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Integrated air quality modelling for a designated air quality management area in Glasgow

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Abstract

Currently, most local authorities in the UK use well-established Gaussian-type dispersion models to predict the air quality in urban areas. The use of computational fluid dynamics (CFD) in integrated urban air quality modelling is still in its infancy, despite having an enormous potential in assessing and improving natural ventilation in built-up areas. This study assesses the suitability of a general CFD code (PHOENICS) for use in integrated urban air quality modelling for regulatory purposes. An urban air quality model of a designated air quality management area in the city centre of Glasgow has been developed by integrating traffic flow data for urban road networks, traffic pollutant emission data and a three-dimensional CFD dispersion model of a complex configuration of street canyons.

The results are in good agreement with field measurements taken during the continuous monitoring campaign, and show that a general CFD code has indeed the potential for regulatory use. Although this numerical tool has demonstrated satisfactory performance, it is observed that small differences in monitoring station positioning may yield significant variations of the measured mean concentration, due to large values of horizontal and vertical local concentration gradients. Although, at this stage, the accuracy of the developed Glasgow urban air quality model is highly dependent on the experience of its users, it is believed that use of a CFD code (such as PHOENICS) could benefit urban planners, architects, HVAC engineers and all other professionals interested in public health.

Keywords: Built environment; Natural ventilation; Air quality; Computational fluid dynamics

1. Introduction

In Glasgow, as in most cities in the UK, cars remain the most convenient means of transport. However, the increasing density of traffic leads to much greater traffic emissions and consequently greater air pollution, especially in the central city areas where buildings form a complex configuration of street canyons. Exceedance of the prescribed air quality standards [1] in the city centre of Glasgow is frequently associated with the present planning policy, in which the city of Glasgow is zoned according to uses, generating the need to travel from one zone to another [2]. Of special importance is the concentration of business premises, shopping, entertainment and leisure facilities, universities and historical heritage sites in the city centre and of housing in suburbs. That is, the main reason that the population of the city of Glasgow itself is only 650,000 inhabitants, while the metropolitan area of Glasgow accounts for approximately 2,500,000 people [3]. Furthermore, the exposure of the population to air pollution associated with traffic has become significantly more important as the city council has been changing its policy, now

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supporting the creation of new residential developments within the city centre [4], which will inevitably lead to the formation of deeper street canyons, reducing the natural ventilation. In order to deal with the air quality problems, the city council has designated the city centre of Glasgow as a local air quality management (LAQM) area [5].

Part IV of the Environment Act 1995 lays down the system of LAQM in the UK [6], which now plays a key practical part in the strategy to achieve air quality objectives in urban areas, based on the EU directive 96/32/EC [7]. This framework directive on ambient air quality assessment and management defines the general legislative structure. The directive is supplemented by related daughter directives [8,9], which define standard air quality thresholds and, what is more important from the modelling standpoint, the minimum requirements for the assessment of air quality levels in the EU countries [10].

All these legal requirements have been summarised in the technical guidance on the LAQM [11], published in 2003, to provide local authorities with a robust tool to assess and manage air quality in UK cities. Following the technical guidance, the vast majority of local authorities have regarded computational fluid dynamics (and wind tunnel simulations) as too complex to use. As might be expected, use of the well-established Gaussian dispersion models has been suggested, as they have reached maturity [12]. An example is the atmospheric dispersion modelling software (ADMS) developed by CERC [13] and widely used in the UK, and frequently coupled with the traffic flow software called SATURN [14].

Although having an enormous potential in assessing and improving natural ventilation in built-up areas, especially in a complex configuration of street canyons, the use of CFD in integrated urban air quality modelling is still in its infancy. This study aims to assess the suitability of a general CFD code for use in integrated urban air quality modelling for regulatory purposes. By integrating data on traffic flow in urban road networks, traffic pollutant emissions and a three-dimensional model of a complex configuration of street canyons into a CFD dispersion model (PHOENICS), an urban air quality model of a designated LAQM in the city centre of Glasgow has been developed. The modelled results were compared with experimental results obtained during the continuous monitoring campaign in 2002.

In order qualitatively to assess an urban air quality model, one has to be aware of the flow patterns that develop around buildings, which govern the distribution of pressure and concentration. The vast majority of studies are focussed on physical processes within a single street canyon, i.e. the concentration distribution is represented as a function of idealised geometrical characteristics of street canyons, wind direction and wind speed [15–19].

