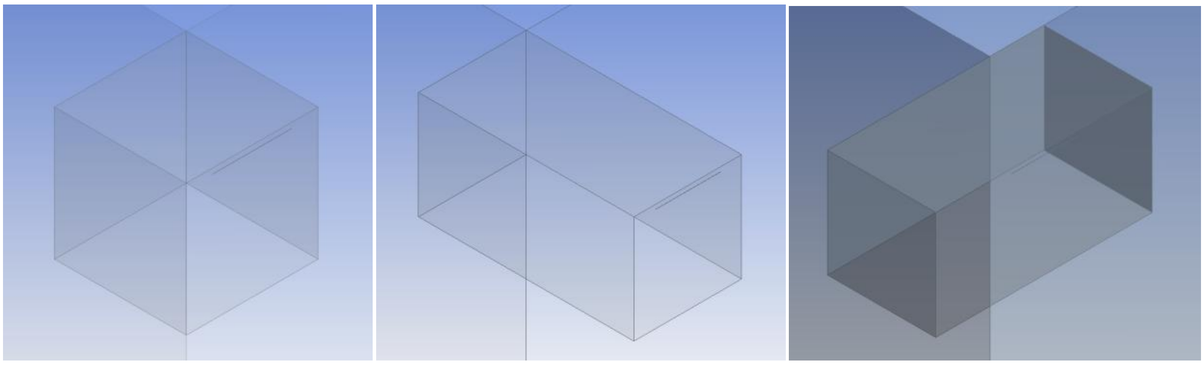
INTRODUCTION

Air infiltration is important towards the optimal design of energy efficient buildings. Moreover, being an uncertain phenomenon, affected by various factors, it is recognized as one of the major losses in residence buildings [1]. Steady state measurements of infiltration rates offer a simple and easy way of estimating an enclosure's airtightness level. The dynamic characteristics of air infiltration have been pointed out by Hill and Kusuda [2] and therefore challenges arise upon that field. The role of the climate parameters and location characteristics on average infiltration rates has also been studied by Sherman [3]. Turbulence causing wind gustiness is recognized as one major factor that affects infiltration [4]. In

addition, building aerodynamics contributes to air infiltration too. In that context, modelling approaches have been presented by Haghighat et al. [5, 6], while the theoretical background of the flow equations through cracks has also been studied [7, 8, 9].
Computational fluid dynamics (CFD) could be a useful tool, generating interesting results and helping understand the role of flow features under unsteady conditions. Numerical studies could contribute to the prediction of potential leakage areas and the evaluation of their contribution to leakages rates. Therefore, a supplement based on numerical methods to the flows through cracks should be imposed.

CASE STUDY

The current numerical study deals with the influence of wind gust to the infiltration rate of a bluff body ('box') on which cracks of various size are located on different sides. Three cracks/openings are studied; (i) of 3mm height (referrred as A), (ii) of 6mm height (referrred as B) and (iii) of 30mm (referrred as C). The lenght of the cracks/openings is 1,5*m* in all cases. Three different internal volumes are also researched (fig. 1). The volumes V_2 and V_3 are equal and double the cubic volume V_1. In addition, three different locations of cracks are examined; (i) the first case refers to one crack/opening across the windward side, 10*cm* below the roof of the 'box' (notation: F), (ii) the second case refers to two cracks of the same size, both situated across the windward side, one 10*cm* below the roof of the 'box' and the other 10*cm* above the ground (notation: FF), (iii) the last case refers to two cracks of the same size, one situated across the windward side, 10*cm* below the roof of the 'box' and the other across the leeward side, 10*cm* above the ground (notation: FB). Four cases of wind load (wind gusts of different frequencies) are used as inlet boundary conditions.



(a) (b) (c)

Figure 1. The three different volumes V_1 (a), V_2 (b) and V_3 (c) simulated and tested.

In total 3*3*3*4 = 108 cases are studied. The notation adopted follows the general rule:
(size of the crack)(volume of the 'box')(location of the cracks)-(frequency of the wind gust).
The table 1 presents the notation for the crack A (3*mm*), the cubic volume (V_1) and the wind gust frequency $\omega_1 = 1/2\pi$. In a similar way, a notation of 2 or 3 or 4 at the end of the notation shows the other frequencies ω_2, ω_3 and ω_4 respectively.

