Report

Review of the Clean Air Act provisions for dispersion from small gas boilers

Report to the Department for Environment, Food and Rural Affairs, the National Assembly for Wales the Scottish Executive and the Department of the Environment for Northern Ireland

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AEA Technology Environment
netcen
Gemini Building
Harwell
Didcot, Oxfordshire
OX11 0QR
Telephone 0870 190 6437
Facsimile 0870 190 6386

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	Name	**Signature**	**Date**
Author	John Abbott		
Reviewed by	Peter Coleman		
Approved by	Peter Coleman		

Executive Summary

This report describes modelling studies carried out to establish the adequacy of the current guidance relating to the determination of chimney heights for gas boilers, provided by the third edition of the Chimney Heights Memorandum, to prevent exceedances of the statutory ambient air quality objective for nitrogen dioxide. Issues other than pollutant dispersion are not considered, for example, issues related to the optimisation of the installation design. The main conclusions and recommendations are as follows.

Chimney heights for conventional natural draught gas boilers determined by proper application of the third edition of the Chimney Heights Memorandum are likely to be sufficient to prevent local exceedences of the air quality objectives for nitrogen dioxide.

Application of the Memorandum for the determination of chimney heights for large condensing boilers may lead to unsatisfactory dispersion because of the low efflux velocity associated with flues for these boilers. For condensing boilers with low NO_x burners and heat inputs less than 1.5 MW the Memorandum is likely to be adequate to prevent local exceedences of the air quality objectives for nitrogen dioxide. Larger condensing boilers (of which there are currently very few) may require more detailed assessment.

Chimney heights for room-sealed boiler flues and their placement with respect to nearby buildings, ventilation inlets, opening windows etc. should be determined by direct application of the Memorandum in the same fashion as for any other flue, since the nature and quantity of the pollutants emitted in the flue gases is just the same. While the Memorandum does not exclude this type of plant, current industry practice may not always be consistent with it.

Exceedence of the hourly objective for nitrogen dioxide in the vicinity is not likely for fan-diluted emissions discharging below roof level but meeting the requirements of the Chimney Heights Memorandum. However, the margin of safety inherent in the Memorandum for fan-diluted discharges below roof level is much smaller than that applied to conventional discharges above roof level.

Exceedence of the annual mean objective for nitrogen dioxide is possible for larger fan-diluted installations discharging below roof level. The industrial emissions calculator developed for local air quality review and assessment (LAQM.TG(03)) will allow those installations requiring more detailed assessment to be identified. The application of the industrial emissions calculator to small gas boilers should be encouraged.

In theory it is possible to install modular boilers with aggregate capacity considerably in excess of 366.4 kW without coming under the provisions of the Clean Air Act 1993 regarding chimney height determination. Localised high concentrations of nitrogen dioxide are possible on the face of buildings close to the discharge points of modular gas boilers. However, the area of potential exceedence of the hourly objective for nitrogen dioxide is very small.

There is the possibility that installations of modular boilers with large aggregate capacity could lead to potential exceedences of the annual mean objective for nitrogen dioxide. The industrial emissions calculator developed for local air quality review and assessment (LAQM.TG(03)) will allow those installations requiring more detailed assessment to be

identified. The application of the industrial emissions calculator to small gas boilers should be encouraged.

We conclude that the correct application of the Chimney Heights Memorandum for the determination of chimneys serving small gas boilers should not lead to exceedances of the air quality objective for nitrogen dioxide and it is not necessary to amend the current guidance.

It is noted that the margins of safety inherent in the Memorandum's guidance differ markedly with smaller margins of safety applied to fan-diluted boilers discharging below roof level than those applied to conventional boilers discharging above roof level. However, on balance the margin of safety is likely to be adequate to control short-term exposure of members of the public. If similar margins of safety were applied to both boiler types would lead to more stringent requirements for fan-diluted discharges below roof level and for condensing boilers.

Contents

1 Introduction

Gas boilers are widely used in commercial and industrial premises for space and water heating and steam generation. The discharges from boilers with heat inputs of less than 20MW are regulated under the Clean Air Act 1993.

The Clean Air Act (Section 14(2)) requires that an occupier of a building shall not knowingly cause or permit a furnace to be used in a building to burn gaseous matter at a rate equivalent to 366.4 kilowatts or more unless the height of the chimney serving the furnace has been approved. Approval may be granted by a local authority if they are satisfied that the height of the chimney will be sufficient to prevent gases from the chimney from becoming prejudicial to health or a nuisance.

The Third Edition of the Chimney Heights Memorandum does not have the force of law but provides guidance to local authorities on relatively simple methods of calculating the approximate height of chimneys desirable in normal circumstances for appliances between 150kW and 150MW gross heat input excluding gas turbines, incinerators or direct fired heating systems. Appliances between 20MW and 150MW are regulated by either local authorities, the Environment Agency, the Scottish Environment Protection Agency or the Industrial Air Pollution Inspectorate in Northern Ireland.

Many of the gas boilers used in commercial and industrial premises fall within the provisions of the Act. The Chimney Heights Memorandum method is widely used to determine the chimney heights for these boilers. For example, the method has been included in the Institution of Gas Engineers and Managers utilization procedure IGE/UP/10. However, Institution of Gas Engineers and Managers have commented that the methods provided by the Memorandum may be inappropriate for some boiler installations. In particular, it has been suggested that the guidance should be reviewed for:

- Appliances between 70kW net input (below which they are covered by the Building Regulations) and 366.4 kW;
- Groups of boilers with aggregate capacity greater than 366.4 kW;
- Groups of room sealed appliances over 70 kW;
- Condensing appliances;
- Fan diluted systems where emission levels are less than those implied in the Memorandum;
- Natural draught and mechanical flues where emission levels are less than those implied in the Memorandum;
- Efflux velocities less than 6 m/s;
- The construction of buildings close to existing chimneys.

Statutory air quality standards and objectives have been introduced since the third edition of the Chimney Heights Memorandum was published in 1981. The Air Quality (England) Regulations 2000 and Air Quality (England)(Amendment) Regulations 2002 (Similar regulations apply in Scotland, Wales and Northern Ireland) provide objective limits for a range of air pollutants. Local authorities are required to review and assess air quality in their area to help ensure the objectives are not being exceeded. Relevant objectives for pollutants emitted from gas boilers include the following objectives for nitrogen dioxide:

> 200 $\mu g\ m^{-3}$ as an hourly mean not to be exceeded more than 18 times a year to be achieved by 31 December 2005;

40 $\mu g\ m^{-3}$ as an annual mean to be achieved by 31 December 2005;

This report describes modelling studies carried out to establish the extent to which the current guidance relating to the determination of chimney heights for gas boilers is adequate to ensure exceedances of the air quality objective for nitrogen dioxide do not occur. Issues other than pollutant dispersion are not considered: for example issues related to the optimisation of the installation design and more general health and safety issues are not addressed.