Although a study of individual street canyons is an essential start in understanding fundamental processes of dispersion of air pollutants, the superimposition and interaction of flow patterns associated with adjacent buildings predominately governs the dispersion of air pollutants within a built environment [20–26]. Summarising discussions of the above-mentioned studies, it has emerged that if a general CFD code is to be used in urban air quality modelling for regulatory purposes, the concentration distribution function has to take into account the following parameters:

$$\begin{aligned}\text{Concentration distribution} \\ = f(&\text{width, height, length, canyon orientation,} \\ &\text{wind speed, atmospheric stability, building} \\ &\text{geometry, upwind building configuration,} \\ &\text{intersection location and geometry).}\end{aligned}$$

2. Methodology

2.1. Urban air quality monitoring

During the continuous monitoring campaign in 2002, the experimental data were measured at five different locations in the city centre using both fixed and mobile monitoring stations. The three fixed, self-contained monitoring stations were placed at carefully chosen sites to represent the diversity of Glasgow's microenvironments (Fig. 1):

(1) Glasgow Kerbside: an urban kerbside location in Hope Street where air pollution hotspots are expected;

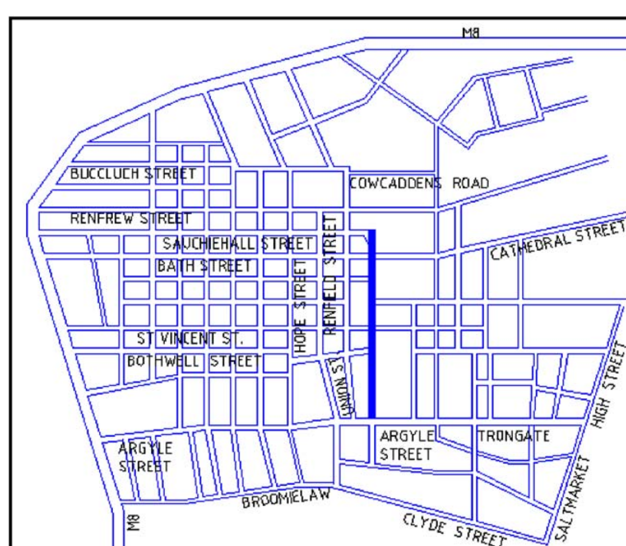

Fig. 1. Designated air quality management area in Glasgow.

(2) Glasgow Centre: an urban centre location at St. Enoch Square, representative of population exposure over the averaging times associated with the regulatory values;
(3) City Chambers: an urban background location at the junction of Montrose Street and Cochrane Street.

Taking into account the size of the designated air quality management area in Glasgow, air pollution was additionally monitored using the automatic monitoring equipment contained in an air-conditioned trailer. The two locations were selected according to the traffic flow data in order to give more detailed information on local air pollution differences within the street canyons in the designated air quality management area:

(4) urban street canyon location in Union Street;
(5) urban street canyon location in Renfield Street.

The monitoring trailer (Fig. 2) was equipped with instruments for the continuous monitoring of carbon monoxide (API Model 300 Gas Filter Correlation CO Analyser), oxides of nitrogen (API Model 200A chemiluminescent $NO/NO_2/NO_x$ analyser) and particulate matter, PM_{10} (TEOM Series 1400a, Rupprecht & Patashnick Co.). During the period of interest in this study (January–December 2002), AEA Technology audited the performance of the monitoring equipment twice. The equipment was found to be operating to an acceptable standard [27].

As shown in Fig. 3, the pattern of diurnal variation of carbon monoxide is characterised by higher concentrations during the peak hours and slightly lower concentration during the middle of the day, as can be observed at all fixed monitoring stations. The correlation coefficient of carbon monoxide hourly averaged concentrations indicates a strong correlation between monitoring data series. The correlation coefficients vary from 0.94 for the City Chambers and Glasgow Kerbside site, up to 0.97 for the Glasgow Centre and Glasgow Kerbside site. Note that the SATURN traffic model, used in this study, forecasts peak hour by flows and speeds, and gives an averaged value over 12 h (07.00–19.00). In order to find the correlation between different annually averaged monitoring measurement series and the traffic flow data, the needed statistics are provided over 12 h only.

Fig. 2. Monitoring trailer in Renfield Street.

