NIST Technical Note 1666

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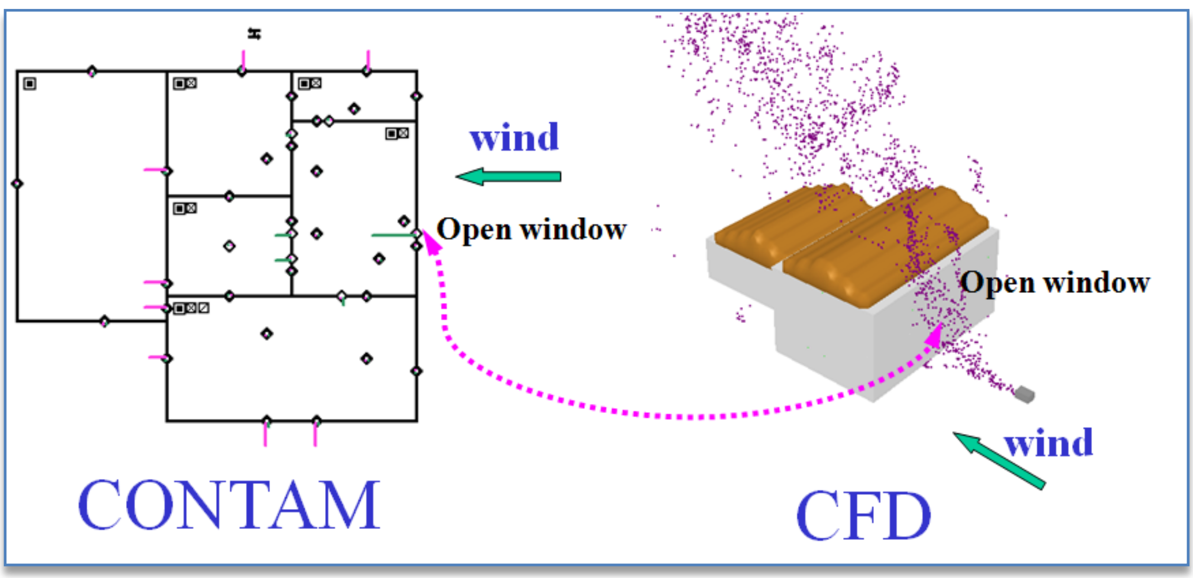

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Liangzhu (Leon) Wang
Steven J Emmerich
Ryan Powell
Building Environment Division
Building and Fire Research Laboratory

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Abstract

The U.S. Centers for Disease Control and Prevention (CDC) has reported that up to half of non-fatal CO poisoning incidents during the hurricane seasons in 2004 and 2005 involved generators operated outdoors but within seven feet of the home. The U.S. National Institute of Standards and Technology (NIST) conducted a study for CDC to examine the impact of distance of gasoline-powered portable electric generators on indoor CO exposure. The study was based on computer simulations of CO transport outdoors and subsequently within the building and included two phases. The two phases involved multiple simulations of portable generator operation outdoors for a one-story manufactured house and a two-story house.

This report presents the second phase of the study using the CONTAM indoor air quality model coupled with two computational fluid dynamics (CFD) models, CFD0 and NIST Fire Dynamics Simulator (FDS), to predict CO concentrations near and within a generic two-story home. In addition to the parameters considered in Phase I, i.e., weather conditions, generator location and distance, this study also considered the effects of the generator exhaust temperature and speed. While it was found that the exhaust temperature and speed may affect CO levels near the house significantly, in general, the results supported the conclusions of the first phase study. In this second phase, it was necessary to locate the generator further than 4.6 m (15 ft) from the two-story house to avoid high indoor CO concentrations. A distance of 9.1 m (30 ft) (the next closest distance modeled) generally resulted in low CO entry indoors, especially with the exhaust pointing away from the house which caused 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 maximum indoor CO level can be reduced to 3 % of the case with exhaust pointing towards the house under the same wind speed.

Therefore, in most cases, to reduce CO levels for the house and conditions modeled in this study, it was helpful to point the generator exhaust away from the house and position the generator at a distance of more than 4.6 m (15 ft). However, one exceptional case existed when the wind speed was 5 m/s, for which indoor CO could still reach 107 mg/m^3 because this wind speed was strong enough to push down the CO plume near the house but not enough to dilute the CO.

Keywords

Generator; carbon monoxide; CONTAM; computational fluid dynamics; exposure; indoor air quality; health; multizone airflow model; simulation

Nomenclature

A	Generator exhaust pointing away from the open window
B_L	Larger of upwind building face dimensions
B_S	Smaller of upwind building face dimensions
DW	Generator placed downwind to the open window
FR	Family room
GD	Generator placement distance from the open window
H	Height
KIT	Kitchen
L	Length
LV	Living room
p	Exponent for wind profile
PD	Generator exhaust pointing direction
S	Simulation
T	Temperature, ˚C
T_{in}	Inside air temperature, ˚C
T_{out}	Outside air temperature, ˚C
TWD	Generator exhaust pointing towards the open window
u	Wind velocity at height z, m/s
u_0	Wind velocity at reference height z_0, m/s
UW	Generator placed upwind to the open window
W	Width
WD	Wind direction clockwise relative to the north
WS	Wind speed, m/s
z	Height, m
z_0	Reference height, m

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 (CPSC 2003). 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 neighbors (CPSC 2006). When a generator is operated outside, the power cord often needs to go though a slightly open, unlocked door or window. 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 (Marcy and Ascone 2005). The U.S. Centers 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 ft) of the home (CDC 2006). 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" (OSHA 2005; FEMA 2006), whereas others recommend that a generator not be used "within 10 feet of windows, doors or other air intakes" (EPA 2005). 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 long, to prevent voltage drop and possible overheating of wires" (CPSC 2006). The use of short extension cords may result in placement of the generator such that a significant amount of CO enters the home.

