

NIST Technical Note 1637

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Powered Generator Use on Indoor Carbon
Monoxide Exposures

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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 guidance provided on the safe operating distance of a generator is often neither specific nor consistent. Furthermore, some generator manufacturers recommend the use of extension cords to be "as short as possible, preferably less than 15 feet long, to prevent voltage drop and possible overheating of wires." However, the use of short extension cords may result in placement of the generator too close to the home to reduce the likelihood of the entry of CO. This study modeled multiple scenarios of a portable generator operated outdoors using the CONTAM indoor air quality model coupled with a computational fluid dynamics (CFD) model to predict CO concentrations near and within a home. The simulation cases included both human-controllable factors (e.g., generator location and exhaust direction and window opening size) and non-controllable factors (e.g., wind, temperature, and house dimensions). For the house modeled in this study, 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 winds perpendicular to the open window resulted in more CO infiltration than winds at an angle, and lower wind speed generally led to more CO entry. To reduce CO entry, the generator should ideally be positioned outside of airflow recirculation region near the open windows.

Keywords

Generator; carbon monoxide; generator safe operating distance; CONTAM; computational fluid dynamics; indoor air quality; health; multizone airflow model; poisoning; simulation

Nomenclature

A	Generator exhaust pointing away from the open window
A_g	Wind with an angle
B_L	Larger of upwind building face dimensions
B_S	Smaller of upwind building face dimensions
D	Downwind
DW	Generator placed downwind to the open window
FR	Family room
GD	Generator placement distance from the open window
KIT	Kitchen
LV	Living room
LVFRKIT	Living room, family room and kitchen
N	The north direction
OS	Size of the open window
P	Wind perpendicular to the open window
PD	Generator exhaust pointing direction
Perp	Perpendicular wind
R_{lw}	Size of leeward recirculation zone
S	Simulation
T	Temperature; Generator exhaust pointing Towards the open window
T_{in}	Inside air temperature
T_{out}	Outside air temperature
U	Upwind
UW	Generator placed upwind to the open window
WD	Wind direction clockwise relative to the north
WS	Wind speed
<i>Greek Symbol</i>	
Δ	Difference

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 through a slightly open, unlocked door or window. An investigation of the U.S. Consumer Product Safety Commission showed that five out of 104 deaths caused by generator CO poisoning 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 required a generator not to be used “within 10 feet of windows, doors or other air intakes” (EPA 2005). While these guidelines seem to 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.

This paper presents a series of numerical simulations of the entry of CO from a generator exhaust into a one-story house. A matrix of simulation scenarios was created to consider multiple factors contributing to the CO entry, including human-controllable factors (e.g., the generator location and exhaust direction and window opening size) and non-controllable factors (e.g., wind, temperature, and house dimensions). The transient indoor CO profiles were modeled using the CONTAM indoor air quality model (Walton and Dols 2005) integrated with a computational fluid dynamics (CFD) model, CFD0 (Wang 2007), which was used to predict outdoor CO dispersion near the house. Several values of generator placement distance were evaluated under different weather conditions. The results of this study provide some important insights for operating a portable generator safely outdoors.

Problem and Method

Figure 1 shows a general schematic of airflow streamlines near a house and potential factors affecting house CO entry when a generator is placed upwind of a house. Once released from the generator exhaust, CO disperses in the vicinity of a house, and transfers through openings, i.e. open doors/windows/vents, with the air infiltrating into the house. The rate of CO entry into the house is related to the CO level nearby and the amount of air infiltration into the house. Multiple factors affecting outside CO dispersion include the generator placement distance (GD) from the house, the exhaust direction (PD), the generator being positioned either upwind (UW) or downwind (DW) of an opening, wind speed (WS) and direction (WD). In addition to the ambient wind condition affecting the entry rate, other factors include opening size (OS), and outdoor-indoor temperature difference ($\Delta T = T_{out} - T_{in}$). This study used as the opening a partially opened window as shown in Figure 1.

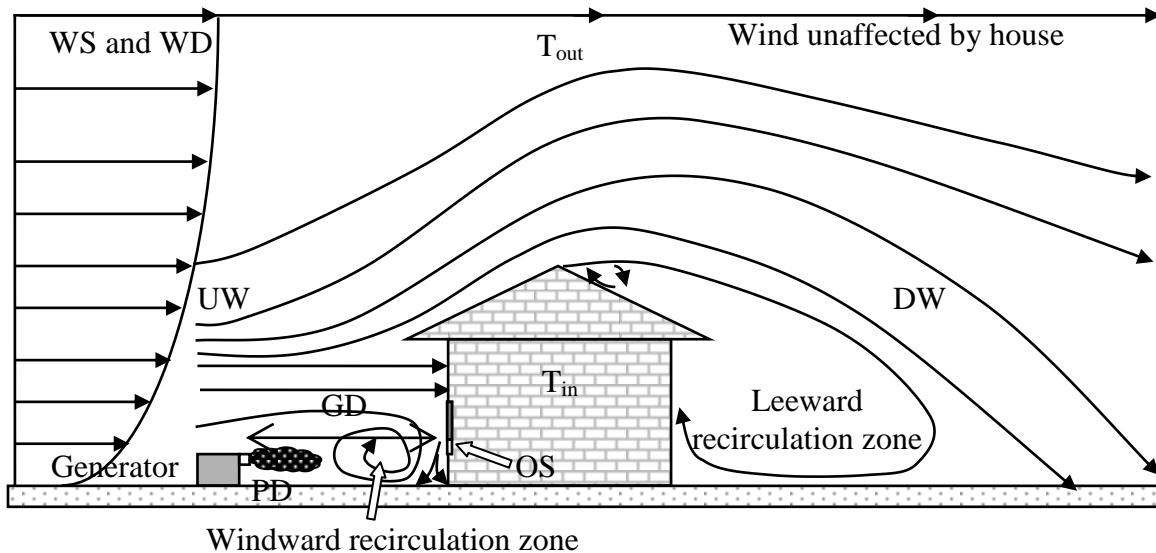


Figure 1. Schematic of airflow streamlines and factors affecting house CO entry when a generator is placed upwind of a house.

These factors were grouped into two categories: 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 1. If all factors were considered together, a full combination would have included 432 ($2 \times 3 \times 2 \times 2 \times 3 \times 2 \times 3$) simulations. The strategy employed in this study was to focus on one or a group of factors to find the worst, medium, and/or best scenarios for house CO entry while keeping other factors as a fixed condition. With this method, the total number was reduced to 56 simulations.