Gas boilers emit a mixture of oxides of nitrogen with the majority as nitric oxide and a small part, typically 5%, as nitrogen dioxide. Nitric oxide reacts in the atmosphere with available ozone to produce nitrogen dioxide. The extent to which conversion takes place depends on the availability of ozone, the intensity of mixing and chemical kinetics.

For most installations, the background concentration of nitrogen dioxide is a significant fraction of the air quality objective. Assessment of the air quality impact of as boiler installations should take account of the background concentration when comparing predicted concentrations with air quality standards and objectives.

A number of methods may be used to take account of both the conversion of oxides of nitrogen to nitrogen dioxide and the background nitrogen dioxide concentration. The following approach has been used in this report based on Department for Environment Transport and the Regions (DETR) Review and Assessment: Pollutant Specific Guidance LAQM TG4(00).For the hourly mean objective:

- Derive the total oxidant concentration (NO_2+O_3) at the nearest automatic monitoring station;
- If the predicted 99.8th percentile contribution from the discharge is less than the 99.8th percentile total oxidant concentration, then the total NO_2 concentration may be assumed to equal the 99.8 th percentile contribution from the discharge plus twice the annual mean background NO_2 concentration;
- If the predicted 99.8 th percentile contribution from the discharge is greater than or equal to the 99.8th percentile total oxidant concentration then the total NO_2 concentration can be assumed to be equal to the 99.8th percentile total oxidant concentration plus 5% of the predicted 99.8th percentile contribution from the discharge.

In practice, 99.8 th percentile total oxidant concentrations are generally less than approximately 180 $\mu g\ m^{-3}$ throughout most of the UK so that the hourly objective is unlikely to be exceeded if the 99.8 th percentile contribution from the discharge is less than 400 $\mu g\ m^{-3}$ NO_x. The Department for Environment, Food and Rural Affairs (DEFRA) latest guidance on Review and Assessment: Technical Guidance LAQM TG (03) applies a similar approach but includes a factor to provide a safety margin when using simplified nomograms.

For the prediction of annual mean nitrogen dioxide concentrations the annual mean NO_x contribution from the discharge is added together with any contributions from local roads to the annual mean background NO_x concentration. Exceedence of the objective is then considered unlikely if the total NO_x concentration is less than specific values provided by LAQM.TG4(00) that are dependent on the location of the nearest road. In practice, the contribution from local roads and the background concentration alone approach or exceed the objective in many locations throughout the UK and will continue to do so in 2005. It is then necessary to consider whether the discharge makes a significant contribution to the potential exceedence. In these circumstances, the Association of London Government (Association of London Government. Air Quality Assessments for planning applications - Technical Guidance

Note) has suggested that a proposed development would not be considered significant if it resulted in an increase of less than 1 $\mu g\ m^{-3}$ in nitrogen dioxide concentrations. A 1 $\mu g\ m^{-3}$ increase in nitrogen dioxide concentrations above background concentrations of 40 $\mu g\ m^{-3}$ corresponds to an increase in annual mean oxides of nitrogen concentrations of approximately 3 $\mu g\ m^{-3}$.

2 Discharge from conventional small gas boilers through natural draught chimneys

The Chimney Heights Memorandum procedure for chimney heights for gas boilers other than certain fan-diluted emissions involves the calculation of the uncorrected chimney height in metres (U) from:

$$U = 1.36Q^{0.6}$$

for gross heat inputs, Q in MW, less than 30MW.

The uncorrected chimney height is then corrected to take account of nearby buildings. In the common case where there is only a single building wider than it is high in the area within a distance of 5U of the chimney, the corrected stack height, C (in metre) is determined from:

$$C = H + 0.6U$$

where H is the height of the building, m.

The calculated stack heights are usually rounded to the nearest metre.

Table 1 shows calculated chimney heights for a building height of 10 m and various heat inputs in the range 70 kW to 20 MW, typical of small boilers.

Table 1: Stack heights calculated for various small boilers

Heat input, MW	Uncorrected stack height, m	Corrected stack height, m	Corrected stack height (rounded to nearest metre)
0.07	0.3	10.2	10
1	1.4	10.8	11
4.5	3.4	12.0	12
20	8.0	14.8	15

The National Atmospheric Emissions Inventory Emission Factor Database uses an emission factor of 4.88 x 10^{-3} kilotonnes oxides of nitrogen as nitrogen dioxide per Mth equivalent to 0.051 g/MJ for industrial and commercial gas boilers. The US EPA compilation of emission factors AP42 provides an estimate of 100 lb/standard cubic foot for standard burners and 50 lb per standard cubic foot for low NO_x burners. These values are equivalent to 0.042 g/MJ and 0.021 g/MJ respectively. A recent article by Ashmore (www.insidecom.co.uk/eibi/editorial/eibi49.html) reported that a modern condensing boiler had average oxide of nitrogen emissions of 19 ppm (oxygen free) equivalent to approximately 0.01 g/MJ. Keston (UK) report average NO_x emissions of 5 ppm (equivalent to approximately 0.003 g/MJ). For this assessment, it has been assumed that gas boilers with conventional burners produce up to 0.05 g/MJ. Boilers with low NO_x burners have been assumed to produce 0.02 g/MJ. These values are intended to provide reasonable upper limits on emissions: it is recognised that some boilers may perform rather better.

The dispersion model ADMS3 was used to predict 99.8 th percentile hourly and annual mean oxides of nitrogen concentration at ground level around the boiler chimney for boiler heat inputs and stack heights shown in Table 1. It was assumed that there was a building 20 m x 20 m x 10 m high adjacent to the chimney with the chimney at the south-west corner of the building. Weather conditions throughout the year were represented by hourly sequential meteorological data for 2000 from Coleshill (near Birmingham Airport). A surface roughness value of 0.5 m was used, typical of suburban areas. In estimating the discharge temperature it was assumed that 20 % of the gross heat input to the appliance enters the flue, with 10.6% percent as latent heat of vaporisation of the water vapour and 9.4 % as sensible heat. Two cases were considered:

- A completely natural draught system fitted with a draught diverter to reduce the carbon dioxide content in the flue to 4% by volume;
- A fan assisted system where the fan is used to assist in overcoming the appliance resistance, but where the major motive force in the flue itself is assumed to be thermal. For this case it was assumed that little dilution occurred so that the carbon dioxide content of the flue gas was 8% by volume.

The flue diameters for gas boilers need to be large enough to ensure the removal of products of combustion. Flue diameters in each case were taken from Institution of Gas Engineers IGE/UP/10 for natural draught flues which reports that experience has shown that these flue sizes are fully adequate for satisfactory operation. Table 2 shows the discharge conditions modelled.