The U.S. National Institute of Standards and Technology (NIST) conducted a study for the U.S. Center 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 involved multiple simulations of portable generator operation outdoors for a one-story manufactured house and a two-story house respectively. In the first phase (Wang and Emmerich 2009), it was found that for the house modeled, 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 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 report presents the results of the second phase of the study. A series of numerical simulations of the entry of CO from a generator exhaust into a two-story house was performed. A matrix of simulation scenarios was created 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). Using a method similar to that employed in the previous phase, transient indoor CO profiles were predicted using the CONTAM indoor air quality model (Walton and Dols 2008). The major change in the second phase is the use of the NIST Fire Dynamics Simulator (FDS) (McGrattan et al. 2010) to determine the outdoor CO profiles. FDS is a computational fluid dynamics (CFD) model, which was used to consider the generator exhaust temperature and speed. These parameters may affect outdoor CO dispersion near the house significantly and had to be neglected due to the limitations of CFD0 (Wang 2007), the program used in the previous phase. Because FDS and CFD0 use different turbulence models and numerical schemes, this study first compared the results of the two programs for several cases. FDS was then used only to simulate the matrix of cases with several values of generator distance under different weather conditions.

Problem and Method

Figure 1 shows a schematic of airflow streamlines near a two-story 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 level near openings in the facade and the amount of air infiltration into the house at these openings. Multiple factors affecting the outdoor CO level 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 direction (WD).

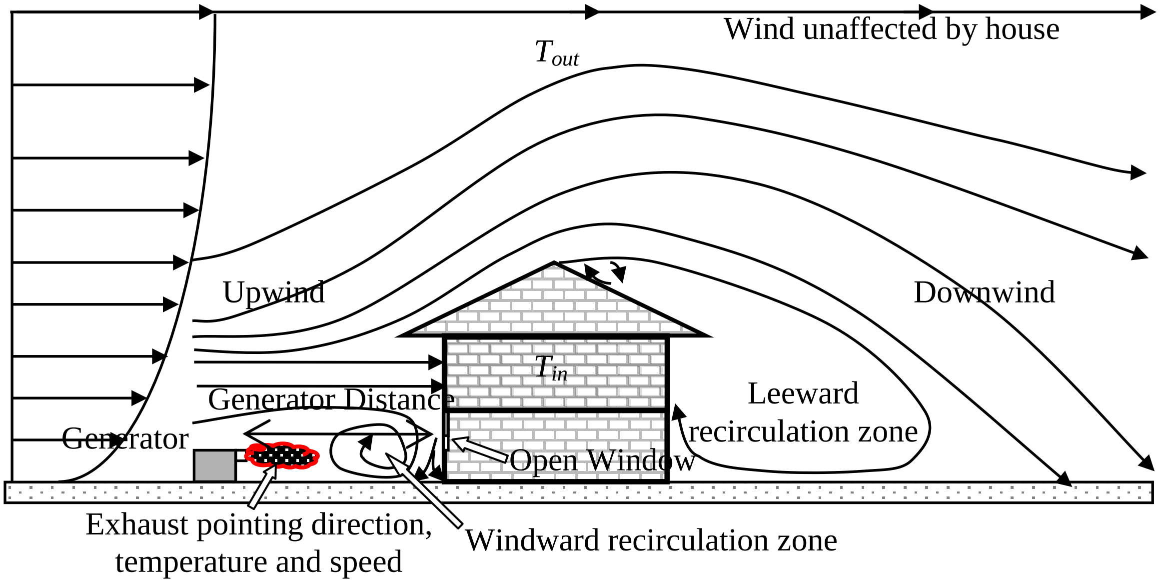


Figure 1. Schematic of airflow streamlines and factors affecting house CO entry when a generator is placed upwind of a two-story house.

The house modeled in this study was based on a two-story 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. 2006). The house includes two bedrooms, a living room (LV), a family room (FR), a kitchen (KIT), and an attached garage as shown in Figure 2(c). 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 wind and buoyancy effects if any.

Figure 2(a) The two-story house modeled in CFD0 (left) and FDS (right)

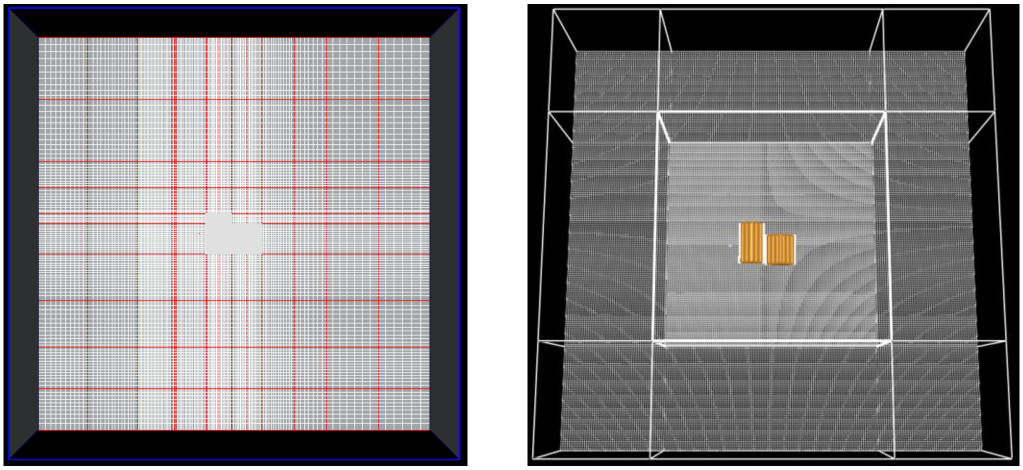


Figure 2(b) The mesh setups in CFD0 (left) and FDS (right)

