COMPUTATIONAL FLUID DYNAMICS MODELLING OF THE POLLUTION DISPERSION AND COMPARISON WITH MEASUREMENTS IN A STREET CANYON IN HELSINKI

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ABSTRACT

Pollution levels in an urban street-canyon area are determined numerically as part of the European research project OSCAR using the ADREA-HF code. Aim of the modelling is to investigate the flow-field and NO\textsubscript{x} concentration in the area and compare with measurements. Results show a tendency of underprediction of concentration by the code attributed mostly to the uncertainty of the emission levels within the studied time frames. The concentration distribution and flow field within the canyon are shown to be highly correlated whereas the in-canyon induced vortex plays a prominent role in the concentration dispersion.

1. INTRODUCTION

The role of Computational Fluid Dynamics (CFD) as a tool for assessing the pollution-dispersion impact on the environment within inhabited areas is increasing due to cost effectiveness combined with accuracy of predictions. Furthermore the limit of pollutant levels set by the World Health Organisation has led to an increased research activity as to the specification of the influence of car emissions on the air quality in urban street canyons. Urban street-canyons consist of building complexes on either side of the street and induce flow recirculations and/or stagnant conditions thus prohibiting the dispersion of pollutants away from inhabited areas.

With respect to CFD applications on environmental flows, a review was carried out by Vardoulakis et al.\cite{7} that includes evaluation of several CFD methods applied in meteorological, wind-tunnel and street canyon studies. In addition, Walton et al.\cite{9} pursued LES (Large-Eddy Simulation) for the problem of mean flow and turbulence in cubic street canyons. Their results show good agreement between simulations and experimental data. Finally, CFD computations using the ADREA-HF code have been carried out by Neofytou et al.\cite{5} in order to parametrically study the pollution in a street canyon by assuming different wind directions.

Model validation by comparing with measurements was carried out by Kukkonen et al.\cite{2,3} in a street canyon (Runeberg Street) in Helsinki. Concentrations of CO\textsubscript{2}, NO\textsubscript{x} and O\textsubscript{3} were provided from a measurement campaign in 1997 and were compared with predictions by the OSPM model, which qualitatively reproduced the observed behaviour in a consistent manner.

The current study is carried out in the framework of the Optimised Expert System for Conducting Environmental Assessment of Urban Road Traffic (OSCAR) project. This project aims at assessing the environmental impact of road traffic in terms of traffic flows, emissions and air pollution. A combined emission measurement and model-prediction campaign was carried out in Runeberg Street in Helsinki, Finland in 2003-2004. NO\textsubscript{x} concentrations at selected time periods are provided by measurements whereas the wind-directions and wind-speeds are measured at rooftop level. Furthermore, emission data for the nearby streets and during the time periods under investigation are also provided. The numerical predictions are carried out using the CFD code ADREA-HF\cite{1}, which also has been used in the past for environmental flow predictions\cite{5,6,8}.

2. METHODOLOGY

2.1 Measurements

The monitoring campaign in Runeberg Street was conducted in 2003 - 2004 (19.2.2003 - 31.12.2004). The aspect ratio of the street canyon is approximately 1:1 and the average weekday traffic volume is approximately 23 000 vehicles/day on the Runeberg Street. Street level air quality measurements and on-site electronic traffic counts were conducted throughout the campaign. Here, the focus is on the time period of 1.1.2004 - 30.4.2004 when additional wind speed and wind direction measurements also took place at the roof level in Runeberg Street. Furthermore, the urban background concentrations of NO, NO\textsubscript{2}, O\textsubscript{3}, PM\textsubscript{2.5}, and PM\textsubscript{10} were measured at a roof level about 1.4 km South-East from the monitoring station of Runeberg Street (at the station of Kaisaniemi) during this time period. NO\textsubscript{x} concentrations, wind-direction and wind-speed data are available with the time resolution of one minute.

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The traffic volumes for each link in the studied area were obtained from a traffic demand modelling system developed by the Helsinki Metropolitan Area Council. The latest update of the system bases on a travelling habit survey conducted in 2000. The system produces daytime traffic volumes for each link, including morning and evening peak hours. Computation of the traffic volumes for other times of a day is based on the information about traffic volumes and their diurnal variations in different monitoring sites in the Helsinki metropolitan area. In 2002 updated emission factors are based on the nationally conducted laboratory measurements of vehicle emissions by Laurikko et al.

2.2 Numerical Method

The methodology consisted in solving the transient, Reynolds averaged, mass and momentum 3D conservation equations for the mean flow and the mass fraction conservation equation for the pollutant dispersion, until steady state conditions were reached. Boundary conditions for the problem were zero gradient and given value for the inflow boundaries, zero gradient for the outflow boundaries, wall functions for velocities at the buildings surfaces and ground and finally zero vertical velocity at the top of domain.