Table 2: Discharge conditions modelled

Scenario	Heat input, MW	Carbon dioxide in flue gas, % by volume	Stack diameter, m	Discharge temperature, ^{o}C	Discharge velocity, m/s
A	0.15	4%	0.21	200	4.9
B	1	4%	0.5	200	5.8
C	4.5	4%	1	200	6.5
D	20	4%	1.7	200	10
E	0.07	8%	0.11	370	11.3
F	1	8%	0.36	370	10.8
G	4.5	8%	0.7	370	12.3
H	20	8%	1.6	370	10

Note: Discharge conditions are approximate: boiler installers should consult IGE/UP/10 for detailed design data

Table 3 shows the predicted maximum 99.8^{th} percentile hourly average and annual mean contributions from the chimney to ground level concentrations. Table 3 shows predicted ground level contributions for standard and low NO_x boilers with emission rates of 0.05 and 0.02 g/MJ respectively.

Table 3: Predicted contributions to ground level oxides of nitrogen concentrations

Scenario	Maximum contribution to ground level concentrations, $\mu g\ m^{-3}$			
	Standard burners		Low NO_x burners	
	99.8th percentile hourly	Annual mean	99.8th percentile hourly	Annual mean
A	51.5	1.1	20.6	0.4
B	44.3	1.8	17.7	0.7
C	79.9	3.7	32.0	1.5
D	95.3	3.8	38.1	1.5
E	67.5	1.1	27.0	0.5
F	32.4	1.3	12.9	0.5
G	58.3	2.6	23.3	1.0
H	89.5	3.4	35.8	1.3

The predicted contribution to 99.8 th percentile concentrations is greatest in the case of the 20MW discharge with 4% oxygen. The largest predicted contribution was 95.3 $\mu g\ m^{-3}$ NO_x. The total environmental concentration of nitrogen dioxide may be conservatively estimated in this case by adding the predicted process NO_x contribution to twice the annual mean background nitrogen dioxide concentration: 95.3+2 x 40 = 175.3 $\mu g\ m^{-3}$. This calculation conservatively assumes that all the oxides of nitrogen in the discharge are converted to nitrogen dioxide. Nevertheless, the predicted concentration is less than the objective of 200 $\mu g\ m^{-3}$. It is concluded that chimneys for small gas boilers designed according to the Chimney Heights Memorandum are likely to be sufficiently high to prevent local exceedence of the 200 $\mu g\ m^{-3}$ hourly objective for nitrogen dioxide.

The predicted contribution to annual mean concentrations is greatest in the case of the 20 MW discharge with 4% oxygen. The largest predicted contribution was 3.8 $\mu g\ m^{-3}$ NOx. Approximately a third of the additional oxides of nitrogen from the boiler will be converted to nitrogen dioxide at background locations away from the stack: thus it is estimated that the boiler will contribute 1.3 $\mu g\ m^{-3}$ to annual average nitrogen dioxide concentrations. In many locations throughout the UK, most notably in central London, background concentrations of nitrogen dioxide are already close to the annual mean objective of 40 $\mu g\ m^{-3}$. In these circumstances, the Association of London Government (Association of London Government. Air Quality Assessments for planning applications - Technical Guidance Note) has suggested that a proposed development would not be considered significant if it resulted in an increase of less than 1 $\mu g\ m^{-3}$ in nitrogen dioxide concentrations. This advice seems reasonable and practicable. It thus appears that natural draught chimneys for conventional small gas boilers designed according to the Chimney Heights Memorandum will not generally contribute significantly (at most 1.3 $\mu g\ m^{-3}$) to annual average nitrogen dioxide concentrations.

3 Condensing boilers discharged through natural draught chimneys

In a condensing boiler, the latent heat of evaporation of the water vapour produced by combustion is obtained by cooling the flue gases so that the water condenses. The volumetric flowrate and discharge temperature (approximately 55 ^{o}C) are reduced for a condensing boiler compared with that for a conventional boiler resulting in a reduction in the buoyancy and momentum of the discharging plume.

The dispersion model ADMS 3.1 was used to predict the contribution from the chimney discharge to 99.8 th percentile hourly and annual mean ground level concentrations of oxides of nitrogen. The chimney heights calculated using the Chimney Heights Memorandum (Table 1) were assumed to apply. It was assumed that there was a building 20 m x 20 m x 10 m high adjacent to the chimney with the chimney at the south-west corner of the building. Weather conditions throughout the year were represented by hourly sequential meteorological data for 2000 from Coleshill (near Birmingham Airport). A surface roughness value of 0.5 m was used, typical of suburban areas. Table 4 shows the scenarios modelled.

Table 4: Scenarios modelled for condensing boilers

Scenario	Heat input, MW	Diameter, m	Discharge velocity, m/s
I	0.15	0.21	1.40
J	1	0.5	1.65
K	4.5	1	1.86
L	20	1.7	2.85

Note: Discharge conditions are approximate: boiler installers should consult IGE/UP/10 for detailed design data

Table 5 shows the predicted maximum 99.8th percentile hourly average and annual mean contributions from the chimney to ground level concentrations. Table 5 shows predicted ground level contributions for standard and low NO_x boilers with emission rates of 0.05 and 0.02 g/MJ respectively.

Table 5: Predicted ground level contributions to oxides of nitrogen concentrations from condensing boilers

Scenario	Heat input, MW	Standard burners		Low NOx burners	
		99.8th percentile hourly	Annual mean	99.8th percentile hourly	Annual mean
I	0.15	54.4	1.9	21.8	0.8
J	1	150.4	5.4	60.2	2.2
K	4.5	417.8	14.1	167.1	5.6
L	20	564.0	24.6	225.6	9.8

Pollutant Specific Guidance (LAQM(TG4(00)) recommends that the total environmental 99.8th percentile nitrogen dioxide concentration is calculated as the 99.8 th percentile background total oxidant (O_3 + NO_2) concentration plus 5% of the 99.8th percentile NO_x contribution from the chimney where the chimney NO_x contribution is greater than the background total oxidant concentration. For background 99.8 th percentile background total oxidant concentrations of 180 μg m^{-3} (not exceeded in most locations), the hourly objective would be exceeded if the chimney NO_x contribution exceeded (200-180)/0.05=400 μg m^{-3}. For background total oxidant concentrations of around 150 μg m^{-3}, the corresponding NO_x contribution allowable from the chimney would be 1000 μg m^{-3}. From Table 5 it is clear that the 400 μg m^{-3} value could be exceeded for standard burners with heat inputs of 4.5 MW or greater. However, in practice nearly all modern condensing boilers use low NO_x burners and are typically below 1.5 MW input. It is thus unlikely in practice that there will be significant exceedences of the hourly objective, although such exceedences are theoretically possible if the Chimney Heights Memorandum method were applied to condensing boilers with standard burners or more than 4.5 MW heat input.