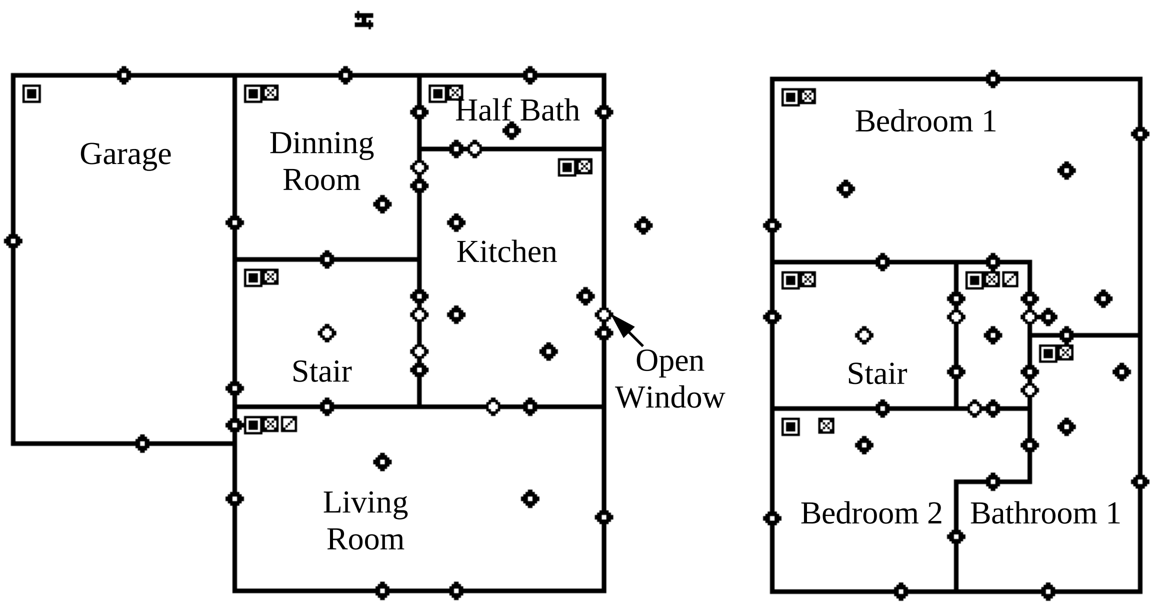


Figure 2(c). The house modeled in CONTAM.
Figure 2. The two-story house model.

Table 1 provides the input parameters for the simulations that do not vary among the cases. The size of the open window and the indoor and outdoor temperatures were considered constant in this study to reduce the total number of simulations. It is noted that the open window size was 0.31 m^2, which corresponded to a window crack of 12 in (H) × 39.4 in (W) (0.3 m × 1 m). Other constant parameters, e.g. the wind profiles and the dimensions of the house, are also given in Table 1. A wind profile for "open terrain" (ASHRAE 2005) is used, as it was in the previous phase . As discussed earlier, the generator exhaust temperature and speed were the new parameters considered in this phase. 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. Both of these parameters could impact the local dispersion of CO significantly, but were not considered in the previous phase due to the limitation of CFD0 to handle non-isothermal simulations. This report used FDS, a large eddy computational fluid dynamics program to include the non-isothermal effects from the generator exhaust.

Table 1. 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 modeled (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

The simulation parameters that varied include human-controllable factors and environmental (non-controllable) factors. A matrix of simulations was developed to consider the combined effects of these factors as illustrated in Table 2. The full combination of all the variables results in 48 simulations, i.e., 2 (PD) × 4 (GD) × 2 (UW/DW) × 3 (WS).

Table 2. Simulation parameter matrix.

S	**Human-controllable Factors**								**Environmental Factors**		
	PD		**GD, m (ft)**				**UW/DW**		**WS(m/s)**		
	TWD	**A**	**1.8(6)**	**4.6(15)**	**9.1(30)**	**10.7(35)**	**UW**	**DW**	**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

S: simulation; **PD**: pointing direction of generator exhaust; **GD**: generator distance from the open window; **UW/DW**: generator upwind/downwind to the open window; **WS**: wind speed; **TWD**: generator exhaust pointing towards the open window; **A**: generator exhaust pointing away from the open window

For numerical simulations using two different programs, it is important to compare the results of both programs modeling the same problem. The lack of experimental data in this study makes this inter-model comparison even more important. Therefore, the first step of the current study was to compare CFD0 and FDS for selected cases in Table 2.

CFD0 and FDS are two CFD programs that differ in several respects. CFD0 solves Reynolds-Averaged Navier-Stokes (RANS) equations with an indoor air zero-equation model (Wang 2007), 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. LES involves the interactions of resolved large scale turbulence eddies and unresolved small eddies (space-wise turbulence structures), for which turbulence effects are not averaged over time so an unsteady calculation is needed. 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.

Figure 2 compares the modeled house in CFD0 and FDS. The FDS mesh was divided into nine sub-meshes, each of which was simulated by one PC in a computer cluster whereas CFD0 used a single mesh for a single PC simulation. Table 3 summarizes the difference of CFD0 and FDS for the simulation of outdoor airflow and pollutant dispersions. FDS is better than CFD0 in simulating non-isothermal cases, such as the high temperature of the generator exhaust, but it needs a higher grid density and more computational cost even when running on a cluster of nine computers. 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 flow features to be established in the calculation domain.

Table 3. Comparison of CFD0 and FDS for the simulation capabilities and costs.

