EXTERNAL SMOKE MOVEMENT AND ITS IMPACT ON STATION DESIGN – GUIDANCE FOR VENTILATION LAYOUT

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DOI 10.3217/978-3-99161-087-8-014 (CC BY-NC 4.0)

ABSTRACT

Space or planning considerations can lead to the need to use pavement level grilles for forced smoke exhaust from metros. The emitted smoke might be ingested into station entrances or stair pressurisation system intakes which could impact the ability to evacuate the station. This challenge is not unique to underground stations - guidance on vent separation distance is available with building codes, but the quantities of smoke in metro application vents can be much higher than commercial buildings. There is very limited similar guidance on vent separation available to the design engineer for metros/stations.

This paper explores the impact of smoke release at low level on key intakes for an assumed vent and entrance location for a simple station and urban configuration. It reviews a range of parameters which could impact upon the design and provides guidance on those which may be of importance. The paper also explores the benefits that an elevated release of smoke can offer so that the visual impact of an additional structure can be considered against the engineering consequences. The paper finally concludes with design advice that can be used during initial station layout. Whilst each station will have a wind microclimate that will affect smoke movement, some simple guidance as a starting point for laying out vents was considered as useful.

Keywords: Atmospheric dispersal, design guidance.

1. INTRODUCTION

Fire and smoke present hazards in underground stations and tunnels. To provide a safe environment to allow the passengers to evacuate in the event of a fire it is common to include a ventilation system. This may be natural or mechanical, but both will result in smoke being released to atmosphere local to the station.

Smoke rejected from the station can present an additional hazard to the station evacuation if the smoke interacts with entry/exits to the station or is drawn into the station via supply intakes. It is tempting in the initial stages of laying out a station to rely on building codes to define separation distances. Building industry standards such as BS 9999 in the UK for stair pressurization systems specifies a minimum separation of 5m [1]. This was presumably based on magnitudes of fire, ventilation, and smoke from buildings. Figure 1 shows the smoke emanating from pavement level grilles from the 2003 Daegu Metro fire in South Korea. The volume of smoke released from the vents and the impacts of wind were considerable, all of which suggests that building fires may not be a suitable proxy for underground station fires.

Figure 1: Daegu metro fire exterior conditions [2]

Smoke plumes and their dispersion in atmosphere have been studied extensively for many years, commonly using the Gaussian dispersion plume model. This approach is used to predict the dispersion of pollutants from a point source (like a chimney) in the atmosphere. It assumes the pollutant spreads in the crosswind (y) and vertical (z) directions according to a Gaussian (normal) distribution, with the mean wind advecting the plume downwind (x direction) [3][4]. The spread of the pollutants is assumed to be Gaussian driven and governed by the standard deviations in y and z which are typically developed from empirical data. This allows the user to select coefficients which will represent typical terrains and atmospheric stability. Over time these types of models have been extended to include for a variety of different factors including amongst others the impact that building wakes may have. The simplest models are variations on the Brigg's Gaussian model. These equations and formulas are often developed for very tall chimneys with minimal infrastructure downwind of the plume. In urban areas, the presence of buildings introduces complex, three-dimensional flow patterns that fundamentally alter plume behaviour compared to open terrain [5].

Buildings can block, deflect, or trap the plume, causing it to recirculate within street canyons or be ejected upwards or sideways at intersections [6]. Turbulence generated by flow separation and wakes around buildings increases the spread of the plume, often bringing it down to ground level more quickly than predicted by open-country models. The plume's path and concentration at any point can fluctuate rapidly due to coherent structures (e.g., vortex shedding, recirculation breakdown) and random turbulence [6]. Urban dispersion models (e.g., ADMS, OSPM) attempt to include building effects by parameterising street canyon recirculation, vertical exchange, and pollutant trapping, but still face challenges in highly mixed or varying environments [5][6][7]. Wind tunnel studies have also shown that buildings significantly affect dispersion patterns, introducing complexities such as recirculation zones, wake effects, and plume splitting. These effects go significantly beyond the empirical corrections that are currently available with the building impact often being reduced to a single coefficient. They also typically underestimate peak concentrations near buildings [5] which is the area of greatest concern for the ventilation engineer.

