DEVELOPMENT OF A FAST TOOL FOR AIR QUALITY CFD MODELLING IN URBAN CANOPIES

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INTRODUCTION

When addressing air quality levels in urban environments, there is a need to determine in detail the concentration distribution in traffic congested street canopies within which maximum concentrations levels usually occur. Concentration hotspots within urban canopies are difficult to estimate or locate due to geometry and flow complexity. CFD models have the capability to resolve such complexities and therefore are a valuable tool to estimate concentration distributions within canopies.

In the present paper, the ADREA-HF CFD modelling system (Bartzis, 1991) capability is assessed based on wind tunnel experiments performed by TNO (van den Hout 1988a, 1988b). The k-ζ turbulence model proposed by Bartzis (2005a) is adopted as it shows better performance to any other in the present configuration on the 2-D analysis (Bartzis 2005b). The experiments concern simplified urban configurations that include roads, buildings and trees. More specifically, the selected tested case involves a line pollutant source, parallel to a long building. The measured concentration of the experimental configuration exhibited strong dependencies from the so-called direct contribution from the pollutant source and the recirculation in the wake of the buildings.

In the second part of the paper, an interpolation methodology was developed to speed up the modelling process of the examined configuration. Concentration values on selected areas (sensor positions) were approximated with respect to wind direction, thus allowing the direct estimation of concentration levels on cases other than the examined ones. The applied interpolation method is the Adaptive Neuro-Fuzzy Inference System (Jang 1993) that incorporates fuzzy if-then rules and also, provides fine-tuning of the membership function according to a desired input output data pair. The strength of this tool lies in its ability to simulate in a non-linear manner any problem from the presented examples.

EXPERIMENTAL DESCRIPTION

The experiments were performed in one of the TNO wind tunnels. The atmospheric boundary layer was simulated on a scale of 1:250. A rotating disk of diameter 2.3m contained the line source, up to 12 receptors and the building blocks were present. Hereafter, the dimensions will be given at full scale values. The line source was 150m long and 2.5m wide. The length of the building configuration along the street was 400m. Beyond 75m from the line source, blocks were placed on the turning disk and further upwind to simulate the roughness of a city (estimated value at 1.9 m). Isobutylene was used as the tracer gas (1 vol. %).

The building models were in the examined case 15m high (h) and 10m wide. The centerline of the source was located at x/H=+1.03 from the downstream building edge. Three sensors were used to monitor concentration and were located at 15m and ±6m from the source (positive towards the buildings). The final value of each one of them was the average from three more sensors at heights 0, 0.75 and 1.5m above ground.

THE MODELLING APPROACH

The ADREA-HF CFD local scale computer code has been used to carry out the modeling (Bartzis, 1991). It is a finite volume transient, three-dimensional, fully compressible transport code, designed to be applied to vapour cloud dispersion predictions at local scale with emphasis on terrains of high complexity. Three different turbulence models were tested: the one equation k-l model, the standard k-epsilon model (Launder et. al. 1975) and the k-ζ model proposed by Bartzis (2005).

Inlet flow conditions have been derived by solving the corresponding 1-D boundary layer problem with roughness zo=1.9m real scale and top wind velocity which produces a wind speed velocity at 10m height the experimental value 2.2m/s. At the top boundary the vertical velocity is taken equal to zero.

The 3D computation domain at wind tunnel scale extended horizontally at from x/H = -20 to x/H=+20, y/H = ±5 and vertically covered the whole boundary layer thickness, which is estimated to be at a height of z/H=6.5. A non-uniform logarithmic grid 84x30x38 has been utilized with minimum grid size near the obstacle $\Delta x_{min}/H$=0.7 mm and $\Delta z_{min}/H$=0.66 mm and maximum one near the domain boundaries Δx_{max}= 13 mm and Δz_{max}=3.3 mm. On the y axis uniform grid with size 3.25 mm was selected.

