NUMERICAL AND EXPERIMENTAL ANALYSIS OF CAR EXHAUST POLLUTANT DISPERSION

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Abstract

The aim of the paper is to compare results obtained by experiments and numerical analysis for vehicle exhaust pollutant emissions and concentrations in urban area. Special attention was paid to problems of vehicle pollutant emission and dispersion caused by cold start. For description of emission sources a multi-point model was applying. In the model every vehicle is treated as a single moveable and changeable source of pollutant emission. The finite volume method was used to discretise equations describing the process of pollutant dispersion. Data on emission of exhaust gas components were obtained by measurements. Measurements were also carried out in order to verify the assumed model of dispersion and method of its discretisation. The paper presents and discuss results of calculation and experiment. Satisfactory compatibility of calculation results and measurements was achieved.

1. Introduction

Estimating the influence of our infrastructure, and in particular of vehicles, on the state of our environment is the subject of much current research. Emphasis has been laid on the problem of assessing the air quality near main roads. What, however, still remains open is the problem of assessing emission and dispersion of pollutants in urban areas such as parking zones and car parks themselves. It is thought that emissions as a result of vehicle motion in and around large car parks can represent a danger to the environment; this is reflected in legal regulations such as §589 of the Polish Statute Book 93/1998. Such areas require us to take into account in models the emission and dispersion of noxious exhaust gases released into the atmosphere during cold start. A large amount of vehicle motion with cold or insufficiently heated engines over relatively short intervals is a source of significant emissions; in unfavourable weather conditions the concentrations of certain noxious exhaust gases can be very high. This problem was also the subject of the latest papers [1,2,3].

In order to define exactly the amount of exhaust gas pollutants emitted by motor vehicles, it is necessary to specify two sets of data: data concerning conditions of vehicle motion and data concerning exhaust gas pollutants produced in those conditions. This approach means determining individual emission characteristics for a given vehicle travelling in defined conditions. Such a solution can be attempted on the micro-scale, but it is essential to take into consideration the uniqueness of conditions of motion (including ambient temperature and engine temperature) and the number and heterogeneity of cars. Cars differ in features such as type of engine, emission standards met by the car, and engine capacity. These parameters have a decisive effect on the amount of exhaust emissions; this also makes it necessary to gather and use sets of data containing a very large quantity of data and parameters. As a result, defining emissions as a function of all these parameters presents a considerable problem [1,4,5].

The problem of estimating pollutant emissions from cars during cold start and motion while engine and catalyst are heating up has been variously reflected in computational methods. They cannot be analysed using universal engine characteristics, which are determined after tests on fully heated engines. The simulation of cold engine operation by artificially reducing coolant
temperature does not correspond to conditions of real engine operation immediately after start. Nor can operation of a cold catalyst be deduced from such tests. It is important to realise that phenomena during cold start and heating of engine are a transient function of many variables, including time of operation, speed of motion, load and ambient temperature. That’s why, the individual emission characteristics appropriate for cold start and the motion of cars during experiments were obtained by measurements on a chassis test stand in BOSMAL Research and Development Centre in Bielsko-Biała.

2. Numerical model

Mathematical description of dispersion process was based on Euler equation in the following form [1,9,10]:

$$\frac{\partial \phi}{\partial t} + \frac{\partial}{\partial x^{(i)}} \left( U^{(i)} \phi \right) + \frac{\partial}{\partial x^{(2)}} \left( U^{(2)} \phi \right) + \frac{\partial}{\partial x^{(3)}} \left( U^{(3)} \phi \right) =$$

$$\frac{\partial}{\partial x^{(i)}} \left( \mu^{(i)} \frac{\partial \phi}{\partial x^{(i)}} \right) + \frac{\partial}{\partial x^{(2)}} \left( \mu^{(2)} \frac{\partial \phi}{\partial x^{(2)}} \right) + \frac{\partial}{\partial x^{(3)}} \left( \mu^{(3)} \frac{\partial \phi}{\partial x^{(3)}} \right) + f - \sigma \phi$$

(1)

where:

- $\phi$ – concentration of pollutants at coordinate point $(x^{(i)}, x^{(2)}, x^{(3)})$,
- $U$ – vector of wind speed with components: $U^{(1)}, U^{(2)}, U^{(3)}$
- $\mu^{(1)}, \mu^{(2)}, \mu^{(3)}$ – eddy diffusivity in directions $x^{(1)}, x^{(2)}, x^{(3)}$ respectively,
- $f$ – rate of pollutant emission from source per unit volume,
- $\sigma$ – coefficient of pollutant absorption (settlement) of pollutants.

