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Dilution of airborne contaminants from through-wall exhausts located on the side of multi-family residential buildings

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Abstract:

Several models exist for predicting dilution from large rooftop exhausts, but their validity has not been assessed for horizontally directed through-wall exhausts such as those that often exist in new multi-family residential construction. Separation distances derived from rules of thumb or simplified versions of these models are prescribed in ventilation standards, but their appropriateness has not been assessed and they are sometimes difficult to achieve in practice. In order to provide more justifiable separation distances, we conducted a series of wind tunnel experiments and computational fluid dynamics (CFD) simulations measuring dilution of a horizontally-directed exhaust from a test building. We then compared these measurements to existing models and assessed the models' validity for this situation. Lastly, we gathered dilution criteria for several contaminants of interest and used wind tunnel and CFD results along with published emission rates to specify a separation distance that is likely to result in acceptable air quality at neighboring intakes. Results show that mitigation of chronic health concerns from cooking, and smoking in dwelling units, as well as odor concerns from bathrooms, can likely be achieved with separation distances of 5 feet or less. To prevent irritation from smoking in neighboring units, a separation distance of 10 feet is recommended. We did not find that furnace exhaust can be diluted sufficiently with separation distances that are feasible on multi-family buildings.

Keywords:

Dilution, dispersion, ventilation, multi-family buildings

1. Introduction

Buildings typically provide for indoor quality (IAQ) through a combination of source control, ventilation and air cleaning. The ventilation systems often include local exhaust, and fresh air intakes that provide outdoor air through mechanical systems (fans) or passive air inlets. In order to avoid the recirculation of high levels of contaminated air coming from exhaust into the fresh air intake in these buildings, engineers must provide for sufficient dilution of the exhaust air before it potentially reaches the location of the nearest air intake.

Many commercial buildings have rooftop ventilation systems. However, many multi-family buildings and particularly new construction use the following unique ventilation approach: Each dwelling unit has dedicated supply ventilation as well as one or more exhaust(s) airflows from the dwelling unit's kitchen, bathroom, dryer, general unit ventilation, or other sources, with all ventilation ducted horizontally through the dwelling unit wall. This "unitized ventilation" method has become more common in multifamily buildings, particularly as some multifamily new construction codes require or encourage balanced ventilation.

In this case each dwelling unit must have a system that provides outdoor supply air at the same rate as it exhausts stale air from the unit. As of the time of this writing, the State of Minnesota requires balanced ventilation for new construction multifamily buildings, and the State of California requires all new construction multifamily buildings to either meet a dwelling unit tightness requirement or provide balanced ventilation. In addition, heat recovery ventilation – which requires balanced ventilation - is becoming more prevalent under energy codes, including ASHRAE 90.1-2019, which requires it for almost all high-rise multifamily dwelling units.

In the absence of a method for continuously sensing pollutants of interest at a building intake (e.g. Zou et al. 2021a; 2021b; 2020; 2019), minimum separation distances between intakes and exhausts are prescribed based on predicted dilution between exhaust and intake. A few simple methods for predicting this dilution currently exist. Well-established methods for predicting the concentration of Gaussian plumes emitted from the rooftops of buildings have existed for many years (ASHRAE 2019) and continue to be improved (Zakeri Shahvari & Clark, 2020). These prediction models are primarily for upward-direct jets of air and have been validated with high-momentum jets (10's of thousands of cubic feet per minute (cfm)) and their validity for the lower momentum jets associated with exhaust ventilation has not been assessed to our knowledge. A significant gap in previous research is understanding of dilution of horizontal ventilation configurations, or how horizontally-emitted exhaust impacts nearby supply air entering the building, and necessary dilutions for ensuring good IAQ for that supply air.

Table 1. ASHRAE Standard 62-1 Table 5-1

Object	**Minimum Distance (ft)**	**(m)**
Class 2 air exhaust/relief outlet	10	3
Class 3 air exhaust/relief outlet	15	5
Class 4 air exhaust/relief outlet	30	10
Cooling tower exhaust	25	7.5
Cooling tower intake or basin	15	5
Driveway, street, or parking place	5	1.5
Garage entry, automobile loading area, or drive-in queue	15	5
Garbage storage/pick-up area, dumpsters	15	5
Plumbing vents terminating at least 3 ft (1 m) above the level of the outdoor air intake	3	1
Plumbing vents terminating less than 3 ft (1 m) above the level of the outdoor air intake	10	3
Roof, landscaped grade, or other surface directly below intake	1	0.3
Thoroughfare with high traffic volume	25	7.5
Truck loading area or dock, bus parking/idling area	25	7.5
Vents, chimneys, and flues from combustion appliances and equipment	15	5

In the absence of a better model, ANSI/ASHRAE Standard 62.1-2019 [2019a] currently allows for prescriptive separation distances based simply on the categorization of the exhaust air to be used, given in Table 1 (Table 5-1 in the Standard). Similarly, ANSI/ASHRAE Standard 62.2-2019 [2019b] provides prescriptive distances with exceptions:

"6.8 Air Inlets:

Minimum distance of 10 ft (3 m) from known sources of contamination (e.g. a stack, vent, exhaust hood, or vehicle exhaust, etc.) for air inlets that are part of the ventilation design.

Except for the following:

> 1. A stretched-string distance of 3 ft (1 m) for ventilation openings in the wall. A stretched-string distance is the shortest distance between emitter and receiver on a building.
>
> 2. No minimum separation distance is required between local exhaust outlets in kitchens and bathrooms and windows.

> 3. No minimum separation distance is required between the two opening when intake air is separated from exhaust air originating in a living space other than kitchens by a combined exhaust/intake termination. For these combined terminations, the exhaust air concentration within the intake airflow shall not exceed 10%, as established by the manufacturer.
>
> 4. Vent terminations covered by and meeting the requirements of the *National Fuel Gas Code* (NFPA 54/ANSI Z223.1)7 or equivalent.”

The source or rationale for these prescriptions is unclear. (Palmiste, Kurnitski, & Voll, 2020) reviewed other published criteria designed to ensure adequate dilution between exhaust and inlet, which we review below in Section 2 and use as a basis of comparison for data generated in this work. They demonstrated a wide variety in resulting required separation distances and conclude that “evidence-based research is lacking for near-field pollutant dispersion and re-entrainment from an exhaust outlet located on an external wall.” This lack of research motivates the current work.

Furthermore, the current prescriptive requirement can be difficult to meet in practice, specifically in multifamily buildings with horizontally vented through-wall exhaust and air intake systems. Figure 1 shows an example configuration. Each dwelling unit’s unitized ventilation system must maintain the minimum distance (typically 10 feet) within its own system, and with neighboring unit’s system, which is challenging with limited wall space.

Figure 1. Example layout of exhausts on multi-family residence.

As the multifamily building market moves towards a broader range of mechanical ventilation systems– including those vented horizontally – it is important to provide designers with as much flexibility as possible, while providing sufficient dilution to maintain good IAQ.

To this end, in this work we:

1) Conduct a series of wind tunnel dispersion experiments in which we generate a dataset of dispersion from building wall horizontal exhausts

2) Supplement these with computational fluid dynamics simulations of buoyancy-driven flows in the same situations

3) Evaluate multiple mathematical models for predicting this dilution

4) Use these models to specify a required separation distance for horizontal exhausts in a more scientifically justifiable way than is provided for in the current literature.

2. Methodology

2.1 Wind Tunnel Modeling

We conducted the wind tunnel analysis using a 1:120 scale replica of a simple building shown in Figure 2. The building was 75 ft (22.9 m) x 150 ft (45.7 m) in plan and 75 ft (22.9 m) tall in full scale. Roughness elements simulated a low-lying suburban terrain with roughness height of 0.35m. The shape of the resulting atmospheric boundary layer and turbulence intensity profile were verified with hot wire anemometers prior to the start of simulations.