The Brigg's Gaussian models are most effective for distances of greater than 100m and durations of more than one hour [5]. These models were originally developed using assumptions of continuous release of pollutant which is not the type of release associated with station fires. Attempts to improve this limitation were developed for short duration releases of pollutants, or puffs. These puffs can be combined with multiple puffs making up a single simulation. This approach offers some improvement when considering mean pollutant concentration but due to advances in CFD, the simple models are no longer considered to be the best approach [7].

Where local and short-term effects are of importance, such as smoke release around metro stations, then it has been recommended that wind tunnel and Computational Fluid Dynamics (CFD) are conducted [5]. Large Eddy Simulation (LES) techniques are useful in this application as they can reasonably portray the dynamic nature of wind flows as well as offering reasonable accuracy and computational costs. Flemming and Rhodes used FDS to study smoke movement from metro fires and concluded that this approach was able to be used when used to assess above ground smoke movement [8]. Noteworthy in their paper is the need to validate the modelling approach and they provide reference to experimental data that can be used to do this. Models can resolve the complex, unsteady flow and pollutant dispersion in urban environments, capturing the effects of individual buildings, street canyons, and intersections.

2. SIMPLIFIED DISPERSION MODELLING

When it is not possible to obtain project specific CFD data, the following considerations are recommended when applying Gaussian models alone.

1. Model the system both with and without building wake interactions to get a spread of potential outcomes.
2. In recognition of the limitations and likely underestimation of Gaussian model predictions apply engineering judgement as to the applicability of the results. The safety factor to apply will depend upon the project circumstances and should be acknowledged as a source of uncertainty.
3. Where available use wind tunnel and CFD data for similar regions to calibrate and validate the empirical correlations used to determine the standard deviations. This is of increasing importance for complex urban and industrial locations.

Following the above steps is extremely challenging for the ventilation engineer as a large proportion of the approach is subjective, with limited guidance on how to select appropriate coefficients. CFD models can be time consuming and thus costly to develop and run and may be disproportionate in the initial stages of a station project design. However, if not considered early any later station design changes that arise can be expensive. It would therefore be useful to develop some simplified design guidance for early stages of projects.

The focus of the remainder of this paper is to try and provide specific data that can be used to inform initial design layout of a station smoke control system. This paper adopts the FDS modelling methodology described by Flemming and Rhodes [8] to develop a data set for a simplified station realm.

3. FDS MODELLING

3.1. General

A highly simplified test domain was developed to keep the results from this paper generic. The domain and analysis assumed that the only features of interest were the smoke release and a station entrance/air intake. Air was assumed to be entering the station entrance mimicking the effect of make-up air from a station smoke exhaust system.

The exhaust vent and intake relationships were tested using a parametric study varying the separation distance between the release point and intake, the external wind speed, the volumetric flow rate of the smoke exhaust, the volumetric flow rate of the intake and the differential height between the smoke exhaust and the intake. In all cases the wind was assumed to be blowing directly across the smoke exhaust vent towards the station intake. The model assumed upstream turbulence indicative of a metro located in an urban environment.

The wind was modelled using the Jarrin approach that was validated by Flemming and Rhodes [8].

The simulations were conducted to achieve quasi-steady conditions. The soot was exhausted at a constant mass fraction and temperature of 90°C. The mass fraction and temperature were selected based on the values measured across a wide range of station smoke control systems that the authors have worked on. They were not indicative of any specific scenario but could be appropriate for a train fire of between 7 and 14 MW. Therefore, the results should be interpreted based on relative comparisons rather than specific values. Warmer smoke would have been more buoyant but the analysis suggests that inertial forces were tangibly larger than buoyancy forces and hence the sensitivity to hotter smoke was not expected to be very high.

