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# Numerical Simulation of Mechanical Ventilation and CO Distribution in Underground Garages

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## Abstract

**This study investigates the CO concentration distribution and airflow characteristics in a residential double-level underground garage under different ventilation conditions using numerical simulation. The realizable k-ε turbulence model was employed with the SIMPLE algorithm for iterative solution. Results show that natural ventilation is insufficient to effectively control pollutant levels, with CO distribution being significantly non-uniform. Under mechanical ventilation, increasing the air change rate enhances airflow uniformity, reduces CO concentrations from 6.4 to 9.6 ppm to 3.2 to 6.4 ppm, and improves pollutant removal efficiency. The findings provide practical guidance for ventilation system design in underground garage environments.**

## Keywords

**Underground Garage; CO Distribution; Numerical Simulation; Mechanical Ventilation.**

## 1. Introduction

As living standards and urbanization levels continue to rise, the number of motor vehicles has grown rapidly, leading to an increasing demand for urban parking spaces [1]. Due to limited land resources, underground garages have become the primary solution for parking. However, their enclosed structure facilitates the accumulation of vehicle emissions, among which carbon monoxide (CO) is of particular concern. During vehicle start-up, idling, and low-speed maneuvering, incomplete combustion generates high concentrations of CO, which is colorless, odorless, and highly toxic [2]. Furthermore, underground garages frequently serve as civil defense shelters during emergencies, where sustained exposure to poor air quality poses additional safety risks [3]. To maintain acceptable indoor air quality, design codes mandate mechanical ventilation systems for underground garages, typically requiring a minimum of six air changes per hour [4]. Nevertheless, in actual operation, many such systems are turned off to reduce energy costs, leaving only natural ventilation-which is largely ineffective in confined underground spaces [5]. As a result, pollutant concentrations frequently exceed safe limits, compromising both user comfort and health. Given the toxicity of CO and its direct impact on human health, understanding its spatial distribution under different ventilation conditions is essential.Numerical simulation has become a widely used tool for predicting pollutant dispersion and evaluating ventilation performance [6]. Compared with traditional experimental methods, this approach offers advantages in cost, efficiency, and the ability to visualize airflow and pollutant transport [7]. By modeling different airflow patterns, supply and exhaust configurations, and air change rates, it is possible to identify ventilation schemes that minimize CO accumulation while maintaining energy efficiency [8]. This study focuses on the spatial distribution of CO in an underground garage and investigates the influence of various ventilation schemes on pollutant control, aiming to provide practical guidance for ventilation system design and operation in underground garage environments.

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# 2. Model Development

## 2.1. Geometry Modeling

Sub-section Headings

The research object of this study is a residential double-level underground garage, with its physical model illustrated in Figure 1. The model was constructed at a 1:1 scale based on the actual garage geometry. To balance computational efficiency and accuracy, reasonable simplifications were applied during the modeling process, ensuring that the omitted details-including driveways, columns, and return air outlets-do not affect the pollutant concentration distribution, emission characteristics, or overall airflow organization within the garage.

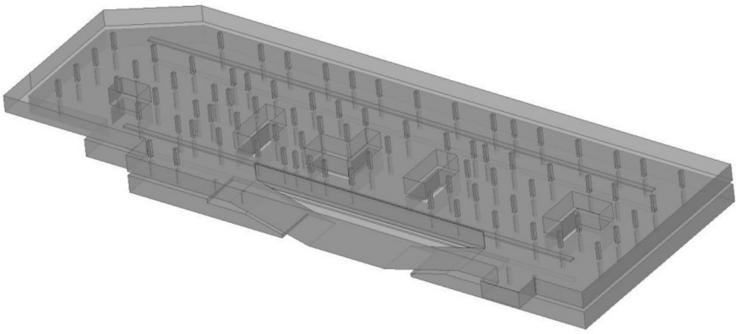

**Figure 1.** Schematic of the underground garage physical model

## 2.2. Mesh Generation

High-quality mesh generation is an essential prerequisite for ensuring the accuracy of numerical simulations, and both excessively coarse and overly refined meshes should be avoided. A mesh that is too coarse may lead to inaccurate results or even convergence failure, whereas an overly dense mesh significantly increases the computational load and prolongs the simulation time. In this study, ANSYS Meshing was employed to generate an unstructured mesh for the physical model, which is well-suited for large-scale spatial geometries. Local mesh refinement was applied at critical regions, including supply and exhaust air outlets, pollutant sources, and garage entrances and exits. The resulting mesh is shown in Figure 2.