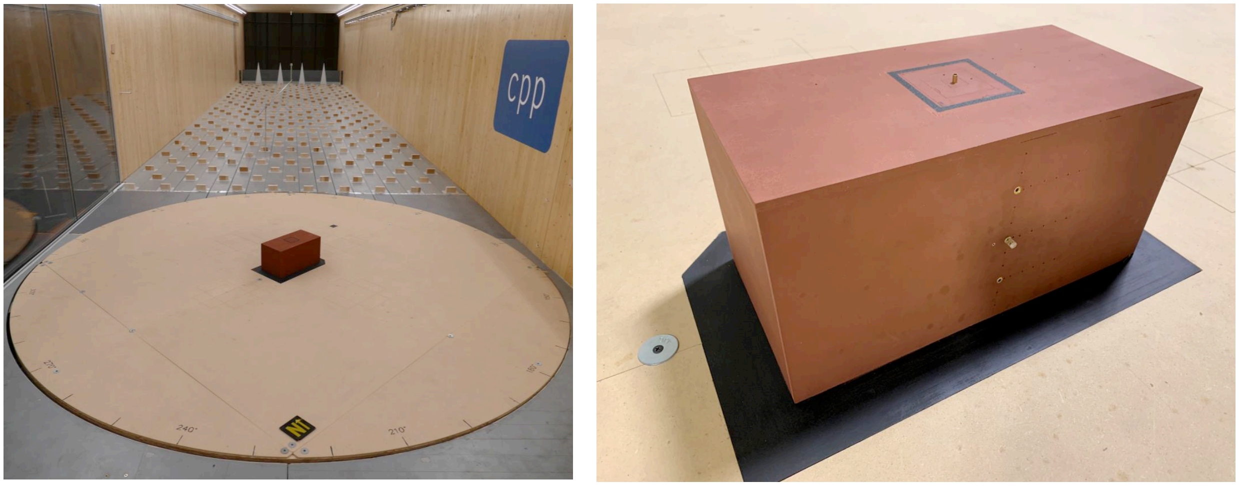

Figure 2. Wind tunnel with building (left) and close-up of building model used in study with exhausts visible

A physical exhaust tube issued from the side of the building along with 11 receptors to measure resulting concentrations. The exhaust was located at a full-scale height of 37.5 ft (11.43 m) above ground, on the lateral centerline of the building face as shown in Figure 2. The map of the exhausts and receptors is given in Figure 3 and vertical locations of receptors is given in Table 2. The receptors located lateral to exhausts are spaced 5 ft (1.5m) apart horizontally.

We simulated an exhaust flow rate of 150 cubic feet per minute (70.8 L/s) in all scenarios, and exhaust air in all cases was isothermal with the surrounding environment to negate any buoyancy effects. When selecting an exhaust air flow rate for the experiments, we considered the following: dwelling unit and bathroom exhaust air flows that are typically 50 cfm, or less for a multifamily dwelling unit, kitchen ventilation exhausts that are greater than 100 cfm to meet the minimum air flow requirements of ASHRAE 62.2, and air flows of about 150 cfm for clothes dryers and combustion devices. Of these exhausts, the ones likely to have the highest contaminants are the latter. Therefore we chose a flow of 150 cfm for the experiments. This translated to a model scale flow rate of 0.0045 cfm.

A full-scale exhaust diameter of 15 inches (0.38 m) was the smallest diameter that could be feasibly simulated in the wind tunnel. This is greater than the diameter of exhausts used in practice. However, we modeled a capped exhaust in the wind tunnel that arrested any horizontal momentum of the jet issuing from the exhaust. This assumption means that results are conservative and largely a function only of near-field fluid dynamics rather than properties of the exhaust itself.

From the exhaust, we released a mixture of 90% inert gas (nitrogen) and 10% tracer gas (ethane) at the required rate to simulate the exhaust plume. The flow rate of the gas mixture was controlled and monitored by a Aalborg DFCS precision mass flow controller (MFC), and the concentration of the tracer gas at each sampling point was analyzed using a Rosemount 400A flame ionization detector.

In the wind tunnel, we conducted a search for critical wind directions and wind speeds for each exhaust, by rotating the turntable and modulating exhaust airflows and assessing resulting concentrations at receptors.

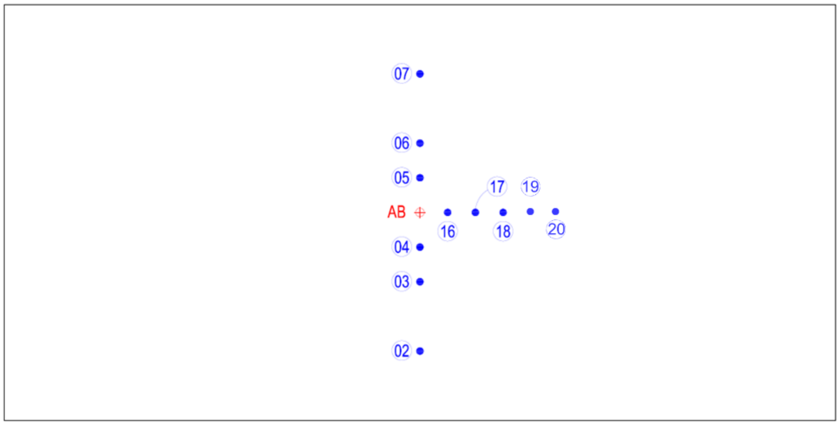

Figure 3. Map of receptors and exhaust on side of wind tunnel model building

Table 2. Vertical locations of receptors

RECEPTOR SCHEDULE			
RECEPTOR NUMBER	**LOCAL BUILDING LEVEL**	**ARCHITECTURAL (FULL SCALE) ELEVATION**	**MODEL SCALE ELEVATION**
2	Wall	12'-6"	1.25"
3	Wall	25'-0"	2.50"
4	Wall	31'-3"	3.12"
5	Wall	43'-9"	4.37"
6	Wall	50'-0"	5.00"
7	Wall	62'-6"	6.25"
16	Wall	37'-6"	3.75"
17	Wall	37'-6"	3.75"
18	Wall	37'-6"	3.75"
19	Wall	37'-6"	3.75"
20	Wall	37'-6"	3.75"

2.1.1 Similarity Criteria

A perfectly similar wind tunnel replica of atmospheric boundary layer flows would hold Reynolds number, Rossby number, Eckert number and Richardson number at those of the full scale situation. However, simultaneously equalizing Reynolds number, Rossby number, Eckert number and Richardson number for the model and the prototype is not possible. Nonetheless, these inequalities are not serious limitations. Reynolds number independence is an important feature of turbulent flows which allows wind-tunnel modeling to be used.

Beginning with Townsend (1956), researchers have found that in the absence of thermal and Coriolis (earth rotation) forces, the turbulent flow characteristics are independent of building Reynolds number provided the building Reynolds number is high enough. The EPA (1981) specifies a Building Reynolds number criterion of about 11,000 for sharp-edged building complexes. For this study, the Building Reynolds number was calculated at approximately 60,000. Additionally, plume rise becomes independent of the stack Reynolds number if the plume is fully turbulent at the stack exit (Hoult and Weil, 1972; EPA, 1981). Hoult and Weil (1972) reported that plumes appear to be fully turbulent for stack Reynolds numbers (exterior) greater than 300. Arya and Lape (1990) showed similar plume trajectories for stack Reynolds numbers (interior) greater than 670 for buoyant plumes and greater than

2000 for neutrally buoyant plumes. For this study, both the exterior and interior stack Reynolds numbers can be neglected, because: 1) No portion of the stack protruded past the exterior building wall; and 2) a cap was installed on the stack to impinge on any laminar flow.

The Rossby number, Ro, is a quantity which indicates the effect of the earth's rotation on the flow field. In the wind tunnel, equal Rossby numbers between model and prototype cannot be achieved without a spinning wind tunnel. The effect of the earth's rotation becomes significant if the distance scale is large. EPA (1981) set a conservative cutoff point at 5 km for diffusion studies. When equal Richardson numbers are achieved, equality of the Eckert number between model and prototype cannot be attained. This is not a serious compromise since the Eckert number is equivalent to a Mach number squared. Consequently, the Eckert number is small compared to unity for laboratory and atmospheric flows and can be neglected.