The results are presented as visibility at head height which was determined for a light reflecting sign and using a mass extinction coefficient of 8,700 m²/kg. This enables the results to be considered in a manner that the tunnel ventilation engineer is familiar with. For information, two trend lines were added to the results at 10m and 20m. The 10m visibility is the limit for tenable evacuation across a wide range of standards [9][10]. The 20m visibility is added to provide a limit that allows for some interaction of ingested smoke with smoke that is not extracted by the ventilation system.

3.2. Initial Findings

An initial data analysis was undertaken which varied separation distance, wind speed, smoke exhaust and intake flow rates which involved 270 parametric FDS simulations. The models predicted the expected fluctuations in wind that can be observed in nature. Therefore, if results are considered at snapshots in time this can mask overall trends. Therefore, all results in this paper are provided as 30s averages taken over the final 30s of the FDS model (when quasi-steady conditions had been achieved). These 30s average results for all 270 cases are presented in Figure 2 with all cases plotted as individual points. To make the chart easier to read and identify potential trends, coloured 'patches' are drawn around the most extreme points for each wind speed. The colours of the patches match the marker shown in the legend (i.e. the 4 m/s bubble is green etc). The two black lines show the 10m and 20m thresholds which were used for indicative assessment purposes.

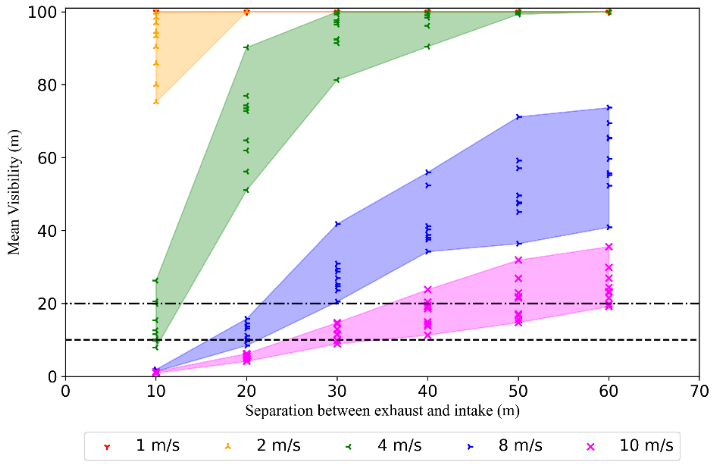

Figure 2: Variation of visibility averaged over 30s with wind speed

The initial data review considered trends against all variables tested. This indicated that variations in the flow rate of the smoke exhaust and intake did not have a significant impact on smoke dispersion, so no further comment is made on either of these variables. The analysis covered a range of 70 to110 m³/s of smoke exhaust and an intake over a range of 10 to 30 m³/s. All remaining runs presented used a smoke exhaust of 90 m³/s and a station intake of 20 m³/s. The results are presented against wind speed as this was the only variable to exhibit a strong correlation between variables.

The visibility at ground level and head height was only reduced below the thresholds of 10 and 20m for wind speeds more than 4 m/s. The impact downstream was significantly increased with wind speed. This result was expected. The key takeaway in this chart though is shown in the coloured patches which show the spread of results that can occur in simulations.

3.3. Height differences

For smoke rejected at ground level the wind interactions were constrained by the ground plane. Elevating the smoke exhaust and intake (for example using small chimneys on the exhaust) so that they were less impacted by the ground plane was considered. Figure 3 shows plots for both exhaust and intake at the top of a single-story building (4m) and a two-story building (8m). For brevity both heights are plotted together but the 8m high results can be distinguished using the larger marker size. The new data are shown by symbols, and the shaded area shows the prior data from Figure 2.