The impact of a commercial or industrial boiler may be considered significant in areas where background concentrations of nitrogen dioxide are already approaching the objective limit of 40 μg m^{-3} if the maximum contribution to annual average nitrogen dioxide exceeds 1 μg m^{-3}. Allowing for incomplete conversion of oxides of nitrogen to nitrogen dioxide in the atmosphere, this may be considered equivalent to approximately 3 μg m^{-3} of oxides of nitrogen. Examination of Table 5 indicates that for condensing boilers with heat inputs less than about 1.5 MW and low NO_x burners, it is unlikely that the boiler will make a significant contribution to nitrogen dioxide concentrations. Since nearly all condensing boilers currently meet these restrictions, it follows that the CHM probably deals with condensing boilers adequately. However, for larger condensing boilers, which may be considered in the future, more detailed guidance may be required.

There is some uncertainty in the application of dispersion models. The general approach to dealing with this uncertainty is to employ a safety margin. The size of the safety margin depends on the sophistication of the modelling assessment. For example, screening nomograms included in Technical Guidance LAQM.TG(03) employ a factor of 4 to provide a safety margin: on the other hand detailed dispersion model supported by monitoring data might employ a much smaller safety margin. Application of the CHM to condensing boilers with low momentum and low buoyancy discharges represents a significant reduction in the margins of safety. However, on balance the margin of safety is likely to be adequate for most condensing boilers.

4 Room-sealed boiler flue systems

Room-sealed boiler flue systems are occasionally used on small to medium sized plant. The boiler room is sealed to prevent the passage of air from anywhere except a single inlet. This inlet is a concentric tube running up the outside of the main boiler flue and terminating a short distance below it. The objective of this arrangement is to provide a form of balanced flue. Since the combustion air inlet and the flue outlet are close together it is possible in principle to avoid the large fluctuating pressure differences between them that can occur in conventional boiler systems in strong winds.

There has been a suggestion that the Chimney Heights Memorandum should not be applied for the determination of stack heights for room-sealed appliances. The applicability of the CHM has been considered by Hall, 1987. He recommended that chimney heights for room-sealed boiler flues and their placement with respect to nearby buildings, ventilation inlets, opening windows etc. should be determined by direct application of the CHM in the same fashion as for any other flue, since the nature and quantity of the pollutants emitted in the flue gases is just the same. The appears to be no reason to modify this advice.

5 Fan diluted emissions

5.1 INTRODUCTION

For fan diluted emissions from furnaces rated at less than 6 MW using very low sulphur fuel (including natural gas) the corrections for building effects and the minimum height requirements contained within the CHM are not applied. The CHM allows flue gases from such furnaces to be emitted at height U, which may be below the roof level of the building so long as the following requirements are met:

a) The emission velocity must be at least 75/F m/s where F is the fan dilution factor, defined as V/V_0 where V is the actual gas volume and V_0 is the stoichiometric combustion volume. For natural gas V_0 is 0.26 m^3/s per MW thermal input.
b) The outlet must not be within 50 U/F of a fan-assisted intake (except for the intakes for combustion air or fan dilution air) where U is the uncorrected stack height calculated from the heat input.
c) The outlet must not be within 20U/F of an openable window on the emitting building.
d) The distance to the nearest building must be at least 60U/F.
e) The lower edges of all outlets must be at least 3 m above the ground, with the exception of units with thermal inputs of less than 1 MW where 2 m is permissible.
f) The outlets must be directed at an angle above the horizontal-preferably at about 30^o-and must not be under a canopy.
g) Flue gas should not be emitted into an enclosed, or almost totally enclosed well or courtyard.

It is uncertain how these requirements were derived. The Memorandum refers to a background paper by Barrett and Wallin- however Hall and Kukadia report that the paper was never written.

Predicting ground level concentrations in the vicinity of buildings for discharges below roof level is not straightforward. Four alternative models were therefore used:

- Simple correlations derived from the results of wind tunnel models;
- The large eddy simulation model, FDS3;
- The dispersion model, ADMS 3.1;
- The industrial emissions calculator provided in support of Review and Assessment: Technical Guidance LAQM TG(03).

5.2 CORRELATIONS DERIVED FROM WIND TUNNEL STUDIES

Wind tunnel results are often expressed in terms of a dimensionless concentration coefficient K, expressed as

$$K = \frac{CuL^2}{q}$$

where C is the local concentration, u is a reference wind speed. L is a reference length scale and q is the emission rate. For assessment of separation distances, it is convenient to set the reference length scale as the separation distance, S. Many wind tunnel results for dilution factors from vents on the surface of buildings have been represented by $K=1/B_1$ where B_1 is a constant. Meroney (1982) presented values for B_1 derived by Briggs, 1975 (0.25), Scorer and Barrett, 1962 (0.14) and Wilson, 1976 (0.11).

For gas boilers the rate of emission of oxides of nitrogen is related to the heat input, Q by q=kQ where k is typically 0.05 g/MJ for standard burners and around 0.02 g/MJ for low NOx burners.[Emissions are given as mass of oxides of nitrogen as nitrogen dioxide].

The uncorrected chimney height U is estimated in the CHM by $U=1.36\ Q^{0.6}$. This may be approximated reasonably well in the range 366 kW to 6MW by $U=1.36\ \sqrt{Q}$.

Substituting into the expression for K above gives:

$$C = \frac{k}{1.36^2 B_1 u}\left(\frac{U}{S}\right)^2$$

Evaluating for k=0.020 g/MJ, B_1=0.14, u= 3 m/s and U/S=F/60 corresponding to the required distance to the nearest building 60U/F given in the Memorandum for typical fan dilution factors of 10 gives C=715 μg m^{-3}. Allowable oxides of nitrogen contributions for the prevention of exceedences of the 99.8th percentile hourly average nitrogen dioxide objective of 200 μg m^{-3} depend on total background oxidant concentrations and are typically in the range 400-1000 μg m^{-3}. It is thus possible that the CHM provides adequate separation in some situations: however exceedence of the objective is possible in other circumstances. The simple correlation of wind tunnel data does not take account of the buoyancy and momentum of the discharge and so it is expected that it will lead to an overestimate of local concentrations.

5.3 LARGE EDDY SIMULATION

Further assessment of the dispersion of fan diluted emissions was carried out using the large eddy simulation model FDS3 in order to provide a more detailed assessment of the potential impact of fan diluted emissions, taking into account the buoyancy and momentum of the discharge.

Simulation was carried out over two simulation domains covering the immediate space surrounding the discharge point and the larger space including the whole building and the area downwind of it.