The Richardson number describes the relationship between momentum and buoyancy effects in flows subject to each. As buoyancy effects scale with characteristic length scale cubed, it is often prohibitive or quite challenging to simultaneously scale momentum effects and buoyancy effects in a scale model, as it was in this study. For this reason, all wind tunnel runs were done in isothermal conditions. In most cases, neglecting buoyancy effects in the near field of the exhaust will add negligible error as flows are dominated by momentum effects in this region (e.g. Meroney et al 1990).

However, in order to verify this assumption, we conducted a parallel computation fluid dynamics (CFD) simulation campaign in which we varied the exhaust temperature to assess the effects of buoyancy on flow, described presently.

2.2. Computational fluid dynamics simulations

For all CFD simulations, we simulated a domain with a height of 40 ft (12 m), width of 25 ft (7.6 m), and depth of 10 ft (3 m) in the commercial software package ANSYS Fluent. A mesh size of 2.2 million cells was determined to be sufficient after grid sensitivity tests. The k-omega SST turbulence model was used in all simulations. No slip conditions were assumed at the building wall and radiation effects were neglected.

Top and bottom faces of the domain were assumed to be pressure boundary conditions at ambient pressure. Vertical surfaces were set to symmetry boundary conditions. Uniform wind at 1 m/s was modeled coming from the surface opposite the wall (wind impinging on wall), corresponding to the nominally “calm” condition, the least wind velocity modeled in the wind tunnel. The turbulence intensity of the wind was set at 20% at the domain boundary as was measured in the wind tunnel. In all cases a two-part gas was emitted from the exhaust consisting of N_2 and a tracer gas with equal molecular weight to N_2. All results are normalized by exhaust concentration in order to render the exhaust concentration irrelevant.

We first as closely as possible mocked up the conditions simulated in the wind tunnel in order to validate and calibrate the CFD simulations, with a small plate arresting the momentum of the exhaust jet, 18 inches from the exhaust and parallel to the building. The exhaust jet and surrounding air were isothermal and we tuned the turbulence intensity of the exhaust jet until dilution values at surrounding receptors similar to the wind tunnel results were achieved, resulting in a 20% turbulence intensity at the exhaust.

We then varied both the geometry and the temperature of the exhaust: We modeled exhaust-ambient temperature differences from 0-40°C for three different geometries (plate-arrested jet as in wind tunnel, free exhaust, and downward directed exhaust cap as is commonly used in practice (see Figure 4)). We attempted to bound the problem in this way, assuming situations encountered in practice would fall somewhere between the free jet and the jet fully directed by the termination.

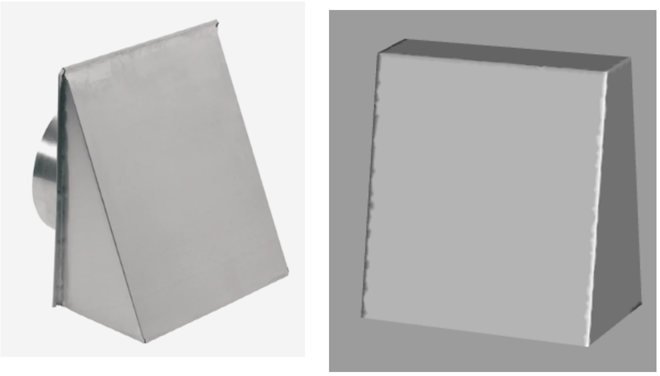

Figure 4. Typical downward-direct exhaust cap (left) and CFD representation (right)

2.3 Mathematical Modeling

We compared wind tunnel results to each of several published prediction models for dispersion from building exhausts. As mentioned previously, these are reviewed in Palmiste et al. (2020) and others are included in Rock et al. (1999). We present them again presently, along with assumptions and modifications to the models that were necessary in the current work. Where possible we used as inputs the actual physically modeled parameters from the wind tunnel. Any other assumptions are given below.

2.2.1 ASHRAE Standard 62.1

ASHRAE Standard 62.1-2019 Appendix B gives a "Simple Method" and "Velocity Method" for determining adequate separation, derived in part from Peterson and Ritter (2016). In the Simple Method, exhaust air is simply categorized as and a distance prescribed as given in Table 1. In the Velocity Method, the model for required separation distance, L, requires inputs of exhaust airflow rate, Q, exhaust discharge air velocity, U, and required dilution factor, DF. The model can be rearranged to present resulting predicted dilutions as a function of L, Q, and U, as is done in other models. Dilution factors are discussed below in Section 2.3. Special provisions are made for changes in the model with respect to the direction of U:

- If exhaust is directed away from the outdoor air intake at an angle that is greater than 45 degrees from the direction of a line drawn from the closest exhaust point to the edge of the intake, U is given a positive value.
- If exhaust is directed toward the intake bounded by lines drawn from the closest exhaust point to the edge of the intake, U is given a negative value.

- If exhaust is directed at an angle between the two above cases, *U* is zero.
- For vents from gravity (atmospheric) fuel-fired appliances, plumbing vents, and other non-powered exhausts, or if the exhaust discharge is covered by a cap or other device that dissipates the exhaust airstream, *U* is zero.
- For hot-gas exhausts such as combustion products if the exhaust stream is aimed directly upward and unimpeded by devices such as flue caps or louvers, add 500 fpm (2.5 m/s) upward velocity to U.

Standard 62.1 also gives a broad allowance for an explicit calculation of concentration of pollutants of interest at inlets, presumably by wind tunnel analysis, computational fluid dynamics or otherwise, and comparison against accepted criteria. In addition to the calculations shown in ASHRAE 62.1 Appendix B, ASHRAE 62.1 recently adopted addendum ag, which modified Appendix B to a calculation that depends on exhaust airflow (cfm) for horizontal exhaust, and wind speed. However, the calculation in ASHRAE 62.1 addendum ag assumes that concentration in the airflow remains the same. For example, a 400 cfm kitchen exhaust hood would exhaust four times the pollutant as a 100 cfm kitchen exhaust. For multifamily dwelling units, this is not the case. Consequently, we did not compare results to ASHRAE 62.1 addendum ag.

2.2.2 ASHRAE Handbook of Fundamentals Method

The ASHRAE Handbook of Fundamentals: HVAC Applications: Chapter 46 gives a model that is typically used for analyzing rooftop exhaust stacks with jets directed vertically. According to this model, the dilution at any receptor of interest can be predicted using a model that assumes a Gaussian profile for the plume issuing from an exhaust stack. To do this, roof-level dilution, D_r, is first defined as

$$D_r = \frac{C_e}{C_r} \tag{1}$$

where C_e is the concentration of the contaminants at the stack exit and C_r is the maximum concentration on centerline of the plume.

The plume spread (σ_y and σ_z) is then calculated using the following equations from (Cimorelli et al., 2005).

$$\sigma_y = \left(i_y^2 x^2 + \sigma_o^2\right)^{\frac{1}{2}} \tag{2}$$

$$\sigma_z = (i_z^2 x^2 + \sigma_o^2)^{\frac{1}{2}} \tag{3}$$

where i_y is turbulence intensity in y direction,

i_z is turbulence intensity in z direction and x is the distance from the stack,

σ_o is defined as a function of stack diameter ($\sigma_o = 0.35 d_e$).

Turbulence intensities (i_x, i_y and i_z) are calculated from the following equations:

$$i_y = 0.75 i_x\, ; \quad i_z = 0.5 i_x \tag{4}$$

$$i_x = \frac{n \ln\left(\frac{90.4}{z_o}\right)}{\ln\left(\frac{H}{z_o}\right)} \tag{5}$$

$$n = 0.19 + 0.096 \log_{10}^{z_o} + 0.016\left(\log_{10}^{z_o}\right)^2 \tag{6}$$

Finally, dilution is calculated using the following equation

$$Dr(x) = \frac{4U_H \sigma_y \sigma_z}{V_e d_e^2} \exp\left(\frac{\varsigma^2}{2\sigma_z^2}\right) \tag{7}$$

In the final step, the Handbook requires the designer to choose the surface roughness from Table 1 of Chapter 46 of ASHRAE Handbook: (HVAC Applications) based on the site conditions, calculate the minimum dilution using the equations explained above, and then repeat the calculations for half of the value of surface roughness and 1.5 of that value. , and Finally, the designer chooses the lowest value of dilution as the minimum dilution.

