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CO DISPERSION IN A CAR-REPAIR SHOP: AN EXPERIMENTAL AND CFD MODELLING STUDY

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ABSTRACT

Carbon monoxide (CO) is a highly toxic gas, which is produced by the incomplete combustion of any carbon-based fuel. The level of CO concentration in indoor environments constitutes a serious health hazard for occupational safety, especially for car-repair shop employees who are exposed on a daily basis to vehicle exhaust fumes. However, the topic has not been extensively investigated, as the small number of related references found in the open literature suggests. This work focuses on the investigation of CO production and dispersion using experimental and numerical approaches. Measurements of CO concentration and ventilation air velocities have been performed in an actual operating medium-sized car-repair shop. In addition, a detailed numerical simulation of the developing transient flow-field has been carried out, using the Fire Dynamics Simulator CFD code. The obtained experimental data have been used to validate the CO concentration predictions with overall good qualitative and occasionally quantitative agreement. Different levels of ventilation airflow rates have been numerically investigated; the ensuing CO concentration levels have been compared to current occupational health legislation.

INTRODUCTION

Carbon monoxide (CO) is a colourless, odourless, tasteless, non-irritating but highly toxic gas, which is produced by the incomplete combustion of any carbon-based fuel. The accumulation of CO, especially in inadequately ventilated spaces, constitutes a potential health hazard for the occupants of the building. The effects of CO inhalation can be toxic or even lethal due to the binding of CO with haemoglobin and the formation of carboxy-haemoglobin that eventually leads to the limitation of oxygen delivery to the tissues of the human body. CO intoxication may occur in a wide variety of settings; the two most common sources of CO for acute poisonings are smoke from fire and vehicle engine exhaust fumes (Bateman, 2007).

Numerous research studies exist regarding pollutant dispersion in a variety of interior working environments, such as underground parking garages (Duci et al., 2004), road tunnels (Bari et al., 2005), train stations (Chiam, 2005), public transport interchange station (Lin et al., 2006), schools (Chaloulakou et al., 2003) cinemas and airports (Webb, 2006). However, there are no references available in the free literature, focusing on the potential occupational safety hazards based on CO concentration levels in car-repair shops. This work focuses on CO production and dispersion in a car-repair shop, using both experimental and numerical simulation techniques. The effects of ventilation airflow are also evaluated by performing a relevant parametric study.

EXPERIMENTAL PROCEDURE

Description of the Car-Repair Shop

The experimental investigation has been performed in a typical car-repair shop operating in Greece. The general layout of the facility, along with some basic dimensions, is depicted in Figure 1. The considered car-repair shop can accommodate up to 25 vehicles; it has a total effective area that spans 1261.8m^2, including office space (91.2m^2), a lobby (45m^2) and a warehouse area (145.6m^2). The facility has two entrances; the main entrance (A1), measuring 2.85m x 3m, is positioned in the eastern part, whereas the secondary entrance (A2), measuring 2m x 3m, is located in the southern part. Both entrances remain totally open during a typical working day, thus allowing fresh air to freely enter the facility. A staircase leading to the first floor of the building is located near the north-east corner of the lobby; as a result, there is also a 2m x 2m opening (A3) in the ceiling of the lobby.

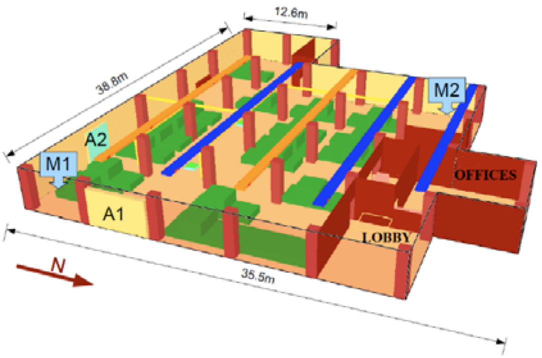

Figure 1: General layout of the car-repair shop.