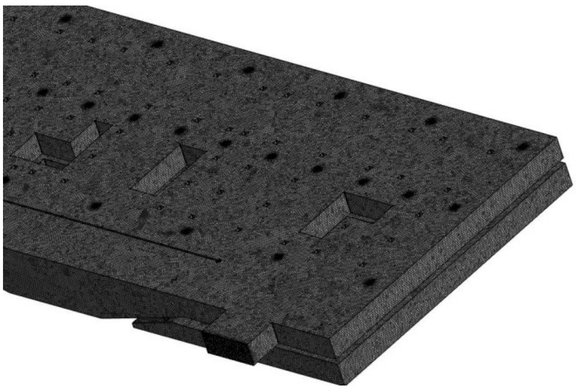

**Figure 2.** Schematic of Mesh Generation

## 2.3. Define Boundary Conditions

The airflow was treated as three-dimensional steady-state turbulent flow with air assumed incompressible. The enclosure structure was modeled as adiabatic, with indoor and outdoor temperatures set at 15°C and 5°C, respectively. Interior walls, column surfaces, and the floor

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were assigned no-slip wall boundary conditions, with the near-wall region handled using the wall function method. CO emissions were modeled as uniformly distributed area sources along the driveway, with the exhaust temperature defined as a constant temperature boundary of 40°C and the source height set at 0.3 m above the floor. Under mechanical ventilation conditions, both supply and exhaust outlets were assigned velocity inlet boundary conditions, with positive velocity values for supply air (airflow directed vertically downward) and negative values for exhaust air (airflow directed vertically upward), with airflow rates evenly distributed according to the design values.

## 3. Numerical Model Theory

This section will introduce the governing equations of indoor flow fields and several assumptions in numerical simulation.

### 3.1. Governing Equations

To obtain the spatiotemporal distribution of the indoor flow field, the finite volume method is employed to discretize the computational domain. The realizable k-ε turbulence model is used to solve the continuity equation, momentum equation, and energy equation for indoor air, and the SIMPLE algorithm is applied for iterative solution.

$$\frac{\partial(\rho\varphi)}{\partial\tau}+\mathrm{div}(\rho\mathbf{U}\varphi)=\mathrm{div}\left(\Gamma\,\mathrm{grad}\,\varphi\right)+S \tag{1}$$

In the equation: $\rho$ denotes fluid density, kg/m$^3$; $\varphi$ is a general variable that can represent the solution variables $u$, $v$, $w$, $T$; $\tau$ denotes time, s; $\mathbf{U}$ is the resultant velocity, m/s; $\Gamma$ represents the diffusion coefficient of variable $\varphi$; $S$ denotes the source term of variable $\varphi$.

### 3.2. Ventilation Case Control

To investigate the influence of different air change rates on the ventilation effectiveness of the underground garage, the existing ventilation configuration and outlet arrangement were kept unchanged, with only the system airflow rate adjusted. The existing outlet arrangement adopts a central supply and side exhaust configuration, with 16 supply outlets and 16 exhaust outlets arranged within the garage. Numerical simulations were conducted at design airflow rates determined by the air change rate method and the concentration dilution method, respectively. The CO concentration distribution characteristics within the garage under different ventilation cases were analyzed to reveal the effect of airflow rate variation on ventilation performance. In this study, three ventilation cases were established to investigate the effects of different air change rates and airflow organization patterns on indoor CO concentration.

