Study of the Impact of Operation Distance of Outdoor Portable Generators under Different Weather Conditions

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Abstract

The U.S. Centres for Disease Control and Prevention (CDC) has reported that up to half of non-fatal carbon monoxide (CO) poisoning incidents during the hurricane seasons in 2004 and 2005 involved generators operated outdoors but within seven feet of the home. Current guidance for safe operating distances of generators is often neither specific nor consistent. A study was conducted to examine the impact of generator distance on indoor CO exposure. The study was based on computer simulations of CO transport outdoors and subsequently into a generic two-story house. This paper presents the simulation results when using an indoor air quality model coupled with a computational fluid dynamics (CFD) model to predict CO concentrations near and within the home. FDS was validated against the measured contaminant dispersion data in a wind tunnel. A parametric study was then conducted for the two-story house to consider the effects on indoor CO levels of generator location, distance, exhaust temperature and speed, and weather conditions. It was found that in most cases, to reduce CO levels for the conditions modelled, it was more effective to point the generator exhaust away from the house and position the generator at a distance of more than 4.6 m.

Keywords

Carbon monoxide; Computational fluid dynamics; Generator emission; Indoor air quality; Multizone airflow model

Introduction

Gasoline-powered portable electric generators are widely used to provide heat and power in U.S. households during power outages, especially during hurricane seasons. During Hurricane Isabel in 2003, portable generators were reported to be sold out in the Washington, DC metropolitan area [1]. As a product of gasoline combustion, carbon monoxide (CO) from generator exhaust can be a significant safety and health issue. Users often place generators near or in their homes based on concerns about generator theft and noise to neighbours [2]. Improper generator location, including placement inside homes, was found to be the primary cause of over 80% of CO poisonings in Texas after Hurricane Ike in 2008 [3], and eight out of ten CO poisoning deaths after a severe ice storm on January 26-27, 2009 in Kentucky [4]. An in-depth investigation by the U.S. Consumer Product Safety Commission of incidents from 1990 to 2004 showed that five out of 104 deaths caused by generator CO poisoning in cases where detailed information was available on generator venting were associated with a generator that was placed outside the home near an open window, door, or vent [5]. The U.S. Centres for Disease Control and Prevention (CDC) has reported that 34% of non-fatal CO poisoning incidents after hurricanes in Florida in 2004, and 50% during Hurricanes Katrina and Rita in 2005, involved generators operated outdoors but within 2.1 m (7 feet) of the home [6]. For a generator operated outside, the power cord often needs to go through a slightly open, unlocked door or window, which increases the chances of CO entry to the inside if the generator is placed too close to a house. However, the guidance for the safe operating distance of a generator is often neither specific nor consistent. Some guidance mentions that a generator should have “three to four feet of clear space on all sides and above it to ensure adequate ventilation” [7, 8], whereas others recommend that a generator not be used “within 10 feet (3.05 metres) of windows, doors or other air intakes” [9]. While these guidelines suggest keeping a generator at a certain distance from a house, some generator manufacturers recommend in their instruction manuals that power cords be “as short as possible, preferably less than 15 feet (4.57 metres) long, to prevent voltage drop and possible overheating of wires” [2]. The use of short extension cords may result in placement of the generator such that a significant amount of CO enters the home.

Many studies have been conducted on outdoor contaminant dispersion either by experiments [10-12] or numerical simulations [13-15], but few have been done on the dispersion of CO emitted from generators, near or inside a house. National Institute of Standards and Technology (NIST) conducted a study for the U.S. Centre for Disease Control and Prevention (CDC) to examine the impact of placement of gasoline-powered portable electric generators on indoor CO exposure in homes. The study was based on computer simulations of CO transport outdoors and subsequently within the building and included two phases. The two phases of the study involved multiple simulations of portable generator operation outdoors for a one-storey manufactured house and a two-storey house respectively. In the first phase [16, 17], a CFD model, CFD0 [18], which is integrated with the CONTAM indoor air quality model [19], was used to model the outdoor CO dispersion around the manufactured house. The study was limited to the isothermal simulations, in which the generator exhaust temperatures and velocities were neglected due to the limitations of CFD0 for modelling outdoor airflows. It was found that for the house modelled, a generator positioned 4.6 m (15 feet) away from open windows may not be far enough to limit CO entry into the house. It was also found that wind perpendicular to the open window surface resulted in more CO infiltration than wind at an angle, and lower wind speed generally led to more CO entry. To reduce CO entry, the generator should ideally be positioned outside the airflow recirculation region near the building.

This paper presents the results of the second phase of the study [16]. One of the purposes of the second study is to consider the generator exhaust conditions, i.e. temperatures and velocities, which may significantly affect outdoor CO dispersion. A generic two-storey house was also modelled by a series of numerical simulations to confirm the findings of the previous phase. Transient indoor CO profiles were predicted using CONTAM. Fire Dynamics Simulator (FDS) [20] was selected to determine the outdoor CO profiles because of its strength of modelling outdoor airflows and the generator exhaust conditions FDS was originally developed for fire simulations. To evaluate whether it is suitable for this study, FDS was validated against measured tracer gas dispersion data from a wind tunnel study. The model was then employed to simulate a matrix of scenarios to consider multiple factors contributing to the CO entry, including human-controllable factors (e.g., generator location and generator exhaust direction) and non-controllable factors (e.g., wind speed and direction, generator exhaust speed and temperature).

Problem

Figure 1 shows a schematic of airflow streamlines near a two-storey house and potential factors affecting house CO entry when a generator is placed upwind of a house. The rate of CO entry into the house is related to the CO concentration near openings in the façade and the amount of air infiltration into the house at these openings. Multiple factors affecting the outdoor CO concentration include the generator placement distance (GD) from the house, the exhaust direction (PD), temperature and speed of the generator exhaust, the generator being positioned either upwind (UW) or downwind (DW) of the house, wind speed (WS) and wind direction (WD). The purpose of this study is to predict the CO levels at the house envelope and inside the house using a parametric study of the contributing factors for indoor CO penetration. The study involves the simulation of outdoor CO dispersion by a CFD model, FDS, and indoor CO levels by CONTAM.

CONTAM is a multizone network computer model, developed at the Engineering Laboratory at National Institute of Standards and Technology (NIST) and used for about 25 years for studies of airflow, contaminant transport and smoke management in buildings. It has been well validated by many previous studies for indoor airflow analysis [21-24]. FDS is a large eddy simulation (LES) CFD model for low-speed and thermally-driven airflows, including smoke and heat transport from fires [20]. Since this paper focuses on the impact of outdoor contaminant distribution on indoor levels by integrating CONTAM and FDS, the fundamental theories and numerical models can be found from the user manuals [19, 25] and are therefore not repeated here. FDS has been used for modelling atmospheric dispersions of smoke plumes and gases [26-28] and has been applied to study indoor airflow [29]. FDS was found to predict well the maximum downwind concentration but to over-predict the concentration for unstable wind conditions. To check its suitability in the current study, a validation of FDS was conducted as discussed in the next section. The validation study also helps us to obtain the experience of setting up boundary conditions, mesh sensitivity studies and analysis of output data when applying FDS to the current study.