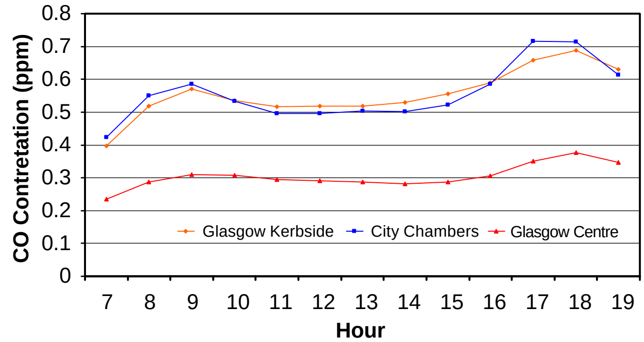

Fig. 3. Comparison of diurnal concentration patterns of CO.

The annual hourly averaged concentration at the Glasgow Kerbside station (Hope Street) is approximately 80% higher than at the Glasgow Centre station (St. Enoch Square). At the kerbside site, the highest concentration occurs during the morning and afternoon peak, which is attributed to the occurrence of higher traffic flow within city centre boundaries.

Comparing these data with the historical dataset from 1979 [28] for the same street in Glasgow, it was noted that the concentration of carbon monoxide now varies much less during the day. Generally, this can be associated with the change of urban development strategy towards 24 h living in cities. The period from 10.00 to 17.00 is known as the middle day peak with the assumed local maximum at 13.00.

Additional monitored data were obtained by collecting 24 h carbon monoxide samples during a 4-week period at each of the chosen monitoring sites. The comparison of averaged hourly data in Union Street and Renfield Street is given in Fig. 4, and correlation coefficients vary from 0.71 for two different data series measured in Union Street up to 0.94 for Renfield Street (November 2002) versus Union Street (February 2002) data series and 0.97 for Renfield Street (August 2002) versus Union Street (Jun 2002) data series. These results show a strong seasonal effect. Moreover, analysis of the diurnal variation of carbon monoxide concentration and to some extent different diurnal concentration patterns indicate a poor natural ventilation within the street canyons.

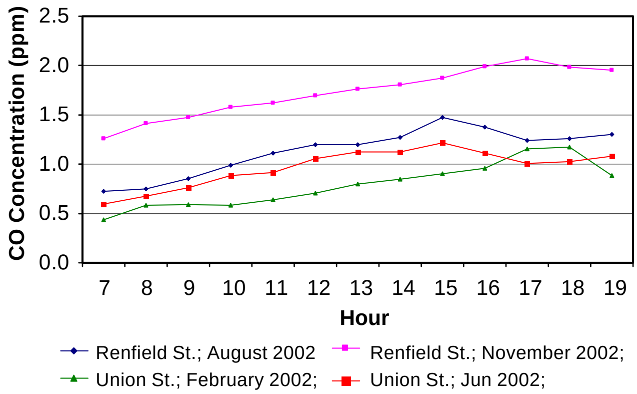

Fig. 4. Comparison of hourly averaged CO concentrations.

2.2. Meteorological data

Within the urban built environment it was not generally possible to obtain a wind orthogonal to the front row of the buildings for long periods, but selecting the 1 h averaging period, over a 12 month period, the prevailing wind directions for numerical modelling could be obtained.

Fig. 5 shows the frequency of wind directions measured at the Bishopton (Reference no.: NS 418711) meteorological station near the city of Glasgow. This new station replaced the Abottinch meteorological station (Reference no.: NGR. 2480E 6667N) 3 years ago. In this study, wind velocity vector data for the 12 months period 1 January 2002–31 December 2002 have been used. Statistics show an annually averaged wind direction of 200°, while the daily averaged value is 210°. The hourly wind direction is approximately 55% of the time between 190° and 280° (counting clockwise from North). Glasgow is sheltered from the easterly and northerly winds; the predominant winds are from a westerly and southwesterly direction. The averaged wind speed is approximately 4 m/s. These results compared well with the historical data obtained from the Abottinch meteorological station over a long averaged period of 10 years (January 1989–December 1998).

As recommended in the technical guidance LAQM.TG(03) [11], the year of meteorological data corresponds with the year of monitoring data that is used for model verification (1 January 2002–31 December 2002).

2.3. Traffic flow simulation

The traffic flow data were obtained using the simulation and assignment of traffic in urban road networks (SATURN) traffic flow simulation software. In order to give an indication of the suitability of the modelled traffic data, the traffic flow along specific road links has been observed over several hours.

