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Carbon Monoxide Concentration in the Garage of a Single-Family House– Experiment and a OneDimensional Model of Carbon Monoxide Concentration

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Carbon Monoxide Concentration in the Garage of a Single-Family House–Experiment and a One-Dimensional Model of Carbon Monoxide Concentration

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Featured Application: Based on the research carried out, this work proposes an original automatic regulation system that is intended to warn against excessive carbon monoxide concentration and to reduce the carbon monoxide concentration in the garage.

Abstract: The paper presents tests of carbon monoxide concentration in a single-car garage equipped with exhaust ventilation, while the combustion engine of a parked passenger car is operating. The main source of carbon monoxide in the garage is the internal combustion engine of a passenger car. Single-car garages are characterized by a relatively small volume, which causes the rapid accumulation of carbon monoxide inside the garage. Currently, the walls of residential buildings and garage doors are characterized by high tightness, which, when the garage door is closed and a combustion car running, may result in too little air exchange in the garage and a significant concentration of pollutants emitted by the combustion engine in the garage. The test results showed significant exceedances of the permissible values (WHO, NAAQS) of carbon monoxide concentrations both with exhaust ventilation on and off. The highest carbon monoxide concentration values (2253 ppm) in the garage were observed when the exhaust ventilation was turned off. The study also developed two one-dimensional models of carbon monoxide concentrations in a garage with the combustion engine of a passenger car turned on for the case of exhaust ventilation turned on and off. The models developed in this work can be used when designing ventilation to estimate carbon monoxide concentrations in garages based on the type of car and the number of air changes.

Keywords: garage; carbon monoxide; combustion engine; carbon monoxide modeling; indoor air pollution; air pollution health impact

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1. Introduction

Car combustion engines generate emissions of many air pollutants, such as dust (PM2.5, PM10), hydrocarbons (HC), carbon monoxide (CO), carbon dioxide (CO2) and nitrogen oxides (NOx) [1]. Carbon monoxide is particularly dangerous and has an impact on human health and life. Carbon monoxide is a highly toxic, odorless and colorless gas, slightly lighter than air, which means it easily mixes with air and spreads indoors [2,3]. Potential sources of carbon monoxide in living rooms include heat sources and devices for heating domestic hot water in which fuels are burned. Carbon monoxide is produced as a result of incomplete combustion in the absence of an adequate amount of oxygen of many fuels, such as coal, wood, fuel oil, gasoline, kerosene and gas. The danger of carbon monoxide poisoning results from the fact that carbon monoxide is a gas undetectable to humans and enters the body through the respiratory system and is then absorbed into the bloodstream. In the human respiratory system, carbon monoxide binds to hemoglobin 210 times faster than oxygen, blocking the supply of oxygen to the body, which poses a serious threat to human health and life. Carbon monoxide prevents the proper distribution of oxygen in the blood and causes damage to internal organs and, above all, damage to the brain. Acute poisoning may result in coronary failure and irreversible damage to the central nervous system [2–7].

In garages where cars are parked, the main source of carbon monoxide emissions are the internal combustion engines of passenger cars. The literature contains research results on carbon oxide concentrations in rooms where cars are parked or repaired [8–10]. In the Quebec City region [8], 33% of car repair shops and car showrooms had atmospheric CO concentrations above 25 ppm, a level considered to pose a risk of chronic health effects. In a single-car garage with a volume of 73 m^3 [9], after 20 minutes of running the car, the carbon monoxide concentration level was 253 ppm for a car without a catalytic converter and 30 ppm for a car with a catalytic converter. Research on a parked passenger car in the garage of a single-family house showed a carbon monoxide concentration of 420 ppm after 47 minutes of operation of the parked car. It should be noted that gaseous pollution in rooms is also associated with sick building syndrome (SBS) [11,12]. In multi-car garages, the concentration of carbon monoxide depends primarily on the number of cars and the type of ventilation installation in the garage [13]. Carbon monoxide emitted by cars affects the level of carboxyhemoglobin (HbCO) in the blood of employees operating garages in city centers [14]. According to the research presented in [15], most men's deaths caused by carbon monoxide, not related to fires, took place in garages or outbuildings.

