Air quality in an underground garage: computational and experimental investigation of ventilation effectiveness

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Abstract

The accumulation of contaminants that comes primarily from inside the building can constitute a potential health hazard in micro-environments where people spend most of their time indoors. The present paper refers to the numerical prediction of carbon monoxide (CO) concentration inside a typical garage in Athens urban area. Specifically, the study was concerned to investigate the indoor air quality and focuses on identifying the appropriate ventilation system as an attempt to improve air quality in workplace micro-environments. The model developed for the simulation of CO levels is used in conjunction with a general-purpose CFD code, PHOENICS that can provide detailed information on the CO concentration and velocity fields in a three-dimensional configuration. The transient variation of CO concentration was simulated under different scenarios of ventilation rates. Experimental measurements on the CO level inside the garage were performed using the portable, electrochemical CO monitor (Solomat’s MPM4100). From the continuous readings, instantaneous readings were stored every 15 s by the data log system. These data were used to verify the simulation results. Finally, the CO exposure of employees and garage’s users is assessed and compared with occupational limit value and recommended public health criteria. The results show that under the proper ventilation conditions the levels of CO concentration decrease and remain below the health based indoor air quality criteria.

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1. Introduction

Air pollution is defined in many air pollution control laws as the presence of one or more contaminants, in such quantities and of such duration as they be or tend to be injurious to human life or property. Carbon monoxide (CO) is a highly toxic gas, emitted as a product of incomplete combustion of hydrocarbon-based fuels. When inhaled, CO binds reversibly with blood hemoglobin to form carboxy-hemoglobin, impairing the oxygen-transport of the blood, as well as the oxygen’s release to body tissues, causing therefore severe and even fatal asphyxiation. Despite the reported elevated CO levels, the risk of humans developing adverse health effects after exposure to CO has not been fully evaluated yet in Athens. The human exposures to CO experienced by some Athenians groups is considered a serious environmental issue [1]. However, there is an increasing demand for indoor concentration measurements, especially inside typical micro-environments with high-expected CO concentrations. The garage micro-environment has been reported as an important determinant of exposure to CO [2]. Experimental measurements of CO levels in enclosed garages were performed for the first time in the Athens urban area. It was found that there were excesses to short and long-term exposure limits to CO [3]. Insufficient or malfunctioning ventilation inside, allows contaminated air to accumulate, and pollutant concentrations to increase. This accumulation of contaminant may cause damages to the garage employees’ health, taking into consideration that exposure to CO covers all their working day. The problem of indoor air quality gives rise to questions concerning the arrangement of fresh air supply [4–7]. Processes involved in ventilation are the most important in determining the quality of indoor air. It is important to get adequate mixing of inlet air with room air, in order to obtain a uniform fresh air distribution. Models have been developed to design the mechanical ventilation in order to improve indoor air quality [8,9]. The evolution, during the last decade, of a large number of multi-dimensional, multiphase models and solutions techniques for simulating fluid flow and concentration distribution.

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dispersion processes, coupled with the development of modern high speed/flow cost computers and work stations has made it possible to use new computational fluid dynamics methods to assess the effectiveness provisions in buildings. A numerical computational model of the flow and concentration behavior in enclosures is a helpful tool to predict the velocity fields as well as the distribution of concentration levels generated inside the garage [10,11]. The advantages in using numerical methods to analyze ventilation performance have been pointed out be Murakami [12] and Liddament [13]. Because the potential health effects of CO on human beings are quite significant, keeping the CO level below a certain value is a matter of concern. Control of pollutant at the source is the most effective means of promoting indoor air quality. An adequate supply of outdoor air is essential to dilute indoor pollutants.

The subject of the present study is the mathematical simulation of CO levels measured inside the garage as well as the assessment of exposure to CO for garage employees and garage users under different ventilation conditions. The entire garage is treated as a single zone. The main ventilation design problem is to find the appropriate ventilation flow that guarantees that concentrations of pollutants are kept below the acceptable threshold limit. The model developed for simulation purposes is used in conjunction with a general-purpose CFD (computational fluid dynamics) code that involves the partial differential equations governing CO levels and ventilation conditions prevailing in three-dimensional buildings of any geometrical complexity. The results are presented in the form of velocity vectors and in CO concentration versus time diagrams. Experimental and numerical results are both compared each other as well as with the occupational limit value and recommended public health criteria.