The large model domain extended 200 m x 200 m x 108 m high with an upwind turbulence conditioning domain extending over an additional 70 m x 200 m x 108 m. Grid resolution throughout the domain was 2 m. An air flow was introduced at the edge of the turbulence conditioning domain to represent the wind with a velocity of 4 m/s at 10 m above ground and a power law velocity profile in the vertical direction given by $u=u_{10}(z/z_{10})^{0.25}$. A zero temperature lapse rate corresponding to neutral stability conditions was imposed. Upwind turbulence was generated by specifying the velocity time series on 30 planar surfaces at the upwind end of the turbulence conditioning domain. The velocity time series on each surface was generated by means of a first order Markov process such that the turbulent kinetic energy and the turbulent length scales in the flowstream were representative of the surface boundary layer. The spacing of the turbulence devices was of the same order as the turbulent length scale.

The small model domain extended 40 m x 40 m x 20 m high with an upwind turbulence conditioning domain extending over an additional 20 m x 40 m x 20 m. Grid resolution throughout the domain was varied between 0.5 m, 1 m and 2 m to allow the assessment of the magnitude of numerical truncation errors. An air flow was introduced at the edge of the turbulence conditioning domain to represent the wind with a velocity of 4 m/s at 10 m above ground and a power law velocity profile in the vertical direction given by $u=u_{10}(z/z_{10})^{0.25}$. A zero temperature lapse rate corresponding to neutral stability conditions was imposed. Upwind turbulence was generated by specifying the velocity time series on 3 planar surfaces at the upwind end of the turbulence conditioning domain. The velocity time series on each surface was generated by means of a first order Markov process such that the turbulent kinetic energy and the turbulent length scales in the flowstream were representative of the surface boundary layer. The spacing of the turbulence devices was of the same order as the turbulent length scale.

The discharge from a fan diluted boiler was represented by a vent 2 m square vent 3 m above the ground midway along the upwind face of a 40 m x 10 m x 10 m high building. The discharge was characterised in terms of dimensionless buoyancy flux and momentum flux parameters. The buoyancy flux parameter is defined as,

$$\frac{F}{U^3 L}$$

where F is the buoyancy flux:

$$F = g\frac{\Delta\rho}{\rho_a}\frac{V}{\pi}$$

The momentum flux parameter is defined as

$$\frac{M}{U^2 L^2}$$

where

$$M = V\frac{\rho}{\rho_a}w$$

In the above:

U=windspeed at the reference height (taken to be the height of the building, 10 m),
w= the gas exit velocity,
L is the length scale, taken to be the height of the building, 10 m
ρ is the density of the flue gas;
ρ_a is the density of the ambient air;
V is the volume emission rate;
g is the gravitational acceleration.

For this assessment, the buoyancy flux parameter was 0.011 and the momentum flux parameter was 0.074. These values were selected to represent the buoyancy and momentum for the discharge from a 5.5 MW boiler with a fan dilution factor of 10.

The simulation was run for 300 seconds in the model time domain, to allow sufficient time for flow patterns to become established and to provide a suitable averaging time period. Average concentrations were calculated over the 180 second period from t=120 seconds to t=300 seconds.

Emission rates were predicted on the basis of IGE/UP/10, which gives an upper bound oxides of nitrogen concentration of 5 ppm at 1% carbon dioxide in the flue gas. This value is approximately equivalent to 0.025 g/MJ for natural gas.

The FDS3 model has been extensively validated by its developers, the US National Institute of Standards and Technology. Its fitness for application to the assessment of dispersion of pollutants from small sources in the vicinity of buildings is demonstrated by comparison with the results of wind tunnel studies in Appendix A.

Fig. 1 shows a side view of the snapshot of the distribution of particles released from the discharge point for the large-scale domain. Fig. 2 shows the predicted 3-minute average concentration on the upwind face of the building. Predicted oxides of nitrogen concentrations are less than 400 $\mu g\ m^{-3}$ except at locations within approximately 8 m of the discharge point. This value exceeds the objective for nitrogen dioxide of 200 $\mu g\ m^{-3}$ as the 99.8 th percentile of hourly means. However, taking account of the incomplete conversion of oxides of nitrogen to nitrogen dioxide it is unlikely that the objective limit will be exceeded for the wind conditions modelled. The Chimney Heights Memorandum Guidance would not allow an openable window to be located on the emitting building at distances less than approximately 8 m from the discharge point.

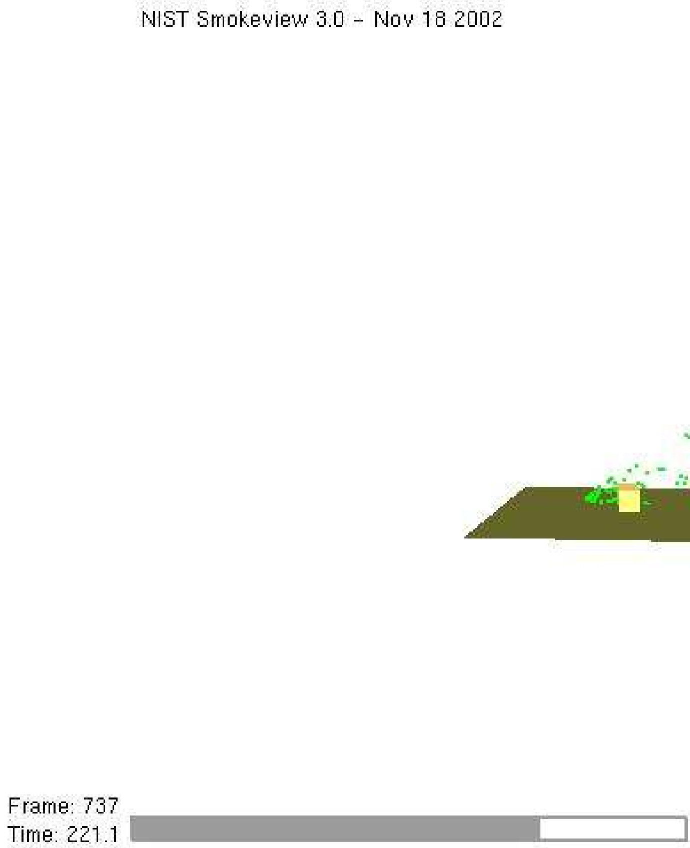

Fig. 1: LES predicted snapshot concentration pattern for fan diluted flue on the upwind side of the building, wind speed =4 m/s at 10 m.