CFD (Computational Fluid Dynamics) programs are used to determine three-dimensional problems in order to accurately simulate the concentration of air pollutants in rooms [16–18]. One-dimensional models are also used in air quality simulations [19–21], which can be used in automatic indoor air quality control systems [22–24].

Smaller single-family houses are currently being built in Poland due to the increasing costs of building houses and purchasing a building plot, as well as the increase in building operating costs [25,26]. Smaller houses are also most often characterized by garages with small volume. The source of carbon monoxide is particularly dangerous in rooms with a small number of air changes and in rooms with a small volume. The aim of the publication is to present the results of research on CO concentrations in the garage of a single-family building when the combustion engine in a passenger car is turned on for various air exchanges in the garage. The study also developed a one-dimensional model for estimating the carbon monoxide concentration in a small garage of a single-family building equipped with exhaust ventilation. The results of the experiment and analysis contributed to the development of an automatic signaling and control system for carbon monoxide in garages of single-family houses. It should be emphasized here that the main research on air pollution in garages focuses mainly on dust [27–29], VOCs [29–33] and carbon dioxide [33,34].

The following sections discuss the rest of this article. Chapter 2 describes in detail the single car garage of a single-family house. Then, the methods of measuring the concentration of carbon monoxide, humidity and temperature in the garage air are described. Section 4 presents the numerical results of carbon monoxide concentration measurements in the garage for various exhaust ventilation flows and their discussion. Additionally, an automatic regulation system was proposed to protect the garage against an increase in carbon monoxide concentration. Section 5 of the publication is a developed model of carbon monoxide concentration based on the measurement results from section 4. The last part describes the conclusions of this work.

2. Subject of This Research

The research was carried out in a single-car garage located in Bialystok, eastern Poland, in a temperate climate. The garage room has a small volume of 43.5 m^3. The length, width and height of

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the garage are 5.74 m, 3.75 m and 2.02 m, respectively. The garage area is 21.53 m^2. The garage is equipped with one triple-glazed window with dimensions of 1.42 m x 64 m and one garage door with dimensions of 2.38 m x 209 m. The experiment was carried out with the garage door closed and the window closed. The garage is equipped with exhaust ventilation with a diagonal fan installed. The walls of the building are made of 0.25 m thick ceramic blocks with a 0.10 m thick layer of Styrofoam.

Measurements were made in February and March 2024. The source of carbon monoxide was a hatchback passenger car equipped with a three-cylinder engine with a displacement of 1.198 cm^3.

3. Materials and Methods

Carbon monoxide, even at low concentrations, becomes dangerous to human health and life. A carbon monoxide concentration of 12,000 ppm can lead to death even in a few minutes [35,36]. The WHO permissible concentration of carbon monoxide over an 8-hour period is 35 ppm [37]. Carbon monoxide concentration at the level of approximately 200 ppm, a person begins to feel symptoms related to poisoning [35,36].

Recommended limits of concentrations of carbon monoxide in indoor air present in Table 1 [37–39].

Air parameters were tested using a Testo 435 and Testo 350 recorder with the following accuracy parameters: carbon monoxide ±2ppm of reading for the range from 0.0 to 39.9 ppm, ±5% of reading for the range from 40.0 to 2000 ppm, ±10% of reading for the range from 2001 to 10000 ppm, temperature ±0.2°C from 0 to +50°C and relative humidity ±2% from 2 to +98%. Recording was performed every 1 minute and the recorded value was the arithmetic average from the samples taken every 5 seconds, i.e. from 12 measurements. Stored data downloaded to a laptop at the end of each measurement series in the garage using software provided by Testo. There were no people or pets in the garage during the experiment.

Table 1. Recommended limits of concentration of carbon monoxide in indoor air [37–39].