In order to adapt this model to horizontally-directed, capped exhaust vents, we needed to make a few assumptions. The first assumption is that $\zeta = 0$, implying no plume rise (typical, and sometimes conservative, assumption when exhausts are capped). Another assumption is that of homogenous turbulence intensity. σ_o is assumed to be equal to d_e as in Zakeri and Clark (2020).

2.3 Dilution Criteria

There are two distinct inputs to any analysis of possible re-entrainment of exhaust air on buildings: 1) the prediction of dilution between the exhaust and intake of interest (discussed above); and 2) the specification of a required dilution referred to as D_r here forward, which is equal to the exhaust concentration, $C_{exhaust}$ divided by an acceptable concentration, $C_{acceptable}$. Alternatively, one could specify $C_{acceptable}$ at the intake directly. The mathematical models given above are attempts at predicting dilution, while required dilution criteria are driven by occupant health and comfort concerns. In this section we briefly review published dilution criteria that are relevant to the problem of multi-family exhausts.

2.3.1 Published dilution criteria

In rare cases, dilution criteria are published directly for certain circumstances, with varying degrees of justification. One example of this is Table B-3 in Standard 62.1 which gives the following values:

- Significant contaminant or odor intensity (Class 3 Air): Dilution required = 15
- Noxious or dangerous particles (Class 4): Dilution required= 50

  **Does not apply to fume hood exhaust.

Similarly, Junker et al (2001) report a required dilution for preventing detection of cigarette smoke at 19,000 m^3 of dilution air per cigarette and a required dilution for preventing eye and nasal irritation of 3000 m^3 per cigarette (Junker, Danuser, Monn, & Koller, 2001).

2.3.2 Concentration limits

More common is the specification of concentration thresholds for individual pollutants of interest. Published criteria are associated with an averaging time. The averaging time is often much longer than a typical exhaust event, with the most common being 1-, 8-, or 24-hour exposure limits. The U.S. EPA sets National Ambient Air Quality Standards (NAAQS) that give the following exposure limits for relevant pollutants and associated averaging times.

Table 3. US EPA-designated exposure limits and associated averaging times

Pollutant [links to historical tables of NAAQS reviews]	Averaging Time	Level
Carbon Monoxide (CO)	1 hour	35 ppm
Nitrogen Dioxide (NO_2)	1 hour	100 ppb
Fine Particles ($PM_{2.5}$)	24 hours	35 µg/m^3

With respect to acute and chronic health concerns, exposure limits for many other pollutants of interest are published but we limit the discussion in this work to CO, NO_2, and fine particles as the most consequential pollutants that are 1) associated with episodic indoor emission events that are treated by exhaust ventilation, and 2) documented as consequential for occupant health in residences (Logue, Mckone, Sherman, & Singer, 2011). For bathroom exhaust dilution, we expect odor concerns to dictate required dilution and thus odor criteria are included in the analysis as shown in Table 4. We do not consider dilution of water vapor, for example from showers, because we don’t expect humidity concerns to govern required dilution in any case.

2.4 Prescription of separation distances for typical scenarios

In order to specify required dilutions, both an acceptable concentration and an exhaust concentration must be specified, as discussed previously. Calculation of an exhaust concentration requires knowledge of the source strength of a pollutant of interest and the exhaust flow rate. The ratio of these two quantities will be the exhaust concentration. In order to establish the exhaust concentration for the most common scenarios encountered in multi-family buildings, we polled the Multi-family Working Group formed under ASHRAE Standard 62.2. The following are the assumptions we used in prescribing minimum separation distances.

2.4.1 Common exhaust scenarios

The following exhaust situations were given as the most common exhaust scenarios in the United States for multi-family buildings. For scenarios with multiple types of exhaust airflows, each airflow is typically ducted separately (e.g., a separate duct for kitchen exhaust than for bathroom exhaust). However, the exhausts may discharge at the same location on the wall (through a shared wall cap) to reduce the number of envelope penetrations. The flow rate in the table shows the combined flow rate for all exhaust streams, even if they are typically vented through separate ducts.:

Table 4. Most common exhaust scenarios for multi-family buildings in the United States

Scenario	Flow rate (m^3/s)	d_e (m)	V_e (m/s)	Description
1	0.16	0.152	8.82	Kitchen, Bath, Dryer
2	0.085	0.152	4.68	Kitchen, Bath
3	0.095	0.152	5.24	Kitchen, Bath
4	0.01	0.101	1.25	Bath
5	0.071	0.152	3.91	Kitchen
6	0.071	0.152	3.91	Kitchen
7a	0.058	0.152	3.20	Kitchen
7b	0.017	0.152	0.94	Bath
7c	0.036	0.152	1.98	Bath
7d	0.066	0.101	8.24	Dryer
8a	0.071	0.152	3.91	Kitchen, Bath
8b	0.071	0.152	3.91	Bath, Dryer
9	0.218	0.2032	12.01	Kitchen, Bath, Dryer

For furnaces, another source of horizontally-directed contaminated exhaust in some multi-family buildings, exhaust flow rates and source strength will be a function of the size of the furnace.

2.4.2 Reference wind speed, $U_{H,}$ and direction

Most models of dispersion require a wind speed as input. Since a designer of a multifamily exhaust often cannot analyze all wind conditions that will be experienced during the operation of the building, simplifying assumptions must be made. All of the wind tunnel experiments conducted in this work showed that the critical wind speed, at which the greatest separation requirements are needed, is essentially a still wind condition: 1m/s ±0.5 m/s-. Therefore we use this value for all calculations that involve wind velocity.

2.4.3 Source strengths and resulting required dilutions

The final input to a dilution criterion is the exhaust concentration, which is a function of the exhaust flow rate and the amount of pollutant being removed. To calculate exhaust concentration, we conservatively assumed the entire pollutant source was being removed by the exhaust. In order to calculate the required dilution, then we simply divided an exhaust concentration (calculated by dividing published source strength for an episodic emission event by exhaust flow rates described previous) by the concentration limit. Resulting numbers and other assumptions are listed in Table 5. For bathrooms, there are no health-based pollutants that are released, but odors are a primary concern for re-entrained air. While few studies have quantified odors from human waste, the one study identified measured odor in pit latrines. Since the water in a toilet will partially mask odors, the concentration limits shown in Table 5 for bathrooms are higher than what would be found in modern toilets in multifamily buildings.

Table 5. Resulting exhaust concentrations and required dilutions for typical scenarios

Source	Pollutant	Concentration Limit	Unit	Time	Reference	Emission Rate	Unit	Reference	Exhaust Flow Rate Assumed	Exhaust Concentration	Unit	Dilutions Required	Comments
Bathrooms	Hydrogen sulfide	0.5–2[1] , 7[2] , 10[3]	ppbv	Perception threshold	1	NA			20-80 cfm	25–55	ppbv	2.5-110	a
	Ammonia	3000–20,000	ppbv						20-80 cfm	50–60	ppbv	-	
	Butyric Acid	10–500	ppbv						20-80 cfm	36	ppbv	1-3.6	
	Methyl mercaptan	1–20	ppbv						20-80 cfm	2–15	ppbv	-	
	Indole	5–20	ppbv						20-80 cfm	0.31	ppbv	-	
	p-cresol	0.05–9	ppbv						20-80 cfm	1.2	ppbv	1-7.5	
	Acetic acid	400–1000	ppbv						20-80 cfm	3–10	ppbv	-	
	Propionaldehyde	50–200	ppbv						20-80 cfm	10	ppbv	-	
	Trimethylamine	50–200	ppbv						20-80 cfm	10–100	ppbv	-	
Cooking	CO	43708[g]	μg /m^3	1 h	10	625	μg/sec	4	150 cfm	8824	mg/m^3	-	c
	NO2	205	μg /m^3			83.5 [b]	μg/sec	4	150 cfm	1179		5.7	
	PM2.5	35	μg /m^3	24 h		7.25E+03	μg/min	5,8	150 cfm	1706		3.1	