### 2. Experimental method—measuring procedure

A Solomat’s MPM4100 environmental monitoring system CO portable monitor was employed to measure CO concentration in a typical central garage [3]. The monitor is equipped with the amperometric two-electrode sensor 1212GS to detect the electrons given up by the CO molecules. The electro-oxidation of the 1212GS to detect the electrons given up by the CO molecules for non-steady flow, the equations for continuity, velocity components, and chemical concentrations can be expressed in the following general conservation form for the general variable \( \phi \) [14]:

\[
\frac{\partial}{\partial t} \left( \rho \phi \right) + \nabla \cdot \left( \rho \mathbf{U} \phi \right) = \nabla \cdot \left( \Gamma_\phi \nabla \phi \right) + S_\phi
\]

where \( \rho \) is the density, \( \mu_i \) the velocity vector components, \( \Gamma_\phi \) the effective exchange coefficient of \( \phi \) and \( S_\phi \) is the source rate per unit volume.

The source rate and the effective exchange coefficient corresponding to each variable \( \phi \) solved for in this study are given in Table 1.

<table>
<thead>
<tr>
<th>Equation</th>
<th>( \psi )</th>
<th>( S_\psi )</th>
<th>( \Gamma_\psi )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuity</td>
<td>( 1 )</td>
<td>( 0 )</td>
<td>( 0 )</td>
</tr>
<tr>
<td>Momentum</td>
<td>( U_i )</td>
<td>( -\rho \psi \phi_i )</td>
<td>( \rho \psi \phi_i )</td>
</tr>
<tr>
<td>Kinetic energy of turbulence</td>
<td>( \rho )</td>
<td>( G - \rho \psi \phi_i )</td>
<td>( \rho \psi \phi_i )</td>
</tr>
<tr>
<td>Eddy dissipation rate</td>
<td>( \varepsilon )</td>
<td>( C_\varepsilon / (\kappa G - C_\varepsilon \rho \sigma^2 / \kappa) )</td>
<td>( \rho \psi \phi_i )</td>
</tr>
<tr>
<td>Concentration</td>
<td>( m_{CO} )</td>
<td>( n )</td>
<td>( \rho \psi \phi_i )</td>
</tr>
</tbody>
</table>

The magnitudes being referred in this table are: \( \mu \) the viscosity, \( \sigma \) the Prandtl number for \( \psi \) and \( G = \mu_i (\partial u_i / \partial x_j) + \rho \psi \phi_i \) the turbulence production rate. The values of the constants \( C_1 \) and \( C_2 \) are 1.44 and 1.92, respectively [14]. The buoyancy sources are included in the appropriate momentum equation.

#### 3.2. The solution method

To solve the set of the model differential equations together with their boundary conditions, a finite-domain technique is used which combines features of the methods of Patankar and Spalding (1972) [15], and Spalding (1980) [16] and a whole-field pressure-correction solver (Markatos and Pericleous, 1984) [17]. The space dimensions are dis-
cretized into finite intervals and the variables are computed at only a finite number of locations, at the so-called “grid points.” These variables are connected with each other by algebraic equations derived by their counterparts by integration over the control volumes defined by the above intervals. This leads to equations of the form:

\[ \sum_n (A \phi_n + C) \phi_P = \sum_n A \phi_n \phi_n + CV \]  

(2)

where the summation \( n \) is over the cells adjacent to a defined point \( P \). The coefficients \( A \phi_n \), which account for convective and diffusive fluxes across the elemental cell, are formulated using hybrid differencing. The source terms are written in the linear form \( S \phi = C(V - \phi) \), where \( C \) and \( V \) stand for a coefficient and a value of the variable \( \phi \). Pressures are obtained from a pressure-correction equation that yields the pressure change needed to procure velocity changes to satisfy the mass continuity. The source terms are linearized. To solve the three-dimensional flow equations the “SIMPLEST” practice of Spalding is followed, in which the finite-domain coefficients of the momentum equations contain only diffusion contributions, the convection terms being added to the linearized source term. The momentum equations are solved by a point-by-point procedure. The pressure-correction equation is solved over the whole-field. The present model is implemented in the general computer program PHOENICS [14].