Recommended CO Concentration (ppm); (%)	Authority
≥6 (0.0006%)	WHO, 2021 [39] Ambient air (24 h)
≥9 (0.0009%)	NAAQS (EPA) [37], Ambient air (8 h)
≥25 (0.0025%)	WHO, 2000 [38] Ambient air (1 h)
≥35 (0.0035%)	NAAQS (EPA) [37] Ambient air (1 h)
≥90 (0.0090%)	WHO, 2000 [38] Ambient air (15 min)

After turning on the measuring equipment and starting recording air parameters, the combustion engine of the car parked in the garage was started, then the garage was quickly left and the garage door was closed. After an hour of the experiment, the entrance gate was opened and after 30 minutes, when the carbon monoxide concentration was zero, the recording of air parameters was stopped. Measurements were made in two locations in the garage, at the front and rear of the car at a height of 1 m [40]. The one-hour measurement recording time was performed at an interval of one minute.

In order to obtain different air exchange values in the garage, the air flow in the exhaust ventilation duct was regulated by changing the rotational speed of the exhaust fan rotor. The rotational speed of the fan rotor is changed by changing the voltage on the fan's electric motor, which is regulated by an autotransformer. The average velocity measurement in the exhaust grille was performed using a Testovent 417 measuring funnel with an accuracy of ±0.1 m/s. The volume flow in the exhaust duct was determined as the product of the average velocity and the cross-sectional area of the measuring funnel, then the number of air changes in the garage was determined from the quotient of the volume flow and the volume of the garage. Before measuring the air parameters, the garage was ventilated by opening the garage door for one hour. After ventilating the garage, the carbon monoxide concentration inside and outside the garage was zero. All measurement series

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presented in the publication start from the moment the combustion engine is turned on in a car parked in the tested garage. The car's combustion engine was turned on when the engine was cold.

4. Results and Discussion

Table 2 shows the numbers of measurement series, measurement duration, average temperatures and relative humidity values in the garage, the number of air changes and average and maximum values of carbon monoxide concentration in the analyzed garage. In measurement series No. 1, measurements were made without ventilation, with the supply fan turned off and the exhaust duct closed. Due to the permissible standards [38] of carbon monoxide concentrations in rooms where people stay, all one-hour average values of the measurement series do not meet the WHO assumptions [38].

Table 2. Parameters of the measurement series: measurement duration, average temperature and relative humidity, number of air changes in the garage, average and maximum concentrations of carbon monoxide in the air.

No. measurement series	Measurement duration	Average internal temperature	Average relative humidity	Number of air changes per hour	Average CO concentration over the entire (1h) measurement period $C_{exp(avg)}$	Average CO concentration over 15 minutes $C_{exp(avg)\_15}$	Maximum value of CO concentration $C_{exp(max)}$
-	min.	°C	%	1/h	ppm	ppm	ppm
series 1	60	8.86	83.45	0	1151	350	2253
series 2	60	10.59	88.05	6	277	163	356
series 3	60	11.86	82.10	8	223	150	265
series 4	60	12.11	88.30	10	177	125	226
series 5	60	12.09	54.60	17	113	95	142
series 6	60	11.24	47.95	37	55	58	85
series 7	60	9.97	77.31	73	29	24	48

In the case of a fifteen-minute measurement period, only series 6 and 7 meet WHO standards [38] in terms of carbon monoxide concentrations. In the case of the NAAQS standard [37], only the 7 series meets the guidelines for permissible indoor concentrations for a one-hour interval.

Figure 1 shows the relationship between average hourly and maximum carbon monoxide concentrations as a function of the number of air changes for the range of air changes from 6 to 73 1/h for measurement series with ventilation turned on (series no. 2-7). The relationship between average hourly and maximum carbon monoxide concentrations as a function of the number of air changes in the garage can be approximated by a power function. As the number of air changes in the garage decreases, the concentration of carbon monoxide in the garage increases.