Furnaces	CO	43708	µg /m^3	1 h		50	µg/BTU	9	30 cfm	28	ppm	-	d, e
	NO2	205	µg /m^3	1 h		53	µg/BTU	9	30 cfm	18	ppm	182	
	PM2.5	35	µg /m^3	24 h		2.9	µg/BTU	9	30 cfm	2050	µg/m^3	58	
Smoking	PM2.5	35	µg /m^3	24 h		.33 mg/min: 10mg/cig*2 cig/h		6	150 cfm	78	µg /m^3	2.2	
	Odor	NA	NA	NA	7	NA		3000 m3/cigarette (irritation), 19000m^3/cigarette (detection) [7]	150 cfm		24 (irritation) 149 (detection)		

a. All gas concentrations at STP, *Likely conservative-exhaust concentrations values taken from pit latrines
b. [5] says 28 kBTU/h=8200W *10ng/J (median of Singer 2017)=82 mg/sec
c. assumes 1 hour cooking event at emission rate, 12mg/m^3 outdoor ambient concentration, and 24-hour exposure limit of 35 mg/m^3
d. assumes 36 kBTUh condensing furnace with powered exhaust
e. assumes 30 cfm exhaust and EPA emission factors

1. (Chappuis, Niclass, Vuilleumier, & Starkenmann, 2015)
   (Sato, Hirose, Kimura, Moriyama, & Nakashima, 2001)
   (Kawadiya, Welling, Grego, & Deshusses, 2020)
2. (“Hydrogen sulfide,” 1955)
3. (D.C., 2013)
   (Persily, 1998)
4. (Dacunto et al., 2013)
5. (Hu, Singer, & Logue, 2012)
   (Dacunto et al., 2013)
6. (Klepeis, Apte, Gundel, Sextro, & Nazaroff, 2010)
7. (Klepeis et al., 2010)
8. (Singer, 2021)
9. (US EPA, 1997)
10. (US EPA, 1990)

3. Results

In this section are the results of the comparison of the models described above with wind tunnel data. In all figures we omit measurement uncertainty bars as this results in cluttered figures that are difficult to read. However, uncertainty in required dilutions induced by measurement uncertainty and averaging of time series of concentrations remained less than 5% of the reported value in nearly all cases, with the greatest relative uncertainty in the least concentration values, which occurred at distances farthest from the exhaust, which are unlikely to control design.

3.1 Comparison of wind tunnel results with velocity method in ASHRAE 62.1

Figure 5 shows the comparison of the wind tunnel data with the more complicated model given in ASHRAE Standard 62.1, organized by the angle of attack of the wind. In Figure 5, "Windward" refers to wind directions that are within 45 degrees of a wind direction that is directly impinging on the side of the building where the exhaust is located. "Side toward" refers to wind directions within 45 degrees of a horizontal vector pointing directly from the exhaust to the receptor; "side away" refers to wind directions pointing from the receptor to the exhaust, or within 45 degrees; and finally "leeward" refers to wind directions impinging on the side of the building opposite the exhaust, and within 45 degrees of this angle.

Also shown are a line denoting the ASHRAE 62.1 model (labeled "62.1") and line showing predicted dilutions that are 40% of the 62.1 model (labeled "0.4 * 62.1") in order to provide a sense of the magnitude of discrepancies. Each of these are given as a function of stretched-string distance. Lastly the prescribed distances given in the simple model in ASHRAE 62.1 are labeled at the top of the graph.

Figure 5 shows a few interesting results. First, the ASHRAE 62.1 Model fails to bound the measured data, in some cases by around an order of magnitude in the dilution prediction. This disparity seems to grow with string distance. The least dilution and greatest disparity with the model was measured for windward and "side toward" wind directions, which is understandable. Furthermore, the 62.1 model seems to predict a greater dependence of dilutions on string distance than the measured data does. For example, little increase in dilution is measured between 10 and 15 feet, which 62.1 model predicts approximately a half order of magnitude increase in dilution. Lastly, implied dilutions for the "simple model" given in 62.1 correspond to approximately 20 for Class 2 Air, 30 for class 3 Air, and greater than 100 for Class 4 air. This can be compared against directly specified dilutions of 15 and 50 for Class 3 and 4 air, respectively, in 62.1.

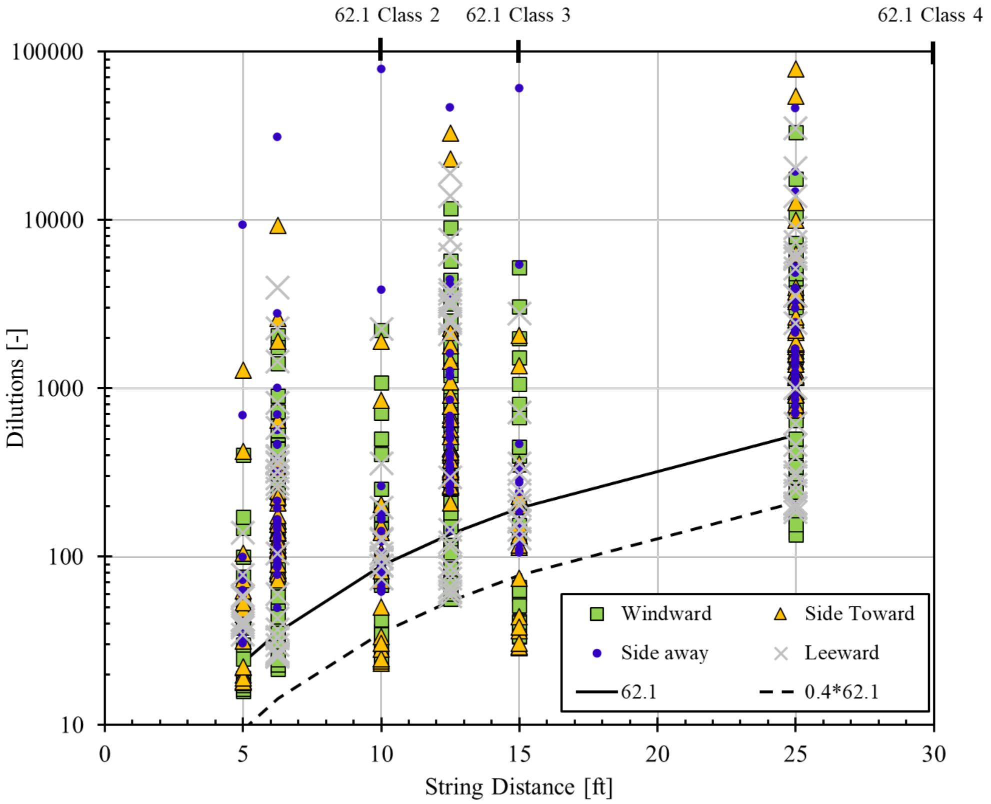

Figure 5. Comparison of ASHRAE Standard 62.1 model with wind tunnel data

Figures 6 and 7 further elucidate this comparison by contrasting the variation of measured dilutions in the horizontal direction away from the exhaust, and in the vertical direction away from the exhaust, respectively. In both Figure 6 and 7, a value of “0” on the x-axis does not imply a stretched string distance of zero, as points may still be vertically separated in Figure 6 and horizontally separated in Figure 7. Figure 6 shows very little reduction in concentration of the exhaust along a horizontal line away from the exhaust, up to 15 feet. Figure 7 shows substantial variation in the vertical distance, but interestingly that substantial dilution happens very close to the source. A dilution of 16 was the least value measured, at five feet horizontally from the source.