CO Concentration Measurements

Two portable gas analysers (MRU Delta 2000CD and Madur GA-40 plus) were employed to simultaneously and continuously measure CO concentrations. Both devices exhibit a total accuracy of ±5% and have a resolution of 1ppm. The measurements were performed over several typical working days starting from 9 a.m. and ending at 3 p.m. Two representative monitoring positions were selected. The first position (M1), as shown in Figure 1, is located at the southeast corner of the facility, lying between the two entrances, corresponding to a well-ventilated (both mechanically and naturally) area that is constantly occupied by employees and is also commonly used by clients as a waiting area. The second position (M2) is located near the northwest corner, far away from all openings of the facility (c.f. Figure 1); exhaust fumes are expected to accumulate in this region. Both gas analyzers were located at a height of 1.6m above the floor, which corresponds to the breathing zone of an average person, and were programmed to record local CO concentration levels in periods of 10s.

The obtained measurements were time-weighted for various time periods, such as 5, 15 and 30 min, in order to allow comparison with respective values suggested by various legal bodies, such as the World Health Organization (WHO, 2000) the National Institute of Safety and Health (NIOSH, 2004), the Greek legislation for occupational safety and the American Conference of Government Industrial Hygienists (ACGIH, 1994). A selection of characteristic Time Weighted Average (T.W.A.) values, based on air quality guidelines for indoor CO concentrations for a typical 8-hour working day, is given in Table 1.

Organisation	Time Weighted Average CO Concentration Guideline Values		
	mg/m^3	ppm	Weighted time
WHO	100	90	15 min
	60	50	30 min
	30	26	1 hr
	10	9	8 hrs
Greece	55	50	15 min
NIOSH	40	35	8hrs
ACGIH	25	29	8hrs

Table 1: Air quality guideline values for indoor CO concentrations.

Related directives indicate that mechanical ventilation systems should be used to ensure that CO levels are constantly kept below the values suggested by the standards, in order to establish an acceptable air quality for the employees.

The variation of CO concentration levels over time, measured in a typical working day are depicted in Figure 2 together with the relevant guideline values to allow direct comparison. The T.W.A. values were obtained using a 15-min averaging time. As expected, CO levels in position M1, which is located near the open entrances, are generally lower than the respective values in position M2. It is evident that in both cases, the measured values are significantly lower than the 15-min T.W.A. limiting values suggested by both WHO (90ppm) and the Greek legislation (50ppm). However, the measured values in position M2 may occasionally exceed the 8-hr T.W.A CO levels suggested by WHO (9ppm). Since even low concentrations of CO may cause headache, nausea, dizziness, weariness, decrease in myocardial oxygen consumption and increase in coronary flow and heart rate (Chaloulakou et al., 2002), a very conservative approach would suggest that even the 15-min averaged values should remain below the suggested 8-hr averaged limit.

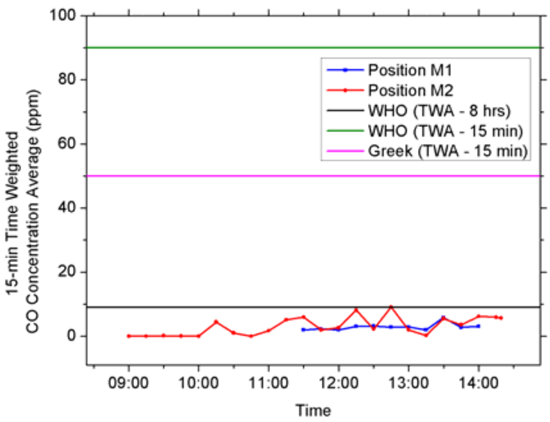

Figure 2: Time evolution of CO concentrations in a car repair shop averaged over 15-min.

Ventilation Airflow Measurements

The installed ventilation system is essentially a “balanced” system, consisting of two distinct branches; the “supply” branch that introduces “fresh” air in the facility (Figure 1, blue-coloured ducts) and the “extraction” branch that removes air from the facility (Figure 1, orange-coloured ducts). A secondary “extraction” branch is installed specifically to remove exhaust fumes from a height of 1m from the ground (Figure 1, yellow-coloured ducts). All branches provide stable pressure conditions to the entire volume of the facility. All the ducts of the main ventilation system are located in a height of 3.5m; the ventilation vents have an orthogonal cross-section, measuring 0.2m x 0.4m, and are positioned on both sides of the ducts, approximately every 6.0m. Mean airflow velocities were measured for every available vent, using a TESTO-435 digital airflow meter.