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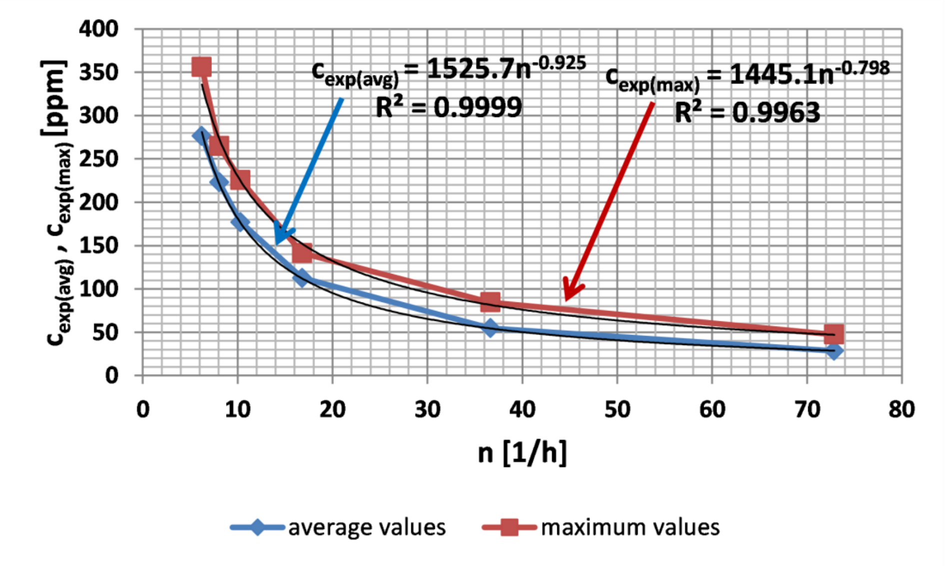

Figure 1. Dependence of average hourly and maximum carbon monoxide concentrations as a function of the number of air changes for measurement series with ventilation turned on.

Figure 2 shows the dependence of carbon monoxide concentration as a function of time and the number of air changes in the garage. With the ventilation turned off (series no. 1), during the 60-minute measurement, a linear increase in carbon monoxide in the garage was noticed, which did not stabilize in this time interval. After 60 minutes, the concentration of carbon monoxide was approximately 2253 ppm, which constitutes a direct threat to human life [36,37]. In the case of operating exhaust ventilation (series 2-7), carbon monoxide increases first, and then the carbon monoxide concentration in the garage stabilizes to a constant value. The stabilization time depends on the number of air changes. The stabilization time of carbon monoxide concentration decreases with more air changes in the garage. In the first few minutes of the measurement (Figure 2), an increase and then a decrease in the carbon monoxide concentration in the garage was noticed, which is caused by starting the cold combustion engine of the car. Starting a cold engine generates a local increase in carbon monoxide concentration, which is caused by the low initial fuel combustion temperature in the engine [41]. The trends in carbon monoxide concentration changes in the garage (Figure 2) for both ventilation on and off are similar to the trends in carbon monoxide concentrations presented in the publications [9,10,19]. The value of carbon monoxide concentrations depends primarily on the number of air changes in the garage, the size of the internal combustion engine and additional optional filters located in the car's exhaust system [19]. In the case of multi-car garages, the carbon monoxide concentration in the room where cars are parked depends primarily on the current number of parked cars [13]. Due to the high traffic of cars in multi-car garages, the trends in carbon monoxide concentration in multi-car garages do not stabilize [13], as in the case of single-car garages in single-family buildings. It should be emphasized that in the garage examined, the only source of carbon monoxide was the combustion engine of a passenger car. In garages, additional sources of carbon monoxide may be boilers [18], power generators [19] and cigarette smoking [42].

Figure 3 shows the impact of opening the external garage door on the carbon monoxide concentration in the garage when the combustion engine of a passenger car is running. The car was parked with its back to the garage door. In the first time interval (1), in the parked car in the garage, the engine was turned off and the garage door was open. During this period, the carbon monoxide concentration was 0 ppm. After six minutes, the car engine was turned on and the carbon monoxide concentration in the next six-minute period (2) was approximately 14 ppm. After closing the garage door, the carbon monoxide concentration began to rise rapidly (3) and after another 8 minutes (3) it reached 290 ppm. Twenty minutes after the start of the experiment, the garage door was opened and the engine was turned off, which resulted in a sharp drop in carbon monoxide concentration to zero

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in the 27th minute of the experiment. The test results (Figure 3) show how important it is to open the garage door before starting the car's combustion engine.