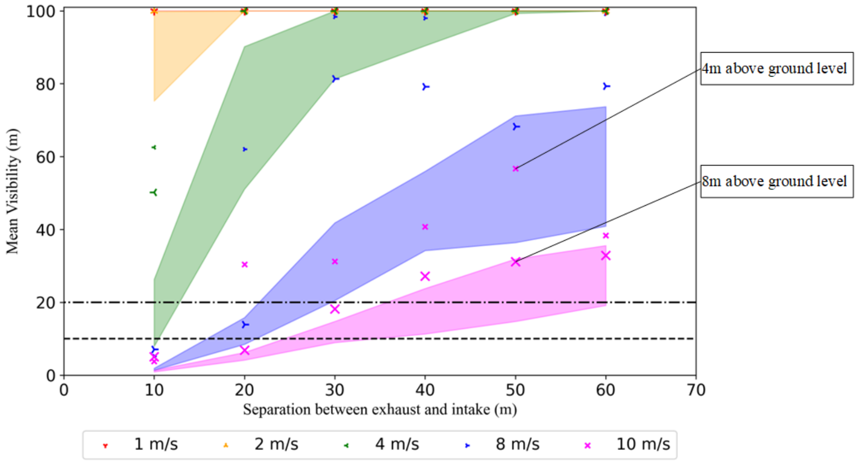

Figure 3: Impact of release height

Figure 3 shows that, all other actions being equal, releasing smoke at height is beneficial even without a height difference between the exhaust and intake. The loss of visibility was reduced at all points downstream. This is true for all wind speeds and shows that the lower elevation of the release of smoke, the greater the required separation that is required. In most cases 4m is shown to be more beneficial than 8m although not in all. This is thought to be due to the nature of the flow disturbance caused by the chimney used to elevate the exhaust and intake locations. However, this was not fully investigated during this paper and remains as a further area of study.

Height differences between the smoke exhaust and the intake were also tested. Depending on the layout these were favourable (intake below exhaust) or adverse (intake above exhaust). This finding was unremarkable and would be in line with an experienced practitioner's expectations. Therefore, this was not shown graphically for reasons of brevity.

3.4. Obstacles between exhaust and intake

Obstructions could consist of vegetation (trees or shrubs), buildings, walls, any other station infrastructure. It is not practicable to discuss many forms of blockages and obstruction within this paper. A generic structure was considered and the layout of the obstructions considered are shown schematically in Figure 4. The first was a thin wall located 2.5m downstream of the smoke exhaust marked ‘A’ in Figure 4. The thin wall was modelled as 1m wide (‘W’) and could be considered as a smoke screen intended to force smoke up. The second was a building which runs the full distance between the exhaust and intake with a 2.5m margin on either end (i.e. as separation distance increases the width of the obstruction increases). The purpose of the building is not relevant to this discussion.

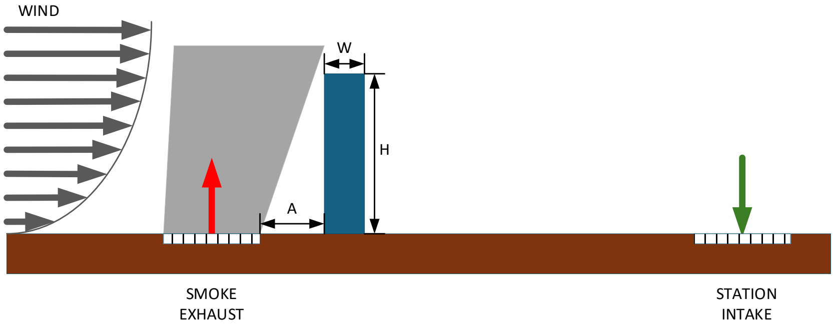

Figure 4: Obstructions used in FDS model

In both cases the obstructions were 10m long in the plane coming in and out of the page (and thus not shown in Figure 4). This 10m dimension was five times longer than the length of the smoke outlet. Time did not permit sensitivity tests to the 10m obstruction length used in the model. The obstruction was located such that the smoke exhaust and intake were on the centre line of the obstruction. This allowed air flow to flow around the obstruction and cause interactions between the building wake and the intake. The obstructions were initially implemented as being 6m high, H in Figure 4, which is representative of a two-story building or a reasonable spacious concourse.