Entrance Airflow Measurements

The main and secondary entrances of the repair-shop remain always open, providing an additional source of natural ventilation. The TESTO-435 digital airflow meter was used to measure the outdoor air supply from the main and secondary entrance. The velocity measurements were recorded every 1s for a period of 20min in three different height levels. The time-averaged values of the obtained measurements that were used as initial conditions in the simulations, are presented in Table 2.

Main entrance (A1)		Secondary entrance (A2)	
Height (m)	Average velocity (m/s)	Height (m)	Average velocity (m/s)
0.7	0.43	0.7	0.43
1.35	0.24	1.4	0.56
2.1	0.21	2.0	0.42

Table 2: Time-averaged values of outdoor air velocities at the entrances of the repair-shop.

NUMERICAL SIMULATION

Presentation of the CFD code

The Fire Dynamics Simulator (FDS) 5.3 is a Computational Fluid Dynamics (CFD) code capable of numerically simulating fire-driven fluid flows. The equations of mass, momentum and energy conservation are solved by assuming low Mach conditions; the solution is updated in time on a three-dimensional, rectilinear grid. A species transport equation is solved to simulate the dispersion of CO inside the computational domain. Turbulent phenomena are taken into account by using the Large Eddy Simulation (LES) approach. The subgrid-scale turbulence is simulated using the Smagorinsky model, utilizing a Smagorinsky constant value of 0.2 (MacGrattan et al., 2009). The numerical time-step is continuously adjusted in order to satisfy the CFL criterion. The minimum time-step used in the simulations was 7.5ms.

Boundary and Initial Conditions

In order to construct the numerical grid, the actual geometry of the facility was utilized. A uniform Cartesian grid was used in the simulations, consisting of 488700 cubic cells measuring 0.2m x 0.2m x 0.2m each. 18 "solid" obstructions were included in the computational domain, representing the average number of the vehicles that typically exist in the car-repair shop; each vehicle was assumed to occupy a volume of 10m^3 (green in Figure 1).

The boundary conditions used in the simulation accurately reflected the large number of outdoor air inlets and gas mixture outlets found in the actual car-repair shop. Outdoor air was assumed to enter through the main (A1) and the secondary (A2) entrance, using measured time-averaged velocity values (Table 2). Outdoor air was also assumed to be introduced through 22 vents located in the "supply" branches of the ventilation system; the respective measured mean velocity values were used as inlet conditions. The "fresh" air introduced to the domain was considered to be free from CO. The gas mixture was allowed to exit the computational domain through an opening at the ceiling of the lobby (A3). Also, the 20 vents of the "extraction" branches of the ventilation system removed the gas mixture at a specified flow rate, according to the respective measurements.

Air was considered to be still at the beginning of the simulations. The initial temperature of the air, as well as the temperature of the "fresh" air introduced in the simulated region, was 0^{o}C. The initial CO concentration level was defined according to the respective CO measurements.

Modelling of Vehicle CO Emissions

In order to estimate the value of the CO mass source term used in the simulations, an appropriate modelling of CO emissions, due to the engine operation of the vehicles in the facility, is needed. Due to difficulties in accurately measuring simultaneously the engine operating time and the exact position of the moving vehicles, a simplifying assumption was employed.

The movement of the vehicles, the engine operating time and the approximate position of the vehicles were recorded, in 30s intervals, for a typical working day. During the measurements it was observed that the vehicles' engines were operated mainly during two phases: vehicles entering or leaving the car-repair shop and vehicles undergoing exhaust emission measurements (in the latter case the vehicle's engine remained in operating mode for a period of 2-3min).

