# Assessment Methodology for CFD Simulations of Wind-driven Building Smoke Exhaust Emissions

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## ABSTRACT

*In 2022, clean air was declared a human right by The United Nations. With ever-increasing urban development, building exhausts in urban environments require careful and considered design. The tunneling required for the expansion of Australian metros and roads brings with it the challenge of exhausting large volumes of smoke in the event of fires.*

*Wind engineers are often required to assess the acceptability of such exhausts, which is made practicable by the increasing capability of CFD coupled with high-performance computing. However, currently the only Australian standards relating to wind-driven building exhaust emissions are AS 1668 parts 1 and 2.*

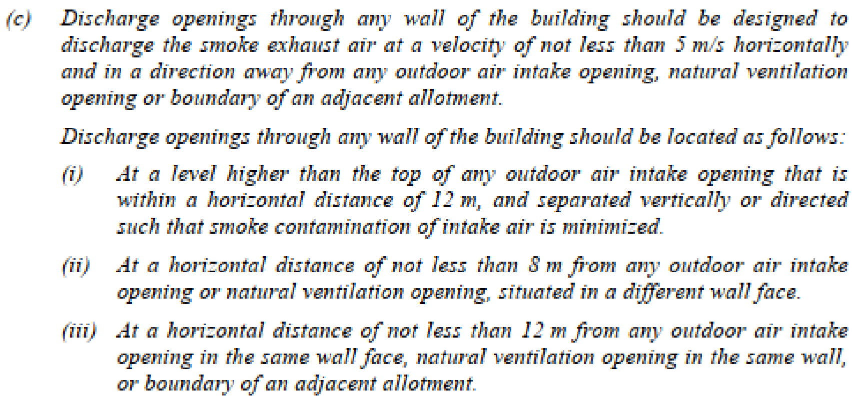
*This paper examines the limitations of current Australian standards in providing appropriate assessment criteria for wind-driven building exhaust emissions, i.e. allowing one to 'appropriately' classify a design as acceptable or unacceptable in terms of the risk of danger or nuisance. Currently, AS 1668.1 provides only guidance for configuration of smoke exhausts and AS 1668.2 prescribes separation distances for discharges containing objectionable effluent from property boundaries and building intakes.*

*A case study is presented, demonstrating that the separation distance guidelines for smoke exhausts do not guarantee acceptable performance, when using legislated one-hour environmental exposure limits for carbon monoxide and nitrogen dioxide as acceptance criteria. Recommendations for changes to part 1 of the standard have been made on this basis, which can also be considered applicable to other discharges covered by part 2. Additionally, assessment methodology suitable to be used in conjunction with CFD simulations and scope for future work are discussed.*

## BACKGROUND

While pollution dispersion studies are conducted to assess a range of hazardous or objectionable pollutants, the scope of this paper is focused on smoke exhaust emissions and their impacts on building openings and intakes. However, some of the findings and recommendations as noted can be considered applicable to other building exhaust pollutants, where there are legislated short-term exposure limits.

Currently, the design of building exhausts is governed by AS 1668.1 (smoke) and 1668.2 (other objectionable discharges). While the prescribed minimum velocity, discharge direction and separation distance in AS 1668.2 must be adhered to, AS 1668.1 "does not seek to lay down firm rules for the location of openings", while also noting that "particularly critical cases may warrant wind tunnel testing of models". The AS 1668.1 guidelines are reproduced in Figure 1 for reference.