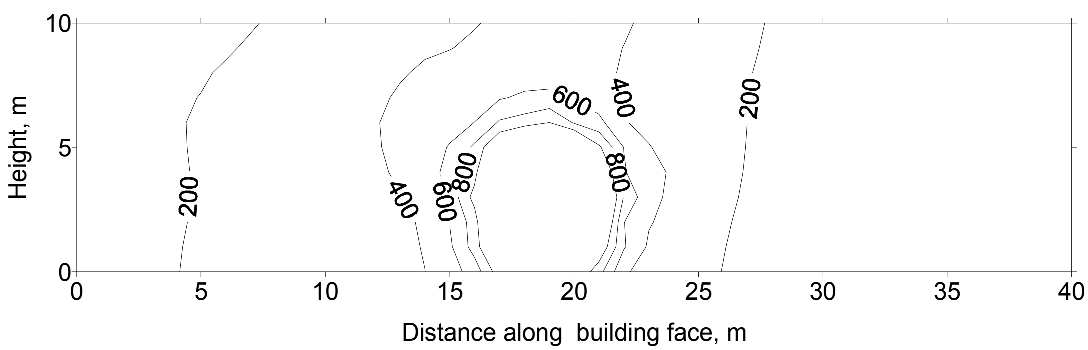

Fig. 2: LES predicted 3 minute average oxides of nitrogen concentrations, $\mu g\ m^{-3}$, on upwind face of the building, 5.5 MW fan diluted flue on upwind face of building, 10 m wind speed of 4 m/s. Source location is 19 m from left and 3 m above ground.

Fig. 3 shows the predicted concentrations on the face of the building at a height 2 m above the ground, at the level of the bottom of the discharge point. It shows predictions made using the large-scale model with 2 m resolution and the small-scale model with resolution of 2 m, 1 m and 0.5 m. The results are broadly similar, although they are clearly influenced to some extent by numerical truncation errors. Nevertheless, all predicted concentrations are less than 400 μg m^{-3} at distances greater than 10 m from the discharge point.

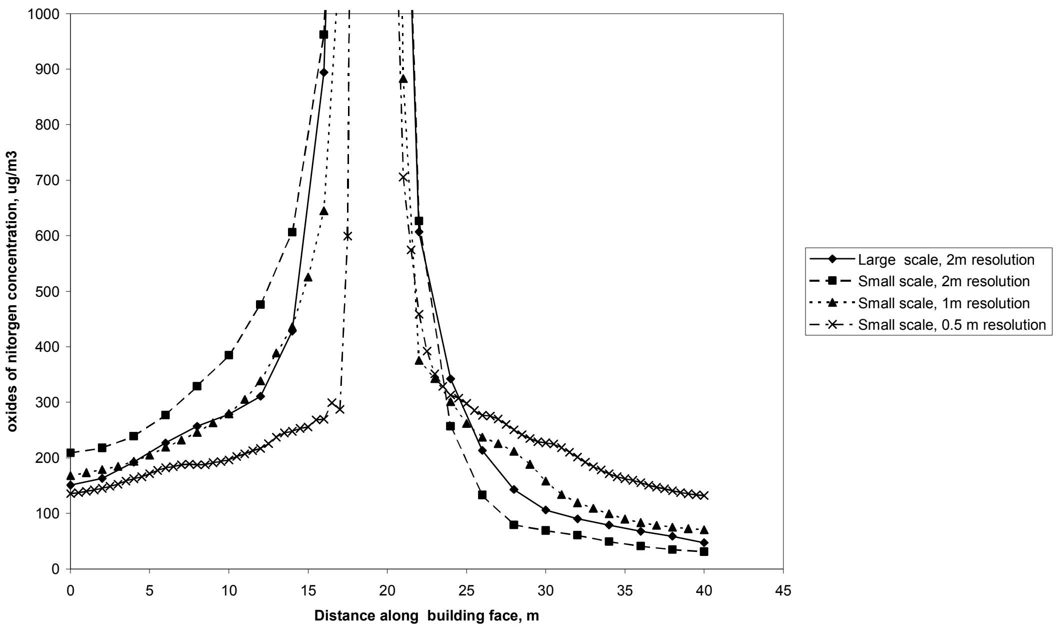

Fig. 3: Three minute average oxides of nitrogen concentrations, μg m^{-3}, on the building face at a height 2 m above ground level. Comparison of results for large scale and small-scale models and grid resolutions of 2m, 1m and 0.5 m. 5.5 MW fan diluted flue on upwind face of building, 10 m wind speed of 4 m/s

Fig. 4 shows the oxides of nitrogen concentrations at ground level in front of the discharge point on the building. The model predicts that the ground level concentrations will be less than 400 μg m^{-3} at distances greater than approximately 22 m. This value exceeds the objective for nitrogen dioxide of 200 μg m^{-3} as the 99.8 th percentile of hourly means. However, taking account of the incomplete conversion of oxides of nitrogen to nitrogen dioxide it is unlikely that the objective limit will be exceeded for the wind conditions modelled. The Chimney Heights Memorandum Guidance would not allow the nearest building to be located at distances less than approximately 22 m from the discharge point.

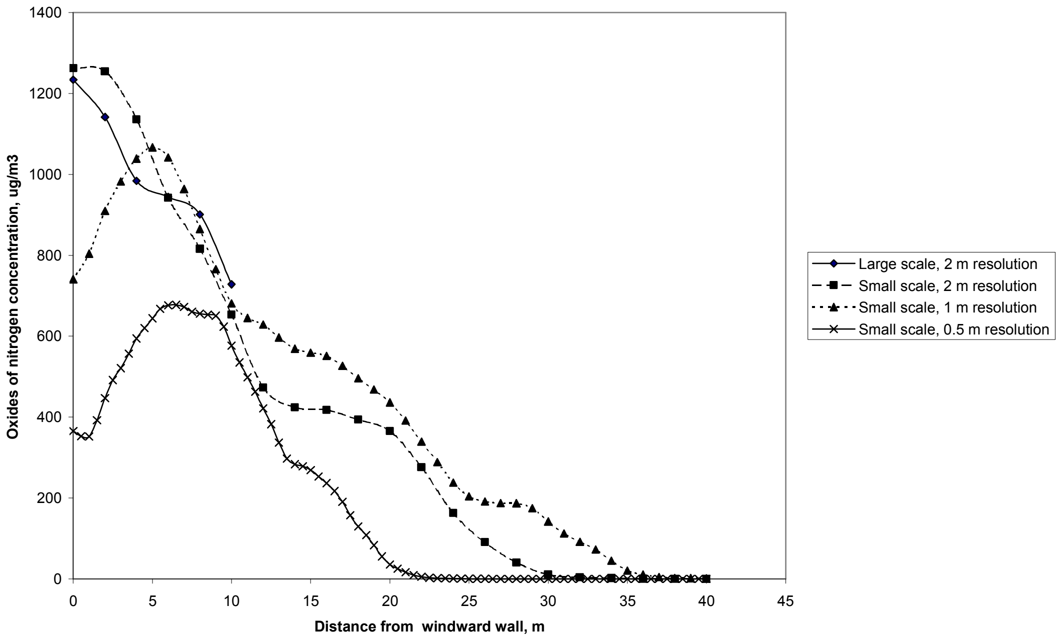

Fig. 4: Three minute average oxides of nitrogen concentrations, $\mu g\ m^{-3}$, at ground level in front of building. Comparison of results for large-scale and small-scale models and grid resolutions of 2m, 1m and 0.5 m. 5.5 MW fan diluted flue on upwind face of building, 10 m wind speed of 4 m/s

Model runs were also carried out for a 10 m wind speed of 1 m/s: predicted ground level concentrations were markedly smaller than those shown in Fig .4: the wall concentrations were similar to those shown in Fig. 3.