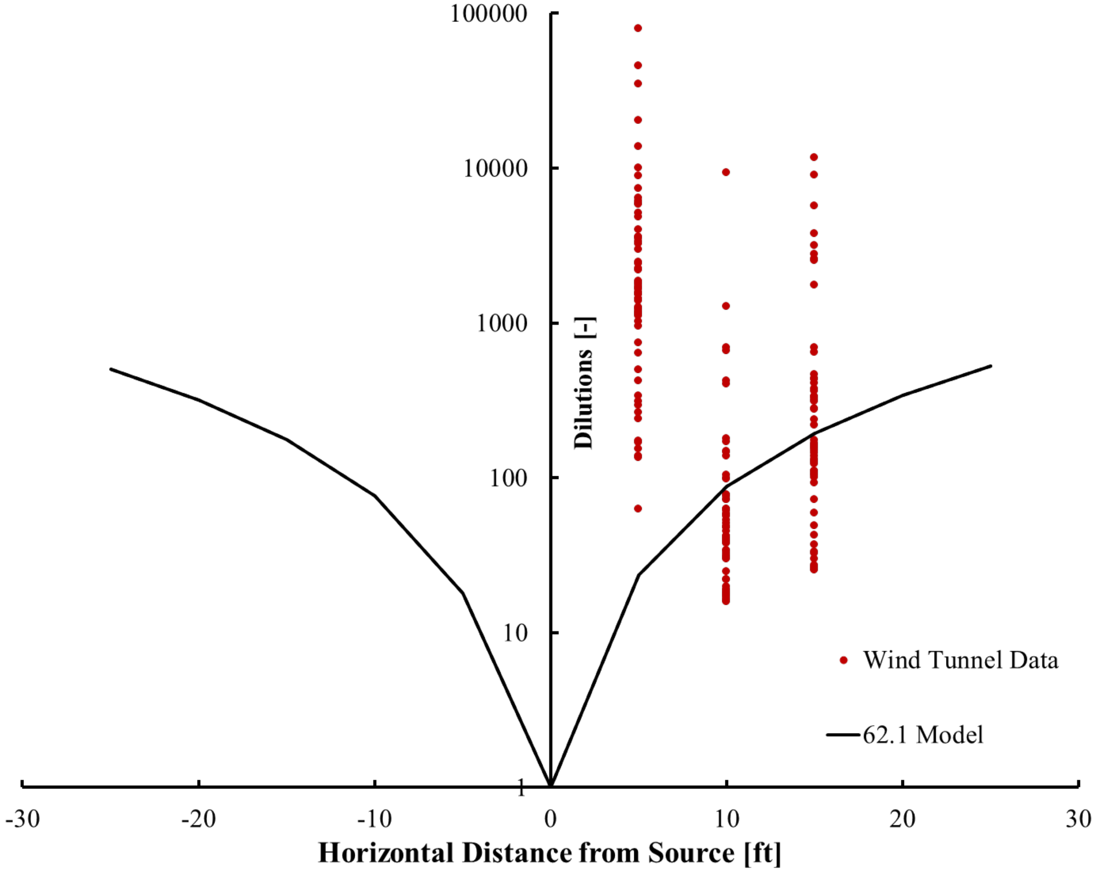

Figure 6. Variation of measured dilutions with horizontal distance from exhaust overlaid with 62.1 model.

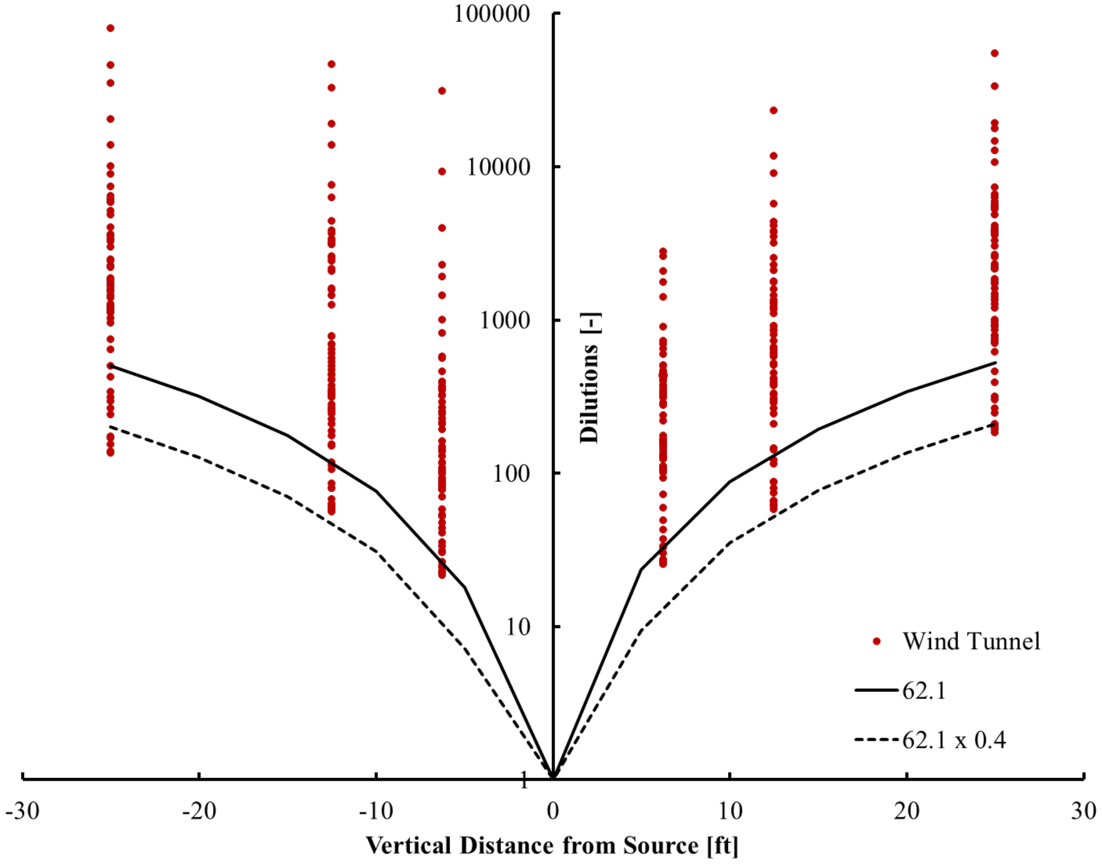

Figure 7. Variation of measured dilutions with vertical distance from exhaust overlaid with 62.1 model.

3.2 Comparison with ASHRAE Handbook of Fundamentals

Figure 8 shows the comparison between the ASHRAE Handbook model and the wind tunnel data. Results are given in terms of measured dilutions, $D_{measured}$, divided by dilutions predicted by the Handbook model, $D_{predicted}$. A value below one implies the Handbook model overpredicted the dilution (is not conservative). Again, we see that this model fails to bound measured data, and the performance of the model worsens somewhat with string distance.