Table 1. Simulation parameter matrix

Focus of Study	S	Human-controllable Factors									Environmental Factors							
		PD		GD(m)			UW/DW		OS(m ²)		WS(m/s)			WD (°)		ΔT (°C)		
		T	A	0.9	4.6	7.6	U	D	0.05	0.31	1	5	10	P	Ag	0	10	-20
Gen. Pointing Direction	1	X		X			X			X		X		X		X		
	2		X	X			X			X		X		X		X		
	3	X		X				X		X		X		X		X		
	4		X	X				X		X		X		X		X		
	5	X			X		X			X		X		X		X		
	6		X		X		X			X		X		X		X		
	7	X			X			X		X		X		X		X		
	8		X		X			X		X		X		X		X		
Gen. Distance & Window Size	1	X		X			X			X		X		X		X		
	2	X		X			X		X		X		X		X			
	3	X		X				X		X		X		X		X		
	4	X		X				X	X		X		X		X			
	5	X			X		X			X		X		X		X		
	6	X			X		X		X		X		X		X			
	7	X			X			X		X		X		X		X		
	8	X			X			X	X		X		X		X			
	9	X				X	X			X		X		X		X		
	10	X				X	X		X		X		X		X			
	11	X				X		X		X		X		X		X		
	12	X				X		X	X		X		X		X			
Envtl. Factors	1	X		X			X			X	X			X		X		
	2	X		X			X			X	X			X			X	
	3	X		X			X			X	X			X				X
	4	X			X		X			X	X			X		X		
	5	X			X		X			X	X			X			X	
	6	X			X		X			X	X			X				X
	7	X				X		X	X		X			X		X		
	8	X				X		X	X		X			X			X	
	9	X				X		X	X		X			X				X
	10	X		X			X			X	X			X	X			
	11	X		X			X			X	X			X		X		
	12	X		X			X			x	X			X				X
	13	X			X		X			X	X			X	X			
	14	X			X		X			X	X			X		X		
	15	X			X		X			X	X			X				X
	16	X				X		X	X		X			X	X			
	17	X				X		X	X		X			X		X		
	18	X				X		X	X		X			X				X
	19	X		X			X			X		X	X		X			
	20	X		X			X			X		X	X			X		
	21	X		X			X			X		X	X					X
	22	X			X		X			X		X	X		X			
	23	X			X		X			X		X	X			X		
	24	X			X		X			X		X	X					X
	25	X				X		X	X			X	X		X			
	26	X				X		X	X			X	X				X	
	27	X				X		X	X			X	X					X
	28	X		X			X			X		X		X	X			
	29	X		X			X			X		X		X		X		

Focus of Study	S	Human-controllable Factors								Environmental Factors								
		PD		GD(m)			UW/DW		OS(m ²)		WS(m/s)			WD (°)		ΔT (°C)		
		T	A	0.9	4.6	7.6	U	D	0.05	0.31	1	5	10	P	Ag	0	10	-20
30	X		X			X			X			X		X			X	
31	X			X		X			X			X		X	X			
32	X			X		X			X			X		X		X		
33	X			X		X			X			X		X			X	
34	X				X		X	X				X		X	X			
35	X				X		X	X				X		X		X		
36	X				X		X	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; OS: open window size; WS: wind speed; WD: wind direction relative to the north; ΔT: outdoor and indoor temperature difference; T: generator exhaust pointing towards the open window; A: generator exhaust pointing away from the open window; U: upwind; D: downwind; P: wind perpendicular to the open window; Ag: wind with an angle

Specifically, the study was ordered as follows. The human-controllable factors were studied first with the weather condition fixed at a 5 m/s wind perpendicularly blowing towards the open window and zero outdoor-indoor temperature difference. The first of the human-controllable factors investigated was the pointing direction of generator exhaust, which was either towards (T) or away from (A) the open window, to find out the exhaust pointing direction that allowed more CO entry for use in the later simulations. Other settings include an open window size of 0.31 m² (a 12 in opening for a window width of 39.4 in), the generator placed either upwind or downwind with a distance of 0.9 m (≈3 ft as comparable to the literature) or 4.6 m (15 ft) away from the window. The combination of multiple factors ended up with eight simulations as shown in Table 1.

The second focus of the study was the human-controllable factors: placement distance of the generator and size of the open window. A generator distance of 0.9 m, 4.6 m, or 7.6 m (3 ft, 15 ft, 25 ft) and an open window size of 0.05 m² (a 2 in crack with the window width of 39.4 in equivalently) or 0.31 m² were studied. This set of variables was used to find the worst, medium, and best scenarios of CO entry in the house considering the generator placement distance and open window size. Using the three scenarios as baseline cases, the study then investigated the impacts of environmental factors by changing the ambient conditions. The variable environmental factors included wind speeds of 1 m/s and 10 m/s; wind directions either perpendicular to the open window or at an angle; outdoor-indoor temperature difference of 0 °C, 10 °C, and -20 °C. These factors result in a total of 36 simulations.

One important parameter that was not varied during the simulation study was the emission rate of CO from the generator. This was kept at 1 kg/h for all cases. Based on tests conducted at NIST, this is a reasonable estimate for a 5 kW generator operated near full load. In reality, the CO emission from any generator will depend on a variety of factor including the engine size and type, the connected electrical load and ambient conditions.

The house modeled in this study was based on a manufactured house on the campus of the National Institute of Standards and Technology (NIST). An aerial view and inside view of the house are shown in Figure 2(a) and Figure 2(c), respectively. The house

includes three bedrooms, living room (LV), family room (FR), kitchen (KIT), and an attached garage.



Figure 2(a). Aerial view of the house.

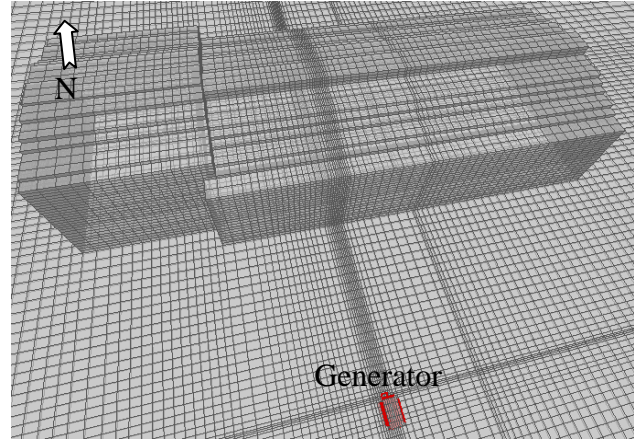


Figure 2(b) Meshed house in CFD.