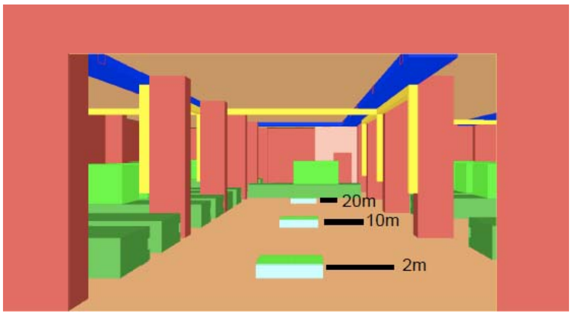

Figure 3: Positioning of "artificial" CO source regions in the computational domain.

Thus, it was decided to use a simplifying assumption, by considering only 3 distinct regions as sources for the CO emissions. These regions were distributed along the axis of the main corridor, which is used for the transfer of each vehicle to its repair position, and were placed at a distance of 2m, 10m and 20m from the main entrance (Figure 3). As a result, the actual position of each operating vehicle was attributed to one of the three regions that acted as "artificial" CO source, each measuring 1.0m^2.

It is well known that the rate of exhaust emissions - resulting from the fuel combustion in the vehicle's internal combustion engine - depends strongly on the operational mode of the vehicle. For light duty vehicles, three operational modes are typically considered: "cold start", "hot start" and "hot stabilized" (ASHRAE, 1995). The start mode includes the first few minutes of starting the vehicle's engine, when the engine is at full choke and operates with a rich mixture. The length of time between the shutoff and the restart of the engine differentiates the "cold" from the "hot" start. The "hot stabilized" mode occurs when the engine is running after the start mode; in general, emission rates in this case are lower than in the start mode. In this work, typical operating conditions for parking garages, which are similar to the vehicle operation inside car-repair shops, are assumed. In the case of a parking garage (ASHRAE, 1995), CO emissions depend on ambient temperature and the vehicle's operational mode, as shown in Table 3. Since the measurements were obtained during the winter season, values for winter "cold start" emissions were used in the simulations.

	"Hot Start" emissions (g/min)	"Cold Start" emissions (g/min)
Summer	1.89	3.66
Winter	3.38	18.96

Table 3: Vehicle CO emissions in parking garages.

In order to calculate the CO mass source terms used in the simulations, the following procedure was followed: For every measured 30s time step, the number of vehicles operating near each "artificial" CO source region was multiplied by the average value of CO emissions for winter and "cold start" conditions. The obtained value was then used to calculate the time evolution of CO mass source that was finally introduced into the FDS code.

RESULTS AND DISCUSSION

Validation of the Results

A 20-min time period, corresponding to the time space 13:06-13:26 in Figure 2, was selected for the simulation. In Figure 4, the obtained CO concentration predictions are compared to the values measured in position M1. Very good levels of agreement are observed, especially during the first 700s of the simulation. After this time point, a drop in CO concentration is evident in the measurements; numerical results describe this trend qualitatively.

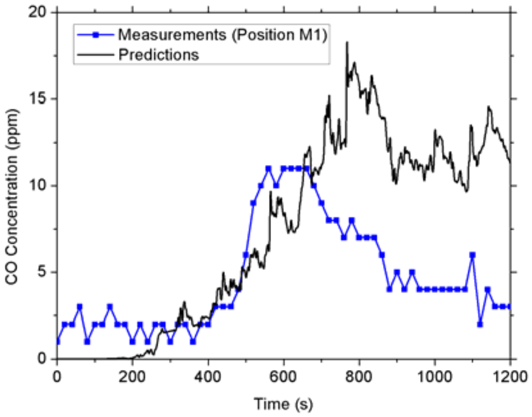

Figure 4: Comparison between experimental data and numerical results in position M1.

Good qualitative agreement is observed also in the case of position M2 (Figure 5); predictions lie quite close to the measured values for the first 1000s of the simulation. The general over-prediction of the measured values is mainly attributed to the simplifying assumption of using the "cold start" CO emission values for the estimation of the CO mass source terms. The overall qualitative and, in certain cases, quantitative agreement between the obtained numerical results and the available experimental data is quite satisfactory, despite the complexity of the occurring phenomena and the simplifying assumptions employed in the simulation.