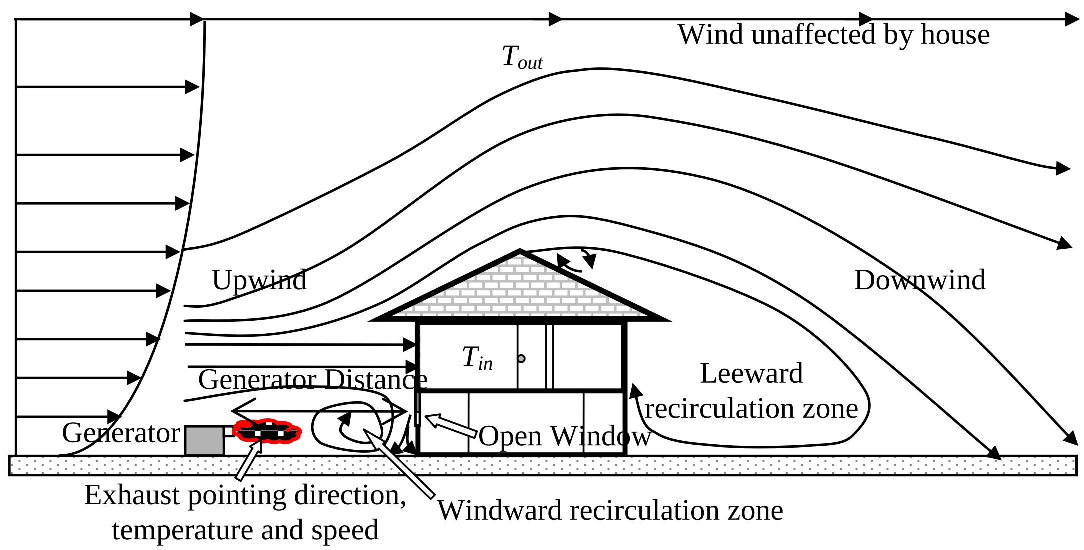

Figure 1. Schematic of airflow streamlines and factors affecting house CO entry when a generator is placed upwind of a two-story house and the exhaust is pointed towards the house.

Validation

Huber et al. [30] conducted a wind tunnel study of tracer gas dispersion around a rectangular-shaped building with its length equal to twice its height and width. The test data have been used for validating numerical simulations in various studies [31-33]. This study therefore used these test data for validating FDS. Table 1 shows the input parameters and boundary conditions used in this study.

For the validation, the predicted non-dimensional concentration by FDS is compared to the measured data. Here, the non-dimensional concentration, K, is defined by

$$K = \frac{C u_0 H_b^2}{Q} \tag{1}$$

Where C is the tracer gas concentration in kg/kg (tracer/air); u_0 is the measured velocity in m/s at the reference height, z_0, which is $1.5H_b$; H_b is the height of the building block in m, and Q is the volumetric emission rate of the tracer source in m^3/s.

The total simulation time is 20 seconds, which gives about 180 large eddy turnover times. Here, the turnover time is defined by $t = H_b/u_0$. The non-dimensional concentration is then averaged over the last 10 seconds (90 large eddy turnover times). The sensitivity of the time period for averaging was also checked for a total simulation time of 40 seconds (360 turnover times) with the last 10 seconds for averaging, which produces similar results of K. Therefore, all simulations were conducted for a total time of 20 seconds with the last 10 seconds employed for obtaining the time-averaged non-dimensional concentrations.

Table 1. Input parameters and boundary conditions for the simulations of tracer gas dispersion around a building block in a wind tunnel.

<table>
<tr><td>Rectangular building block size</td><td colspan="2">L_b (m) × W_b (m) × H_b (m)</td><td colspan="2">0.5 × 0.25 × 0.25</td></tr>
<tr><td>CFD domain size</td><td colspan="2">L (m) × W (m) × H (m)</td><td colspan="2">4.5 × 2.88 × 1.44</td></tr>
<tr><td rowspan="2">Grids for grid-independent studies</td><td rowspan="2">Total grids (million)</td><td>2.3</td><td rowspan="2">Minimum grid size (cm)</td><td>1.5</td></tr>
<tr><td>3.3</td><td>1.3</td></tr>
<tr><td rowspan="3">Boundary conditions</td><td colspan="2">Inflow surface</td><td colspan="2">Prescribed wind profile</td></tr>
<tr><td colspan="2">The ground surface</td><td colspan="2">Smooth</td></tr>
<tr><td colspan="2">Other surfaces</td><td colspan="2">Free flows</td></tr>
<tr><td>Wind profile</td><td colspan="4">$u = u_0(z/z_0)^p$, where $z_0 = 1.5H_b$ m,
$p = 1/6$, $u_0 = 2.35$ m/s</td></tr>
</table>

Two cases with different locations of the tracer source were simulated as shown in Figures 2 and 3. Figure 2(a) and 2(b) show the lateral and vertical concentration distributions, respectively, at the centre line of the building block, for which the source is located at the leeward corner of the building. Figure 3(a) and 3(b) provides the results when the source is at the height of $1.2H_b$ from the ground.

A grid sensitivity study was conducted by using two grid resolutions, 2.3 and 3.3 million for the case of the ground tracer source. Figure 2(a) shows that when the grid is refined from 2.3 to 3.3 million, both results are reasonably close to the experimental data. Each simulation took at least 28 hours on three nodes of 2.2 GHz 64-bit processors in a computer cluster. Thus, to save computational time, the grid of 2.3 million is used for all simulations in the validation studies. Note that Figure 2(b) does not show the results for the case of 3.3 million grids for clarity.

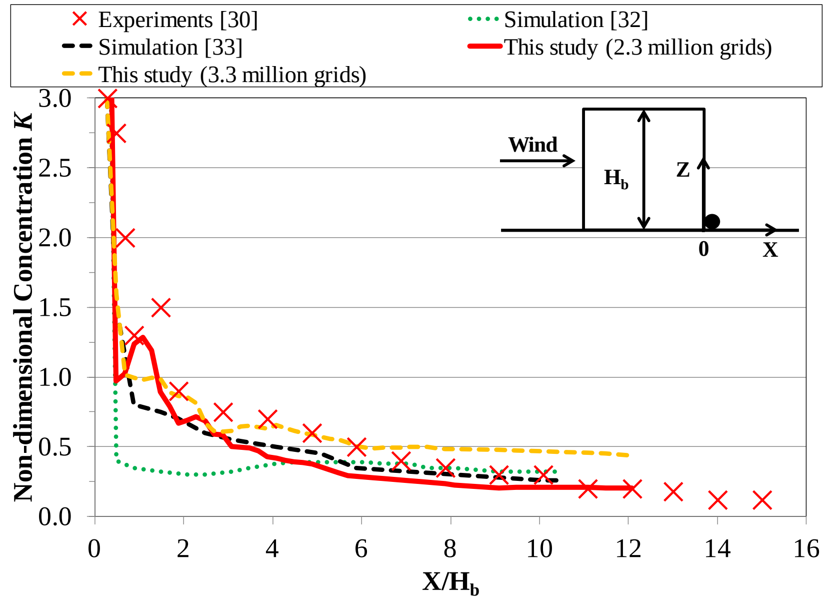

Figure 2(a)