Items	CFD0	FDS
Isothermal simulation	Yes	No
Steady/Transient	Steady	Transient (200 s & 1000 s modeled)
Grids (million)	0.9	3.3
Computational cost (h)	6 on single PC	113 on each of nine PC’s

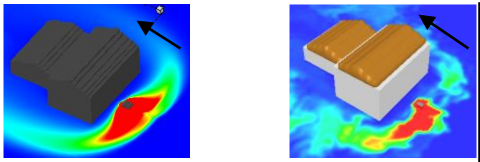
After comparing CFD0 and FDS for the isothermal simulations without considering generator exhaust temperature, FDS was used for all the cases in Table 2, which consider both generator exhaust temperature and speed. FDS was used to simulate the external airflow and CO dispersion around the house, and the calculated CO level of each time step at the house surface was saved in a database file. A separate program extracted the CO level from the database for each opening in the house surface as inputs for the indoor simulations by CONTAM. 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 CO levels in the database were averaged over time to provide a time-averaged CO outdoor level as input to the eight-hour indoor simulations.

Results and Discussions

This section presents the comparison of the results of CFD0 and FDS for the isothermal simulations, in which the generator exhaust temperature and speed were not considered. The results for all 48 cases in Table 2, using FDS for the outdoor simulations and CONTAM for the indoor calculations, are then reported.

Isothermal simulations by CFD0 and FDS

The comparison of CFD0 and FDS for the outdoor CO dispersion was conducted for selected cases under isothermal conditions, in which the temperature and speed of the generator exhaust were neglected. Figure 3 compares the CO levels near the house for different generator distances, wind directions (upwind or downwind of the open window) and wind speeds (as indicated by the arrows in the figure). Generally, both programs predicted similar levels of CO and sizes of the contaminated region. When the generator was located upwind of the open window, the predictions seem better than those when it was downwind. Some major discrepancies can be observed for Figures 3(g), 3(i), and 3(k), where the generator was downwind of the house. These differences may be explained by the different capabilities of RANS and LES models in the simulations of turbulence detachment and recirculation flows. Generally, LES performs better than RANS models for such type of flows. It is also noted that some general conclusions of the previous phase were verified by both programs. Lower wind speed often causes more CO to linger near the house. When the generator is located downwind, CO may be trapped in the recirculation zone behind the house, forming a highly contaminated region. One discrepancy was however found for the simulations in Figure 3(a), in which the region between the generator and the house had low CO levels, although the generator was located only 1.8 m away. In this case, the windward recirculation zone in front of the generator may limit the CO from spreading close to the house, so most of it flows sideways around the house. The formation of the windward recirculation zone may be affected when the generator exhaust speed and temperature are considered. This result shows the necessity of considering the effect of the generator exhaust on CO dispersions near the house, which is presented for the FDS simulations below.



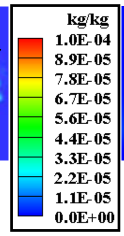


Figure 3(a) S1 (GD = 1.8 m; UW; WS = 1 m/s)

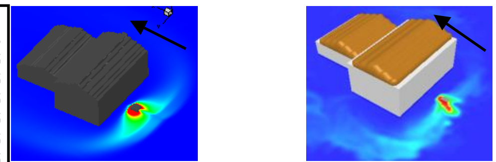


Figure 3(b) S5 (GD = 1.8 m; UW; WS = 5 m/s)

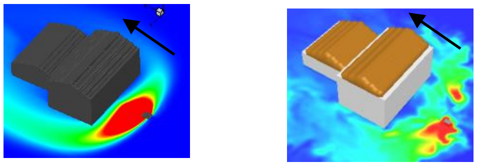


Figure 3(c) S2 (GD = 4.6 m; UW; WS = 1 m/s)

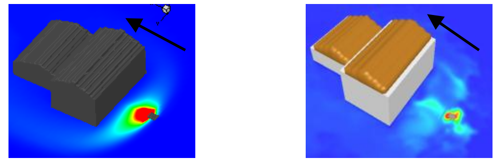


Figure 3(d) S6 (GD = 4.6 m; UW; WS = 5 m/s)

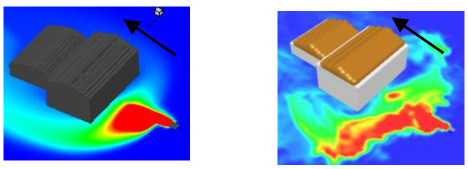


Figure 3(e) S3 (GD = 9.1 m; UW; WS = 1 m/s)

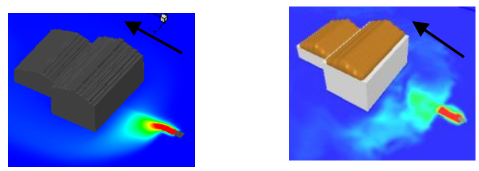


Figure 3(f) S7 (GD = 9.1 m; UW; WS = 5 m/s)

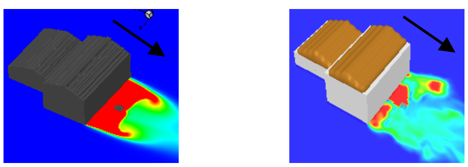


Figure 3(g) S13 (GD = 1.8 m; DW; WS = 1 m/s)

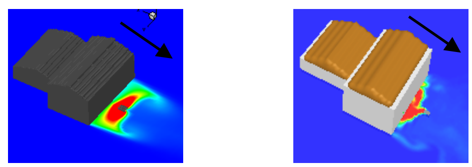


Figure 3(h) S17 (GD = 1.8 m; DW; WS = 5 m/s)

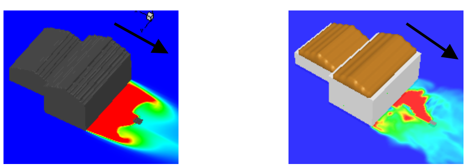


Figure 3(i) S14 (GD = 4.6 m; DW; WS = 1 m/s)

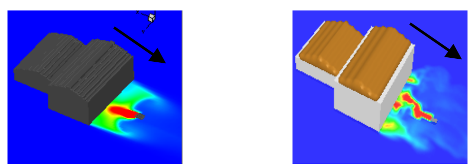


Figure 3(j) S18 (GD = 4.6 m; DW; WS = 5 m/s)