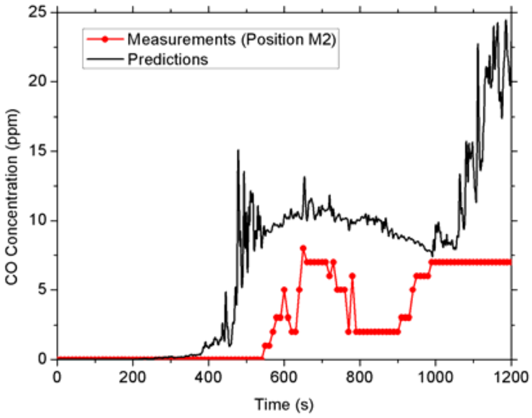

Figure 5: Comparison between experimental data and numerical results in position M2.

Parametric Study

The ventilation system of the car-repair shop currently operates at conditions corresponding to 5 Air Changes per Hour (ACH). The Greek legislation for occupational safety suggests that mechanical ventilation of car-repair shops should ensure at least 8 ACH. The increase of the flow rate of outdoor air supply is expected to ensure better Indoor Air Quality (IAQ) conditions for the employees. In this context, the effectiveness of such a measure is investigated by means of a parametric study.

Two test cases were considered: the first (5ACH) corresponded to the measured operational conditions of the ventilation system, whereas the second (8ACH) referred to a 60% increase of the "supply" (and, respectively, "extraction") airflow rate. Since no detailed measurements were available for the latter case, a simplified approach was followed to estimate the CO production rate. The time evolution of the average number of vehicles with operating engines in the entire car-repair shop was estimated by using available measured data (Figure 6, lower part). The respective values were grouped in 15-min slots and the wintertime "cold start" CO emission values (Table 3) were used to calculate a "global" CO mass source term (Figure 6, upper part).

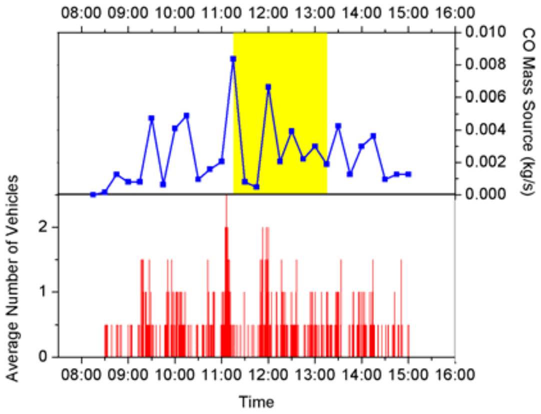

Figure 6: Average number of vehicles and 15-min T.W.A. of CO production mass flow rate.

A single "slit" CO source term, measuring 22m x 0.4m was assumed to be located in the middle of the main corridor, used for the vehicle movement in the car-repair shop (Figure 7); the calculated time evolution of the CO mass flux was applied to the entire "slit" to simulate CO emissions in a typical working day. In this case, there is no need for detailed CO production time measurements; thus, the single "slit" approach can be used in a variety of car-repair shop simulations. A time period of two hours, between 11:15h and 13:15h, was used for the simulation (yellow region in Figure 6). The monitoring position (P1), located in the office space where a large number of employees work, was selected to comparatively assess the two different ventilation level scenarios.

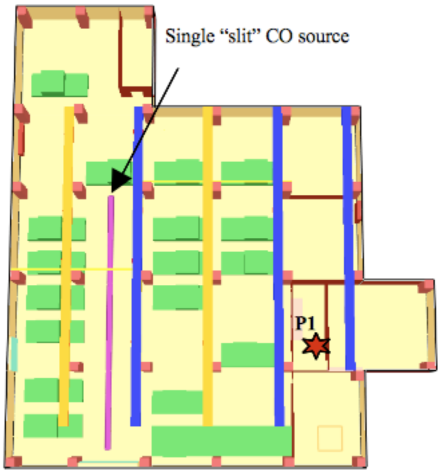

Figure 7: Layout of the continuous CO “slit” source.