3.3. Test cases considered

For the purposes of this study, a fully enclosed central garage, where the ventilation system was deactivated, is selected. Garage capacity is 110 vehicles. The emission of CO inside the garage depends on the number of vehicles entering or leaving the garage. The CO emission rate for a vehicle depends on vehicle characteristics including factors such as the age of the vehicle, the engine power, vehicle operating mode, vehicle speed and the level of the vehicle maintenance. The amount of CO emissions generated inside depends also on the amount of time a vehicle spends in different parking modes [4].

In the present investigation, a volumetric emission rate of 0.4–1 l s per car was assumed [18]. This value represents hot emission conditions. Hot starts are common in this garage where cars are usually parked for short periods. The total number of cars entering or leaving the garage per 15 min intervals was recorded. The total length of time for the car operation inside the garage is 1 min. With those data, the transient source strength every 15 min was calculated. These data which represent CO emission rates at the exit of the garage were used as input data for the numerical simulation of CO levels inside in the absence of ventilation system. A scenario of ventilation rate of 2 m/s was also investigated as an attempt to improve air quality inside the garage (Table 2).

The garage geometry, shown in Fig. 1, as well as the conditions, which prevail in the closed space, is given in Table 2. The reported results have been obtained using a non-uniform grid consisting of 38 cells in \( x \)-direction, 10 cells in the \( y \)-direction and 26 cells in the \( z \)-direction (Fig. 2). The solutions obtained are grid independent, guaranteed by repeated runs using finer grids.

In order to determine the variability of indoor concentration for the given garage two different scenarios were
investigated and compared with the experimental measured CO concentration, one without ventilation system and one with the existence of a mechanical ventilation system.

3.4. Boundary conditions

- At the inlet a fixed mass flow rate is specified as well as the values of velocity.
- At walls, wall functions are used to calculate the wall shear stress.
- The CO concentration, released by cars, is appropriately modeled as mass source.
- The air, which is induced to the garage, is considered clean from CO.

3.5. Grid dependence and computer storage

The calculations have been performed on an Origin 200 Workstation (Silicon Graphics), with a CPU R 10000 processor and main memory 256MB.

3.6. Convergence and time requirements

A converged solution was defined as one that met the following criterion for all dependent variables:

\[
\max_{\phi} | \phi^n + 1 - \phi^n | < 10^{-3} \tag{3}
\]

between sweeps indexed by \( n \) and \( n + 1 \). To improve convergence, an under-relaxation scheme was used. Relaxation of the “false transient” type was used for the three velocity components with a value of the “false time step” set to 0.1. For pressure and CO “linear” relaxation was used with a value of 0.1 and 0.01 respectively. A typical CPU time for a run with the above grid (9880 cells) is 30 min for full convergence.

4. Results and discussion

Fifteen-second continuous readings recorded inside the garage were used to construct longer period TWAs concentrations. The data are summarized in Table 3 in terms of 5, 15, 30 min, 1 and 8 h maximum values. The assessment of indoor air quality was made in relation to the various relevant standards. The Greek occupational limit values have been adopted as the major reference as far as garage employee’s exposure is concerned. Greek occupational law follows the EU’s guideline with respect to CO exposure. The concentrations found in the underground and exit-site represent the exposure not only for the garage occupants, but also for the clients when they park the car by themselves. Thus, WHO air quality guidelines are also presented in this Table.

This study focuses primarily on the validation of the model used as well as investigates the ventilation effectiveness. Some indicative results are given in the following
Table 3

<table>
<thead>
<tr>
<th>Monitoring site</th>
<th>5 min</th>
<th>15 min</th>
<th>30 min</th>
<th>1 h</th>
<th>8 h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inside</td>
<td>92.1</td>
<td>84.3</td>
<td>67.3</td>
<td>57.3</td>
<td>43.2</td>
</tr>
<tr>
<td>Exit</td>
<td>163.6</td>
<td>102.2</td>
<td>68.5</td>
<td>62.2</td>
<td>41.7</td>
</tr>
</tbody>
</table>

Air quality criteria for CO

- Greece (occupational) – 300 – – 50
- ACGIH TLV – – – – 25
- NIOSH REL 200 – – – 35
- OSHA PEL 200 – – – 50
- WHO – 87 52 26 9

Figures. In Fig. 3, the air velocity vector at \( x-z \) cross-section is given for the garage without ventilation system. In Fig. 4, the air velocity vector at \( x-z \) cross-section is given for the garage under consideration but with the existence of a ventilation system. In Fig. 5, the CO concentration versus time is given for both experimental and numerical data, for the first measurement point and also for the second measurement point. For both the cases, no ventilation system is considered. Finally, in Figs. 7 and 8, CO concentration versus time is given for numerical data, in the absence of ventilation and when a ventilation system is applied, for the ‘inside’ and ‘exit’ sites, respectively.