*(c) Discharge openings through any wall of the building should be designed to discharge the smoke exhaust air at a velocity of not less than 5 m/s horizontally and in a direction away from any outdoor air intake opening, natural ventilation opening or boundary of an adjacent allotment.*

*Discharge openings through any wall of the building should be located as follows:*

*(i) At a level higher than the top of any outdoor air intake opening that is within a horizontal distance of 12 m, and separated vertically or directed such that smoke contamination of intake air is minimized.*

*(ii) At a horizontal distance of not less than 8 m from any outdoor air intake opening or natural ventilation opening, situated in a different wall face.*

*(iii) At a horizontal distance of not less than 12 m from any outdoor air intake opening in the same wall face, natural ventilation opening in the same wall, or boundary of an adjacent allotment.*

**Figure 1. Excerpt from AS 1668.1 – guidelines for location of discharge openings**

While the guidelines are practical for industrial centres, in dense urban centres, it may be impossible to discharge away from all openings and adjacent property boundaries without discharging from the building's roof. Additionally, a separation distance-based approach likely does not account for the ability of the urban wind microclimate to redirect flows. The guidelines also allow for configurations such as the one illustrated in Figure 2, which appears likely to produce undesirable outcomes.

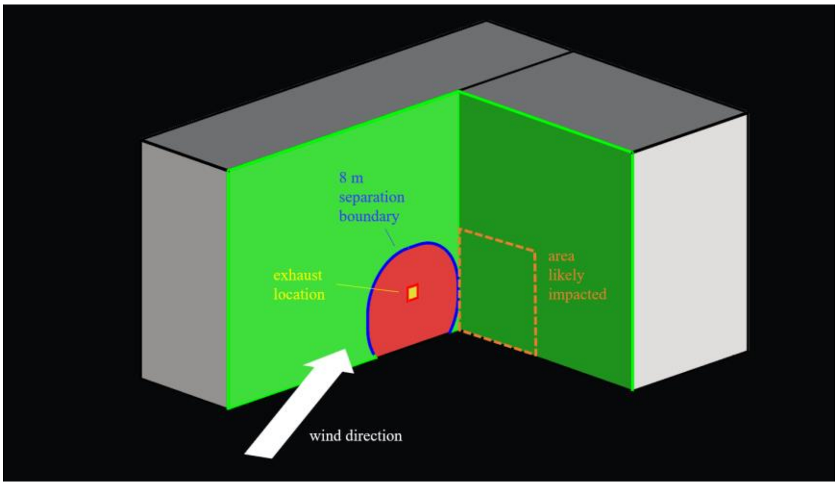



**Figure 2. Illustration of 8 m separation distance for 'different wall faces': there is no distinction between concave and convex corners of buildings!**

## CASE STUDY

Results from recent experience demonstrate that undesirable emission concentrations are indeed possible for exhausts which adhere to the AS 1668.1 separation distance guidelines. While strict adherance to the guidelines would require the discharge to be located above the height of the property adjacent in the direction of discharge (i.e. "in a direction away from [the] boundary of an adjacent allotment"), it is likely that designers will seek an alternative approach, or possible that the adjacent properties are taller.

The modelled scenario is a 100 m-tall building within a typical 'urban canyon' environment, with discharge 20 m above ground and exhaust flow rates typical for a tunnel ventilation exhaust system. For ease of reference, key simulation parameters and methodology are tabulated in Table 1. It is noted that wall boundary conditions where intakes or openings may be located are likely a conservative approximation, compared with modelling outflow from the domain at that location.

**Table 1. Key simulation parameters and methodology**

| Simulatio Settings and Parameters | Description |
|---|---|
| Wind speed and direction | Winds at median wind speed of prevailing wind direction, 4.7 m/s at 10 m height |
| Key simulation settings | RANS, realizable k-epsilon, isothermal |
| Boundary conditions | Log law inlet profile as per AS/NZS 1170.2, top boundary conditions as per Richards and Hoxey's (1993) research, possible intake locations are represented by no-slip wall boundaries |
| Geometry | Domain extents and geometric detail as per AWES-QAM-1-2019 |

To determine whether high concentrations of exhauted smoke should be considered acceptable or unacceptable, the concentrations of certain hazardous compounds contained in smoke have been calculated and compared to legislated one-hour exposure limits.