The obtained CO concentration predictions are depicted in Figure 8. The temporal evolution curves of the CO concentration in position P1 for both test cases are qualitatively similar, following roughly the temporal evolution curve of the CO source term (Figure 6). As expected, predictions in the 5ACH case are almost 4 times higher than the respective predictions of the 8ACH case.

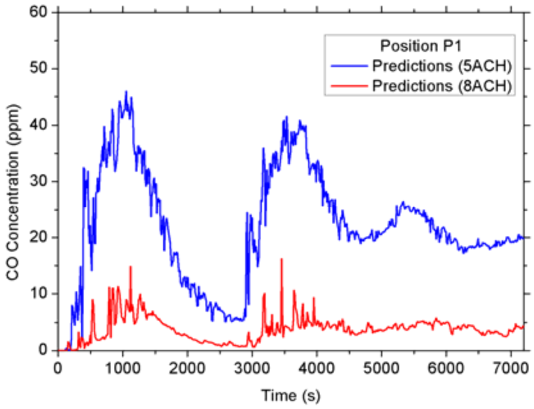

Figure 8: CO concentration predictions (Position P1).

In order to obtain more in-depth information regarding the differences between the two test cases, contour plots of CO concentration at a height of 1.6m above the ground level, 800s after the beginning of the simulation, are shown in Figure 9. In both cases the highest CO concentrations are observed near the main corridor, where the CO “slit” source is positioned. The effect of natural ventilation is evident in the region near the main entrance, where low CO concentration levels are observed. The large differences between the two ventilation scenarios are evident in the lobby and office areas, where no CO is present in the 8ACH case, contrary to the respective predictions of the 5ACH case. As a result, when 8 ACH are used in the ventilation system, a noticeable improvement in IAQ conditions inside the car-repair shop can be clearly seen.

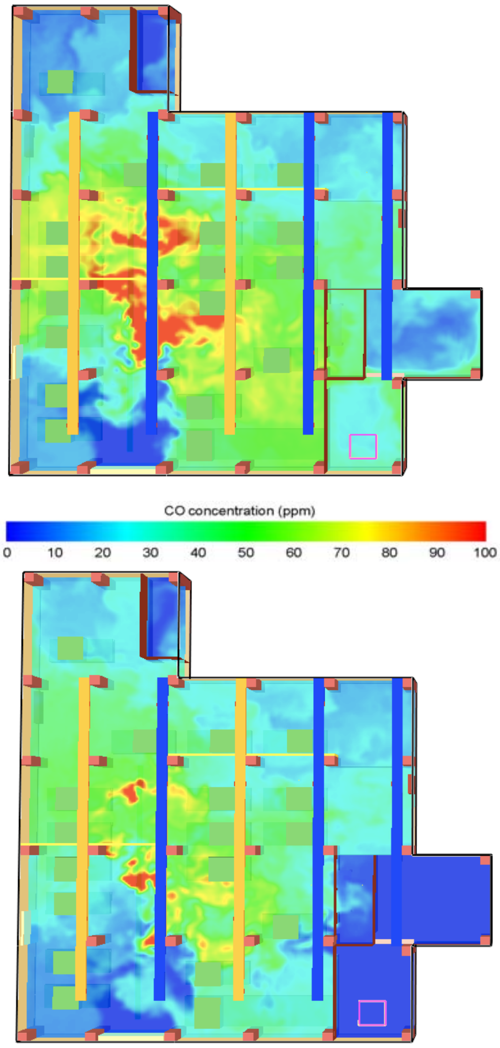

Figure 9: Predictions of the CO concentration levels at a height of 1.6m, 800s after the beginning of the simulation (Top: 5ACH, Bottom: 8ACH).