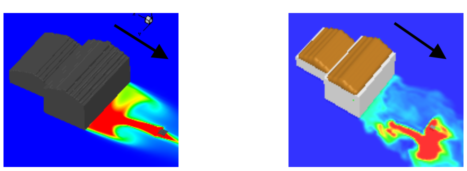


Figure 3(k) S15 (GD = 9.1 m; DW; WS = 1 m/s)

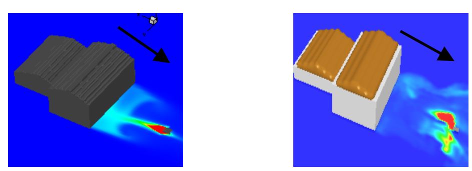


Figure 3(l) S19 (GD = 9.1 m; DW; WS = 5 m/s)

Figure 3. Comparison of CO concentrations obtained with CFD0 (left) and FDS (right) for isothermal simulations without considering generator exhaust speed and temperature for selected cases.

Non-isothermal simulations using FDS

When the generator exhaust speed and temperature are neglected, CO dispersion near the house is solely carried by the air motion induced by the wind. This limitation does not apply when the generator exhaust has a strong jet flow or when the generator exhaust is at a high enough temperature to induce buoyancy flows. The air velocity and temperature of a generator exhaust were measured to be about 7 m/s and 288 ˚C for a specific generator tested in experimental studies of generators (Wang et al. 2010). The combination of the exhaust jet inertia and buoyancy effects, wind speed and direction, generator distance, and pointing direction of the exhaust complicates CO dispersion but are all considered in the FDS simulations. Table 2 lists the 48 cases that were simulated by FDS. Figures 4 and 5 compare the predicted CO levels at the vertical plane of the middle lengthwise of the house (where the open window is located) when 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 2.

The results lead to several interesting observations:

- The combined effects of the exhaust jet inertia and buoyancy direct the CO upwards at an angle to the ground.
- When the exhaust points towards the house (Figure 4),
    - 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 near the house is lower (S1 through S4). The increase in the wind speed may help to dilute the CO, but it also pushes the CO plume down around the house as illustrated by S5 through S8. However, when the wind speed is high enough, as in S9 through S12, the CO can be effectively diluted.
    - When the generator is 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 is located too close to the house, the jet may impact the house wall such that CO is dispersed horizontally along the wall more easily than vertically by the buoyancy. S5 through S12 show that the vertical distribution of CO levels increase with the generator distance.
    - When the generator is 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. It is noted that an empirical equation (ASHRAE 2005) calculates the size of the leeward recirculation zone

$$R_{lw} = B_S^{0.67} B_L^{0.33} \qquad (1)$$

where B_S is the smaller of upwind building face dimensions; B_L is the larger of upwind building face dimensions of building height and width

Application of this empirical relationship is discussed further in the phase 1 report (Wang and Emmerich 2009). Apparently, the exhaust jet affects the formation of the leeward recirculation zone unfavorably so a greater generator operating distance may be required than the empirically calculated value. Moreover, when the wind speed increases from 1 m/s to 5 m/s, more CO is 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 takes over.

- When the generator exhaust points away from the house (Figure 5),
    - Generally, the CO levels near the house are lower than when the generator exhaust points towards the house. Such effects are 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 is located upwind of the house, the wind may 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 illustrates similar trends as the upwind located generator with exhaust pointing towards the house.
    - When the generator is placed downwind of the house (S37 through S48), a distance of 9.1 m seems sufficient to avoid CO being entrained backwards near the house for the wind speed of 1 m/s through 10 m/s.