There is some uncertainty in the application of models. The general approach to dealing with this uncertainty is to employ a safety margin. The size of the safety margin depends on the sophistication of the modelling assessment. For example, screening nomograms included in Technical Guidance LAQM.TG(03) employ a factor of 4 to provide a safety margin: on the other hand detailed dispersion model supported by monitoring data might employ a much smaller safety margin. The CHM guidance on fan-diluted boilers discharging below roof level contains significantly smaller margins of safety than the method applied to conventional discharges above roof level. However, on balance the margin of safety is likely to be adequate to control short-term exposure of members of the public.

5.4 DISPERSION MODELLING

The dispersion model ADMS3.1 was also used to predict ground level concentrations close to the fan diluted discharge from the building. The purpose of using ADMS 3.1 was to enable an estimate of annual mean oxides of nitrogen concentrations to be made because it is not practicable to make predictions of annual mean concentrations using the large eddy simulation model. ADMS 3.1 is not particularly suitable for predicting ground level concentrations very close to building with discharges below the roof level. However, it is expected to provide satisfactory results at distances greater than a few building heights from the source. Fig. 5 shows the predicted annual average contribution to oxides of nitrogen from a fan-diluted flue for a 5.5 MW thermal input boiler discharging 3 m above ground midway along on the west side of a 20 m x 20 m x 10 m high building with discharge point at

(40,49). The modelled contribution from the boiler exceeds 3 μg m^{-3} of oxides of nitrogen at distances of approximately 100 m from the discharge. As discussed in Section 2, a contribution of 3 μg m^{-3} to annual mean oxides of nitrogen concentrations may be considered significant in areas where background concentrations approach the objective for nitrogen dioxide of 40 μg m^{-3} as an annual mean. The use of large fan-diluted boilers in such areas may not be considered acceptable where members of the public may be exposed over the annual mean averaging time (residential properties, schools, libraries, hospitals etc.).

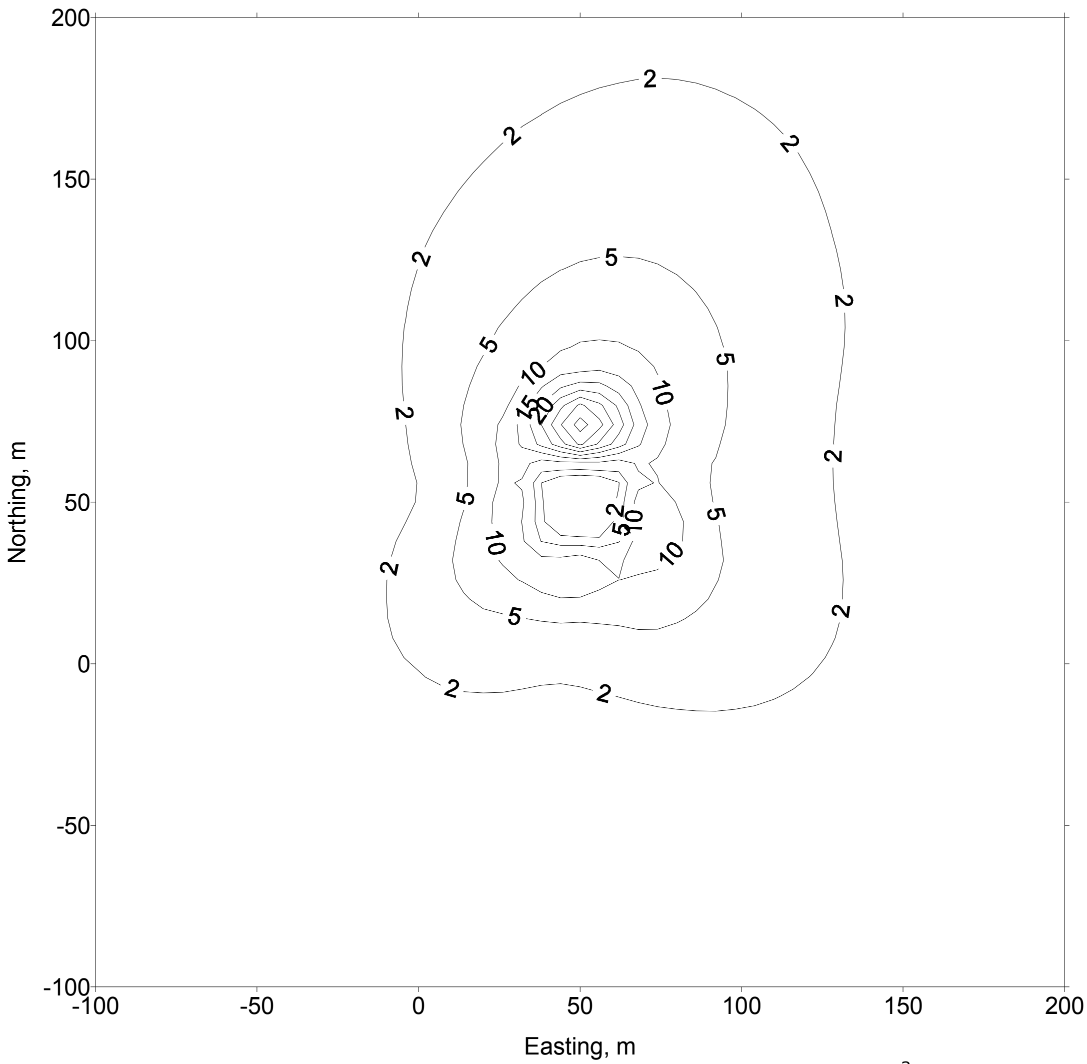

Fig.5: Predicted annual mean oxides of nitrogen concentrations, μg m^{-3}, near a 5.5 MW boiler with fan-diluted flue discharging below roof level.

5.5 INDUSTRIAL EMISSIONS CALCULATOR

An industrial emissions calculator has been developed (Abbott, 2002) for inclusion within 2003 Technical Guidance for local authorities (LAQM TG(03)). The calculator allows the local authority to assess whether detailed investigation is required to assess the potential impact of oxides of nitrogen emissions from industrial sources with low-level emissions. The calculator is intended to provide a conservative assessment of potential impact. The assessment is made on the basis of predicted rates of emission, the discharge height, the location of the nearest location where members of the public may be exposed over the relevant averaging time and background nitrogen dioxide concentrations.