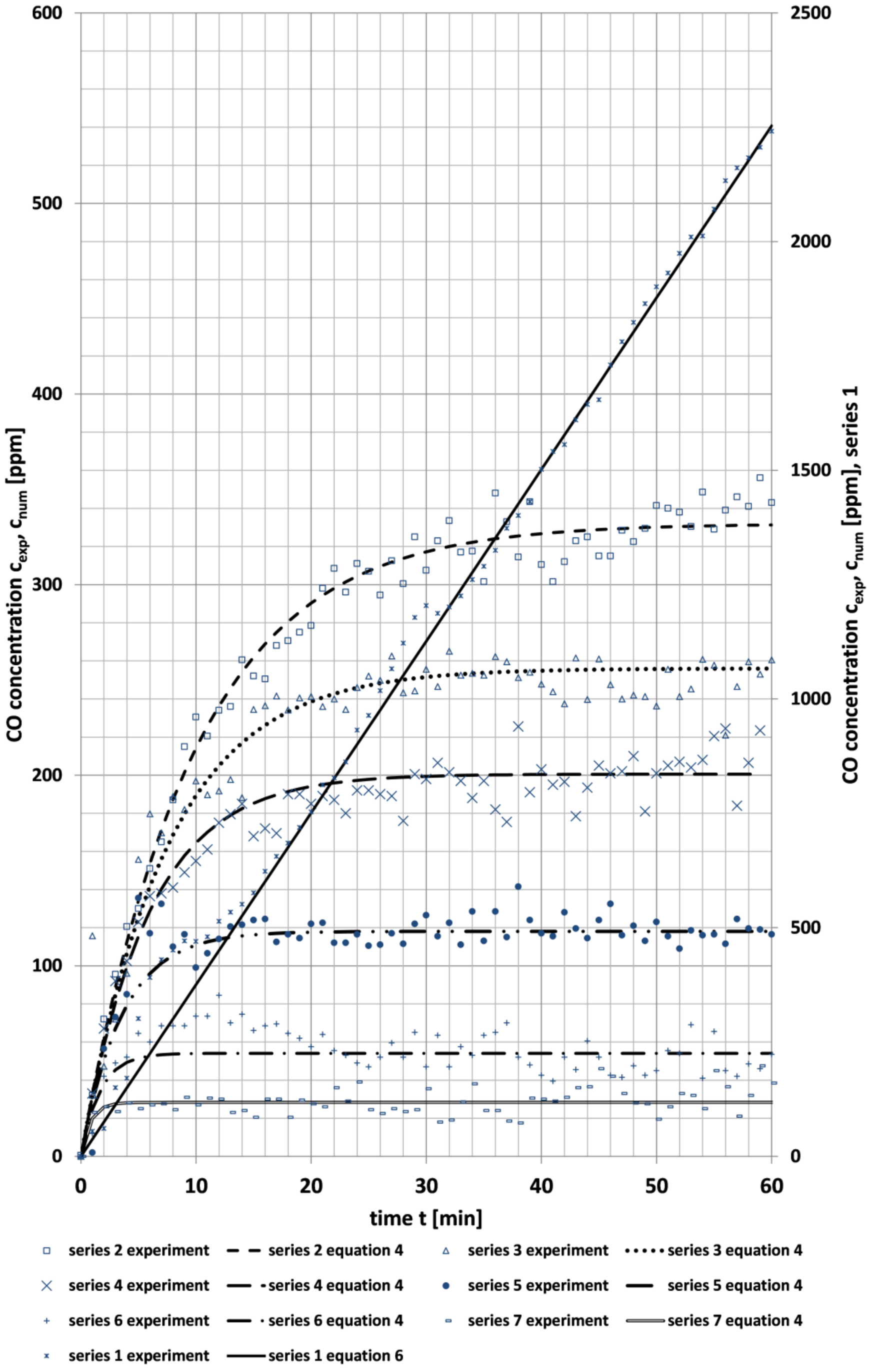

Figure 2. Carbon monoxide concentration as a function of time – comparison with the model.