The computational domain that includes all buildings in the area surrounding Runeberg Street is constructed using actual coordinates provided by the Helsinki Metropolitan Area Council and is shown in Figure 1. It consists of a 900x900x180m area discretised as a 65x65x35 grid which is refined near the measurement location in order to more accurately capture the wind field and concentration distribution. As regards to the comparison with measurements, three different datasets were selected, each covering a 15 minute time period. Each dataset provides values for wind speed and direction at roof level, concentration at street level and urban background concentration at a resolution of one minute. In addition, traffic emissions are provided for every street at a resolution of one hour. Hence, there was one value of emission for every street representing the selected time period of the dataset. The parameters from each dataset do not substantially fluctuate within the 15-minute period and therefore a mean value was derived for each parameter. The aforementioned values for wind speed and direction were used as input data for calculations in order to compare with the value of concentration from the corresponding dataset. In addition, the source of pollution which is principally the emissions from the cars passing along Runeberg and Hesperian streets (Fig. 1) was modelled for each dataset as an area source along the street emitting homogenously and with constant rate. Therefore, three different cases corresponding to each dataset were studied.

3. RESULTS AND DISCUSSION

The datasets selected and the corresponding mean values for the wind speed (WS), wind direction (WD) background concentration of NO\textsubscript{x} (BC in \textmu g/m\textsuperscript{3}) and street level concentration of NO\textsubscript{x} (SLC in \textmu g/m\textsuperscript{3}) correspond to weekdays and are shown in Table 1. The point where the measurements are taken corresponds to x=437.8m, y=500m, z=4m of the computational domain. It can be seen that although ADREA-HF has a tendency to underpredict the measurements, it follows their trend i.e. the prediction increases approximately at the same proportion from case 1 to case 3 so as observed in the measurements (SLC minus BC).
The most important factor of uncertainty in the computations is the definition of the source of emissions. Due to the fact that emission data are given on hourly basis it is not possible to know the exact emissions within the selected 15-minute time frame. Furthermore, the time frame for dataset 2 is between two different hourly emission periods and therefore one should average between the two mean values thus increasing the uncertainty.

<table>
<thead>
<tr>
<th>Dataset/Case</th>
<th>Date</th>
<th>Time frame</th>
<th>WS (m/s)</th>
<th>WD (deg)</th>
<th>BC</th>
<th>SLC</th>
<th>SLC prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15.4.2004</td>
<td>21:39-21:55</td>
<td>1.69</td>
<td>270.3</td>
<td>16.3</td>
<td>48.0</td>
<td>10.2</td>
</tr>
<tr>
<td>2</td>
<td>5.3.2004</td>
<td>21:52-22:13</td>
<td>2.40</td>
<td>254.4</td>
<td>18.9</td>
<td>35.5</td>
<td>12.8</td>
</tr>
<tr>
<td>3</td>
<td>10.3.2004</td>
<td>19:07-19:22</td>
<td>2.14</td>
<td>260.6</td>
<td>56.3</td>
<td>100.3</td>
<td>18.7</td>
</tr>
</tbody>
</table>

Table 1. Overview of datasets and numerical predictions for NOx.

It is very interesting though to see how the concentration distribution is behaving with respect to the flow field. The comparison is carried out between datasets 1 and 2, for which the same source of emissions is assumed. For the height of the measurement point (z=4m) the concentration distribution is shown in Figure 2. First, it can be seen that Hesperian Street barely plays any role to the pollution in its vicinity and that can be attributed to both the fact that Hesperian Street is an open area so the pollutants are more easily convected and diffused away and to the fact that it has less traffic compared to Runeberg Street. Thus, the pollution from the latter is more prominent.

![Figure 2](image1)

Figure 2. Concentration distribution for NOx at z=4m for cases: (a) 1; (b) 2; (c) 3.

Furthermore, it can be seen that the concentration levels are relatively higher for case 1 compared to case 2 at z=4m. This can be explained from the wind field for that height (Fig. 3) where the wind speeds within the street-canyon are relatively higher for case 2 and therefore the dispersion mechanism is more intense. This is caused not only from the higher freestream velocity for case 2 that causes more marked street canyon effects but also from the fact that the wind direction, which is for this case more aligned with Hesperian Street allows wind to enter from Hesperian Street into Runeberg Street thus increasing further the velocity within the latter. Case 3 exhibits the relatively highest concentration levels among all cases due to the higher emissions assumed although the wind velocity within the canyon is between the levels of the other two cases.

![Figure 3](image2)

Figure 3. Wind-velocity field at z=4m for cases: (a) 1; (b) 2; (c) 3.

Figure 4 shows the wind velocity at a lateral plane parallel to the x-axis, at y=500 and within the street-canyon of Runeberg Street, the two lanes of which are also shown. The street-canyon vortex is evident for all cases and this can explain the upwind accumulation of the concentration within the canyon observed in Fig. 2. As the freestream wind deviates from the westerly direction (270°) and increases in terms of velocity...
(gradually case 1 then case 3 and finally case 2) the centre of the vortex is moved upwards and downwind and the wind velocity within the canyon increases.

4. CONCLUSIONS

Pollution-dispersion modelling in an urban area was carried using ADREA-HF code. It seems that the code tends to underpredict the NO\textsubscript{X} concentrations mainly because of the uncertainty involving the emissions for the specific time frames considered here. The concentration field within the main street canyon of Runeberg Street is affected by the presence of Hesperian Street that crosses Runeberg Street and more precisely by the wind entering Runeberg Street from Hesperian Street. Furthermore, the fact that Hesperian Street is an open area results in emissions from Hesperian Street barely playing any role to the concentration within the street canyon. Finally, deviation of wind from a direction perpendicular to the street-canyon and simultaneous increasing of velocity speed causes the in-canyon vortex-centre to move upwards and downwind.

5. ACKNOWLEDGEMENTS

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6. REFERENCES