The results are shown in Figure 5 again retain the same format of Figure 3 with the new results superposed over the shaded areas from Figure 2. This figure shows the results of building of different narrow widths (i.e. just a wall) with small markers and one with the width 5m less than the separation distance, (i.e. if the separation distance was 30m the obstruction width was 25m with the building centred between the exhaust and intake) with large markers.

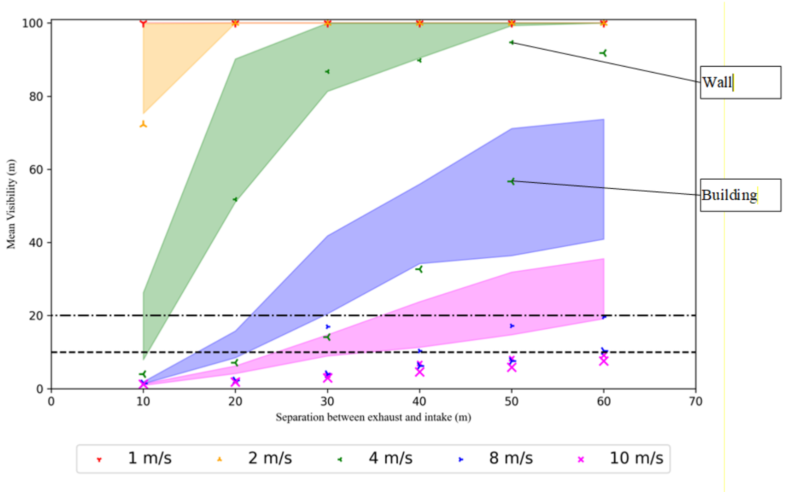

Figure 5: The impact of obstructions between the exhaust and intake for two different building widths

The buildings had a negative impact causing smoke to drop more quickly for all wind speeds. The extra turbulence caused by the obstruction seemed to cause more issues than it resolved. It was observed that the wider buildings caused the greater negative impact upon the visibility results.

The cases shown in Figure 5 were repeated for a building height of 15m rather than 6m. This was the only difference between the obstructed simulation sets. The results from this are presented in Figure 6.

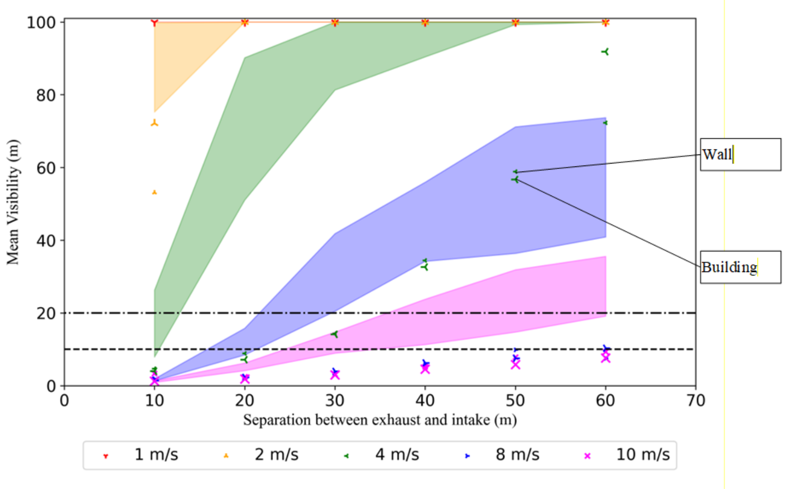

Figure 6: The impact of tall obstructions between the exhaust and intake for two different building widths

The results from the higher building were similar to the lower building at high wind speeds. The impact of the building height though was more pronounced at lower wind speeds with 4 m/s particularly changed as an impact of building height. The visibility became worse as the building height increased. Potentially the impact could have been less if the obstruction was longer/wider than 10m. The effect of building height is therefore wind speed dependent and is of importance to the ventilation engineer.