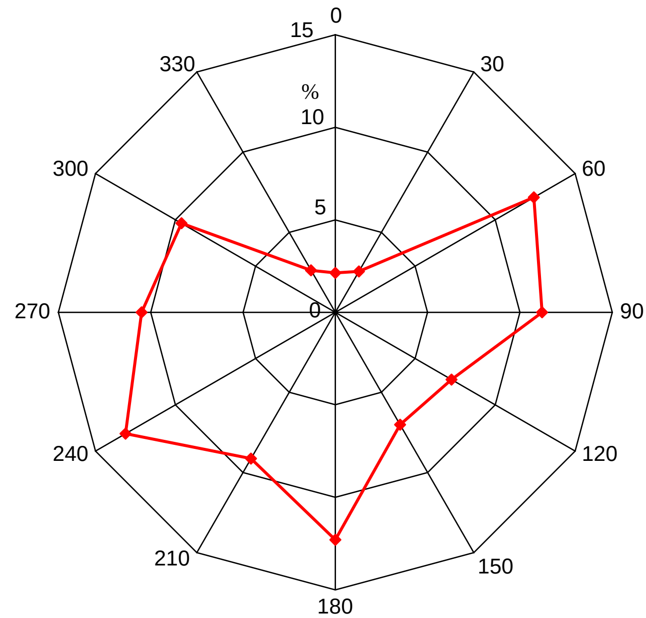

Fig. 5. Annual wind rose for Bishopton Meteorological Station

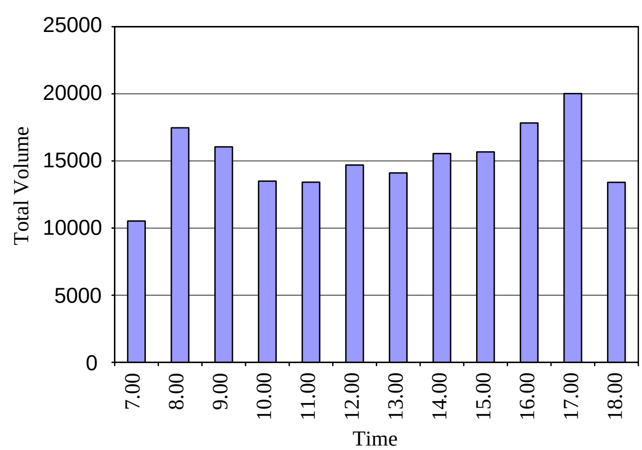

Fig. 6. Diurnal variation of the total traffic volume.

The traffic model forecasts peak hour flows and speeds, and gives an averaged value over 12 h (07.00–19.00). Although the technical guidance [11] suggests an adjustment where there are steep gradients (>15%), this has not be considered. Note that the vehicle composition along specific road sections has not been taken into account either.

A large proportion of journeys along routes approaching the city are by private cars that are overloading the city routes during the three peak periods: (a) in the morning, 08.00–09.00; (b) midday peak, 13.00–14.00 and (c) in the afternoon, 17.00–18.00. The diurnal variation of the total traffic volume is shown in Fig. 6.

For a better illustration of the correlation between traffic flow and AUN measurements data series, correlation factors have been calculated. The calculated value of 0.58, on average, shows the significant positive correlation, but still represents a significant unexplained variation.

As most of the traffic modelling, including both manual and automatic traffic counting campaigns, was provided by the Land Services Department of Glasgow city council, detailed presentation of results and discussion of uncertainties associated with the traffic flow simulation will be the subject of another report.

2.4. Emission factor calculations

The emission factors for urban road traffic have been calculated using the emissions factor toolkit 2e (EFT 2e), developed by Cassella Stanger [29]. The new emission factors published in February 2003 [30] were used in order to comply with the stage 4 reviews and assessments of air quality modelling [31].

The toolkit EFT 2e brings together all the relevant raw data for vehicle emissions: national fleet composition data for urban roads, fleet composition based on European emission standards from pre-Euro I to Euro IV, speed-related emission functions and scaling factors for reductions in emissions for 2002. The traffic fleet composition type 5 has been chosen, due to its compatibility with the SATURN standard interface. The traffic fleet composition has been split into the seven categories: cars, motorcycles, light good vehicles (LGV), taxi, bus and other good vehicles (OGV1, OGV2).

Table 1 summarises the emission factors calculated for the 12 h averaged fleet composition within the city centre. It has to be noted that the emission is approximately five times higher for a vehicle speed of 5 km/h than for a vehicle speed of 40 km/h!

In Fig. 7, the fleet composition has been shown for four different traffic flow regimes: (a) morning peak, (b) midday peak, (c) afternoon peak and (d) 12 h averaged traffic flow. As the emission depends on the calculated fleet composition, four different sets of emissions have been calculated and compared in Fig. 8. Calculating the Pearson correlation coefficient, which takes a value of 0.98 on average, justifies the use of only one average set of emissions, as given in Table 1.