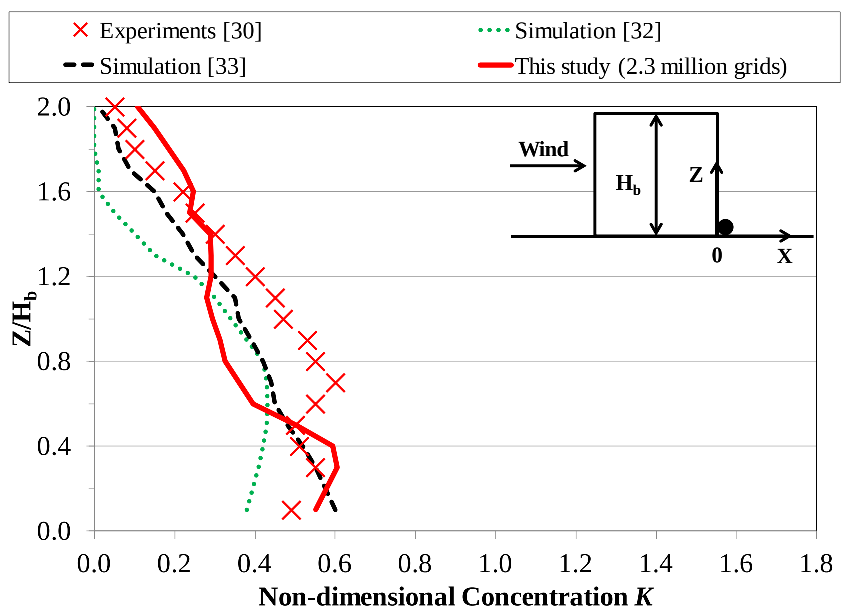

Figure 2(b)

Figure 2. (a) Non-dimensional concentrations in the lateral direction at Z/H_b = 0 and (b) in the vertical direction along the centre line at X/H_b = 3, when the tracer source is located at the ground corner of the building.

Figure 2 shows that the predictions by FDS are closer to the measured data for the lower and upper sections than the middle sections ($1 < X/H_b < 4$ and $0.4 < Z/H_b < 1.2$) for the ground tracer source. To provide further comparison, the numerical simulation results from two previous studies [32, 33] on the same case are included. Neither study provides good estimates for the middle section.

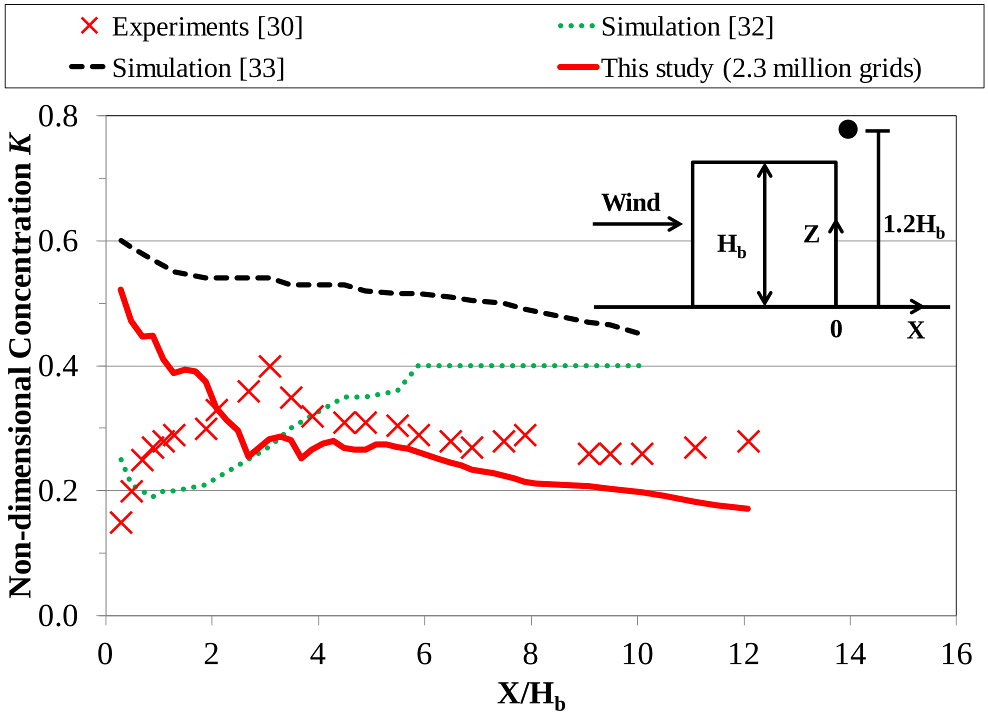

Figure 3(a)

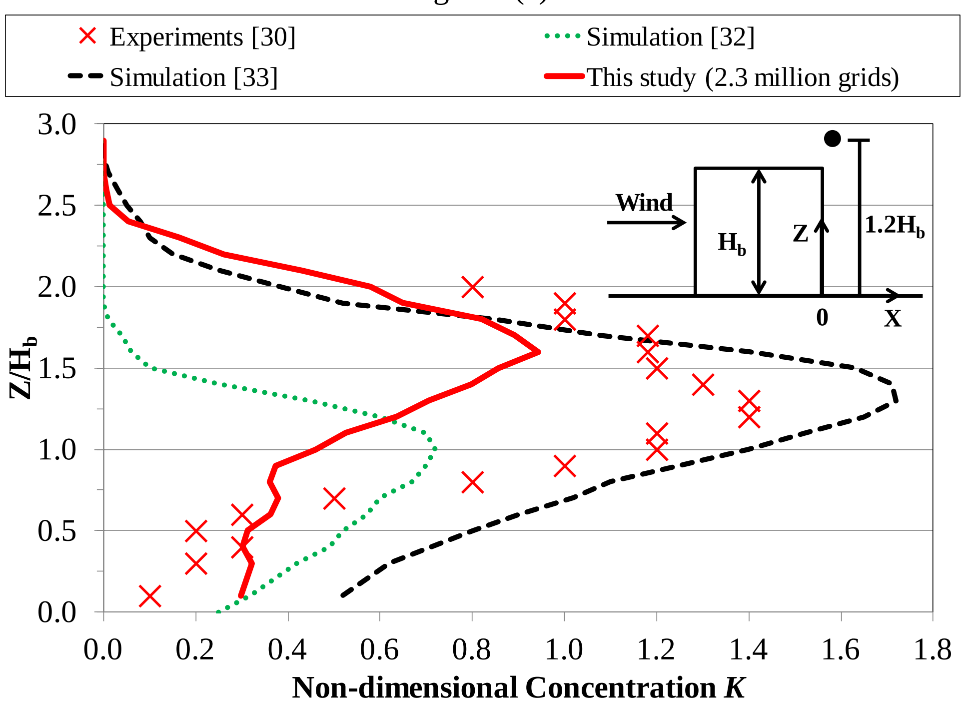

Figure 3(b)

Figure 3. (a) Non-dimensional concentrations in the lateral direction at Z/H_b = 0 and (b) in the vertical direction along the centre line at X/H_b = 3, when the tracer source is located at the 1.2H_b above the ground.