As it is shown in Fig. 3, the air velocity vector at \( x-z \) cross-section is given for the garage with no ventilation system applied, at the human level of 1.8 m height. As it is observed, a minimum value of 0.00006 m/s and a maximum value of 3.11 m/s is governed in the field. Near the entrance and on the ramp for the lower underground level the air velocity has the higher values in contrast with the main field where the velocity values are negligible.

In Fig. 4, the air velocity vector at \( x-z \) cross-section is given again for the same height but with the application of a mechanical ventilation system. As it is presented in this cross-section the velocity values are between 0.0862 and 4 m/s. As it is observed a strong vortex is created at the main field of the garage, fact that causes a better ventilation of the examined space with a velocity value of 2 m/s, value which is above the limits concerning human comfort. However, considering that the clients of the garage stays there only a few moments, it is preferable to raise the air velocity in order to enter fresh air in the garage and extract contaminated air from the space.

In Fig. 5, the CO concentration versus time is given for both experimental and numerical data, for the first measurement point, at an average human height level of 1.8 m. For this case, no ventilation system is considered. As it is shown in this diagram the numerical values of CO concentration are overestimated in comparison with the experimental data. However, it is remarkable to say that for both of them the CO concentration has the same distribution versus time. As it is observed there are high CO values between 13:00 and 14:00 h and after 15:30 h. The 15 min WHO guideline of 87 ppm is exceeded. Concerning the experimental data the Greek occupational TLV–TWA is not exceeded. However, the maximum 8 h recorded at this measurement site

Fig. 3. Air velocity field at \( x-z \) cross-section without ventilation system (m/s).
Fig. 4. Air velocity field at $x-z$ cross-section with ventilation system (m/s).

Fig. 5. CO concentration field vs. time at “exit” measurement point without ventilation system.

Fig. 6. CO concentration field vs. time at “inside” measurement point without ventilation system.
approach significantly this limit. It is 83.4% of the criterion (see Table 3).

In Fig. 6, the CO concentration versus time is given for both experimental and numerical data, for the second measurement point, at an average human height level of 1.8 m. For this case, no ventilation system is also considered. As it is shown in this diagram, the numerical values of CO concentration are overestimated in comparison with the experimental data. However, it is remarkable to say that for both of them the CO concentration has the same distribution versus time. As it is observed there are high CO values close at 10:30 h and between 13:00 and 14:00 h and after 15:30 h. These values are under the 15 min WHO guideline. In terms of Greek occupational TLV–TWA, it is not exceeded by the experimental data (see Table 3). The highest 8 h CO concentration measured at this site is 86.4% of the criterion.

In Fig. 7, the CO concentration versus time is given for both experimental and numerical data, for the first measurement point, at an average human height level of 1.8 m. For this case, again a sufficient ventilation system is considered. As it is observed the 15 min CO concentrations show a considerable reduction over time and CO levels are maintained well below the WHO guideline.

5. Conclusions

This paper deals with the simulation of CO concentration in different sites inside a typical central garage. Specifically, the study investigates the dispersion of indoor CO levels under two different conditions, with no mechanical ventilation and when mechanical ventilation of 2 m/s was applied. Experimental measurements of CO levels at the ‘exit’ and ‘indoor’ sites were also conducted and gave good agreement with the numerical results. The study was also concerned to investigate the indoor air quality. Thus, the measured results were compared with short and long-term exposure limits to CO. The results appeared to be very interesting and demonstrate that numerical solutions are very effective for ventilation design purposes. The design of an efficient ventilation system will result in a better quality of air inside buildings.
As far as short and long-term health problems are concerned CO compound, reducing CO levels in occupational spaces is an important issue. It was found that when ventilation was applicable the CO levels inside the garage fulfill the indoor air quality acceptance requirements.

References