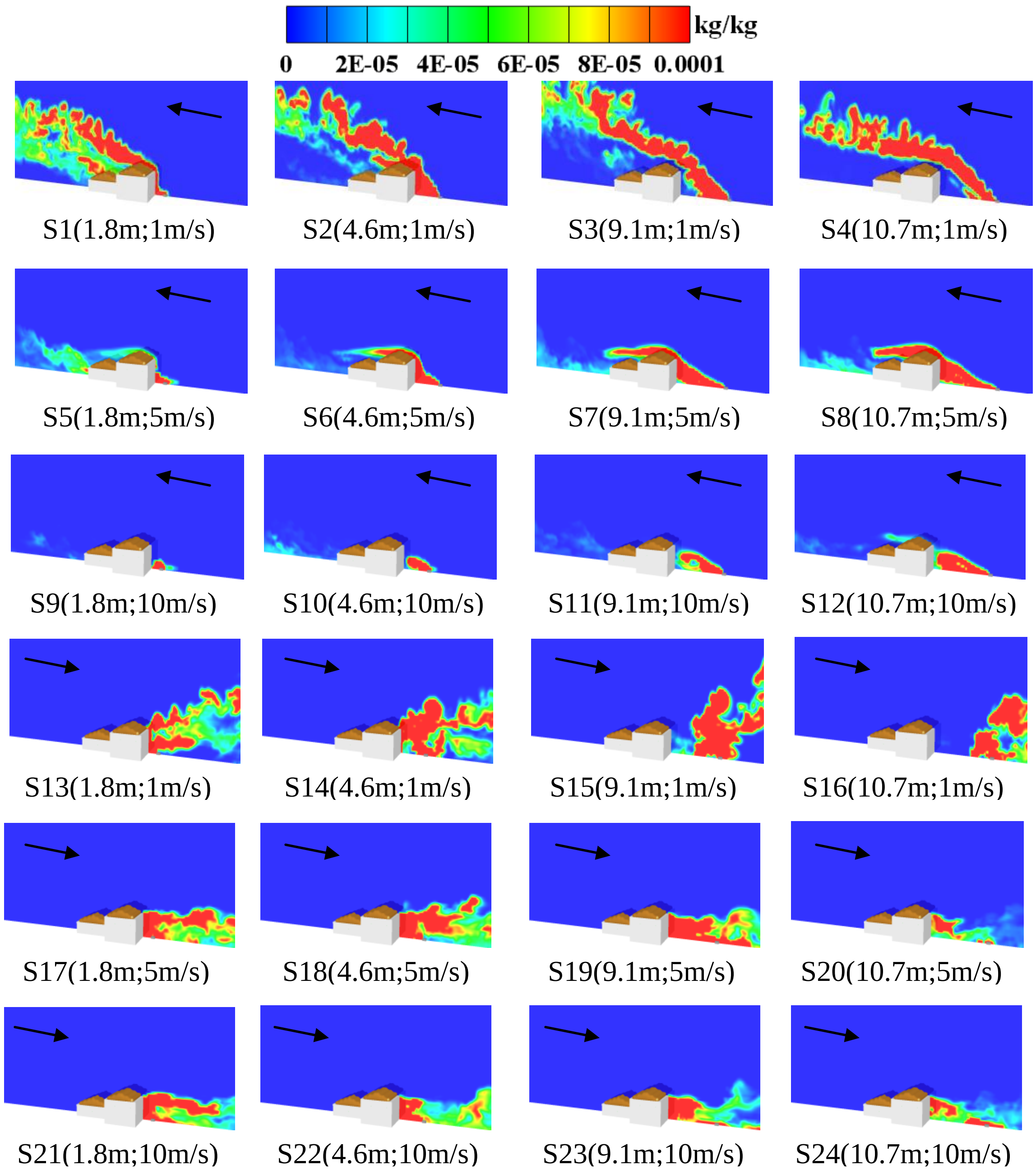


Figure 4. Comparison of CO levels at the middle lengthwise plane of the house for different generator distance, location, wind direction and speed when the generator exhaust pointed towards the house.

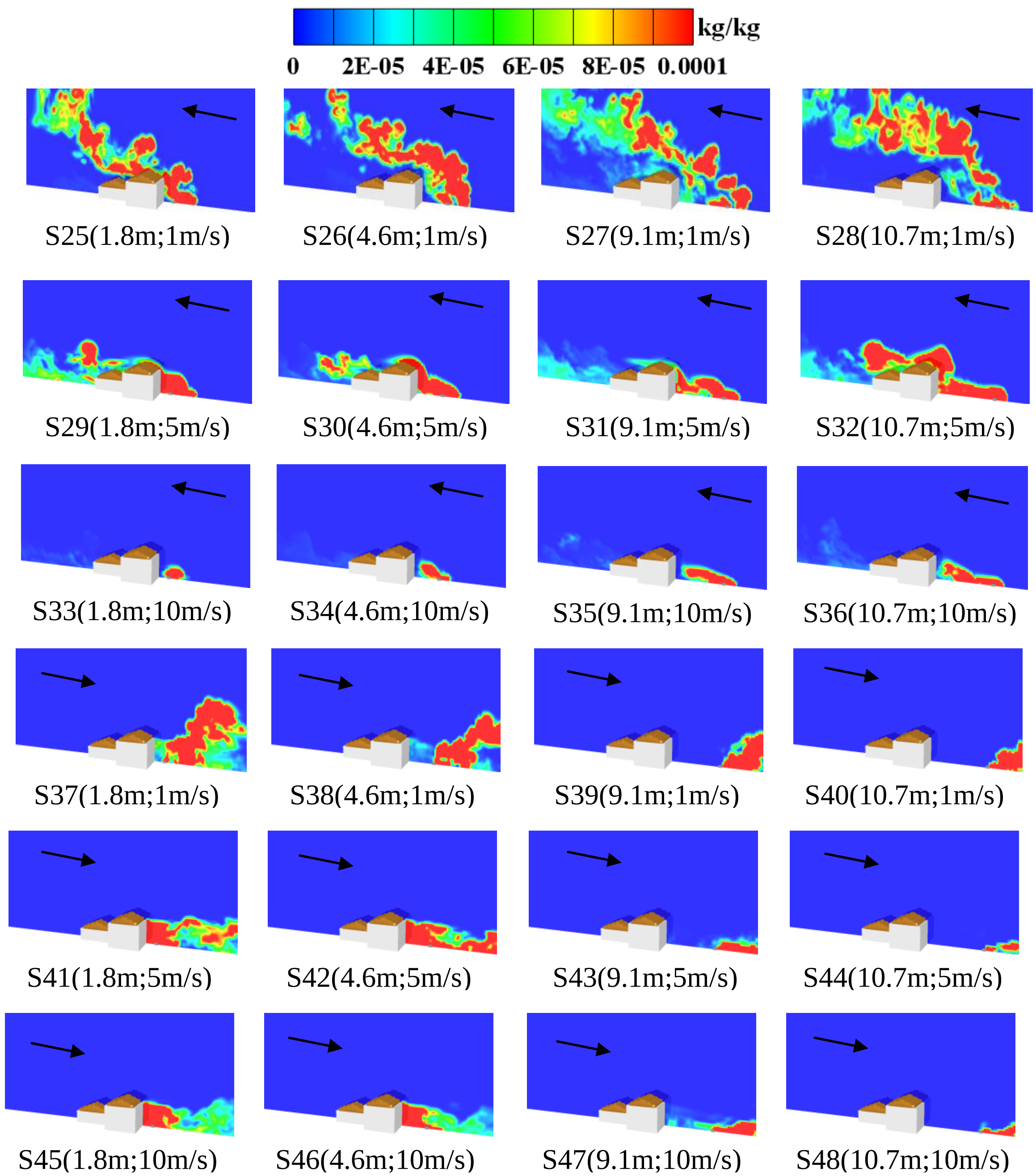


Figure 5. Comparison of CO levels at the middle lengthwise plane of the house for different generator distance, location, wind direction and speed when the generator exhaust pointed away from the house.