Table 1
Averaged CO Emission as a function of vehicle speed

Vehicle speed (km/h)	Emission (g/km vehicle)
0	2.147
5	10.640
10	5.981
15	4.329
20	3.472
25	2.929
30	2.546
35	2.255
40	2.026

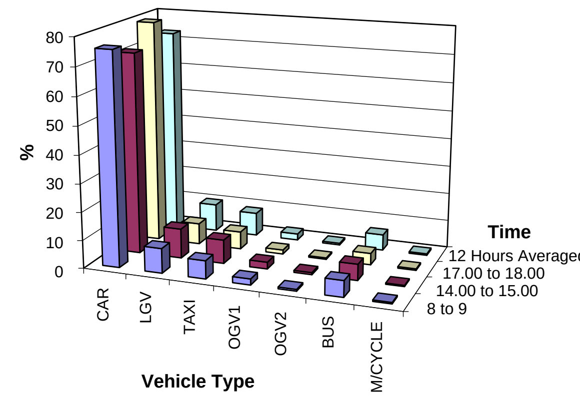

Fig. 7. Calculated traffic fleet composition during four different traffic flow regimes in the city centre.

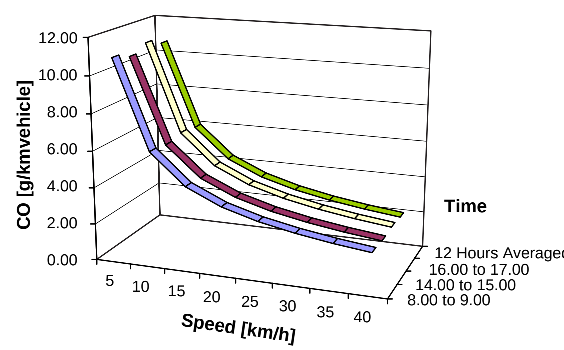

Fig. 8. Estimated emission factors as a function of the vehicle speed and assumed vehicle composition during four different traffic flow regimes.

2.5. CFD modelling

The dispersion of pollutants in urban areas is dominated by modifications of the atmospheric flow caused by buildings. A preliminary study by authors highlighted the fundamental problems of microscale CFD models, which lie in the physical difficulties of modelling the effect of turbulence, and also the accuracy of the spatial discretisation of complex urban geometries, the numerical procedures applied, the boundary conditions and the physical property selected.

The majority of studies have been based on single street canyon geometry and the isotropic two-equation, standard k–ε turbulence models, ignoring the effect of turbulence anisotropy on the dispersion characteristics in urban street canyons. This effect is considered in the preliminary study, through the introduction of different turbulence models tested on a staggered crossroad, rather than a single street canyon as the appropriate representation of an urban unit. All modelled results were compared with experimental data obtained using

Table 2
Summarised mathematical model

General transport equation of the incompressible steady-state flow $\partial_i(\rho U_j \Phi) - \partial_i(\rho \Gamma_\Phi \partial_i \Phi) = S_\Phi$

Equation	Φ	Γ_Φ	S_Φ
Continuity	1	0	0
Moment	U_i	ν_{eff}	$-\partial_j P$
Concentration	C	$\nu_{\text{eff}}/\sigma_C$	0
Turbulent kinetic energy	k	$\nu_{\text{eff}}/\sigma_k$	$G-\varepsilon$
Dissipation rate	ε	$\nu_{\text{eff}}/\sigma_\varepsilon$	$(k/\varepsilon)(C_{\varepsilon 1}G - C_{\varepsilon 2}\varepsilon - \alpha\varepsilon)$

Constitutive relations:

$G = \nu_t(\partial_k U_i + \partial_i U_k)\partial_k U_i$; $\nu_{\text{eff}} = \nu_{\text{lam}} + \nu_t$; $\nu_t = C_\mu k^2/\varepsilon$

$\alpha = C_\mu \eta^3(1-\eta/\eta_0)/(1+\beta\eta^3)$; $\eta = Sk/\varepsilon$; $S = \sqrt{2S_{ij}S_{ij}}$; $S_{ij} = 0.5(\partial_j U_i + \partial_i U_j)$

Turbulence model coefficients:

σ_k	σ_ε	σ_C	$C_{\varepsilon 1}$	$C_{\varepsilon 2}$	C_μ	η_0	β
0.7194	0.7194	1.0	2.42	1.68	0.0845	4.38	0.012

the BLASIUS wind tunnel at the University of Hamburg, Germany. The RNG k–ε model as developed by Yakhot [30] gave the most accurate results [31]. Furthermore, different discretisation methods were tested [32], resulting in the use of the hybrid discretisation scheme [33]. Finally, Cartesian coordinates have been used in connection with the partial solution algorithm (PARSOL) [34] and body fitted coordinates (BFC) [35], to analyse the effect of the grid on the dispersion of air pollutants [36–38].