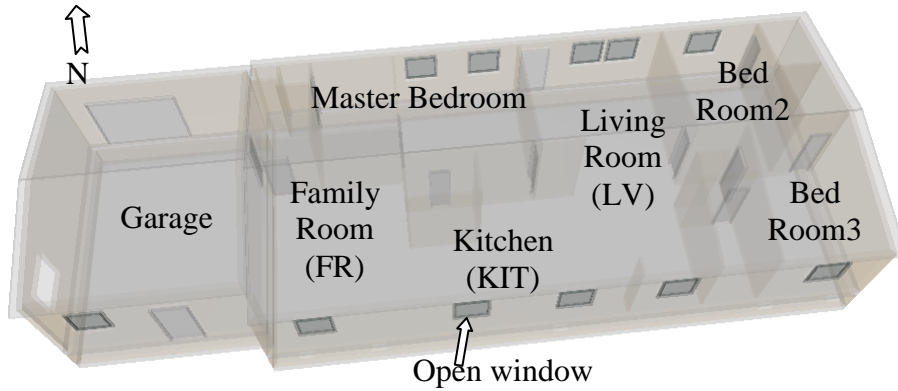


Figure 2(c). Inside view of the house.

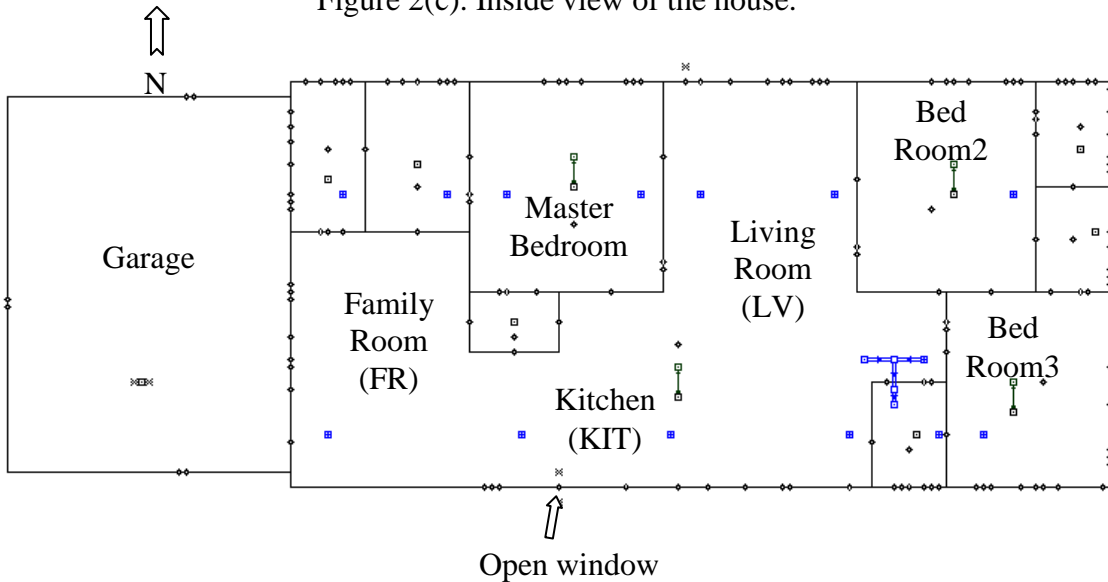


Figure 2(d). The house modeled in CONTAM.
 Figure 2. The manufactured house to be modeled.

A simulation to predict external CO dispersion and internal CO transient profiles involved a two-step procedure. First, a computational fluid dynamics (CFD) program, CFD0 (Wang 2007), was used to simulate the external airflow and CO dispersion around the house. Figure 2(b) shows the orthogonal structured mesh used in one of the CFD simulations when a generator was placed a certain distance from the house. The CFD simulations predicted CO distribution at the house envelope corresponding to different wind directions, which was saved in a database file. The file contained CO concentrations for each point on the house envelope for each wind direction simulated. In considering the surrounding wind condition correctly, a profile of atmospheric wind for “open terrain” (ASHRAE 2005) was used based on the surrounding condition of the actual house. Figure 3 illustrates the wind profiles used in the simulations for a reference wind speed of 1 m/s, 5 m/s, and 10 m/s at the height of 10 m (33 ft) above the ground.