The basic protection commonly used and recommended [15] as protection against carbon monoxide poisoning is carbon monoxide detection sensors combined with an alarm. When the acoustic carbon monoxide alarm goes off, leave the room quickly.

Based on the research conducted, an automatic signaling and control system for carbon monoxide in garages of single-family houses was proposed (Figure 4). The system consists of a regulator (1), a carbon monoxide sensor (2), an exhaust fan (3) connected to the exhaust ventilation duct (4), an acoustic alarm (5) and an electric actuator (6) that opens the garage door (7). If a significant concentration of carbon monoxide is detected by the carbon monoxide sensor (2), the fan (3) is turned

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on at the maximum rotor speed, the alarm is activated by the acoustic generator (5) and the garage door (7) opens using the electric actuator (6).

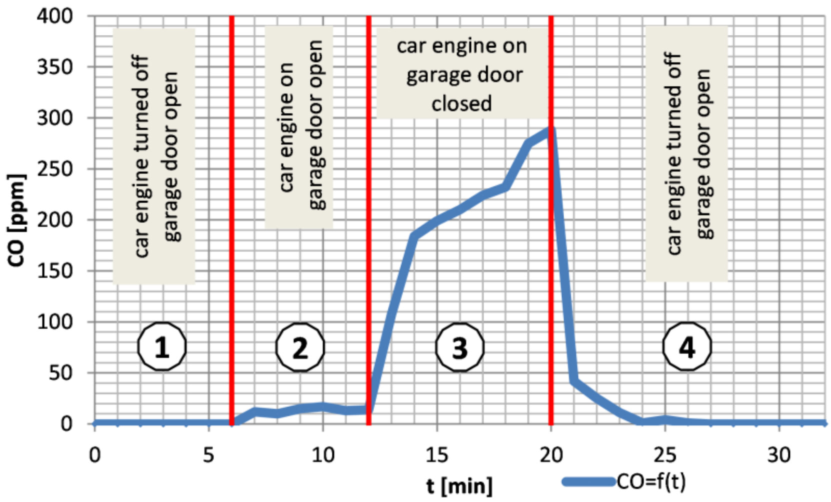

Figure 3. Carbon monoxide concentration as a function of time - the impact of opening the garage door on the carbon monoxide concentration when the combustion engine in a car is running.

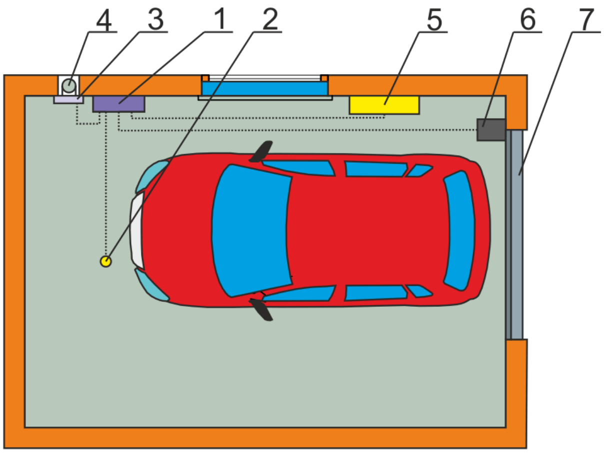

Figure 4. Schematic diagram of the garage protection system against carbon monoxide: 1- regulator, 2 - carbon monoxide sensor, 3 - exhaust fan, 4 - exhaust ventilation duct, 5 - acoustic signal, 6 - electric actuator, 7 - garage gate.

4. One-Dimensional Model of Carbon Monoxide Concentration in a Garage

The balance of carbon monoxide concentration in the garage consists of carbon monoxide supplied from outside c_a or carbon monoxide c_i removed from the garage through the supply and exhaust ventilation and carbon monoxide Q_e generated by the internal combustion engine of the car located inside the garage:

$$V\frac{dc}{dt} = nV(c_a - c_i) + Q_e, \tag{1}$$

where: t [h] is the time, V [m^3] is the volume of the garage, and n [1/h] is the number of air changes in the garage.