Summarising results of the preliminary study, a three-dimensional flow model has been setup using the incompressible steady-state Navier–Stokes equations, coupled with the continuity equation and pollutant concentration conservation equation. Details of the mathematical model used are given in Table 2.

As a consequence of limited computer resources at present, it has to be stressed that the model would not have been functional without the following simplifications in the computational setup:

- *Linearisation of minor irregularities in street direction*: The Victorian architecture of the city centre of Glasgow gives an opportunity to align the direction of the selected streets. As a consequence of this minor geometrical simplification, a significant reduction in the number of the cut cells has been achieved.
- *Rotation of the supportive plate of the solid model*: Although the geometry of the city centre is composed of almost regular parallel arrays of buildings, their direction is rotated by 14° (anticlockwise) from the North–East (N–E) direction (Fig. 9). This is an important issue when applying the non-uniform Cartesian grid to urban air quality modelling. The number of cut cells increases rapidly, limiting the capability of the hardware to model numerically such an extensive problem. To overcome this problem, a notional supportive plate has been introduced and the solid model of the city centre has been mounted on it (Fig. 9). This simple technical solution enables the alignment of the solid with the direction of the non-uniform Cartesian grid, reduces the number of cut cells and allows a more efficient use of very limited computer power.
- *Minimisation of numerical diffusion*: As can be seen from Fig. 9, considerable irregularities in the geometry of street canyons occur in the North to North–East part of the city centre, which can result in significantly high levels of numerical diffusion. The most suitable solution for that part of the city is to apply refined non-uniform Cartesian coordinates in connection with the PARSOL embodied in the PHOENICS code [34].

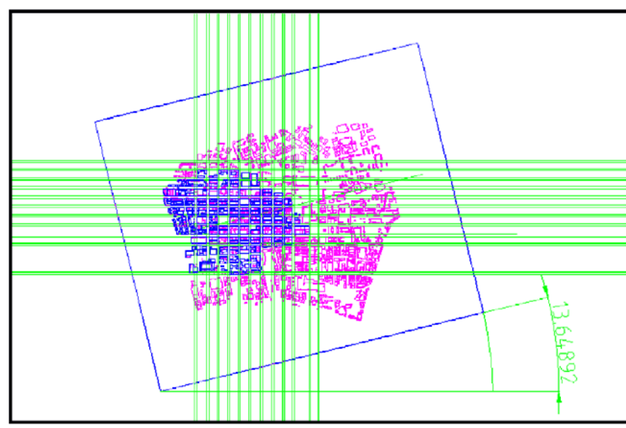

Fig. 9. Rotation of supportive plate of the solid model.

Finally, to scale down the extensive CPU requirements of the model, a different non- uniform grid was used, in order to increase the resolution in regions where gradients are large. The grid was designed to provide the highest possible resolution near the ground and roofs, as in regions next to windward and leeward sides of street canyons. The minimal number of cells required has been setup as NX = 222, NZ = 236, (horizontal) and NY = 45 (vertical).

3. Discussion

Numerical modelling was done for two prevailing wind directions and five different wind speeds, as follows: (a) wind speed: 2, 5, 6, 11 m/s; (b) wind direction: westerly and southwesterly. The wind velocity vectors are representative of the meteorological patterns observed in the area. The aspect ratio of street canyons in the computational domain varies from 0.8 to 1.1.

Fig. 10 illustrates the distribution of carbon monoxide within the designated air quality management area in the city centre of Glasgow. Results are obtained at the height of 1.75 m, assuming that the prevailing wind is a westerly, blowing at 6 m/s. The qualitative analysis is similar to findings obtained in wind tunnel experiments: (a) lower concentration at windward side of street canyons which are almost perpendicular to the wind direction, (b) higher concentration at leeward side of street canyons which are almost perpendicular to the wind direction, (c) washing out and accumulation effects along those canyons whose axes are parallel to the wind direction.