Case	Size of crack-opening	Volume	Location
AV_1F-1	3*mm*	V_1	one crack on the windward side (10*cm* from roof)
AAV_1FF-1	3*mm*	V_1	two cracks on the windward side (one 10*cm* from roof and the other 10*cm* from ground)
AAV_1FB-1	3*mm*	V_1	one crack on the windward side (10cm from roof) and one on the leeward side (10cm from ground)

Table 1. Example of the notation followed. Here, the notations of the studied cases for the crack A (3*mm*), the cubic volume (V_1) and the wind gust frequency ω_1 (= $1/2\pi$) are presented.

METHODOLOGY

The CAD model was developed in ANSYS Design Modeler^{TM} 12.1. The CFX-mesh method of the ANSYS Mesh program (involved in ANSYS Workbench) was used to mesh the domains. The fluid dynamic package ANSYS CFX 12.1 was used as solver for the numerical simulations. Pressure distribution around a building is important to get correct prediction of the pressure gradients and consequently of the air infiltration through the envelope. Among the available turbulence models, the Shear-Stress-Transport (SST) model, a two equation *k-ω* based model [10], was imposed. The reason for that is the inclusion of transport effects into the formulation of the eddy-viscosity. This results in a major improvement in terms of flow separation predictions [11]. In addition, other relevant studies have shown a good agreement between SST model and full scale data, better rather than compared with standard *k-ε* and RNG *k-ε* models [12]. A period of 30*sec* was assumed to be the total time per run, while the timestep was selected to equal to 0,5*sec*. At the inlet of the domain, a fully turbulent velocity profile was assumed based on the equation:

$$u = 7 + 4 * \sin(\omega * t) * \left(\frac{y}{y_{ref}}\right)^{\frac{1}{7}} \tag{2}$$

where u is the wind velocity, the factor $4 * \sin(\omega * t)$ governs the frequency of the wind gust and $\left(\frac{y}{y_{ref}}\right)^{\frac{1}{7}} y$ is the 1/7 power-law factor that describes the wind profile. The exponent factor v = 1/7 corresponds to a widely applicable regarding low surface roughness and well exposed sites from which conventional National Climatic Data Center (NCDC) data are available [13]. At y = 2,5m (the height of the studied box, while y_{ref} = 10m is the reference height), the velocity of the inlet boundary is according to (1):

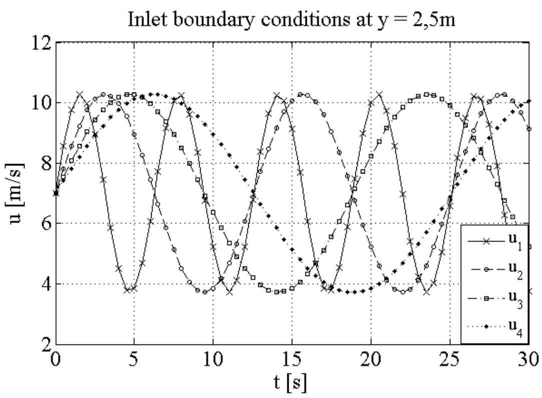
$$u = 7 + 3{,}82 * \sin(\omega * t) \tag{3}$$

As said above, the factor ω formulates the frequency of the wind gust. Four different frequencies – cases of wind gusts were simulated. As shown in the figure 1, ω_1 = 1/2π[*rad/s*] and T_1 = 2π[*sec*], ω_2 = 1/4π[*rad/s*] and T_2 = 4π[*sec*], ω_3 = 1/6π[*rad/s*] and T_3 = 6π[*sec*], ω_4 = 1/8π[*rad/s*] and T_4 = 8π[*sec*]. Figure 2 shows u against t at y = 2,5m.
The instantaneous mass flow rate Q_m and thus the instantaneous volumentric flow rate Q_v across the crack(s)/opening(s) are calculated during the run interval time (30*sec*) for every case (figure 3). The infiltration phase is assumed to have positive values. In contrast, the exfiltration period has negative values. In figure 3 (as well as done in the rest cases), the first 4*sec* have been excluded, because during that time period the domain was not yet under fully turbulent conditions. Both the infiltration and exfiltration rates follow a sinusoidal function, similar to the velocity of the inlet boundary condition does. Based on the Q_v, accepting its sinusoidal form and assuming that the mathematical behavior of the later does not change within an hour, the equivalent air change rate ΣACH_i extrapolated over time t_{tot} = 1h is calculated (the superscript *in* declares the infiltration phase:

$$\Sigma ACH_i^{in} = \frac{3600}{V}\left(\int_0^{t_{tot}} Q_v dt\right) \tag{4}$$