Figures 4 and 5 show only the CO levels visually for a middle vertical plane, where the open window is located. Comparisons of the average CO levels at the house envelope provide quantitative differences for all the 48 cases in Table 2. Figures 6 and 7 illustrate the CO levels averaged over time for all the windows and doors of the house for the exhaust pointing towards and away from the house, respectively.

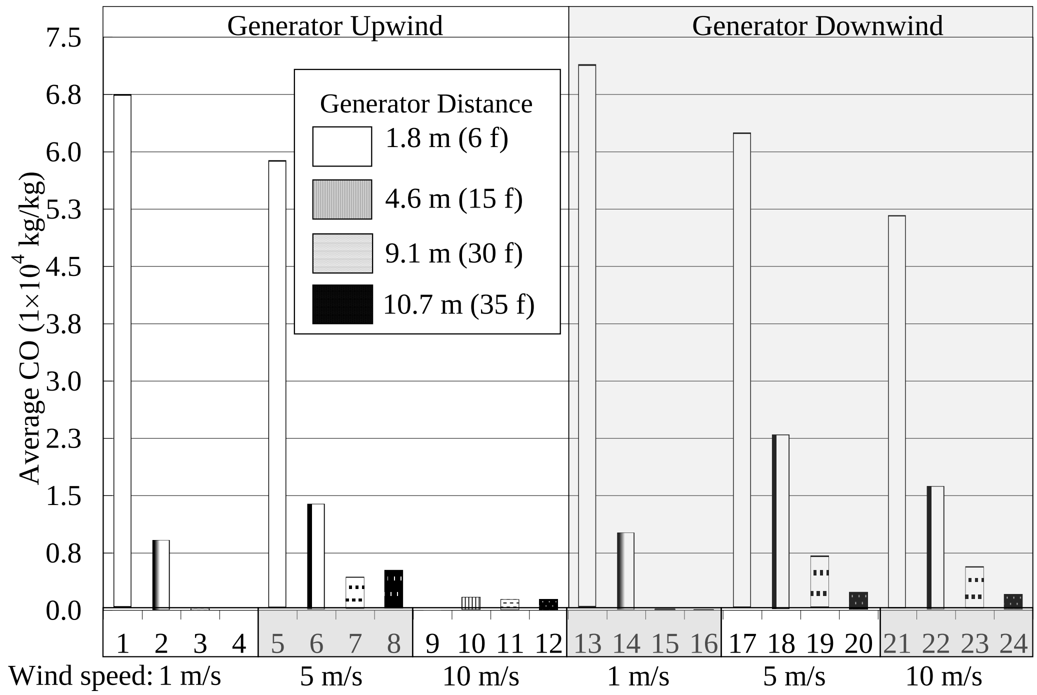


Figure 6. Comparison of time-average CO levels for all windows, doors and other leaks at the house envelope when the generator exhaust pointed towards the house (for CO in air, 1.0 kg/kg ≈ 1.2×10^6 mg/m^3 at 20.9 ˚C and 101.325 kPa).

As shown in Figure 6, the CO levels at the house window, door, and other leaks decrease significantly with the further placement of the generator when the exhaust points towards the house. When the generator is placed at 1.8 m, the higher wind speed dilutes CO more effectively. A wind speed of 5 m/s, however, may increase CO levels on the house envelope due to the "push-down" effects of wind on the CO jet as discussed previously. The "push-down" effects are counteracted by a wind speed of 10 m/s, which confirms the previous observations regarding Figure 4.

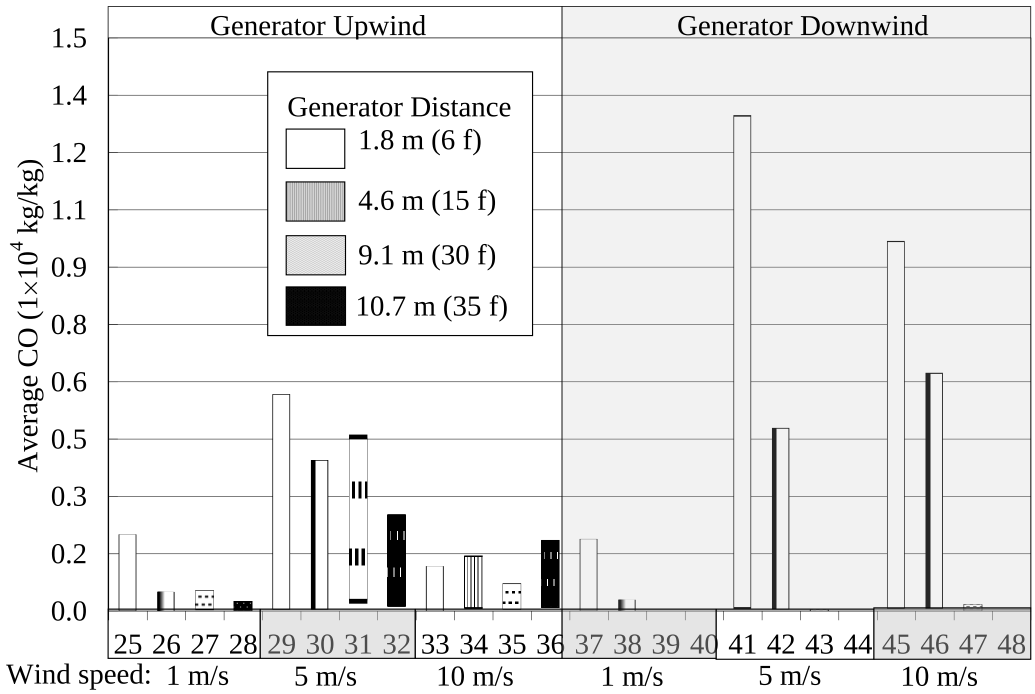


Figure 7. Comparison of time-average CO levels for all windows, doors and other leaks at the house envelope when the generator exhaust pointed away from the house.