When the tracer source is located above the ground as shown in Figure 3, the prediction is poor near the leeward corner of the building ($0 < X/H_b < 2$ in Figure 3(a)). The simulation by Li and Stathopoulos [32] provides better prediction for this region while overestimating the concentration for $X/H_b > 6$. For the vertical concentration distribution in Figure 3(b), the study of Selvam (1997) seemed to predict the general trend well but it overestimated the lateral distribution as illustrated in Figure 3(a). Therefore, none of the simulations provide results that are consistently close to the measured data. Blocken and Stathopoulos [30] have tried to improve the simulation results on the same data set by using different Schmidt number for the outdoor dispersion model, and concluded that it is still challenging for CFD to model air pollutant dispersion around buildings [34]. The improvement of FDS simulation is beyond the scope of this paper.

Method

The first phase of the study used CFD0.

FDS and CFD0 are two CFD programs that differ in several respects. CFD0 solves Reynolds-Averaged Navier-Stokes (RANS) equations with an indoor air zero-equation model [35], whereas FDS solves spatially-filtered unsteady Navier-Stokes equations. FDS is capable of resolving large scale eddies while grid-unresolved eddies are destroyed, which is why it is referred to as large eddy simulation (LES). RANS models focus on time-averaging flow features and their interactions with turbulence effects (time-wise turbulence fluctuations), for which a single turbulence model is used for each turbulence scale. RANS models have a lower computational cost than LES models, but they are not as good as LES at capturing time-dependent anisotropic large eddies, which are often seen in outdoor simulations. As a RANS program, CFD0 has limited capabilities for non-isothermal outdoor airflows.

In this study, FDS was therefore used to simulate the external airflow and CO dispersion around a house, which was then provided for each opening in the house envelope as inputs for the CONTAM indoor simulations.

There is no information provided back from CONTAM to FDS so this method is a “one-way coupling” procedure. It is believed that the one-way coupling method is appropriate when the opening area of a building is less than 20% of the façade area [36]. The opening area in this study is far less than the total façade area so the one-way coupling of FDS and CONTAM is appropriate. Another method of coupling is the “two-way coupling”, where two simulation models, e.g. a CFD model and a multizone model, exchange information to each other. Interested readers can refer to the study of one of the co-authors on the “two-way coupling” [35].
The house modelled was based on a two-storey house defined as one of the prototype houses in a collection of house models developed by NIST to represent the housing stock of the United States (house model DH-10 of Persily et al. [37]). Due to the page limit, detailed leakage characteristics of the house are not provided here but can be found from the mentioned report. The house includes two bedrooms on the second floor, another two

bedrooms in the basement (not shown), and a living room, a dining room , a kitchen , and an attached garage on the first floor as shown in Figure 4(b). The basement has the same layout as the second floor thus it is not shown in the figure. The open window was located in the middle of the wall adjacent to the outdoor generator. The rest of the windows and doors of the house surface were closed but did have some air leakage. The air conditioning system of the house was assumed not to be operating, so air and CO infiltration was driven by only wind and buoyancy effects.

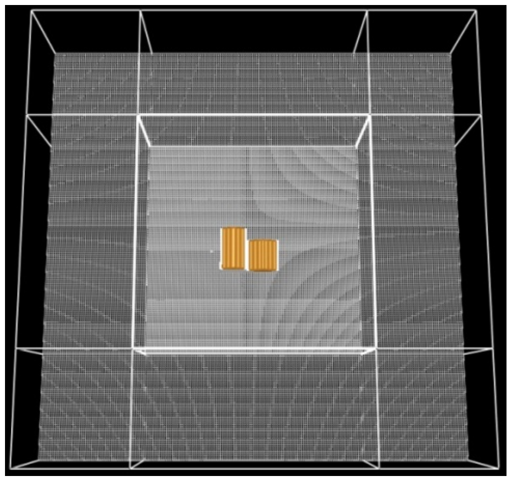

Figure 4(a)

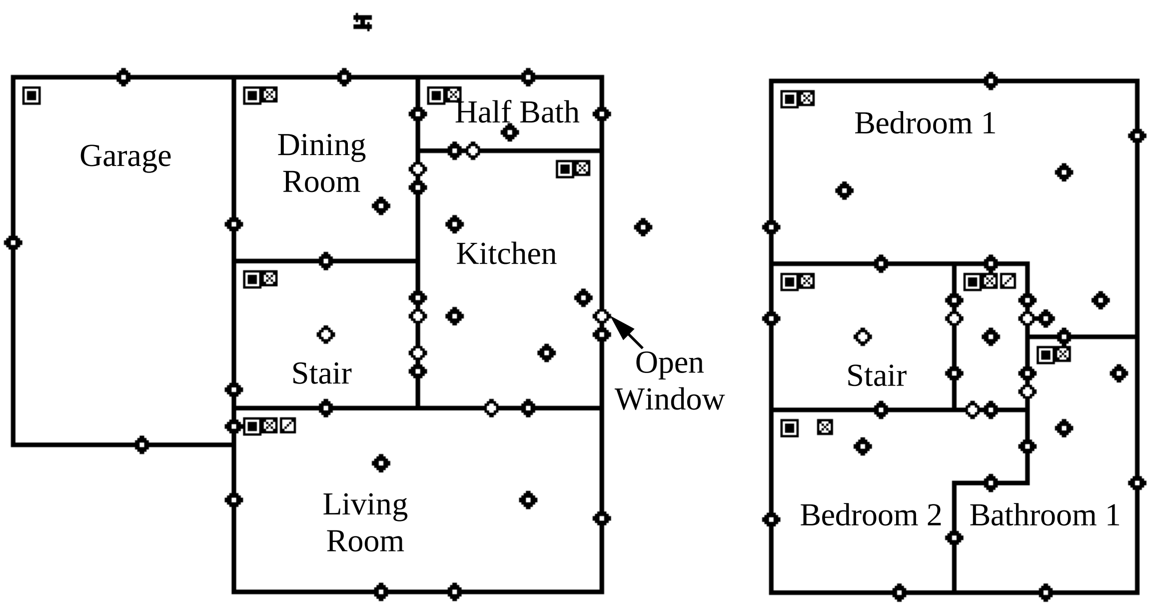

Figure 4(b)

Figure 4. (a) The two-storey house modelled in FDS and (b) in CONTAM.

Table 2. Constant parameters of the simulations.