Carbon monoxide (CO) and nitrogen dioxide ($NO_2$) are two such hazardous compounds for which; (a) the concentration at the point of discharge can be estimated (with relative ease), and (b) assessment can be made against legislated exposure limits. The one-hour exposure limits for carbon monoxide and nitrogen dioxide in each state, along with the national standards, are tabulated below.

**Table 2. One-hour environmental exposure limits for carbon monoxide and nitrogen dioxides in Australian states and territories**

| State/Territory | CO ppm | $NO_2$ ppm |
|---|---:|---:|
| National | only 8hr | 0.08 |
| South Australia | 25 | 0.08 |
| Western Australia | 25 | 0.12 |
| Queensland | only 8hr | 0.08 |
| Victoria | only 8hr | 0.12 |
| New South Wales | 60 | 0.08 |
| Tasmania | only 8hr | 0.12 |

The concentrations of these pollutants can be estimated if we assume that; (a) all smoke generated is captured by the exhaust system and (b) the fluid entrained by the exhaust system is 100% smoke (in some cases a more accurate estimate of the smoke-air mix may be obtained from fire modelling results). The following equation can be used to calculate the mass fraction of either CO or $NO_2$ in the exhausted smoke:

$$Mass\ fraction\ of\ pollutant = \frac{HRR}{H_{comb}} \times \frac{Y_{pollutant}}{\rho_{exhaust} \times Q_{exhaust}}$$

Descriptions of the parameters and the values assumed for this study are provided in Table 3.

**Table 3. Estimations and assumptions for combustion parameters**

| Symbol | Description | Value | Unit | Reference |
|---|---|---|---|---|
| $HRR$ | Fire heat release rate | 10,000 | kW | Assumption, based on project experience |
| $H_{comb}$ | heat of combustion | 12870 | kJ/kg | Tewarson 2002 |
| $Y_{pollutant}$ | Yield of CO | 0.0705 | $kg_{pollutant}$ /$kg_{fuel\ burned}$ | Tewarson 2002 |
| $Y_{pollutant}$ | Yield of $NO_2$ | $1 \times 10^{-5}$ – $8.3 \times 10^{-4}$ | $kg_{pollutant}$ /$kg_{fuel\ burned}$ | Hull et al 2008 |
| $\rho_{exhaust}$ | Density of exhaust gases (smoke) | 1.15 | $kg/m^3$ | Assumption, smoke cools to ambient temperature |
| $Q_{exhaust}$ | Volumetric flow rate of exhaust gases (smoke) | 300 | $m^3/s$ | Assumption, based on project experience |

As the modelling assumes that all gases contained in the smoke are transported together, either CO or $NO_2$ will be governing, depending on the estimated yield of each gas. The yield of $NO_2$ depends on the conversion of nitrous oxide (NO) to $NO_2$ as the smoke cools, as well as the combustion conditions, and can vary as widely as the range stated in the table above (Hull et al 2008). For this reason, only CO results are presented and assessed against the most onerous one-hour exposure limit, 25 ppm to determine the acceptability of the simulated smoke exhaust. I.e. either CO concentrations are governing, or there are more areas (than those shown in the below images) exceeding the exposure limits, depending on the $NO_2$ yield. The simulation results show significant façade areas beyond the 12 m separation boundary where the most onerous one-hour CO exposure limit of 25 ppm is exceeded, for all cardinal wind directions at median wind speed.