The annual average infiltration rate n is also calculated in order to be compared with ΣACH_i [14]:

$$n = \frac{ACH_{50}}{20} \tag{5}$$



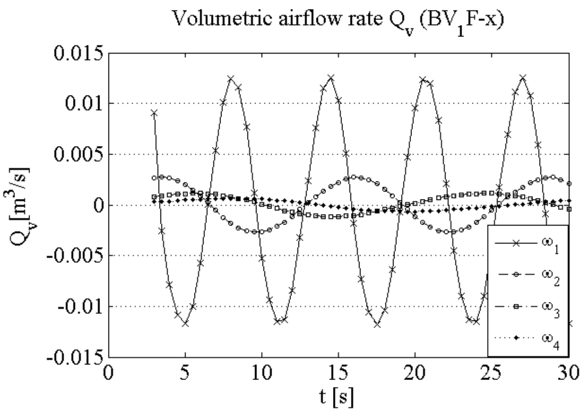


Figure 2. Inlet boundary conditions at y = 2,5m.

Figure 3. Variation of volumetric airflow rate Q_v through crack B (6*mm*) against time for each gust frequency ω.

RESULTS

The equivalent air change rate ΣACH_i is plotted against gust frequency ω_i and is shown in figures 4, 5 and 6. The annual average air change rate is also shown. The leakage rate increases with ω_i for the cases of (i) one crack on the windward (fig. 4) and (ii) two cracks on the windward side (fig. 5). The impact of ω_i seems to become much more significant in higher frequencies (slightly parabolic form) for those cases. It plays an important role for a single zone model with leakages located perpendicular to the main wind flow direction, while it becomes the dominant factor for high frequencies. Again, ω governs the wind-induced pressure difference across the envelope of the 'box', which is the driving force of the air infiltration (and exfiltration) through leakage areas of such size. In addition, the ΣACH_1 for the highest gust frequency ω_1 is higher compared to annual average infiltration rate n, for the small crack(s) A and B (3*mm* and 6*mm*) (fig. 4a, 4b and 5a, 5b).

In contrast, the other set of cases (one crack on the windward and one crack on the leeward side), shown in figure 6, seems to be slightly influenced by ω_i. The flow pattern of cross ventilation is totally affected by the volume and the size of the crack(s)/opening(s).

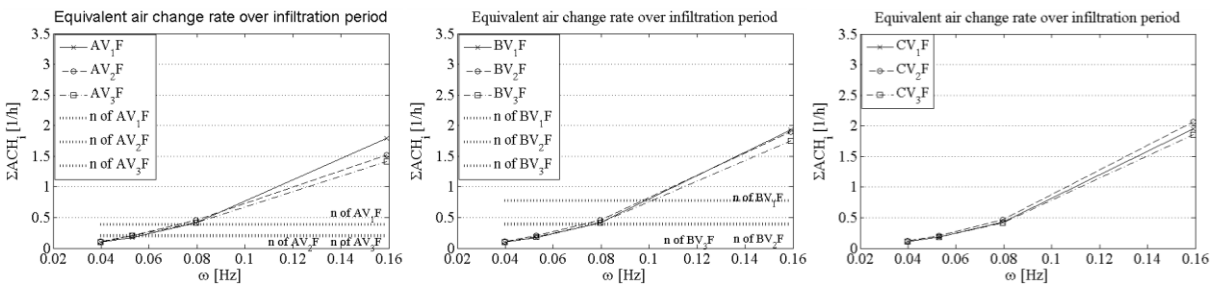


Figure 4. The equivalent air change rate over an infiltration period for the cases of one crack on windward side.

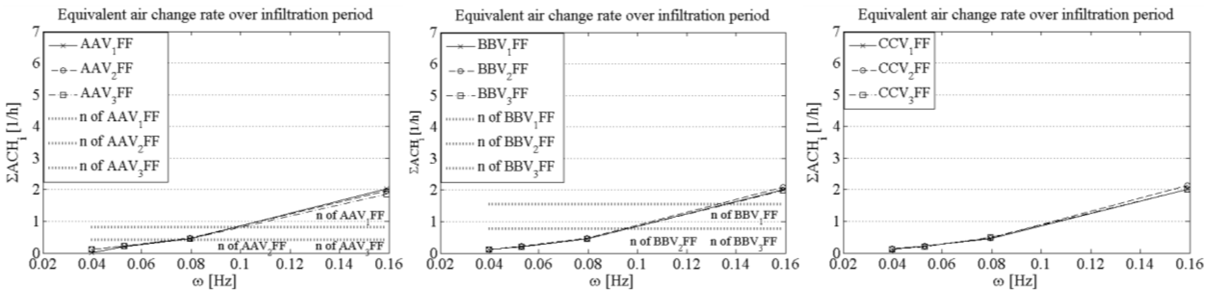


Figure 5. The equivalent air change rate over an infiltration period for the cases of two cracks on windward side.