CFD MODELING RESULTS

Following a detailed analysis of the results presented by van der Hout (1988a) the values of the mean concentrations at the locations of the three sensors were compared to the values of the model estimations for different wind directions. In order to minimize the influence of the wind speed and the source strength from the concentration estimates, the adjusted concentration value was calculated as

$$C^* = C\, u_{10} / Q \qquad (2)$$

where u_{10} is the wind speed at the corresponding 10m height and Q the volumetric flow rate of the source. The mean concentrations for each sensor are presented on Table 1 and their profiles from Figures 1-3 respectively, and compared against actual measuremnts on Figure 4.

Table 1. Mean concentration values

	Sensor 1	Sensor 2	Sensor 3
Measurements	112.71	677.24	177.08
CFD	116.99	218.08	34.842

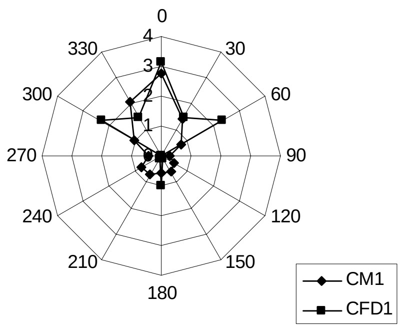

Fig. 1 Model vs. Data profile (sensor 1)

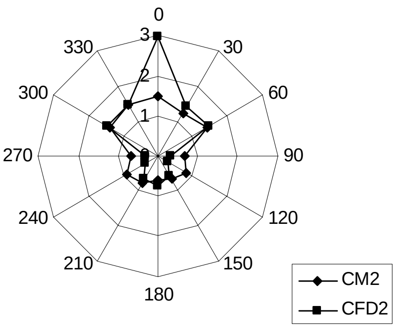

Fig. 2 Model vs. Data profile (sensor 2)

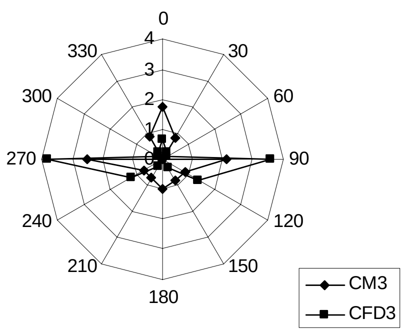

Fig. 3 Model vs. Data profile (sensor 3)

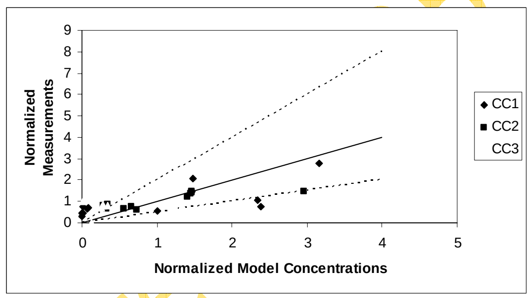

Fig.4 Model Comparison

The analysis shows that the CFD modeling tool tends to underpredict measured concentration by a factor of 3 on sensor 2 and by a factor of 5 on sensor 3. Model derived concentration profiles match reasonably well with experimental ones. It can be observed (Fig. 4) that the majority of the data are within a factor of 2. As expected profiles exhibit symmetric properties with respect to the North-South axis. Therefore, for interpolation activities can only be confined in the range between 0-180 degrees.

The largest error of sensor 1 is observed for 60 deg and when the wind has a southern component where smaller concentrations than the actual are estimated. Sensor 2 profile matches better with experimental one but it exhibits an overestimate of the North wind. The highest discrepancy is observed on sensor 3; however, the data need to be looked further since experimental concentrations at certain directions are comparable to the concentrations very near the building.

ANFIS

An Adaptive Network based Fuzzy Inference System can incorporate fuzzy if-then rules and also, provide fine-tuning of the membership function (Ai,Bj) according to a desired input output data pair. A first order Sugeno fuzzy model is used as a means of modeling fuzzy rules into desired outputs.

$$\text{if } X_1 = A_i \text{ and } X_n = B_j \text{ then } f_i = p_i X_1 + q_i X_n + r_i \qquad (1)$$

The estimation of the output values is done through a series of successive steps for the estimation of the relative strength of each rule that is expressed as the product of the membership function of each variable. The final results are defuzzified using a weighted average procedure. A back-propagation training method is employed to find the optimum value for the parameters of the membership functions and a least squares procedure for the linear parameters on the fuzzy rules, in such a way as to minimize the error between the input and the output pairs.