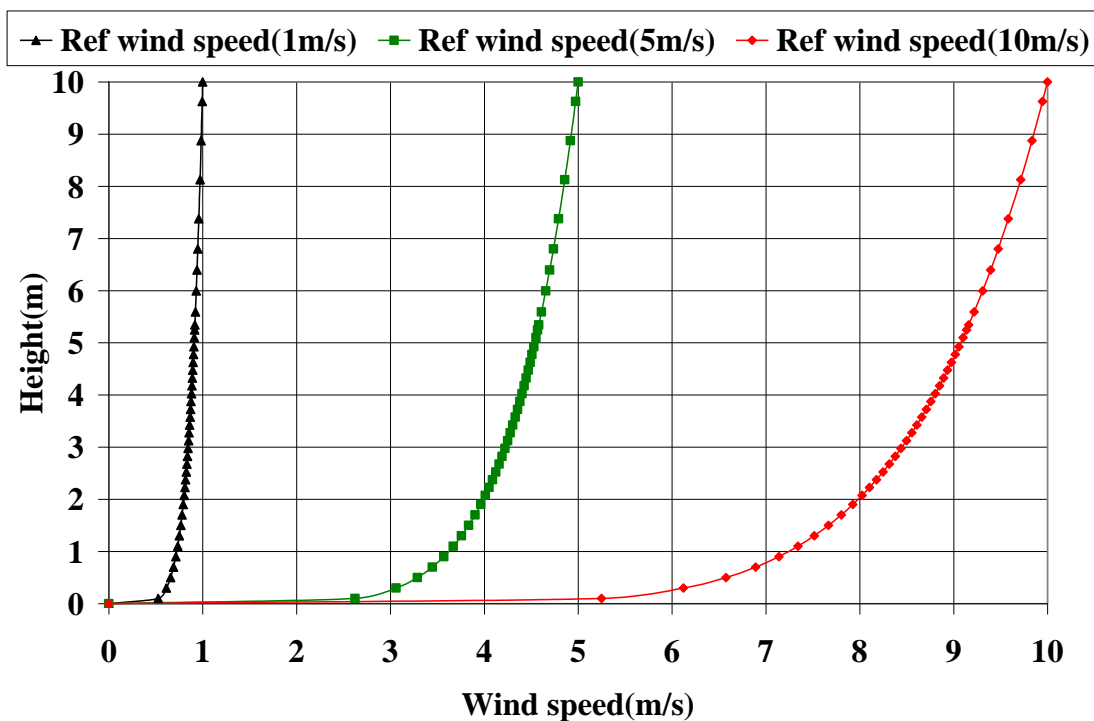


Figure 3. Wind profiles for the reference wind speeds of 1 m/s, 5 m/s, and 10 m/s at the height of 10 m above the ground.

The second step in the effort was to predict transient CO profiles in the house using CONTAM. Figure 2(d) shows the house as modeled in CONTAM. The CONTAM model uses the CFD results for CO concentration for each opening/crack of the house as the entering concentration for any air infiltrating at that crack/opening. The model is then used to predict a CO profile for each room of the house for a period of eight hours, which is a reasonable runtime for a generator (Brown 2006).

The CO hazard was evaluated using both the peak value of CO level in the house and the resulting percentage of carboxyhemoglobin (%COHb) level. %COHb is one of the most commonly used indicators for CO exposure (Haloulakou et al. 2000; Inkster 2004) and can be predicted from mathematical models. One of the most precise mathematical models is the Coburn-Foster-Kane (CFK) model, which has been broadly used and validated by many previous studies (Peterson and Stewart 1975; EPA 2000; EPA 2001). The CFK model takes into account important variables such as exposure duration, alveolar ventilation, partial pressure of CO in the inhaled air, blood volume, diffusivity of the lung for CO, and rate of endogenous CO production (Stewart 1975). Equations (1) and (2) show the CFK equation in its integral form during a time period of Δt . The peak value of the %COHb in the house provides a criterion of CO exposure for different simulations under various affecting factors.

$$[COHb]_t = [COHb]_{t-1} + \left(\frac{V_{CO}}{V_b} - \frac{[COHb]_{t-1} P_{O_2}}{MBV_b([OHb]_{max} - [COHb]_{t-1})} + \frac{P_{CO}}{BV_b} \right) \Delta t \quad (1)$$

(EPA 2001)

$$[\%COHb]_t = \frac{[COHb]_t}{[OHb]_{max}} \times 100 \quad (2)$$

where P_{CO} , partial pressure of CO in the air inhaled (mm Hg), was determined by

$P_{CO} = C_{CO}/1316$, in which C_{CO} is the CO concentration in ppm(v). The initial $[COHb]_0$ is typically 1.659×10^{-3} ml/ml for a non-smoker, which is equivalent to the $[\%COHb]_0$ of 0.75 % (EPA 2001).

Results and Discussions

The fifty-six simulations in Table 1 were conducted, which focused on the effects of generator exhaust direction, generator placement distance from the house, size of the open window, and environmental factors.

Human-controllable factor: generator exhaust pointing direction

Generator users may point the exhaust towards an open window as shown by Figure 4(a) or away from the window in Figure 4(b). As defined in Table 1, eight simulations were conducted for the generator exhaust pointing direction when the generator was placed 0.9 m (3 ft) or 4.6 m (15 ft) upwind or downwind of the open window. A wind perpendicular to the south wall of the house was set as 5 m/s fixed and the outdoor-indoor temperature difference was set to 0 °C.

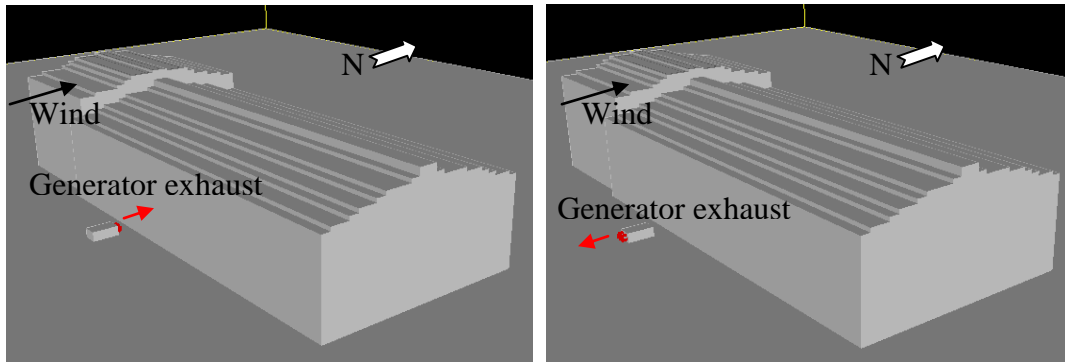


Figure 4(a). Generator exhaust pointing towards the house.

Figure 4(b). Generator exhaust pointing away from the house.

Figure 4. Study of generator exhaust pointing direction.

Figure 5 presents the eight simulations of generator exhaust direction for the different rooms in the house. Note that the living room (LV), family room (FR), and kitchen (KIT) were modeled and reported as a single zone of LVFRKIT in Figure 5 and afterwards in this paper. As shown in Figure 5(a), when the generator was placed 0.9 m upwind from the house, the maximum CO level occurred in the LVFRKIT for both cases with the exhaust pointing towards (S1) and away from (S2) the open window. It seems that the exhaust pointing direction does not significantly affect CO entry, with a maximum concentration of 142 mg/m³ in case S1 and 134 mg/m³ in case S2. In the cases S3 and S4, for which the only difference was a wind direction of North and the generator downwind (DW) of the open window, the maximum CO concentration occurred in Bedroom 3, although the CO level itself was small. The wind direction thus seemed to play a more important role than the exhaust pointing direction.