House and Garage	House dimensions, L (m) × W (m) × H (m)	9.76 × 6.22 × 6.1
	Garage dimensions, L (m) × W (m) × H (m)	7.32 × 7.32 × 3.86
	Size of the open window (m^2)	0.31
	Indoor temperature, T_{in} (˚C)	20.9
Generator	Dimensions, L (m) × W (m) × H (m)	0.75 × 0.5 × 0.5
	CO generation rate (kg/h)	1.0
	Exhaust temperature (˚C)	288.0
	Exhaust speed (m/s)	7.0
	Total running time modelled (h)	8
Environment	Outdoor temperature, T_{out} (˚C)	20.9
	Wind profile (m/s)	$u = u_0 (z / z_0)^p$, where z_0 = 10.0 m, p = 0.14, u_0 = 1, 5, or 10 m/s

Table 2 provides the input parameters for the simulations. The size of the open window and the indoor and outdoor temperatures were considered constant in this study. The open window size was 0.31 m^2, which corresponded to a window crack of 0.3 m (H) × 1 m (W). Other constant parameters, e.g. the wind profiles and the dimensions of the house, are also given in Table 2. A wind profile for "open terrain" [38] was used. Measurements of a 6.5 kW generator yielded an average exhaust temperature of 288°C and an exhaust velocity of about 7.0 m/s [39].

For each FDS simulation, the mesh with a total grid number of around 3.3 million was divided into nine sub-meshes, each of which was simulated by one node in a computer cluster. The computational time for each run was often above 113 hours. Because FDS is a LES CFD code, transient simulations of 200 seconds for a wind speed of 5 m/s and 1000 seconds for 1 m/s were studied. In this way, the incoming wind sweeps across a distance of 96.8 m, five times the distance from the entry to the exit planes of the house, to allow the full turbulence structures to be established in the calculation domain. Because the indoor simulation spanned a time period of eight hours, whereas the outdoor FDS simulations only calculated for 200 s or 1000 s, the last 100 s CO levels were averaged over time to provide a time-averaged CO outdoor level as input to the eight-hour indoor simulations. The indoor CONTAM simulation was selected to be eight hours, which is a reasonable runtime for a generator [40], with a transient simulation time step of 10 seconds.

Table 3. Simulation parameter matrix.

Case	Human-controllable Factors								Environmental Factors		
	Pointing Direction		Generator Distance (m)				Upwind/Downwind		Wind Speed (m/s)		
	Towards[a]	**Away**[b]	**1.8**	**4.6**	**9.1**	**10.7**	**Upwind**	**Downwind**	**1**	**5**	**10**
1	X		X				X		X		
2	X			X			X		X		
3	X				X		X		X		
4	X					X	X		X		
5	X		X				X			X	
6	X			X			X			X	
7	X				X		X			X	
8	X					X	X			X	
9	X		X				X				X
10	X			X			X				X
11	X				X		X				X
12	X					X	X				X
13	X		X					X	X		
14	X			X				X	X		
15	X				X			X	X		
16	X					X		X	X		
17	X		X					X		X	
18	X			X				X		X	
19	X				X			X		X	
20	X					X		X		X	
21	X		X					X			X
22	X			X				X			X
23	X				X			X			X
24	X					X		X			X
25		X	X				X		X		
26		X		X			X		X		
27		X			X		X		X		
28		X				X	X		X		
29		X	X				X			X	
30		X		X			X			X	
31		X			X		X			X	
32		X				X	X			X	
33		X	X				X				X
34		X		X			X				X
35		X			X		X				X
36		X				X	X				X
37		X	X					X	X		
38		X		X				X	X		
39		X			X			X	X		
40		X				X		X	X		
41		X	X					X		X	
42		X		X				X		X	
43		X			X			X		X	
44		X				X		X		X	
45		X	X					X			X
46		X		X				X			X
47		X			X			X			X
48		X				X		X			X

a: generator exhaust pointing towards the window; b: generator exhaust pointing away from the window.

Results and Discussions

The comparison of CFD0 and FDS for the outdoor CO dispersion was conducted for the isothermal conditions, in which the temperature and speed of the generator exhaust were neglected. It was found that some discrepancies were observed in the regions of turbulence detachment and recirculation flows. However, generally both programs predicted similar levels of CO and sizes of the contaminated region. Since isothermal simulations are not the focus of the second phase, they are not included in this paper but can be found from the report of the second phase [41].

This section will focus on the FDS results considering the generator exhaust conditions. Figures 5 and 6 compare the predicted CO levels for the vertical plane located at the middle length of the house (where the open window is located) with the generator exhaust pointed towards and away from the house, respectively. The wind speed is indicated by the arrow, and the generator distance and wind speed are reported in the brackets following the simulation case number in Table 3.

The results lead to several observations:

- The combined effects of the exhaust jet inertia and buoyancy directed the CO upwards at an angle to the ground.
- With the exhaust pointing towards the house (Figure 5):
    - For low wind speed, the buoyancy effect of the jet tends to lift the CO plume above the house. For greater generator distances from the house, the CO concentration near the house was lowered (S1 through S4). The increase in the wind speed may have helped to dilute the CO, but could also drive the CO plume down around the house as illustrated by S5 through S8. However, when the wind speed was high enough, as in S9 through S12, the CO would be effectively become more diluted.
    - When the generator was located upwind of the house, generator positions further away from the house may allow enough space for the CO jet to develop better. When the generator was located too close to the house, the jet may impact the house wall such that CO would be dispersed horizontally along the wall more easily than vertically by the buoyancy. S5 through S12 show that the vertical distribution of CO levels would increase with the generator distance.
    - When the generator was located downwind of the house (S13 through S24), a distance of 10.7 m may not be enough to avoid high CO levels at some locations near the house for some cases. Apparently, the exhaust jet affects the formation of the leeward recirculation zone unfavourably so a greater generator operating distance may be required than 10.7 m. Moreover, when the wind speed was increased from 1 m/s to 5 m/s, more CO would be entrained back towards the house for the same generator distance. However, these wind speed effects are limited for higher speeds, such as 10 m/s (S21 through S24), when the dilution effect of the wind dominates.