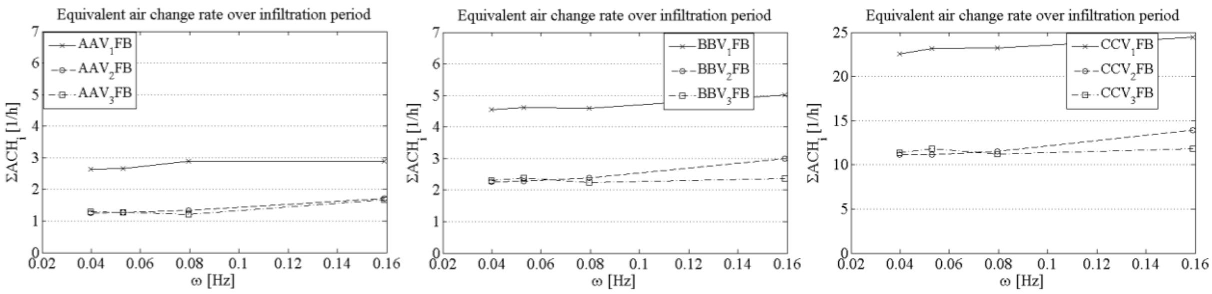
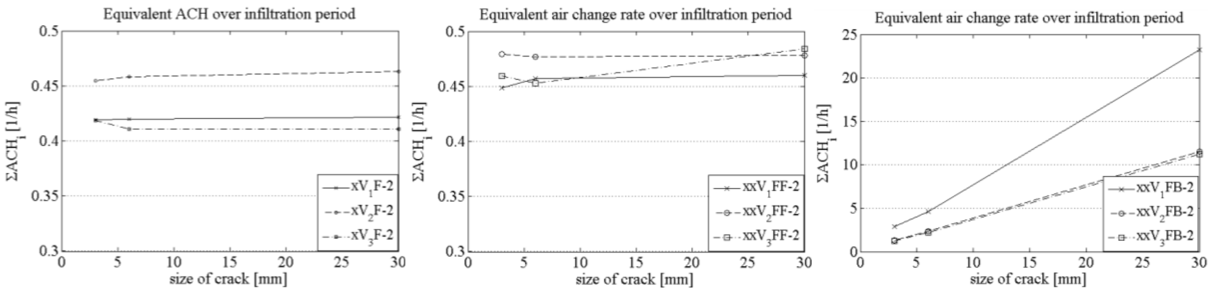


Figure 6. The equivalent air change rate over an infiltration period for the cases of one crack on windward side and one crack on the leeward side.

The equivalent ΣACH_2 for the gust frequency ω_2 against the size of the crack(s)/opening(s) d is presented in figure 7. For the cases of one crack on the windward side (no outlet), the ΣACH_2 of volume V_2 is higher compared to the cubic volume V_1 (V_2 = 2V_1); the crack A (3*mm*) of V_2 gives higher equivalent ΣACH_2 than the crack of 6*mm* or even of 30*mm* of V_1 (fig. 7a). That fact is also valid for the cases of two cracks located on the windward side. The lower inertia forces (compressibility) of V_2 seems to affect the flow rate through the crack(s) (fig. 7b). The influence of d to the infiltration rates appears to be negligible for such sizes.



(a) (b) (c)

Figure 7. The equivalent air change rate against the size of the crack. (a) one crack on the windard side, (b) two cracks on the windward side and (c) one crack the windward side and one crack on the leeward side.

In contrast, the V_3 (V_3 = V_2) does not 'behave' as V_2 does but like V_1 in the case of one crack on the windward crack (fig. 7a); the inertia forces (compressibility) of V_3 appears to be approximately the same compared to V_1. It could be reasonable to claim that the difference is due to the elongated side. In V_2, the later is along the wind direction, while in V_3 it is perpendicular to that, increasing the resistance of the volume. For the cases of two cracks-openings on the windward side of V_3, the ΣACH_2 increases with the d (fig. 7b). Indeed, in the later case, the driving forces caused by the existence of cracks seem to be more important, explaining also the weaker impact of the volume.