4. DESIGN IMPLICATIONS AND RECOMMENDATIONS

The results show that for some situations more than 50m may be needed between intake and exhaust which is significantly more than some building code requirements and suggest. A key early question to be resolved by the ventilation engineer is how much reduced visibility can be accepted at the entrance? One might argue that as long as the visibility is greater than 10m the situation is acceptable; however, lower visibility incoming air may mix with smoke in the station and result in an overall worsening of the outcome.

Greater separation was required for higher wind speeds and it is recommended that local microclimate information is obtained as early as practicable within the project and reviewed in the context of the design wind speed and extent of risk the project may accept. Releasing smoke at low elevation resulted in more smoke spread closer to ground level so where practicable release at height is recommended. Little sensitivity was shown to smoke exhaust and intake flow rates.

The impact of buildings is significant and was shown to be impacted by the height and overall shape of the building. The analysis highlighted the complexity of the problem with a two story building being shown to make the test case more vulnerable to cross contamination. Whilst the same was true for a five story building the impact was much more significant at the middle range of wind speed. This implies that changes in the building landscape, for example from over-site and adjacent site developments, should be subject to rigorous analysis to ensure that they don’t generate a significant adverse impact on the system prior to their acceptance. Where over-site development is permitted or expected it is recommended that the buildings have microclimate studies undertaken very early in their development. This will enable suitable design modifications to be established early in the process. It is also recommended that a smoke stack through the building should be included where possible to minimize the risk of cross contamination to both the station and the development.

5. CONCLUSIONS

This paper presented a CFD study on the potential for cross contamination of smoke in underground station environments. The findings highlight several key considerations for the design and layout of ventilation systems in such settings.

Firstly, the results indicate that separation distances more than those noted in building codes are probably required. Secondly, wind speed and smoke release height play an important role in smoke dispersion. Finally, the impact of buildings and other obstructions was shown to be significant, with the height and shape of these structures affecting the potential for cross-contamination. The impact of the buildings tested was shown to be non-linear. However, it is acknowledged that further research is needed to provide quantified recommendations. Where buildings need to be considered it is recommended that a safety margin is included within initial station layout.

The findings in this paper are intended to guide the early stages of project development, with the understanding that detailed CFD analysis will be necessary at later stages.

6. REFERENCES

[1] British Standards Institute, 2017, Fire safety in the design, management and use of buildings – Code of Practice, BS 9999

[2] Associated Press, http://news.bbc.co.uk/1/hi/world/asia-pacific/2774561.stm, Retrieved on 10th October 2025

[3] Gary A. Briggs (1965) A Plume Rise Model Compared with Observations, Journal of the Air Pollution Control Association, 15:9, 433-438

[4] Turner DB, 1970, Workbook of atmospheric dispersion estimates, US Department of Health Education and Welfare

[5] Woodward H, Gallacher D, Robins A, Seaton M, ApSimon H, 2021. A review of the applicability of Gaussian modelling techniques to near-field dispersion, ADMLC project ADMLC-R11.

[6] ADMS User guide, 2023, Cambridge Environment Research Consultant Ltd.

[7] Bentham JHT, 2003. Microscale Modelling of Air Flow and Pollutant Dispersion in the Urban Environment. Ph.D. Thesis. Imperial College London.

[8] Flemming C. and Rhodes N., 2018, A validation of the fire dynamics simulator for smoke dispersion from metro stations, 9th Int Conf Tunnel safety and ventilation, Graz

[9] British Standards Institute, 2020, Fire safety in the design, management and use of rail infrastructure – Code of practice, BS 9992

[10] NFPA, 2026, Standard for fixed guideway transit and passenger rail systems, NFPA 130