Comparison of distribution of the pollutant for the same wind direction, but different wind speeds, 2 m/s, 5 m/s and 11 m/s, shows that considerable differences can be observed in concentration values. During low wind periods, convective transport of the pollutant is greatly reduced, causing higher concentration at the very lowest levels of street canyons. In contrast, during periods of very high wind speed, influence of the washing out effect increases significantly, generally lowering the concentration levels within the city centre. Note that the convective transport of pollution from the surrounding built environment areas has been neglected.

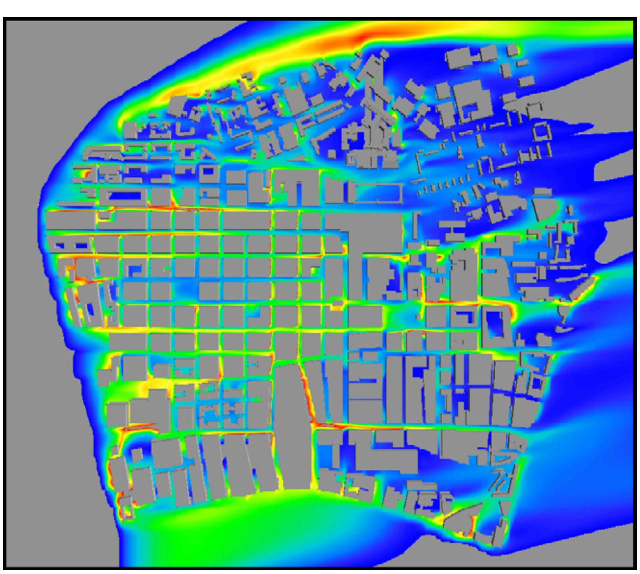

Fig. 10. Concentration distribution in Glasgow city centre.

The spatial location of the highest concentration within the city centre shows that the kerbside site in Hope Street (Fig. 9) does not present the hotspot when assessing the level of carbon monoxide. That segment of Hope Street is permitted for access by bus and taxi vehicles only, which are predominantly diesel engined.

The concentration levels of carbon monoxide (ppm) was modelled for a southwesterly wind direction and wind speeds of 2, 5, 6 and 11 m/s. Although concentration levels are to some extent lower due to the geometrical layout of the city as a whole, main features of concentration fields have not changed significantly.

Despite the very encouraging results of the qualitative analysis, Table 3 gives an overview of errors obtained using the named models at five different locations within the city centre of Glasgow. As expected, the best estimated results have been obtained at locations where the monitoring equipment is located in a semi-open urban built environment (St Enoch Square). Relative errors between the numerical and field results of 10% are observed in most cases. However, a relatively high error of 75% has been calculated during the day of low wind intensity. When this result is excluded, the R^2 value for St. Enoch Square is 0.81. However, a Pearson correlation coefficient of 0.91 and the almost absolute consistency in over-predicting results are a strong sign of systematic error.

A standard deviation of 0.14 ppm has been calculated when the monitoring equipment is positioned at the windward side of a street canyon, and/or when the wind direction is almost parallel to the street canyon axis (Cochrane St.). A Pearson coefficient in this case of 0.65 shows significant correlation between measured and predicted values.

It has been calculated that the concentration is always over-predicted (standard deviation is 0.39 ppm) at sites where the monitoring equipment is located near the leeward side of the street canyon (Union St., Renfield St.). Although this consistency in predicted results and the significant correlation of 0.91 gives a strong hint of the existence of a systematic error, it is believed that the statistical sample is not representative enough. The differences obtained are probably due to an improper physical representation of the microscale dispersion of air pollutants in the vicinity of walls. Results obtained for the street canyon, where the monitoring equipment is located in the vicinity of windward side (Hope St.), show an excellent averaged relative error of 14% and the