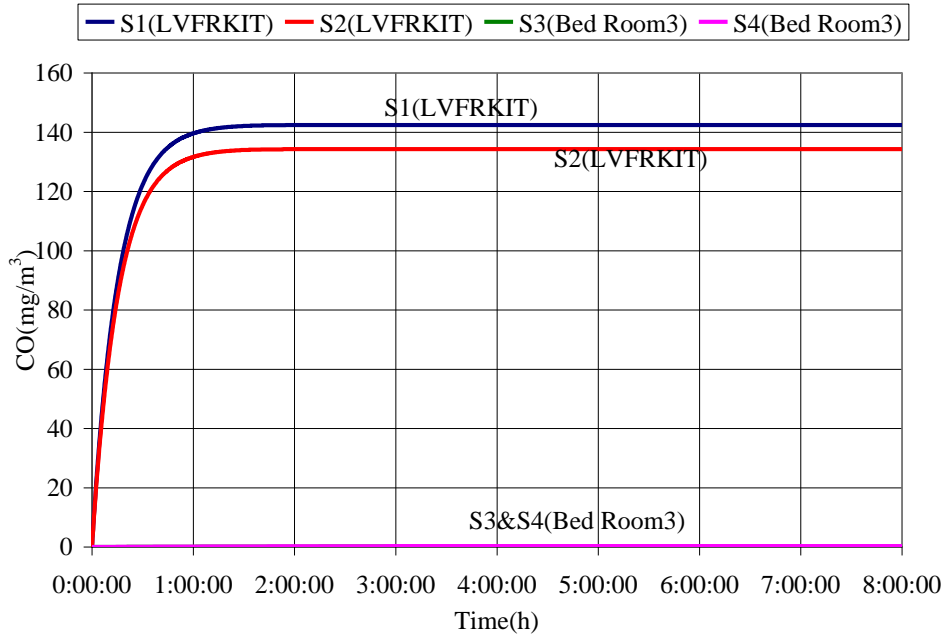


Figure 5(a). Maximum CO levels in the house for the generator exhaust pointing directions when the generator was placed 0.9 m from the house.

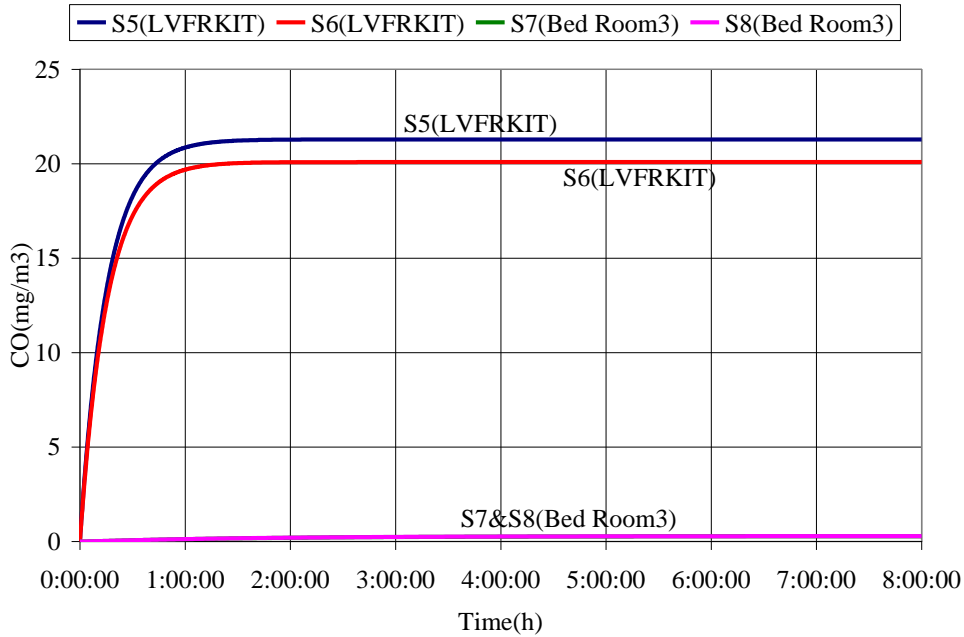


Figure 5(b). Maximum CO levels in the house for the generator exhaust pointing directions when the generator was placed 4.6 m from the house.

Figure 5. Results for generator exhaust pointing directions.

Unsurprisingly, the generator placement distance was also a significant factor to the house CO entry. Figure 5(b) illustrates that when the generator was placed 4.6 m (15 ft) from the house, the maximum CO level was significantly less than the corresponding case when the distance was 0.9 m (3 ft). For simulation S5, the CO level was only 21 mg/m³ in LVFRKIT compared to the 142 mg/m³ in S1. Similar trends were observed for S6 through S8. Overall, these simulations show that compared to the exhaust pointing direction, the generator placement distance and the wind direction were more important factors, which were analyzed further. The following simulations employed an exhaust pointing direction towards the open window, since it generally causes higher CO entry than the exhaust pointed away from the house.

Human-controllable factors: generator placement distance and open window size

The distance of generator placement from the house is a user's decision. Apparently, increasing the distance aids in avoiding CO hazards. Other concerns, however, may impact the generator location, including concerns about the generator being stolen, noise to neighbors, and limited extension cord length (CPSC 2006). Therefore, a minimum distance for safe generator operation outdoors is of great interest. However, the answer is not straightforward, as CO dispersion around a house is significantly affected by the aerodynamics near a house, which is closely related to house geometry, e.g. shape and dimension, and weather conditions such as wind speed and direction.

A simple demonstration can be made by revisiting Figure 1. The interaction of the house and the wind creates two major eddies, i.e., windward and leeward recirculation zones, with the latter generally being wider than the former. The existence of these two recirculation zones may "trap" CO to create a local region with fairly high CO levels. Figure 6 shows more clearly how the recirculation zones affected CO dispersion around the house. When the generator sits upwind 0.9 m (3 ft) away from the house but inside the windward recirculation zone, i.e. Figure 6(a), much of the CO is trapped at the corner of the house, which potentially could cause more CO entry into the house. If the generator is moved farther away from the house, e.g. 4.6 m in Figure 6(c) and 7.6 m in Figure 6(e), the CO is diluted by the wind to achieve a lower level near the house. A similar observation could be made when the generator is placed downwind of the house in Figures 6(b), 6(d), and 6(f), with the exception that the leeward recirculation zone is generally larger than the windward one. As a result, a distance of 4.6 m (15 ft) may not be far enough as shown in Figure 6(d). When the distance is increased to 7.6 m (25 ft), CO is well diluted outside the recirculation zone (Figure 6(f)).