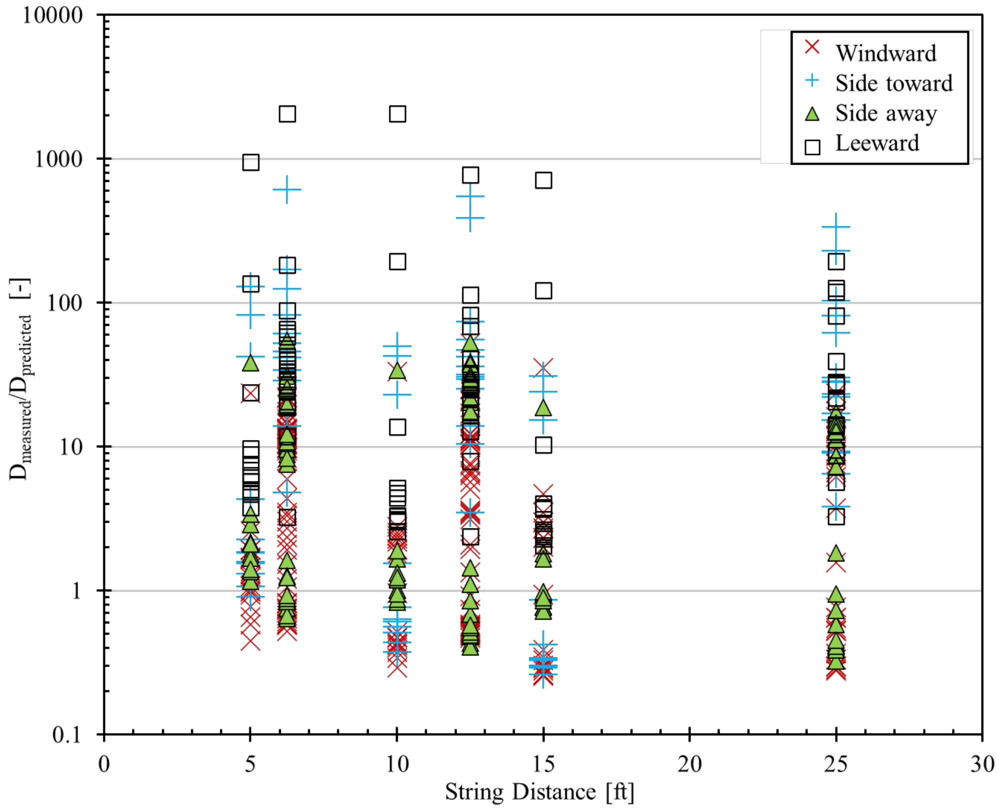

Figure 8. Comparison of ASHRAE Handbook model with wind tunnel data

3.2 Effects of Buoyancy

Next we present the results of the CFD simulations. Figure 9 shows the results of the validation simulations with a cap similar to the wind tunnel: a circular plate 18 inches in front of the exhaust. Also in this figure we include the lower bound of the the wind tunnel data for the situation modeled, showing good agreement with the CFD results. Interestingly, we see a small region near the exhaust in which the jet is detached from the wall and dilutions are greater than they are farther from the source. At approximately 3 ft (1 m) from the source, the jet attaches to the wall and dilutions decrease. The reattachment owes to a well known phenomenon called the Coanda effect. As the jet moves further from the source, it expands and entrains ambient air, thus diluting the exhaust contaminants.

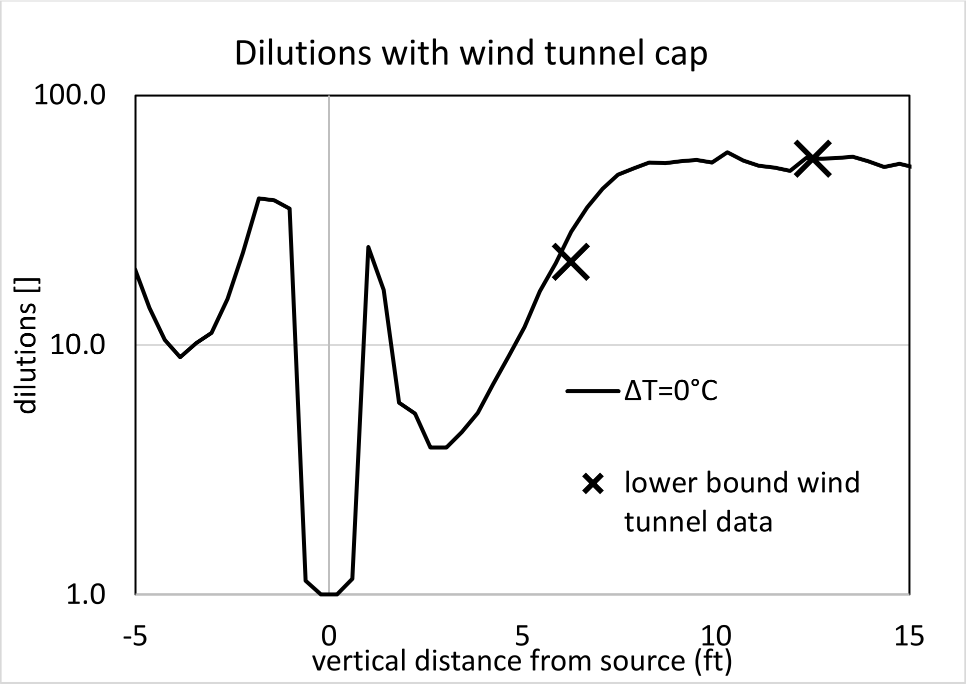

Figure 9. Results of validation CFD simulations with cap similar to wind tunnel

Next in Figure 10 we show the results of the uncapped exhaust simulations. In this case buoyancy effects decrease dilution below the isothermal case, likely owing to a buoyancy forces moving the pollutants more quickly to the receptors above the exhaust, before as much entrainment can occur as in the isothermal case. However, even at the greatest temperature difference modeled (40° C), simulated dilutions were greater than 100 and substantially greater than the conservative wind tunnel results.

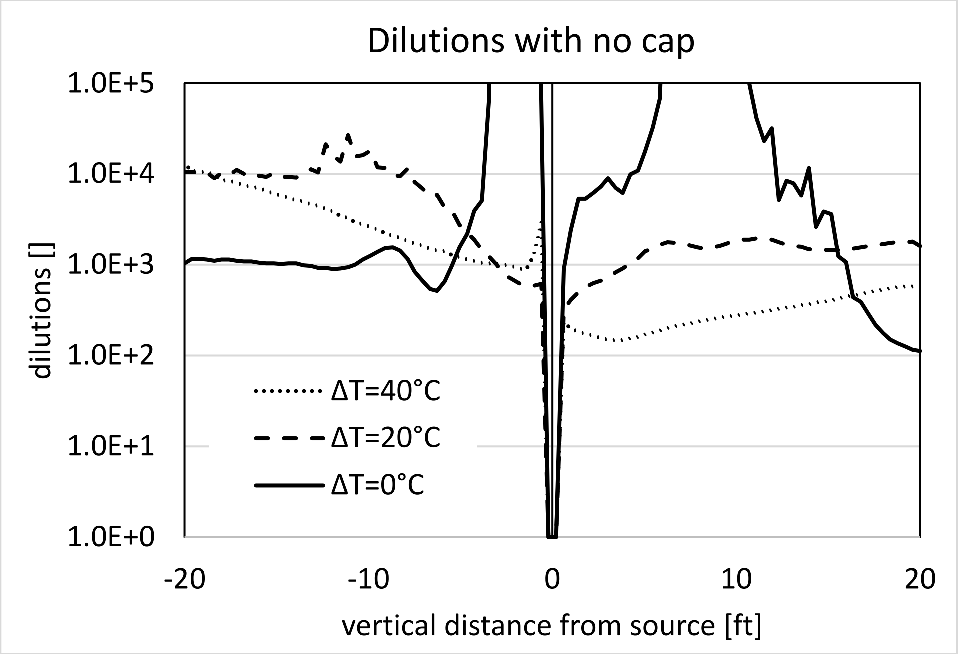

Figure 10. Results of CFD simulations with no cap

Lastly in Figure 11 we show the results of the downward directed exhaust simulations, given as a graph of dilutions as a function of distance (left) as well as a contour plot of resulting concentrations at the wall (right). Blue regions of the contour plot are regions in which concentration is essentially zero, or dilutions infinite. As might be expected, dilutions at locations above the exhaust quickly become greater than 100 right next to the exhaust for all temperature differences. At locations below the exhaust, fluid mechanics appear to be dominated by momentum effects and are again insensitive to exhaust-ambient temperature difference. Dilutions at locations below the exhaust are quite low, reaching only approximately 3 at a distance of 20 feet from the exhaust. However, concentration quickly drops in the horizontal direction, meaning dilutions are near infinite at any location that is 3 feet or more in the horizontal direction from the downward-directed exhaust.