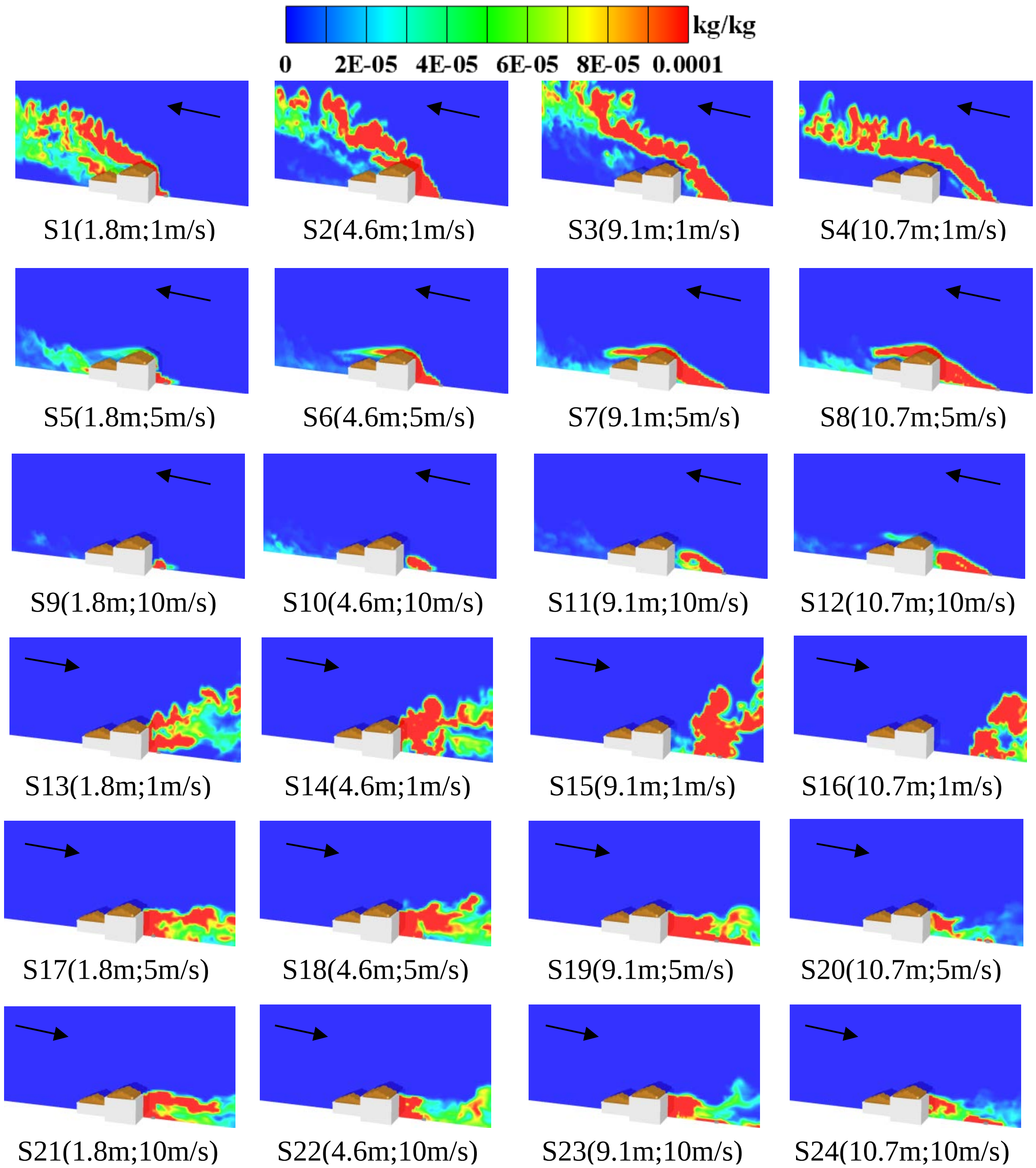

Figure 5. Comparison of CO levels at the middle lengthwise plane of the house for different generator distance, location, wind direction and speed when the generator exhaust pointed towards the house (for CO in air, 1.0 kg/kg ≈ 1.2 × 10^6 mg/m^3 at 20.9°C and 101.325 kPa).

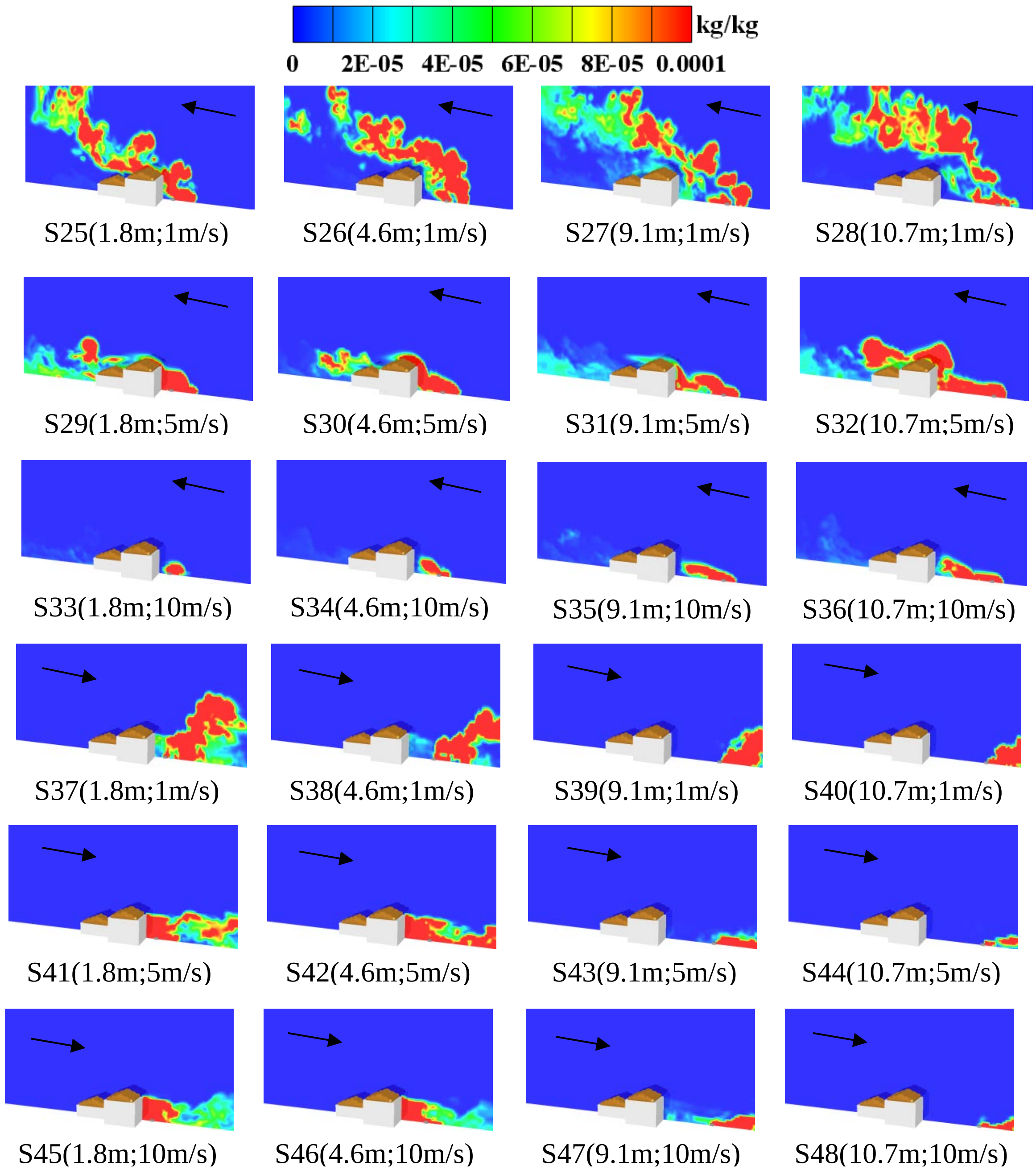

Figure 6. Comparison of CO levels at the middle lengthwise plane of the house for different generator distance, location, wind direction and speed when the generator exhaust pointed away from the house.