Important information regarding the developing flow-field can be obtained by examining snapshots of the velocity vector predictions inside the car-repair shop. In Figure 10, velocity vector predictions obtained at a height of 1.6m above the floor, 800s after the beginning of the simulation are depicted for the two test cases considered. In general, it is evident that higher mean velocities prevail in the 8ACH case, due to the 60% increased ventilation air flow rate, compared to the 5ACH case; higher velocities result in higher levels of dilution, leading to lower CO concentration levels (Figure 9). The effects of both the “supply” and the “extraction” ventilation branches can be observed; free ventilation becomes evident in the regions close to the main and secondary entrance. In the north-west corner of the facility, regions of intense recirculation develop in both cases, thus explaining the higher CO concentration values measured in position M2, compared to the simultaneous measurements in position M1 (Figure 2).

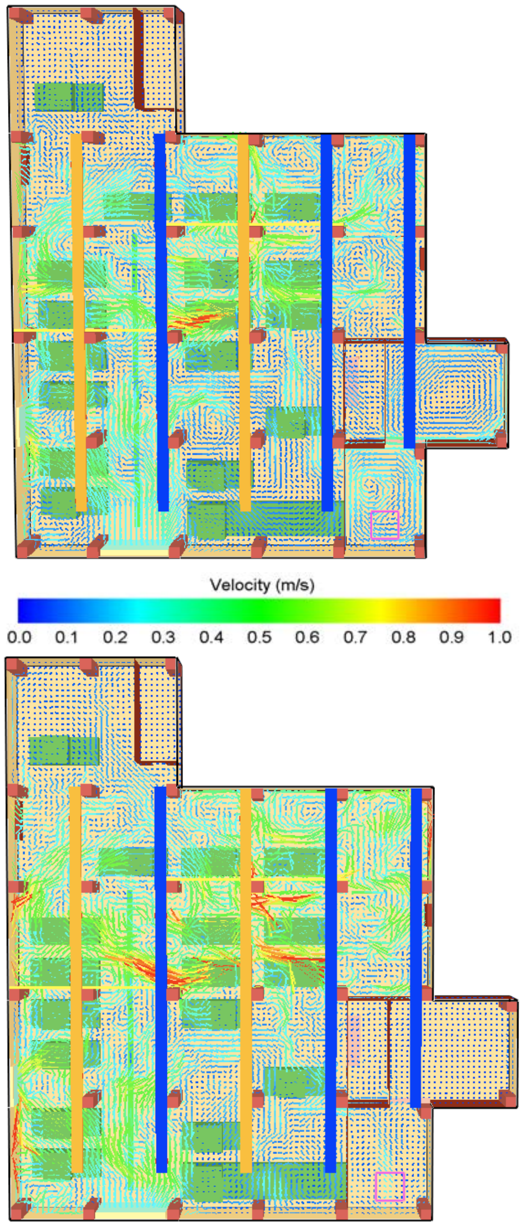

Figure 10: Predictions of gas mixture velocity vectors at a height of 1.6m above floor, 800s after the beginning of the simulation (Top: 5ACH, Bottom: 8ACH).

CONCLUSION

The levels of CO concentration in indoor environments may pose a serious health hazard for occupational safety, especially in the case of car-repair shops, where employees are exposed on a daily basis to vehicle exhaust fumes. In this work, CO production and dispersion has been investigated using both experimental and numerical simulation approaches.

Measurements of CO concentrations and ventilation flow rates have been performed in an actual medium-sized car-repair shop. In addition, a detailed numerical simulation of the developing transient flow-field has been carried out, using the Fire Dynamics Simulator CFD code. The obtained experimental data have been used to validate the CO concentration predictions. Good qualitative and, occasionally, quantitative agreement has been achieved; the complexity of the developing flow, in conjunction with the numerous simplifying assumptions employed in the simulations, render the obtained results acceptable for engineering purposes.

A numerical parametric study has been performed, investigating various ventilation air flow rates; the ensuing CO concentration levels have been compared to current occupational health legislation. In this frame, a generalized CO mass source term has been developed, based on records of the average number of vehicles entering or leaving the car-repair shop.

The ability of CFD tools to support the design or re-design of mechanical ventilation systems to improve the indoor air quality for the employees has been demonstrated. CFD results provide the designer with information regarding the developing flow and concentration fields inside the considered facility, thus allowing testing the impact of different ventilation scenarios in terms of indoor air quality.

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