Although this study modeled a specific case, it shows that a minimum distance of safe generator operation could be closely related to the recirculation zones of the house, especially the leeward zone, which is often larger than the windward one. An empirical estimate of the size of the leeward recirculation zone (R_{lw}) for a general case is provided by Equation (3) (ASHRAE 2005):

$$R_{lw} = B_S^{0.67} B_L^{0.33} \quad (3)$$

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. When $B_L > 8B_S$, $B_L = 8B_S$ should be used. When a building has varying roof levels or wings separated by at least a distance B_S , the building dimensions should be determined only by the height and width of the building face below the portion of the roof in question (ASHRAE 2005).

Applying Equation (3) to the house in this study, $R_{lw} = 6.7$ m (22 feet). Therefore a generator distance of 7.6 m (25 feet) from the house is far enough to help avoid CO being trapped in the leeward recirculation zone.

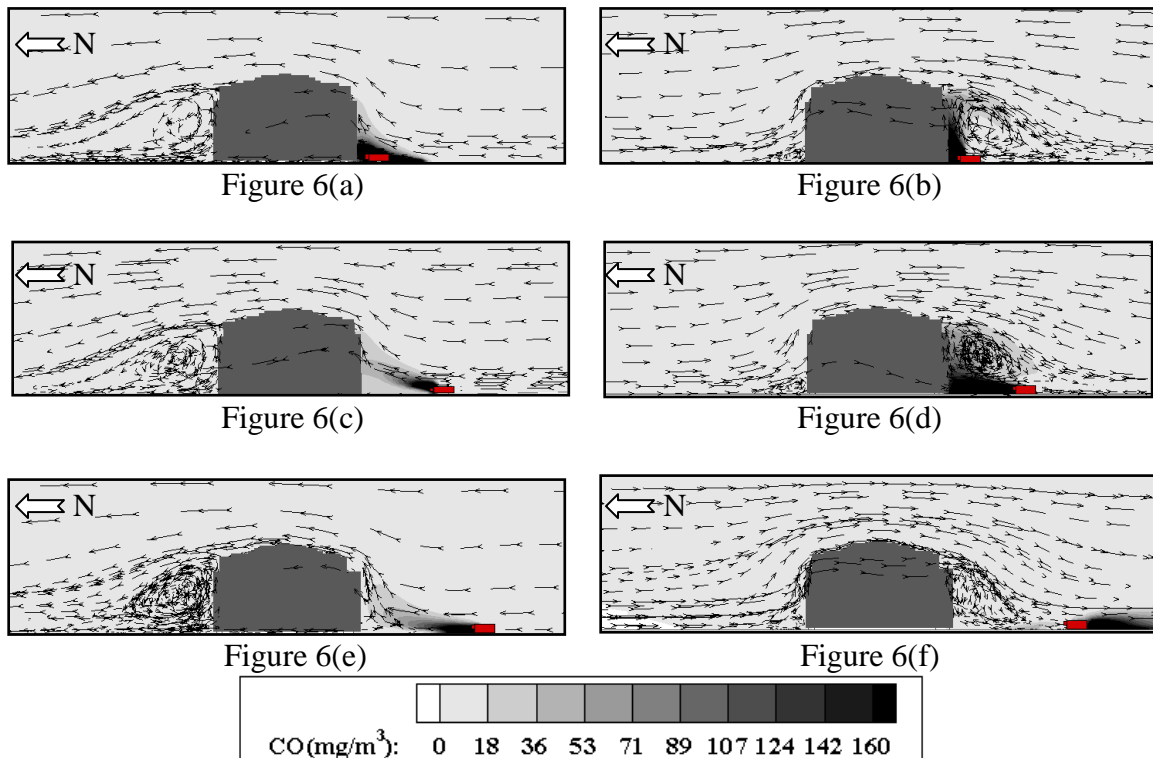


Figure 6. The study of generator placement distance and open window size. Streamlines and CO levels for the simulation (a) S1 and S2; (b) S3 and S4; (c) S5 and S6; (d) S7 and S8; (e) S9 and S10; (f) S11 and S12.

After predicting the CO levels near the house, the CO entry rate into the house can be calculated considering the effect of the open window size. Figure 7 compares the peak CO and %COHb levels in the house for different generator distances and open window sizes. The worst scenario of CO entry, with the highest CO level of 142 mg/m^3 and %COHb = 16.4 %, occurred in simulation S1. In S1, the generator was placed 0.9 m upwind to the house with an open window size of 0.31 m^2 . As a comparison, the best case was the simulation S12, where the generator distance was 7.6 m downwind and the open window size was 0.05 m^2 . The simulation S5 was found to be the medium case, with the CO value closest to the average value of all 12 cases, 27 mg/m^3 (3 %COHb). The worst,

medium, and best scenarios were used as baseline cases to populate a series of simulations with the focus of studying non-controllable environmental factors on CO entry.