The concentration of carbon monoxide in clean, fresh outdoor air is small and will be ignored in further calculations (c_a=0), therefore equation (1) can be written in the following form:

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$$V\frac{dc}{dt} = -nVc_i + Q_e\,, \tag{2}$$

After integrating equation (2), a model of the change in carbon monoxide concentration as a function of time t was obtained:

$$c_{num} = \frac{Q_e}{nV} + \left(c_{t=0} - \frac{Q_e}{nV}\right)e^{-nt}\,, \tag{3}$$

where: $c_{t=0}$ [ppm] is the initial concentration of carbon monoxide in the garage.

Assuming that the garage was ventilated before the measurement, the initial concentration of carbon monoxide can be assumed to be negligible ($c_{t=0}$ [ppm]), therefore model (3) can be simplified to the following form:

$$c_{num} = \frac{Q_e}{nV}\left(1 - e^{-nt}\right), \tag{4}$$

If the exhaust ventilation fan in the garage is turned off (n≅0), formula (1) takes the following form:

$$V\frac{dc}{dt} = Q_e\,, \tag{5}$$

After assuming a zero initial value of carbon monoxide concentration (c_a=0) for t=0 and integrating equation (5), a model for a garage with exhaust ventilation turned off was obtained in the form of a linear function:

$$c_{num} = \frac{1}{V}Q_e t\,, \tag{6}$$

The relative error of models (3) and (6) was determined according to the following formula:

$$\delta c_{num} = \left|\frac{c_{\exp} - c_{num}}{c_{\exp}}\right| 100\%\,, \tag{7}$$

where c_{exp} is the carbon monoxide concentration measured in the garage, and c_{num} is the carbon monoxide concentration determined using equation (3) or (6).

The average relative error of the model for all measurement series was 8.98%. A graphical comparison of the results from the model and experiment is shown in Figure 2. Carbon monoxide change trends are similar to those determined from 3D models (CFD) [17,18]. First, the carbon monoxide concentration increases, and then the carbon monoxide concentration stabilizes [43].

The developed algorithm can be used to estimate the carbon monoxide concentration in the garage, which should be the basis for designing garage exhaust ventilation in single-family buildings.

5. Conclusions

The research results indicated a significant problem of high carbon monoxide concentration in a small garage in a single-family building with a parked car and the combustion engine running. If exhaust ventilation is turned off and the garage door is closed, the carbon monoxide concentration increases linearly over a one-hour period to the value 2253 ppm. In the case of a small garage with the exhaust fan turned off, a dangerous to human life carbon monoxide concentration (376 ppm) was reached after just five minutes. When ventilation is turned on, the concentration of carbon monoxide stabilizes, but it does not reach a safe level of carbon monoxide concentration for human health. The results of testing the carbon monoxide concentration in the garage indicated that carbon monoxide should be taken into account when designing the efficiency of exhaust ventilation in garages.

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In this work developed the carbon monoxide concentration model in the garage in a single-family house. The average relative error of the model was 8.98%. The model developed can be implemented in automatic control regulators for exhaust ventilation in the garage.

Very good carbon monoxide reduction effects were achieved by completely opening the garage door. The electric actuator controlled by the created model, that opens the garage door can be used as an actuator in an automatic regulation system to reduce the accumulated carbon monoxide in the garage in an emergency.

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Conflicts of Interest: The authors declare no conflicts of interest.

Nomenclature

c_a	concentration of carbon monoxide supplied from outside to the garage (ppm)
c_i	concentration of carbon monoxide removed from the garage (ppm)
$c_{t=0}$	initial concentration of carbon monoxide in the garage (ppm)
n	number of air changes (1/h)
t	time (h)
Q_e	carbon monoxide generated by the internal combustion engine of a car in a garage (μdm^3/h)
V	garage volume (m^3)

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