The above equation describes dispersion (advection and diffusion) of any pollution dispersed in accordance with some assumptions. The finite volume method was used to discretise equations describing the process of pollutant dispersion [1,7,8]. This method needs also some algorithms done to obtain numerical stability, which has been applied in model. A meteorological pre-processor, based on relationships resulting from the Monin-Obukhov theory, was used to define eddy diffusivity and profile of air speed in the lower layer in the atmosphere [1,6].

3. Description of the experiment

Experiments were carried out in order to verify the correctness of algorithms and programs for analysing dispersion of pollutants in open domains. The experiment chosen for detailed description below is that characterised by acceptable stability of the atmosphere and of the measuring track. Results of experiments and calculations for concentrations of carbon monoxide, hydrocarbons and nitric oxides are given.

Ten identical passenger cars with a gasoline engine of 1.2 dm$^3$ capacity were used in the experiment. The engines, oil and coolant were the same temperature as the ambient temperature ($4^\circ$C). The points of emission were moved 2 metres in the opposite direction to that of vehicle motion. Cars remained stationary for the first 10 seconds after the engine was started. Then they set off simultaneously and travelled approximately along the sides of the rectangle marked on Fig.1 in bold lines, at a steady speed of around 2 m/s. Motion was anti-clockwise and lasted
about 5 minutes. Emission and concentration of pollutants were measured using an FISCHER-ROSEMOVNT NGA 2000-MLT gas analysers.

Concentrations were measured at a height of 0.5 m at points marked S₁ and S₂ in Fig.1. The HC and NOₓ emission characteristic (appropriate for cold start and the motion just described were obtained by chassis test stand in BOSMAL) is shown in Fig.2 and Fig.3 which clearly demonstrates that the maximum emission of exhaust gases occurs in the interval of \(0,60\) s after engines were started; this will be of significance for the results of calculations and measurements.
Emission characteristic of CO for vehicles used in the experiment and results of measurements of CO concentrations are presented in [1]. Experiments were carried out with an angle of inclination of the wind vector $\alpha \equiv 225^\circ$ to axis $x^{(1)}$ and speed approx. 1 m/s at a height of 2 metres. After about 12-13 s there is a sudden increase of gases in sensors S1 and S2; this is due to the form of emission characteristics (Fig. 2,3) and the time necessary for displacement of the pollutant plume from the right-hand side of the domain as a result of advection. After about 70 s, when rates of emission from the vehicles are much lower, concentrations gradually decrease in all cases, as can be seen in Fig. 4.

**Fig. 4. CO concentration measured by sensors S1 and S2**

### 4. Numerical calculations and comparison of results

Numerical calculations to verify the correctness of the models and algorithms of solving equations of dispersion were carried out using the meteorological pre-processor described in [1,6]. As there was considerable cloud cover on the day of experiments, we assumed neutral atmospheric conditions [6,10]. Averaged wind speed (over the duration of the experiment) and temperature were determined at a height of 2 m by using a thermo-anemometer. Ambient pressure was obtained from a weather station. Parameters for the pre-processor and the method of modification vertical $U^{(3)}$ component of the field of wind speed near the building was described in detail in [1]. The domain investigated was divided into elements with a volume of $0.5 \text{ m} \times 0.5 \text{ m} \times 0.1 \text{ m}$. It is assumed that the sources of emission have the characteristics...
obtained by measurement (Fig. 2, 3) and are at a height of 0.29 m above the ground. Calculations were carried out according to the two-cycle scheme of decomposition with an integration step of $\Delta t = 0.1\,s$. Boundary conditions were assumed to be those in reality, i.e. reflection from planes was assumed: for $x^{(1)} = 0$ and $x^{(3)} = 0$ and conditions $\phi = \phi_0$ on other sides. Results of calculations of HC and NOx concentrations for sensors S1 and S2 are shown in Fig. 5 and Fig. 6 for HC and Fig. 7 and Fig. 8 for NOx, together with the results of measurements.