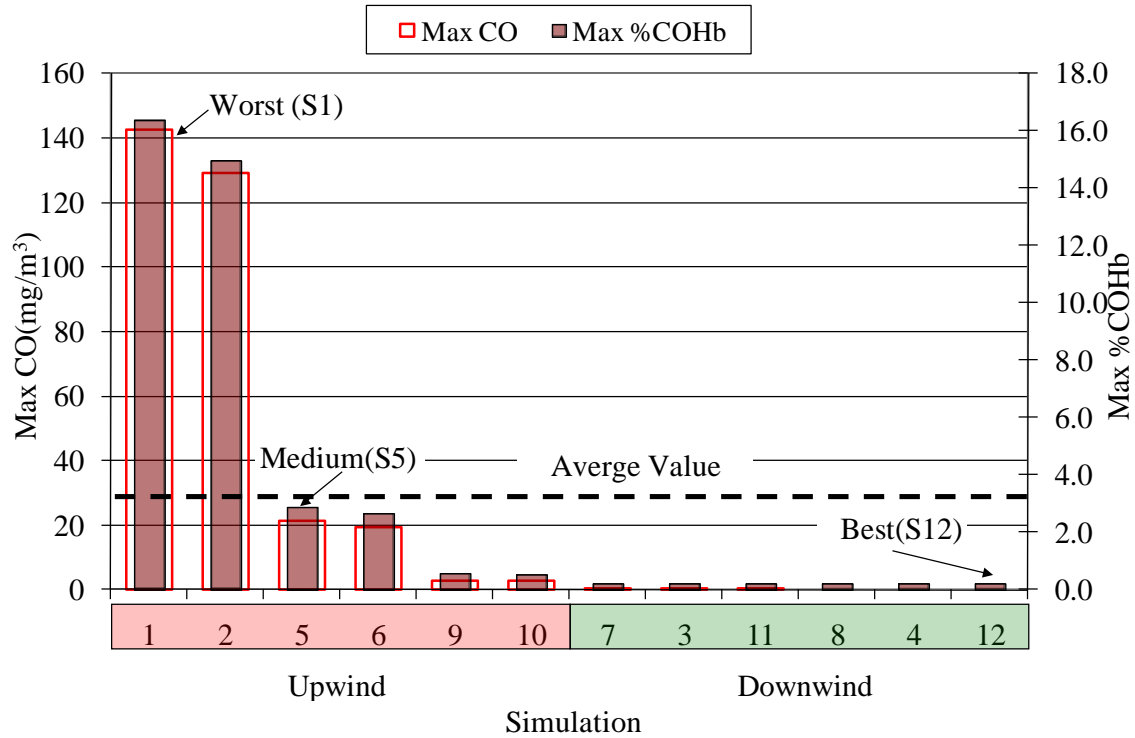


Figure 7. Maximum CO levels and %COHb for generator placement distance and open window size.

Note from Figure 7 that the predicted peak CO levels in the house were not as high as expected when the generator was placed downwind as in S3, S4, S7, and S8, although the CO was trapped inside the leeward recirculation zones in Figures 6(b) and 6(d). This difference occurred because, for the specific case modeled in this study, the predicted airflow direction of the open window was all outflow (from the house to the ambient) and CO was not brought into the house as a result. Other situations could occur that would reverse the airflow direction and bring CO into the house. Therefore, due to the existence of leeward recirculation zones with high CO levels, S3, S4, S7, and S8 were still considered CO hazardous cases. A generator distance of 4.6 m (15 ft) was considered not safe enough to avoid excessive CO exposure. It was also noted from Figure 7 that both levels of %COHb and maximum CO are useful evaluation criteria of CO hazards. To simplify the analysis, maximum CO levels are used as the only CO hazard evaluation criterion in the remainder of this paper.

Non-controllable factors: environmental factors

The studies of human-controllable factors assumed a single set of weather conditions: 5 m/s wind speed with wind perpendicular to the south/north wall, and an outdoor-indoor temperature difference of 0 °C. With the worst, medium, and best cases identified under these weather conditions, additional simulations were performed to investigate how weather conditions affect CO entry. As shown in Table 1, a total of 36 simulations were conducted with wind speed of 1 m/s or 10 m/s, a range of wind directions, and temperature differences of 0 °C, 10 °C, and 20 °C. In fact, the actual total number of simulations was over 36 because a series of simulations was tried for a range of wind angles from 0° to 330° clockwise from the north. It was found out that when a wind was 210° clockwise from the north, the CO level at the house envelope was generally higher than other wind angles. Therefore, this wind direction was selected as a representative case for wind at an angle.

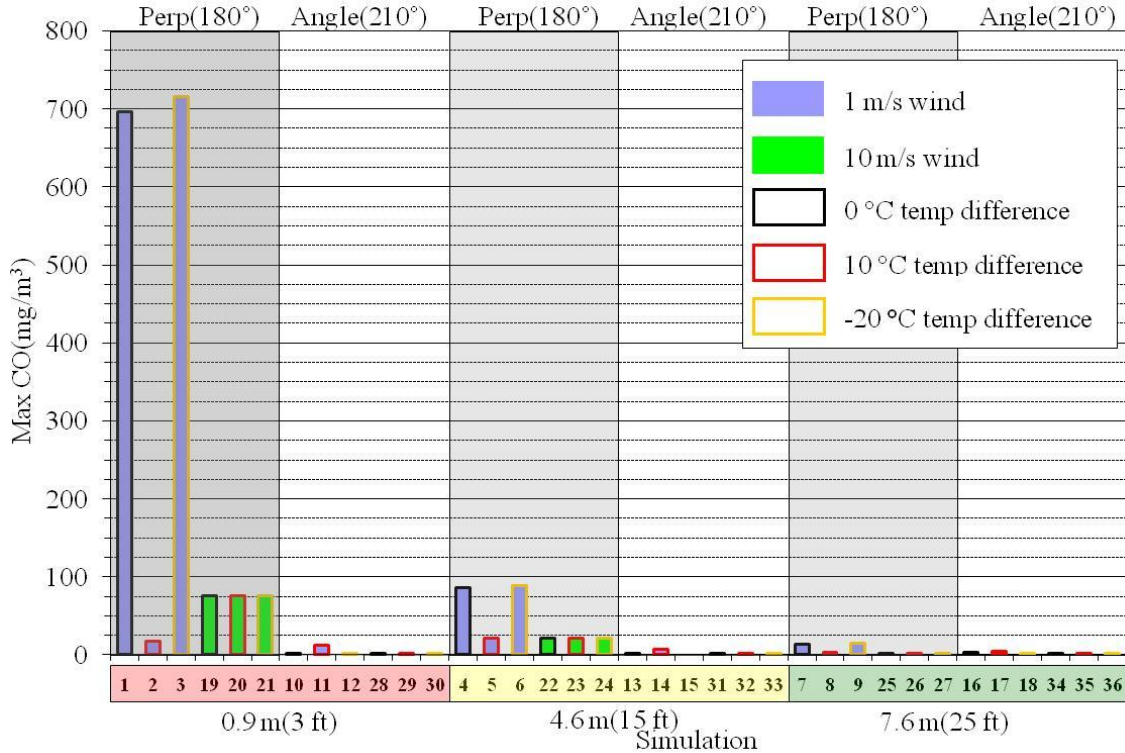


Figure 8. Maximum CO levels showing the effects of environmental factors on CO entry.