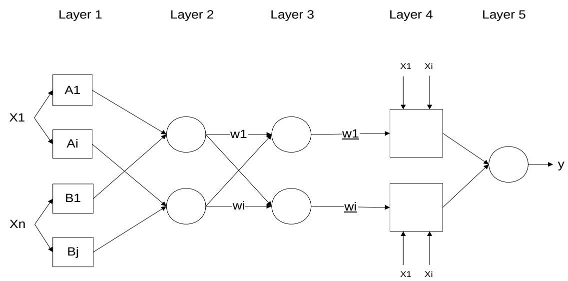

Fig5. ANFIS architecture

INTERPOLATION RESULTS

If CFD modelling tools are to be integrated in real time decision and emergency response systems then it is a necessity that they produce fast predictions. As current state-of-the art CFD models computational time is not suited for such applications then fast alternative solutions should be employed. In this paper an interpolation approach is proposed that aims to emulate the CFD model output instantaneously. The ANFIS modelling system was preferred because it has the capability to deal with imprecise information (fuzzy part) and is inherently non-linear. For comparison purposes two common interpolation approaches were also included: linear and spline.

Due to high symmetry of the experimental configuration and derived CFD results the interpolation analysis was conducted only using half of the data, from 0 to 180 degrees. A "training set" was formed using CFD derived data every a specified range of degrees. The different cases studied include data every 10, 20 and 30 degrees. An "evaluation set" was set to contain CFD derived results for 45 and 135 angles and an additional "checking set" consisted of those data not used in the "training set" where applicable. These data sets were used to monitor the model performance and have not been included during the building of the neuro-fuzzy model or the interpolation methods. The developed ANFIS system had a generalised bell with 2 membership functions for each input (two components of wind speed).

Table 2. Percentage Error

		Sensor 1		Sensor 2	
		Eval. Set	Ch. Set	Eval. Set	Ch. Set
10 deg	ANFIS	2.50	-	1.13	-
	Linear	4.01	-	2.96	-
	Spline	1.12	-	0.90	-
20 deg	ANFIS	9.27	55.27	1.45	15.81
	Linear	13.30	256.45	9.28	23.31
	Spline	41.29	198.77	2.73	18.21
30 deg	ANFIS	62.73	87.65	25.53	31.86
	Linear	37.40	107.03	28.33	19.88
	Spline	124.78	128.70	34.05	30.42

The analysis of the interpolation methodologies shows that modelling sensor concentration results is not very easy case because of discontinuities in the values especially in sensor 1. This explains high percentage errors in the "checking set" of sensor 1. The curve describing Sensor 2 is smoother which is reflected in the lower values of both evaluation and checking set errors.

Figure 6 displays the percentage error of the checking set with different number of training patterns. As expected the more data are used for developing the interpolation schemes the lowest are the prediction errors. This can be used to specify the number of CFD runs required to achieve a desired percentage error.

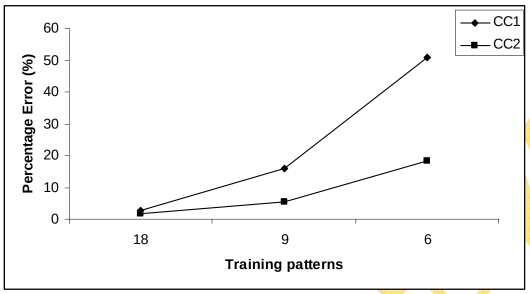

Fig6. Percentage Error as a function of interpolation points

CONCLUSIONS

The present paper described the CFD modelling of simplified urban configurations consisting of a rectangular building with a linear source representative of a road. The ADREA-HF code used incorporating the κ-ζ turbulence was introduced. The model produced mean concentrations over the entire wind rose were comparable to the experimental ones with the exception of Sensor 3. On this sensor higher discrepancies were observed for the North wind which is an indication for a re-examination of the experimental results. Finally, several interpolation methodologies were examined in an attempt to produce fast modeling of concentration values with the least number of CFD runs. The nonlinear ANFIS approach gave best results, although further research is needed to further assess the proposed approach

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