Table 3
Model validation statistics

Direction		W		SW		W		SW		W		SW		W		SW		Average
Street	% (ppm)	2 m/s		2 m/s		2 m/s		2 m/s		6 m/s		6 m/s		11 m/s		11 m/s		(%)
Hope Street	P	16 U	1	25 O	0.5	8 U	0.46	10 U	0.45	25 O	0.25	8 U	0.46	7 O	0.32	43 O	1	23
	M		1.2		0.4		0.5		0.5		0.2		0.5		0.3		0.7	
St. Enoch Square	P	75 U	0.1	15 O	0.23	10 U	0.11	10 O	0.22	10 O	0.11	10 O	0.22	25 U	0.3	13 O	0.34	21
	M		0.4		0.2		0.1		0.2		0.1		0.2		0.4		0.3	
Cochrane Street	P	29 U	0.5	20 O	0.36	14 U	0.43	17 O	0.35	17 U	0.25	16 O	0.35	35 U	0.45	60 O	0.48	26
	M		0.7		0.3		0.5		0.3		0.3		0.3		0.7		0.3	
Union Street	P	8 O	1.4		N/A		N/A	50 O	1.2		1.3	50 O	1.2	14 O	1.6		N/A	31
	M		1.3		N/A		N/A		0.8		N/A		0.8		1.4		N/A	
Renfield Street	P		N/A	130 O	0.7	75 O	1.4		N/A		N/A		N/A		N/A		N/A	102
	M		N/A		0.3		0.8		N/A		N/A		N/A		N/A		N/A	
Average (%)		32		48		27		22		18		21		20		39		

P—predicted values; M—measured values; O—overpredicted results; U— underpredicted results.

impressive R^2 value of 0.97, when results for the strong (11 m/s) southwesterly wind are excluded.

The model shows absolute consistency, 100%, in over-prediction of field results within street canyons where the wind direction is almost perpendicular to the street axis. It has to be noted, if analysing separately, that the model shows very high consistency (90%) in over-predicting the concentration, when the prevailing winds are southwesterly. On the other hand, due to alignment of computational cells with westerly winds, the model gives encouragingly accurate results with a calculated relative error of 25% on average.

Note that, the modelling quality objectives are set by European Union Directive 2000/69/EC [8], and the recommended value for 8 h running mean and 1 h averaged concentration of carbon monoxide is 50% and 60%, respectively.

It has to be noted that centrally located vortices are not formed when the wind incident is oblique to the street canyon axis (southwesterly wind) and the wind speed is lower than 6 m/s. However, due to elevated kinetic energy when the wind speed is setup to 11 m/s, the expected centrally located vortex has been formed. As in the previous cases, it has been shown that increased levels of pollution occur near the leeward side, but, when the wind speed is very low and the wind direction is oblique to the axis, it can be observed that large local concentration gradients exist only at the bottom of the street canyon. The concentration range in all six cases varies from 0.1 to 3.0 ppm, while the velocity maximum is setup to 6, 2 and 11 m/s, respectively. The influence of the wind speed on pollutant dispersion is demonstrated. It is observed that for low wind speeds the change of vertical concentration gradients tends to be very small, preventing the pollutant from dispersing all over the cross-section of a street canyon. In contrast to this, a very high wind speed of 11 m/s increases the natural ventilation, especially in the case of an oblique wind direction.

Table 4
Assessment of local concentration gradients

Wind incident	Local concentration gradients	
	Small	Large/medium
Perpendicular	Upper leeward side Vortex centre	Lower leeward side (large) Bottom of the canyon (large)
	Lower windward side	
Oblique	Upper leeward side Vortex centre	Lower leeward side (medium)
	Lower windward side	Bottom of the canyon (medium)

However, the formation of vortices and consequently the prediction of pollutant concentrations in street canyons is subject to considerable uncertainty. It has to be stressed that the mentioned local wind field within the canyon is unlikely to occur if the wind direction changes rapidly in time. Summarising modelled results across the computational domain, three different zones of the street canyon appear to be very convenient locations to monitor air quality (Table 4). Note that, apart from local concentration gradients, there are two other issues which presumably have to be considered when deciding if a location is suitable for air quality monitoring: firstly, the practicality of the location in the real physical domain and, secondly, the level of turbulence intensity at the chosen location. Satisfying all three requirements may determine an appropriate location for positioning of the air monitoring equipment.

4. Conclusions

Numerical modelling of flow patterns and pollutant dispersion in a real complex configuration of street canyons can never result in explicit rules, as numerous assumptions and considerations are needed. To focus on the geometric impact of urban flow, several suggestions could be made using this study: (a) crossroads introduce lateral eddies into the canyon, (b) small differences in monitoring station positioning may yield significant variations of the measured mean concentration, due to large values of horizontal and vertical local concentration gradients, (c) monitoring stations positioned at the lower leeward side of a street canyon might lead to an inaccurate assessment of pollution level within a street canyon and (d) in the upper part of the street canyon iso-concentration lines are almost parallel.

PHOENICS coupled with SATURN and EFT 2e predict concentration levels in urban street canyons reasonably well; although it systematically over-predicts in high concentration zones. From the generally high accuracy of predictions it has been shown that CFD has the potential to be used in integrated urban air quality modelling for regulatory purposes.

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