Regarding the cross air flow (fig. 7c), the ΣACH_2 seems to be completely connected to size of the cracks-openings for all the cases, while the volumes behave in analogy to a steady state case and the role of the volume of the enclosure is not important anymore.

CONCLUSION

A single zone model ('box') was simulated and studied numerically under unsteady wind conditions. Four wind gust frequencies were used to describe the inlet boundary conditions. Three sizes of cracks-openings located on the 'box' in three different ways were tested (no outlet, inlet-outlet on the same windward side and cross air flow). In addition, three enclosures were studied, in order to explore the role of the volume. In total 108 cases were solved with the shear-stress turbulent model (SST). The equivalent air change rate ΣACH_i, extrapolated over time t_{tot} = 1*h*, was calculated and was shown against (i) the gust frequency

ω_i and (ii) the size of the crack(s). Comparisons with relevant annual average infiltration rates were also presented. The influence of the frequency of the gust, the internal volume of a relatively airtight building and the location of the leakage area seem to be critical factors under climate conditions. The ΣACH_i increases with ω_i for the cases of one or two cracks located on the windward side. The impact of ω_i seems to become much more significant in higher frequencies (slightly parabolic form). The gust frequency seems to be the dominant factor for a single zone model with leakages located on the same side perpendicular to the main wind flow direction. In contrast, in case of cross air flow the infiltration rates seems to be slightly influenced by ω_i. The internal volume of the enclosure plays also an important role on the leakage rates under unsteady wind conditions in cases of no outlet or of both inlet and outlet being on the windward side. The inertia forces (compressibility) of the volumes is a major parameter when air infiltrates the envelope across the windward, while the size of the cracks does not seriously affect the rates. The location of the cracks is finally of high importance; in case of cross air flow, the gust frequency slightly affects the leakage rates and the enclosure 'behaves' in analogy to the steady state case.

REFERENCES

[1] Shaw C.-Y. 1981. *A correlation between air infiltration and air tightness for houses in a developed residential area*, National Research Council Canada, Ottawa.

[2] Hill J.E., Kusuda T. 1975. *Dynamic characteristics of air infiltration*, ASHRAE Trans. 81 (1) 168–185, ASHRAE, New York.

[3] Sherman M. H. 1986. *Estimation of infiltration from leakages and climate indicators*, Energy and buildings Vol. 10, 81–86.

[4] Haghighat F., Brohus H., Rao J. 1999. *Modelling air infiltration due to wind fluctuations – a review,* Building and environment Vol. 35, 377–385.

[5] Haghighat F., Rao J., Fazio P. 1991. *The influence of turbulent wind on air change rates – a modelling approach*, Building and environment Vol. 26, 95–109.

[6] Haghighat F., Rao J., Riberon J. 1992. *Modelling fluctuating airflow through large openings*, 13th AIVC conference, Nice, France.

[7] Baker P.H., Sharples S., Ward I.C. 1987. *Airflow through cracks*, Building and environment Vol. 22, 293–304.

[8] Walker I.S., Wilson D.J., Sherman M.H. 1997. *A comparison of the power law to quadratic formulations for air infiltration calculations*, Energy and buildings Vol. 27, 293– 299.

[9] D.W. Etheridge 1977, *Crack flow equations and scale effect*, Building and environment, Vol. 12, 181 – 189.

[10] Menter F.R. 1994. *Two-equation eddy-viscosity turbulence models for engineering applications*, AIAA Journal, Vol. 32, no 8. 1598–1605.

[11] ANSYS Inc. 2009. *ANSYS CFX-Solver Modeling Guide,* ANSYS CFX 12.1 help manual.

[12] Guha, T.K., Sharma, R.N., Richards, P.J. 2009. *CFD modeling of wind induced mean and fluctuating external pressure coefficients on the Texas Technical University building*, EACWE 5.

[13] Elliott D.L. 1979. *Adjustment and Analysis of Data for Regional Wind Energy Assessments*, Workshop on Wind Climate, Asheville, North Carolina.

[14] Sherman M.H. 1998. *The use of blower-door data*, Lawrence Berkeley National Laboratory.