**Table 1.** Variable control

| Case | Supply Air Volume (m$^3$/h) | Exhaust Air Volume (m$^3$/h) | Airflow Organization Pattern |
|---|---|---|---|
| A | / | / | Natural Ventilation |
| B | 33066 | 36741 | Ceiling Supply and Ceiling Return |
| C | 51256 | 56952 | Ceiling Supply and Ceiling Return |

## 4. Analysis of Simulation Results for Different Ventilation Methods

Under natural ventilation conditions, the distributions of CO concentration and velocity at a horizontal cross-section located 1.5 m above the floor corresponding to the occupant breathing zone on the second basement level are shown in Figure 3 and Figure 4.

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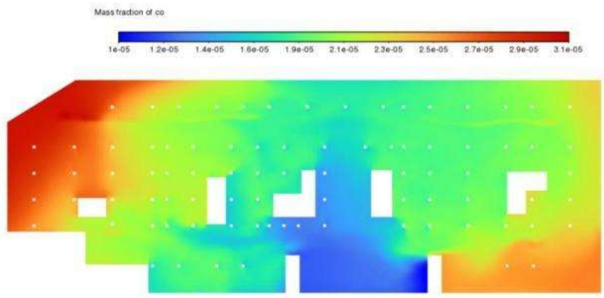
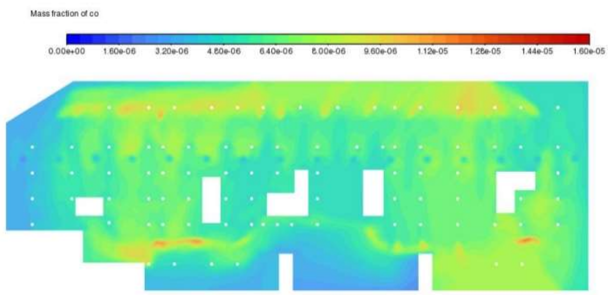
## 4.1. CO Concentration Distribution

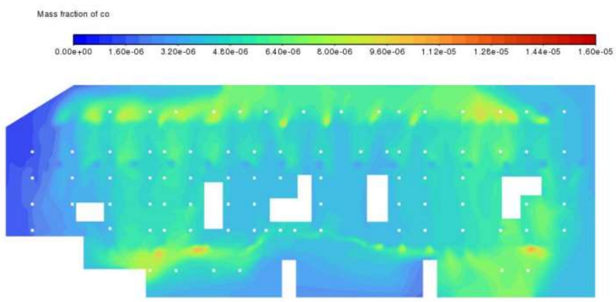
Figure 3 presents the CO concentration distribution at the 1.5 m horizontal plane of the garage under different ventilation conditions. Under natural ventilation conditions (Case A), the CO concentration distribution on the second basement level is significantly non-uniform, with relatively lower concentrations in the central region and higher concentrations along the sides and corners. The lower-central area near the ramp entrance experiences stronger local airflow disturbances due to air exchange with the first basement level, which promotes pollutant dilution and results in comparatively lower CO concentrations in this region. Under Case B, the CO concentration within the garage is predominantly distributed in the range from 6.4 to 9.6 ppm, with a minimum value of 2.35 ppm and a maximum value of 12 ppm, indicating that the corresponding air change rate is sufficient to effectively reduce the pollutant level within the garage. Compared with Case B, the CO concentration in Case C primarily ranges from 3.2 to 6.4 ppm. The area of low-concentration regions increases while the high-concentration zones near the exhaust outlets diminish, indicating that the increased ventilation rate enhances both the dilution and removal of pollutants within the garage.




(a) Case A




(b) Case B




(c) Case C

**Figure 3.** CO Concentration Distribution at the 1.5 m Elevation

## 4.2. Velocity Distribution

Figure 4 presents the velocity distribution at the 1.5 m horizontal plane of the garage under different ventilation conditions. Under natural ventilation conditions (Case A), the overall wind velocity in the second basement level is low and unevenly distributed, with most areas