Figure 7 shows that when the exhaust is pointed away from the house, the maximum average CO at the house envelope is only 1.3×10^{-4} kg/kg (S41), which is 17 % of the maximum value (S13) in Figure 6. In most cases (S27, S35, S39, S43, and S47), where the generator is placed at 9.1 m, the CO level is less than 0.2×10^{-4} kg/kg, which is only 3 % of the maximum value (S13) in Figure 6. These results seem to show that a distance of 9.1 m may help to reduce CO levels at the house envelope significantly. However, S31 was an exception, which has a CO level even higher than 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 may help CO to flow well around the house before being diluted by the wind. Note also that among all 48 cases in Figures 6 and 7, the CO level near the house is generally higher when the generator is located downwind of the house rather than upwind, which is consistent with phase 1 results.

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 8 hours and the indoor and outdoor temperature difference was zero. It is noted that when the generator was placed downwind of the house, the predicted CO levels in the house were minimal. This was due to the same reason as observed in the previous phase: the predicted airflow direction at the open window was from the house to the outdoors, so the outdoor CO was not carried into the house despite the presence of CO at the house surface. Therefore, Figure 8 shows only the cases for the generator located upwind of the house. It is found that pointing 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 97 % when the exhaust points away from the house (S29 in Figure 8) compared to the case when it points towards the house (S5 in Figure 8). 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 always results in a lower CO level both outdoors and indoors. It is also found that, when the exhaust was 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 the 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 CO appears to be still high, 84 mg/m^3 (S32). Therefore, the combination effects of wind direction and speed, generator distance, exhaust temperature and speed 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 modeled in this study, it was helpful to point the generator exhaust away from the house and position the generator at a distance more than 4.6 m (15 ft).

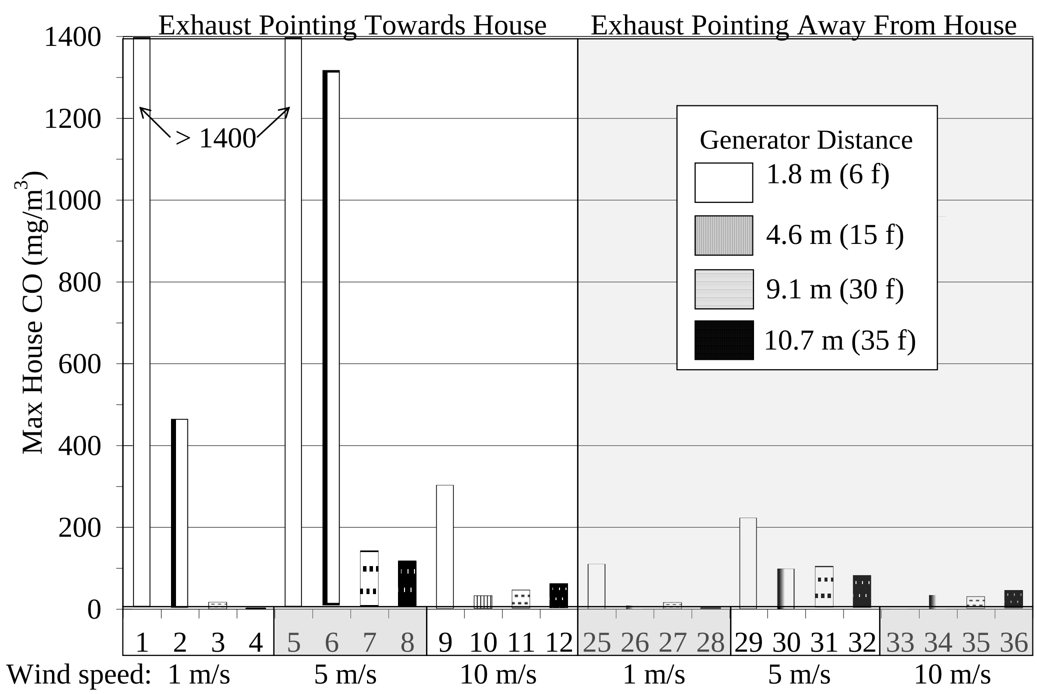


Figure 8. Maximum indoor CO in the house when the generator operated upwind of the house for 8 hours under zero indoor and outdoor temperature difference.

A few limitations to the interpretation of these results should be noted. While this study considered models of typical houses 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 to a larger size or poorly tuned engine, generator exhaust at a different temperature or velocity, and the opening of additional windows among others. Some physical effects are not included such as variable wind direction and speed, impact of nearby structures, and elevation differences between house and generator. Thus, any conclusions drawn from this study will not apply to every possible situation. Additionally, it is strongly recommended that experimental work be pursued to further verify and strengthen the conclusions of this study.

Conclusion

As a continued effort to provide information for determining safe distances for operating generators outside residences, this study investigated CO dispersion from a generator and its infiltration into a generic two-story house. In general, the results supported the conclusions of a first phase study which found that a distance of a generator positioned 4.6 m (15 ft) away from open windows may not be far enough to limit CO entry into a modeled manufactured house. In this second phase, it was also necessary to locate the generator further than 4.6 m (15 ft) from the two-story house to avoid high indoor CO concentrations (the next closest location modeled was 9.1 m (30 ft)). When the generator was moved even further to 10.7 m (35 ft), CO levels for both the house envelope and inside the house decreased but not significantly. The predicted CO indoors could still reach around 100 mg/m^3 when the wind speed is 5 m/s (S8 in Figure 8).

A new finding of this second phase was that the generator exhaust temperature and speed may affect CO levels near the house significantly. Pointing the generator exhaust away from the house caused 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 be 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 result was seen because a wind of 5 m/s 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. Therefore, the combined effects of wind direction and speed, generator distance, exhaust temperature and speed 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 the conditions modeled 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 (15 ft). If the generator is located more than 4.6 m (15 ft) 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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