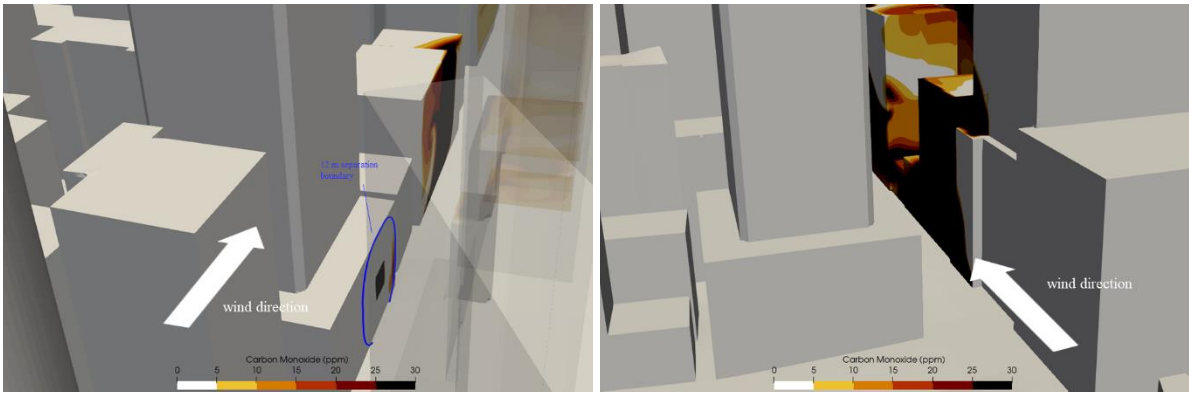



**Figure 3. Northerly winds**

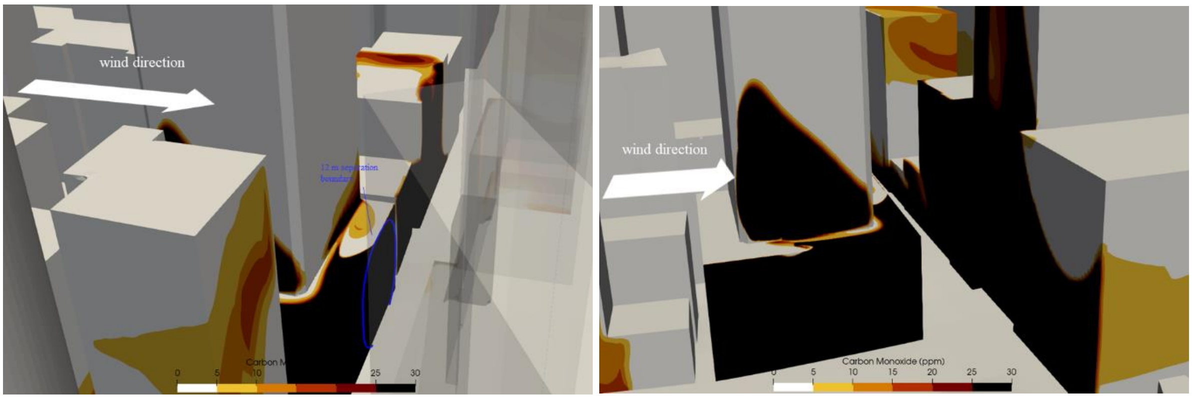



**Figure 4. Easterly winds**


**Figure 5. Southerly winds**

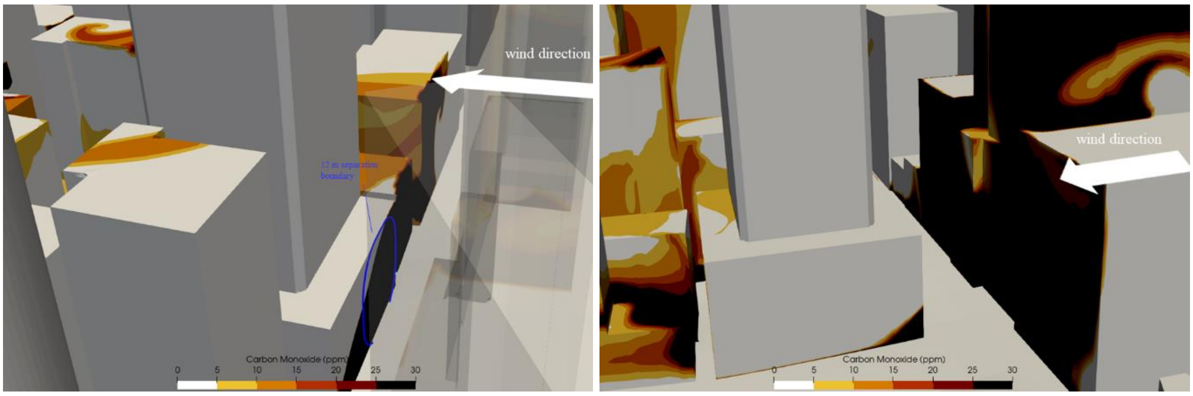



**Figure 6. Westerly winds**

## RECOMMENDATIONS AND FURTHER RESEARCH

The results from the case study demonstrate that for the modelled scenario, and similar scenarios, separation distances are not an effective method of guaranteeing acceptable outcomes. A more appropriate means of determining the acceptability of building smoke exhaust designs would be to adopt a performance solution approach, based on legislated exposure limits. Such an approach should only be applicable to building openings and intakes and would (a) prescribe when CFD is required and when it is recommended, and (b) detail a set of assessment criteria based on exposure limits of hazardous compounds, containing (i) a list of applicable hazardous compounds to assess and (ii) reference to relevant legislation where exposure limits are published. The trigger clauses could be the current AS 1668 guidelines and requirements, from existing research (e.g. ASHRAE Handbook Chapter 46, CIBSE TM21, Petersen et al 2011), or be formed based on the results of new studies.

One challenge with providing a set of quantitative assessment criteria is deciding what an acceptable number of hours per year (or exceedance probability) is. While determining this number is beyond the scope of this paper, it is noted that the Tasmanian Air Pollution Monitoring Plan (2001) defines a one-hour-per-annum exceedance as the acceptability limit. It is also noted that tunnel fires are rare events, and the determination of an acceptable exceedance probability should therefore also consider the likelihood of a fire occurring, or frequency of discharge for other emissions.

Calculation of the concentration of a certain pollutant at a certain exceedance probability is possible, provided that the spectrum of possible wind conditions is adequately represented and statistically modelled. This requires that (a) an appropriate number of wind directions are simulated, (b) an appropriate number of wind speeds per direction are simulated, such that each speed simulated is attributable to a certain % of wind events from that direction, and (c) calm conditions are modelled appropriately. Additionally, the concentration of pollutants at an intake should be considered in conjunction with the number of air changes per hour in the occupied space too determine the likely one-hour (or shorter term) exposure level of pollutants to occupants.