Fig. 5. HC concentration for sensor S1 - experiment (e1) and calculations (c1)

Fig. 6. HC concentration for sensor S2 - experiment (e2) and calculations (c2)

Fig. 7. NOx concentration for sensor S1 - experiment (e1) and calculations (c1)
Comparison of calculations and measurements indicates satisfactory correspondence of results in the qualitative sense. Quantitative analysis is, however, difficult. Fig. 9 shows the average values of the function of concentration $\phi$ for HC and NO$_x$ in the interval $(0, \tau)$ calculated by the formula:

$$\phi_\tau = \frac{1}{\tau} \int_0^\tau \phi(t)dt$$  \hspace{1cm} (2)

for $\tau = 300s$.

Comparison of values obtained from calculations and measurements (assumed to be the reference value) demonstrates that average CO concentration over a period of 5 minutes was calculated with an error of about 6 % [1]. But concentration over this period for HC and NO$_x$ was calculated with bigger error of about 13.5 % for HC and 12 % for NO$_x$.

Table 1 presents an influence of the length of time period for averaging concentration on difference ($E$) between measurement and calculation values for both sensors. The difference was obtained by using the following algorithm:

1° Interval $(0, 300s)$ was divided into subintervals with length $\tau$, 
2° For each subinterval an average value was calculated:

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Fig. 8. NO$_x$ concentration for sensor S$_2$ - experiment (e2) and calculations (c2)

Fig. 9. Average HC and NO$_x$ concentration in the interval $(0, 300s)$
\( \phi_{r,c}^{(m)} \) - for data from measurement in sensor \( S_m \),
\( \phi_{r,n}^{(m)} \) - for data from numerical calculation in sensor \( S_m \),
using formula (2), for given subintervals with length \( \tau \).

3° The percentage error was calculated:

\[
E_m = \max_{\phi_{r,n}^{(m)} \neq \phi_{r,c}^{(m)}} \left| \frac{\phi_{r,n}^{(m)} - \phi_{r,c}^{(m)}}{\phi_{r,c}^{(m)}} \times 100\% \right| \text{ for } m = 1,2.
\]  \( (3) \)

Formula 3 means, that maximum value from the set of values higher than average was choosen.

<table>
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<tr>
<th>( \tau ) [s]</th>
<th>CO</th>
<th>HC</th>
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<td>( E_1 ) [%]</td>
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It can be observed that generally the difference between results of calculation and measurement decreases when the length of time period increases. The longer the period of averaging results the more accurately results of calculation will in turn reflect reality.

5. Conclusions

In summary it can be stated that the experiments in measurements and calculation demonstrate the correctness of models, algorithms and computer programs used, and thus the algorithms are useful at the design (prognostic) stage of work. The error between results of calculation and measurement decreases as the time of averaging increases. The important reasons for the divergence in the courses of function \( \phi \) in Figs. 5 -8 are that:

- in calculations local fluctuations of the field of wind speed, caused by vehicle motion and natural variability of this field during the experiment, are left out of consideration,
- micro-phenomena accompanying mixture of fuel and air, especially changes in their density and temperature, are left out of consideration,
- it is assumed that the emission characteristic obtained on a test stand ideally represents emission rate in traffic conditions in a car park,
- it is assumed that parameters characterising the atmosphere are constant.

Despite these considerations I feel that the models and computer programs are correct and enable predictive calculations to be made that will define pollutant concentrations caused by mobile sources of emission. The longer the period of averaging results and the closer data for calculation are to reality, the more accurately results of calculation will in turn reflect reality.
References


NUMERYCZNA I EKSPERYMENITALNA ANALIZA DYSPERSJI ZANIECZYSZCZEŃ EMITOWANYCH PRZEZ SILNIKI POJAZDÓW