- For the generator exhaust pointing away from the house (Figure 6),
    - Generally, the CO levels near the house were lower than when the generator exhaust was pointing towards the house. Such effects would be more apparent for lower wind speeds when the generator is located upwind of the house (S25 through S28) and for all cases with the generator downwind (S37 through S48).
    - When the generator was located upwind of the house, the wind would push the CO plume down close to the house for a wind speed of 5 m/s (S29 through S32) or dilute CO more effectively for a wind speed of 10 m/s (S33 through S36), which would be similar to the trends seen for the upwind location with the exhaust pointing towards the house.
    - When the generator was placed downwind of the house (S37 through S48), a distance of 9.1 m was sufficient to avoid CO being entrained backwards near the house for wind speeds of 1 m/s through 10 m/s.

Figures 7(a) and 7(b) illustrate the CO levels averaged over time for all the windows and doors on the house envelope for the exhaust pointing towards and away from the house, respectively. As shown in Figure 7(a), the CO levels at the house window, door, and other leaks decrease significantly with greater distance of the generator when the exhaust was pointing towards the house. When the generator was placed at 1.8 m, the higher wind speed would dilute CO more effectively. A wind speed of 5 m/s, however, would increase CO levels on the house envelope due to the “push-down” effects of the wind on the CO jet as discussed previously. The “push-down” effects could be counteracted by a wind speed of 10 m/s, which is consistent with the previous observations regarding Figure 5.

Figure 7(b) shows that when the exhaust is pointed away from the house, the maximum average CO at the house envelope would be only 156 mg/m^3 (S41), which is 17% of the maximum value (S13) shown in Figure 7(a). In most cases (S27, S35, S39, S43, and S47), where the generator was placed at 9.1 m, the CO level was less than 24 mg/m^3, which would be only 3% of the maximum value for S13. These results show that a distance of 9.1 m could help to reduce CO levels at the house envelope significantly. However, S31 was an exception, which has a CO level even higher than for a generator distance of 4.6 m (S30). This may be explained by the combined effects of the wind “push-down” effect and the generator distance: a distance of 9.1 m would help CO to flow well around the house before being diluted by the wind. Note also that among all 48 cases, the CO level near the house was generally higher when the generator was located downwind of the house rather than upwind.

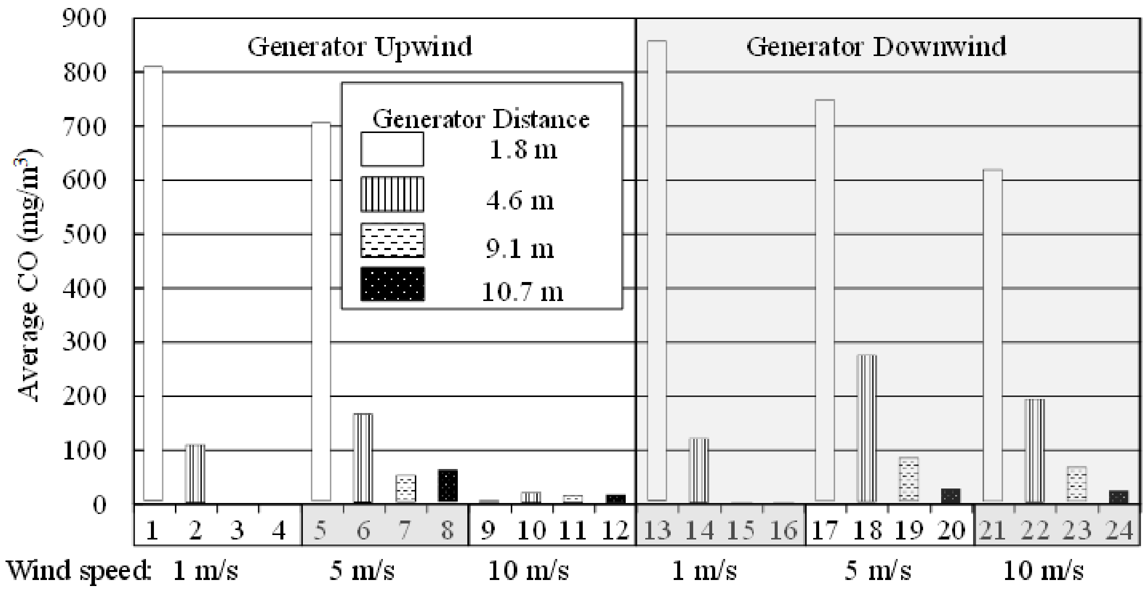

Figure 7(a)

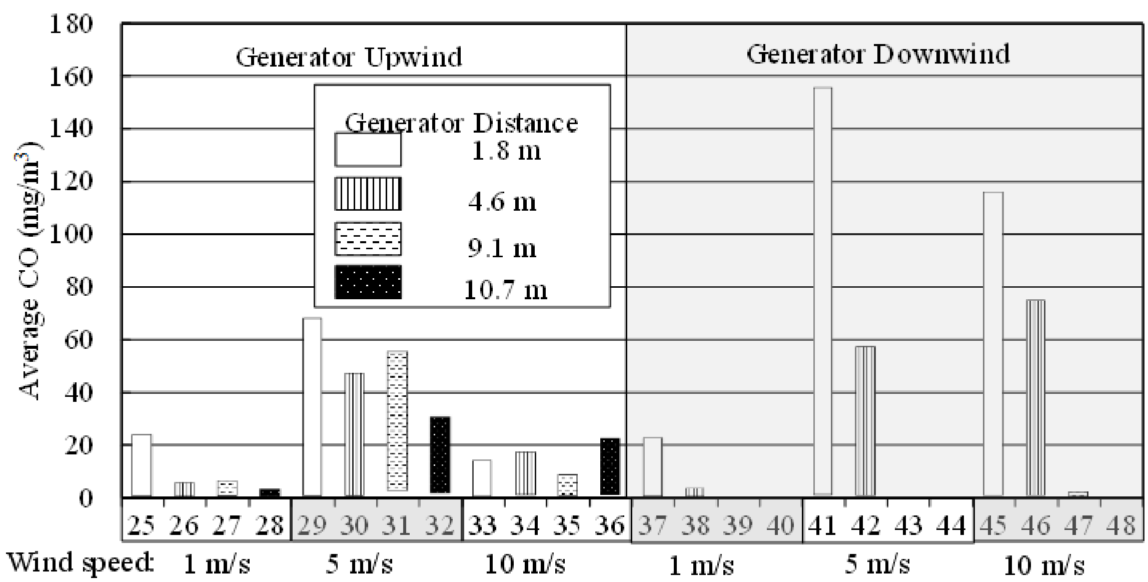

Figure 7(b)

Figure 7. Comparison of time-average CO levels for all windows, doors and other leaks at the house envelope. (a) When the generator exhaust was pointing towards the house; and (b) when the generator exhaust was pointing away from the house.