Figure 8 compares the maximum CO levels in the house for various weather conditions. Generally, a lower wind speed is associated with a higher rate of CO entry. This effect can be explained by a stronger wind facilitating CO dilution and causing the CO in the recirculation zones to disperse more easily. A higher wind speed also causes more air infiltration into the house so that the CO level in the house was diluted more quickly. In addition to the wind speed effect, the generator placement distance plays a major role in CO entry. The CO concentration reaches 715 mg/m³ (%COHb = 51 %) when the

generator was 0.9 m upwind of the open window for a wind speed of 1.0 m/s in simulation S3. Wind direction was another major factor. A sharp drop of CO levels could be observed when the wind was from an angle rather than perpendicular to the open window. However, when the generator was moved far enough away from the house, i.e. 7.6 m (25 ft), the peak CO levels were minimal regardless of wind speed and direction. A distance of 7.6 m (25 ft) thus seemed to be reasonably safe for the house in question. Variation in CO levels occurred for the generator distance of 4.6 m (15 ft), which could be as high as 89 mg/m^3 ($\%COHb = 11 \%$), showing that 4.6 m (15 ft) was not necessarily an acceptable operating distance for the house modeled in this study.

The outdoor-indoor temperature difference, ΔT , affected the CO entry indirectly by contributing to the infiltration of outdoor air. The air infiltration pattern was not determined only by the wind effect but rather by a combination of buoyancy and wind effects, which can be shown by comparing S1 and S2 in Figure 8. When ΔT was zero, as in S1, and wind speed was just 1.0 m/s, the air flowed into the open window and brought CO into the house. Whereas under the same conditions, except with an outside temperature $10 \text{ }^\circ\text{C}$ higher than the inside in S2, the buoyancy effect dominated the wind effect and the airflow direction was reversed. The green bar in Figure 9(a) shows the airflow at the open window became an outflow in S2. Consequently, the peak CO in the house for S2 dropped sharply as shown in Figure 8. When the wind speed was strong enough, e.g. 10 m/s in S19 – S21, the buoyancy effect caused by the change of ΔT was insignificant compared to the wind effect. The airflow at the open window was thus always inflow (i.e., the green bar for S20 in Figure 9(b)). The variation of CO levels of S19-S21 in Figure 8 was minimal for a range of ΔT from $-20 \text{ }^\circ\text{C}$ to $10 \text{ }^\circ\text{C}$.

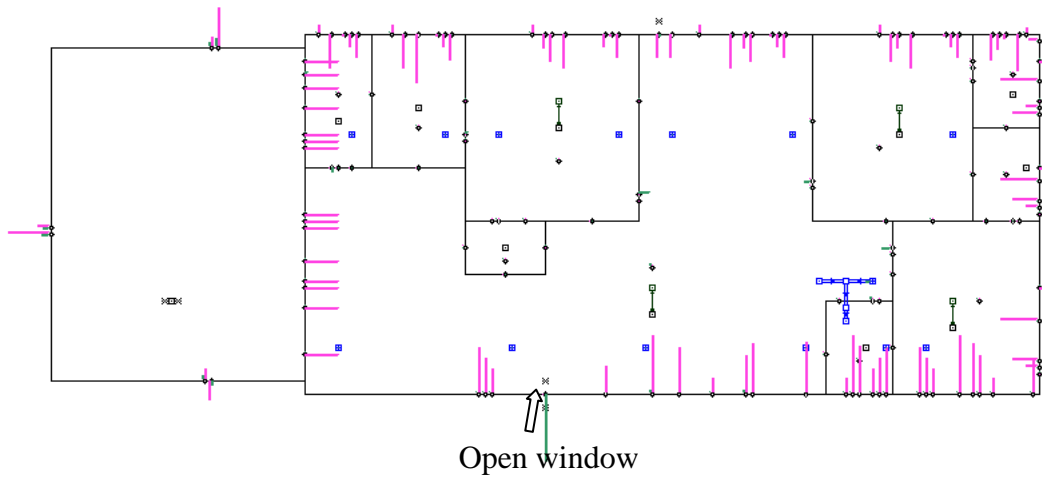


Figure 9(a)

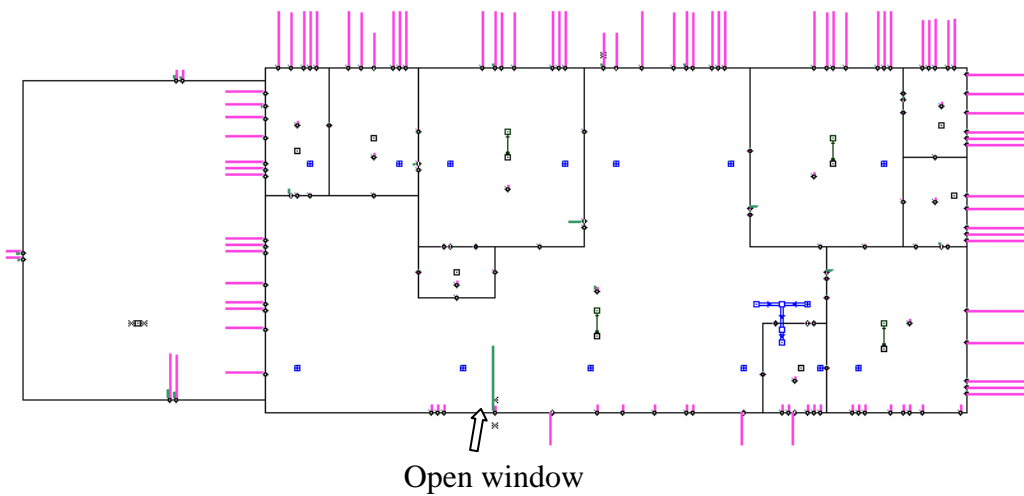


Figure 9(b)

Figure 9. CONTAM simulation results of airflow rates and pressure drops for the simulation (a) S2 and (b) S20 for the study of environmental factors.

Conclusion

Through a series of simulations on a one-story manufactured house, this study found that positioning a generator 4.6 m (15 feet) from open windows may not be far enough for the house modeled to avoid excessive CO entry. Ideally, the generator should be positioned outside of airflow recirculation regions near the open window. As for human non-controllable factors, a perpendicular wind to the open window often led to more house CO entry than wind with an angle. Lower wind speed generally caused more entry of CO when the outdoor-indoor temperature difference was relatively small so that the CO entry by buoyancy effect could be neglected. When the buoyancy effect was significant, the infiltration of airflow and CO were determined by the combined forces of wind and buoyancy. Major CO entry into the house occurred primarily when the generator was placed inside the airflow recirculation zone, the size of which was found to be related to the dimensions of the house. General guidance for the safe operating distance of a generator could be developed considering the size of the airflow recirculation zone and the house dimensions.

Acknowledgements

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