## CONCLUSION

The complex wind microclimates of dense urban centres present a significant possibility of undesirable outcomes for building smoke exhausts, even ones which comply with the AS 1668.1 design guidelines. While it is noted that tunnel ventilation exhausts discharge smoke at very high flow rates compared to other building exhausts, it is possible that, in certain cases, the AS 1668.2 separation distance requirements for non-smoke building exhausts also do not guarantee acceptable preformance. To quantify when performance is acceptable or unacceptable, concentrations of hazardous compounds can be compared against legislated short-term exposure limits. A case study of a generic over-station model has demonstrated that it is possible for significant areas of facades nearby a smoke exhaust, well beyond the recommended separation distances, to be exposed to carbon monoxide levels exceeding the one-hour exposure limit. Depending on assumptions made about the combustion process, the area of facades where the nitrogen dioxide exposure criteria is exceeded may be larger.

As it is now practicable with advancements in computing to conduct assessments based on exposure limits and exceedance probabilities, considering the full spectrum of wind conditions, it is recommended that a performance solution approach is developed as an alternative to prescribed or recommended seperation distances. It is acknowledged that a substantial body of work is required to define an appropriate assessment method and set of criteria. This includes determining appropriate trigger clauses, determining acceptable exceedance probabilities and recommending appropriate CFD (or wind tunnel) methodology, notably for calm for calm conditions (e.g. comparing RANS, LES, LBM and wind tunnel testing, and neutral vs. non-neutral atmospheric conditions). This paper may contribute to the justification for such work.

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