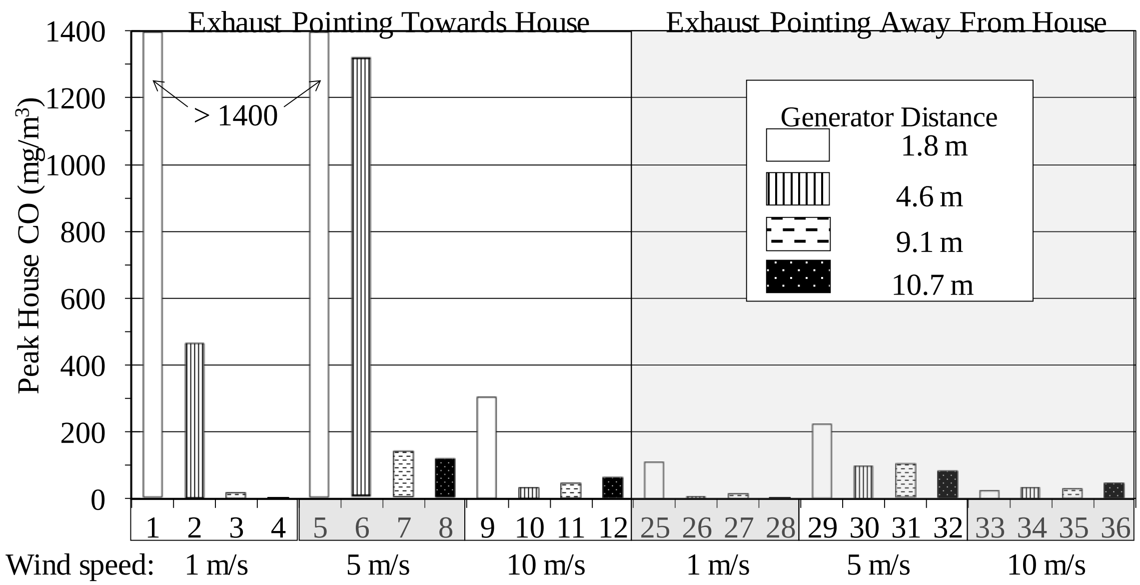

Figure 8. Maximum indoor CO in the house when the generator was operating upwind of the house for 8 hours under zero indoor and outdoor temperature difference.

To study how much CO enters the house, Figure 8 compares the peak CO levels in any room of the whole house predicted by CONTAM when the generator operated for eight hours and the indoor and outdoor temperature difference was zero. Note that the CO threshold limit value (TLV) for an eight-hour exposure is 25 ppm(v) (29 mg/m^3) as promulgated by the American Conference of Governmental Industrial Hygienists [42]. The immediately dangerous to life or health (IDLH) level, which is based on the effects that might occur as a consequence of a 30-minute exposure, is 1200 ppm(v) (1,380 mg/m^3) for CO [43]. In the first phase of the study [16], we used both the house peak value and a calculated percentage of carboxyhemoglobin (%COHb) level to predict personal exposure. The house peak value was found to be consistent with the %COHb results so we used the peak value in this paper. It is noted that when the generator was placed downwind of the house, the predicted CO levels in the house were minimal. These lower CO levels occurred because the predicted airflow direction at the open window (Figure 4(b)) was from the house to the outdoors, so the outdoor CO was not carried into the house. Therefore, Figure 8 shows only the cases for the generator located upwind of the house.

It is found that pointing the generator exhaust away from the house can reduce indoor CO entry significantly. Even for a generator distance of 1.8 m, the indoor CO level can be reduced by 97 % when the exhaust is pointed away from the house (S29) compared to the case when it points towards the house (S5). Therefore, no matter whether the generator is upwind or downwind of the house or the wind speed, a generator exhaust pointing away from the house would always result in a lower CO level both outdoors and indoors.

It is also found that, when the exhaust is pointed away from the house, a generator distance of 9.1 m appears to result in low CO entry indoors. The indoor CO can be 17 mg/m^3 for the wind speed of 1 m/s in S27 and 31 mg/m^3 for 10 m/s in S35. It appears that a wind speed of 5 m/s is the worst case for the same generator distance (S31), where a maximum indoor CO level of 107 mg/m^3 is reached. Compared to 1 m/s or 10 m/s, the wind of 5 m/s is strong enough to push down the buoyancy-driven CO plume close to the house but not enough to dilute the CO outdoors. If the generator is placed further away to 10.7 m from the house, the resulting CO peak concentration was 84 mg/m^3 (S32). The combined effects of wind direction and speed, generator distance, exhaust temperature and exhaust velocity would make it hard to develop a simple correlation of indoor CO entry with these factors. However, the bottom line is, in most cases, to significantly reduce CO levels for the house and conditions modelled in this study, it would be helpful to point the generator exhaust away from the house and position the generator at a distance more than 4.6 m.

A few limitations to the interpretation of these results should be noted. The foregoing discussion of CONTAM simulation results focused on house CO peak values to compare different generator distance under various weather conditions. Detailed CO distributions in the house were not discussed because of the huge amount of data generated (eight-hour multi-room simulations with a time step of 10 seconds for all 48 cases), and it is beyond the scope of the paper. While this study considered a model of a typical house and a range of typical conditions, these conditions are not comprehensive in terms of generator performance, house features, or weather conditions. Factors that could lead to higher indoor concentrations include generators with higher CO emissions due, for example, to a larger electrical load or a poorly tuned engine, generator exhaust at a different temperature or velocity, and the opening of additional windows. Also, some physical effects are not included in this analysis such as variable wind direction and speed, impact of nearby terrain structures, and elevation differences between house and generator. Thus, any conclusions drawn from this study may not be applicable to every possible situation. Additionally, experimental work is necessary to further verify the conclusions of this study.

Conclusions

This study investigated CO dispersion from a generator and its entry into a generic two-storey house. In general, the results supported the conclusions of the previous phase study which found that a generator positioned 4.6 m (15 ft) away from open windows would not be far enough to limit CO entry into a modelled manufactured house [44]. This study further found that it would be advantageous to locate the generator further than 4.6 m from the two-storey house to avoid high indoor CO concentrations (the next closest location modelled was 9.1 m). When the generator was moved further to 10.7 m, CO levels for both the house envelope and inside the house would decrease but not significantly.

It was also found that pointing the generator exhaust away from the house would cause the maximum CO at the house envelope to be only 17% of that when the exhaust is pointing towards the house. With the exhaust pointing away, the peak indoor CO level can be reduced to 3% of the level with the exhaust pointing towards the house under the same wind speed. An exception was observed for a case with intermediate wind speed, where the indoor CO could reach 107 mg/m^3. This occurred for a wind speed of 5 m/s, which was strong enough to push down the CO plume near the house but not enough to dilute the CO as effectively as a wind of 10 m/s.

The combined effects of wind direction and speed, generator distance, exhaust temperature and speed could make it hard to develop a simple correlation of indoor CO entry with these factors. However, in most cases, to significantly reduce CO levels for the house and the conditions modelled in this study, it was helpful to point the generator exhaust away from the house and position the generator at a distance greater than 4.6 m. If the generator is located more than 4.6 m with the exhaust pointing away from the house, then there is additional benefit in avoiding placing it upwind of the house.

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