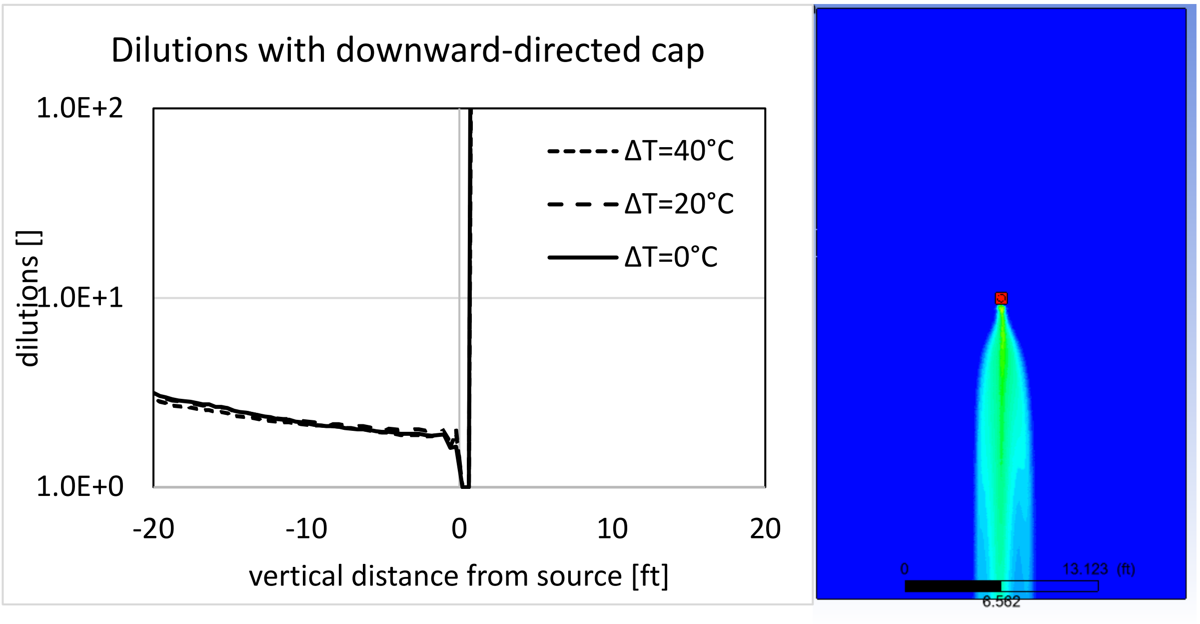

Figure 11. Results of CFD simulations with downward directed cap

In summary we see that unconstrained jets in which buoyancy forces are allowed to have the greatest effects result in dilutions that are more than adequate in most situations and substantially greater than those measured in the wind tunnel. Conversely, when a cap directs the flow and the resulting jet is subject primarily to momentum forces, buoyancy effects are not significant.

4. Discussion and prescription for multi-family exhausts

A few interesting broad lessons can be taken from the results shown in Section 3. First, existing models used for specification of separation distance on buildings do not seem to be appropriate for horizontally-directed through-wall exhaust. This is not surprising as these models are typically built for dispersion under a dominant wind direction that is parallel to the surface from which the exhausts protrudes (such as a roof) and for cases in which the exhaust plume has momentum that carries it at least some distance from the building surface, thus making it less subject to all the well-documented local fluid mechanical phenomena near the building surface such as wakes, recirculation zone, small and large eddies, etc.

This lack of a correspondence between the physical situation modeled in the existing models and that of the MF through-wall exhausts results in a relationship between distance from exhaust (string distance) and measured data that is not approximated by the models, especially in the near field. In fact, little variation in dilution seems to occur in the horizontal direction up to fifteen feet from the exhaust. Variation in the vertical direction is more pronounced with minimum dilutions measured as a function of vertical distance from exhaust being 16, 18, 31, and 139 for 0 ft, 6.25ft, 12.5 ft and 25 ft in the vertical direction. This latter phenomenon, however, may change if more buildings were added to the wind tunnel, inducing more turbulence and irregular and sometimes vertical velocity vectors.

However, in the very near field, which may be of most interest to designers, no evidence was generated in the current work that a dilution of less than 16 times should be expected beyond five feet of the exhaust, except directly below a downward-directed exhaust. It should be noted that five feet was the shortest string distance at which a receptor was placed in the wind tunnel study and measurement uncertainty will dominate at any closer distances

4.1 Minimum string distances for through-wall exhausts on multi-family buildings.

Considering the wind tunnel results, CFD results, and the calculated required dilutions in Table 5, we can suggest a minimum separation distance criterion that is more rigorously backed with experiments than the current prescriptions, while providing more flexibility for designers. This is accomplished by first establishing an exhaust concentration by dividing the relevant source strength by the exhaust flow rate in cases where exhaust concentration or required dilutions are not published. Required dilutions are then calculated by dividing the exhaust concentration calculated by the acceptable concentration criterion. The dilutions calculated in the wind tunnel can then be consulted to determine a distance at which the required dilution can be achieved, with the caveat that intakes should not be located under a downward directed jet. Using this analysis we come to the following recommendations:

- For health concerns associated with cooking exhausts ($PM_{2.5}$ and NO_2 from gas stoves) and second hand smoke from neighboring MF units, a separation distance of five feet (corresponding to dilutions of 16 or more) is likely sufficient. Perhaps a shorter distance would suffice but five feet is the least distance at which measurements were made in the current study. We do not account for the large list of cooking odors that may be of concern. Data on the concentrations of constituent compounds that may be detectable or offensive for different populations, or equivalently their required dilution to prevent offense, is scarce. If this data is generated in the future it can be compared with wind tunnel results presented herein to establish a criterion.
- For smoking odors and concerns from fine particle exposure from smoke from general unit exhaust, data suggests a separation distance of 5 feet or less (2.2 dilutions) is likely sufficient to mitigate chronic health concerns. 24 dilutions, achievable with 7-12 feet of separation, is needed to minimize acute nasal and eye irritation of occupants to neighbors' exhaust but not render the smoke smell undetectable. A horizontal distance greater than 25 feet may be likely to prevent detection (149 dilutions required), which is not likely feasible in most MF buildings. We present this with the assumption that smoking odors will be one of the most offensive odors issuing from a unit exhaust, although there may be others. This also assumes that fine particles behave similarly to gases and are not affected considerably by gravity or diffusive forces as would be large or ultrafine particles, respectively.
- Through-wall furnace flues exhaust combustion products in quantities proportional the heating output of the furnace, among other variables. Designers should consult available references (e.g. (Traynor, Apte, & Chang, 1996)) to determine emissions factors for these devices, and compare them with acceptable limits to determine required dilutions. We include a representative example that assumes a 36 kBTU/h through-wall condensing furnace and a 30 cfm powered exhaust. For these narrowly circumscribed conditions, 182 required dilutions are calculated (corresponding to a vertical separation greater than 30 feet), which is likely quite difficult to achieve in practice. This is driven by the NO_2 criterion. Dilutions required for larger furnaces will scale linearly for the same exhaust flow rate. Other conditions will need to be verified individually.
- Finally, for bathroom exhaust, a recommended separation distance of approximately 5 feet was estimated based on the current work. This ensures 16 or greater dilutions, according to the wind tunnel data, which is within the range of required dilutions from the most offensive bathroom exhaust constituents analyzed. We recommend a dilution factor at the low range of possible dilution factors calculated here, since our calculations are based on concentration measurements from a pit latrine, and modern toilets will mask odors better than latrines. If more appropriate data is generated for modern toilets, a value in the middle or high end of the range of dilution factors should be chosen.
- In all cases, exhausts should not be directed toward intakes, even when placed at distances as great as 20 feet (6m) from the source.

Conclusions and recommendations

In summary, while reasonable separation distances for health-based contaminants and some odors may be achievable for through-wall multifamily vents, odors and combustion products from furnaces require separation distances that are impractical for the single case analyzed in this work, owing to dilutions required for NO_2 that are well beyond those measured in this work. Increasing horizontal separation is not an effective strategy to achieve greater dilution (up to 15 ft), while increasing vertical separation is a better dilution strategy, provided exhaust jets are not directed toward intakes that are vertically separated. We recommend that ASHRAE standards governing separation distances between through-wall exhausts and intakes on sides of buildings could be changed as follows:

- For bathroom exhaust: 5 feet
- For kitchen exhaust: 5 ft
- For dwelling ventilation exhaust: 10 ft (linear interpolation based on smoking irritation)

Furthermore, we find that the ASHRAE Standard 62.1 dilution model and the ASHRAE Handbook of Fundamentals dilution model are not appropriate for horizontally directed through-wall exhausts.

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