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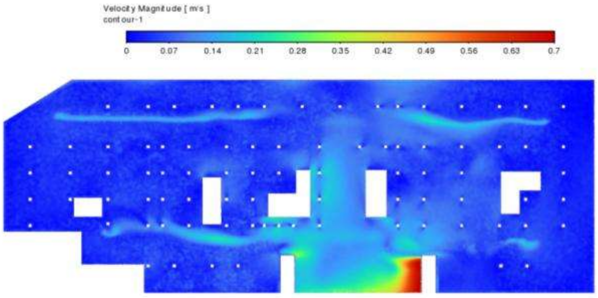
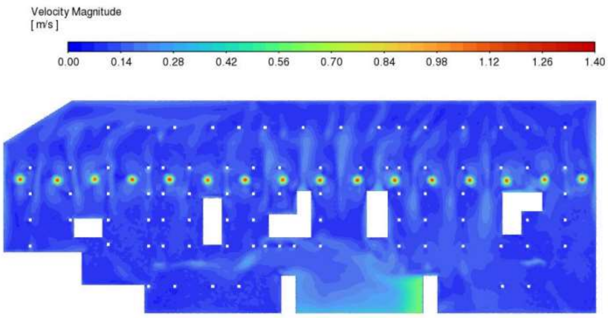
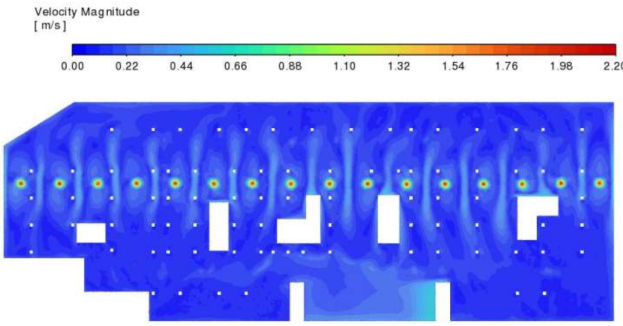
maintaining speeds of approximately 0.1 m/s. Elevated velocities are only observed in the vicinity of the ramp connecting to the first basement level, indicating that the ramp serves as the primary air exchange pathway and the main supply and exhaust route for this level. In Case B, the velocity at the 1.5 m horizontal cross-section is generally low, ranging primarily from 0 to 0.14 m/s, with a maximum velocity of approximately 1.29 m/s. This indicates that airflow disturbance is limited under this condition. Although a dominant airflow pattern from the central region toward the exhaust outlets on both sides is established, the velocities in the deeper and peripheral areas of the garage remain relatively low, with localized stagnation observed in certain zones. In Case C, as the system airflow rate increases, the supply air jet intensity is significantly enhanced, resulting in an overall increase in cross-sectional velocity, with the local maximum velocity rising to approximately 2.20 m/s. Compared with Case B, the dominant airflow pattern in the central region becomes more clearly defined, and the transport capacity toward the exhaust outlets on both sides is strengthened. The extent of low-velocity regions is reduced, indicating that increasing the ventilation rate is beneficial for enhancing both air circulation and pollutant transport within the garage.




(a) Case A




(b) Case B




(c) Case C

**Figure 4:** Velocity Distribution at the 1.5 m Elevation

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## 5. Conclusion

This study investigated the CO concentration distribution and airflow characteristics in a residential double-level underground garage under three ventilation conditions through numerical simulation. The results indicate that natural ventilation alone is insufficient to effectively control pollutant levels in enclosed underground garages, with CO concentrations showing significant spatial non-uniformity and the ramp serving as the primary air exchange pathway.Under mechanical ventilation, increasing the air change rate significantly enhances supply air jet intensity and improves overall airflow uniformity. CO concentrations are reduced from the range of 6.4 to 9.6 ppm in Case B to 3.2 to 6.4 ppm in Case C, with low-velocity stagnation regions notably diminished and pollutant removal efficiency considerably improved. These results confirm that mechanical ventilation is essential for maintaining acceptable CO levels, and a higher air change rate yields better pollutant control performance.The findings provide a practical reference for the design and optimization of ventilation systems in underground garage environments. Further research could investigate the influence of different supply and exhaust outlet configurations, as well as varied pollutant source distributions, on ventilation performance.

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