Table 6 shows the rates of emission from low-level sources allowed by the calculator before more detailed assessment is required. The calculations have been based on a discharge height for fan-diluted flues of 3.5 m above ground.

Table 6: Screening emission limits for low level sources: larger emissions require detailed assessment

	Allowable rate of emission, tonnes per annum					
	Background nitrogen dioxide concentration,μg m^{-3}					
Distance of nearest receptor, m	30	32	34	36	38	40
20	0.49	0.39	0.29	0.19	0.1	0.05
50	1.65	1.32	0.99	0.66	0.33	0.16
100	4.5	3.6	2.7	1.8	0.9	0.45
200	13.1	10.5	7.9	5.24	2.62	1.31

These values may be converted into boiler heat inputs assuming an emission of 0.020 g/MJ for natural gas (low NO_x burners) and assuming constant operation at full load. The allowable boiler inputs calculated in this way are shown in Table 7.

Table 7: Screening limits for boiler capacity: larger boilers require more detailed assessment

	Allowable boiler heat input, MW					
	Background nitrogen dioxide concentration, μg m^{-3}					
Distance of nearest receptor, m	30	32	34	36	38	40
20	0.6	0.5	0.4	0.2	-	-
50	2.1	1.7	1.3	0.8	0.4	0.2
100	5.7	4.6	3.4	2.3	1.1	0.6
200	16.6	13.3	10.0	6.6	3.3	1.7

5.6 SUMMARY

Initial assessment of the impact of fan diluted flues for gas boilers discharging below the roof level of buildings on local concentrations of nitrogen dioxide using simple correlations derived from wind tunnel studies suggested that use of these flues could lead to potential exceedences of the hourly average objective of 200 μg m^{-3} for nitrogen dioxide.

More detailed analysis taking account of the discharge momentum and buoyancy was therefore carried out using a large eddy simulation model. This more detailed analysis indicated that exceedence of the hourly objective was not likely where the Chimney Heights Memorandum guidelines are followed. However, the margin of safety inherent in the CHM guidance for fan-diluted discharges below roof level is markedly less than that applied to conventional discharges above roof level.

Consideration was then given to the possibility of exceedence of the annual mean objective for nitrogen dioxide of 40 μg m^{-3}. Predictions made using the dispersion model ADMS 3.1 indicate that the use of fan-diluted flues discharging below roof level may make a significant contribution to oxides of nitrogen concentrations in areas where the background nitrogen dioxide concentration approaches the objective.

A simple industrial emissions calculator has been developed separately for DEFRA for use in local authority review and assessments. Application of the calculator will identify those installations where there is a risk of exceedence of the annual mean objective and more detailed assessment beyond that provided by the Memorandum will be required.

6 Modular boiler systems

Boiler manufacturers are able to meet boiler requirements in some cases by installing more than one small boiler on a modular basis. Individually these boilers may have heat input ratings less than the Clean Air Act lower limit of 366.4 kW and so the occupier or installer might consider that the provisions of the Act regarding chimney heights do not apply although the aggregate capacity of the installed boilers is greater than the limit.

Section 64(6) of the Act indicates that where more than one boiler discharges through a single chimney then the chimney height should be determined on the basis of the aggregate capacity of the boilers. However, where each boiler of capacity less than 366.4 kW discharges through an individual chimney the Act may not apply and discharges below roof level may be allowed.

The Chimney Heights Memorandum is applicable down to 150 kW and its application might be considered best practice even though it is not required by the Act. Installations of boilers with heat inputs less than 70 kW are designed according to the building regulations.

The discharge from a row of five 150 kW gas boilers installed at 4 m intervals along the upwind face of a 40 m x 10 m x 10 m high building was modelled using the large eddy simulation model FDS3 for a wind speed of 4 m/s. Each boiler was assumed to discharge horizontally 3 m above the ground. The heat content of the discharge was assumed to be 25% of the boiler rating. It was assumed that the discharge had little momentum.

Model runs were carried out for the large-scale and small-scale domains described in Section 5.2.

Average NO_x concentrations were calculated on the upwind face of the building and at ground level in front of the building. Fig.6 shows the predicted concentrations on the face of the building (large scale model) for low NO_x burners with emissions factors of 0.02 g/MJ. Fig. 7 shows predicted concentrations at ground level in front of the building. The concentrations fall below 400 $\mu g\ m^{-3}$ within a few metres of the discharge.

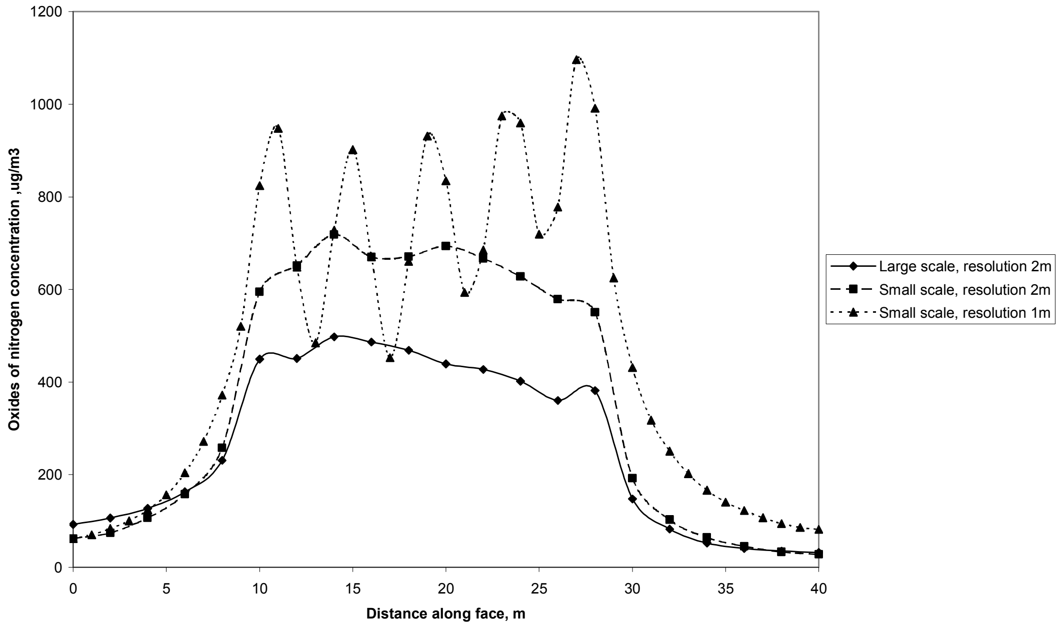

Fig. 6: Three minute average oxides of nitrogen concentrations on the building face at a height 2 m above ground level. Comparison of results for large-scale and small-scale models and grid resolutions of 2m and 1m. Five 0.15 MW boiler flues on upwind face of building, 10 m wind speed of 4 m/s

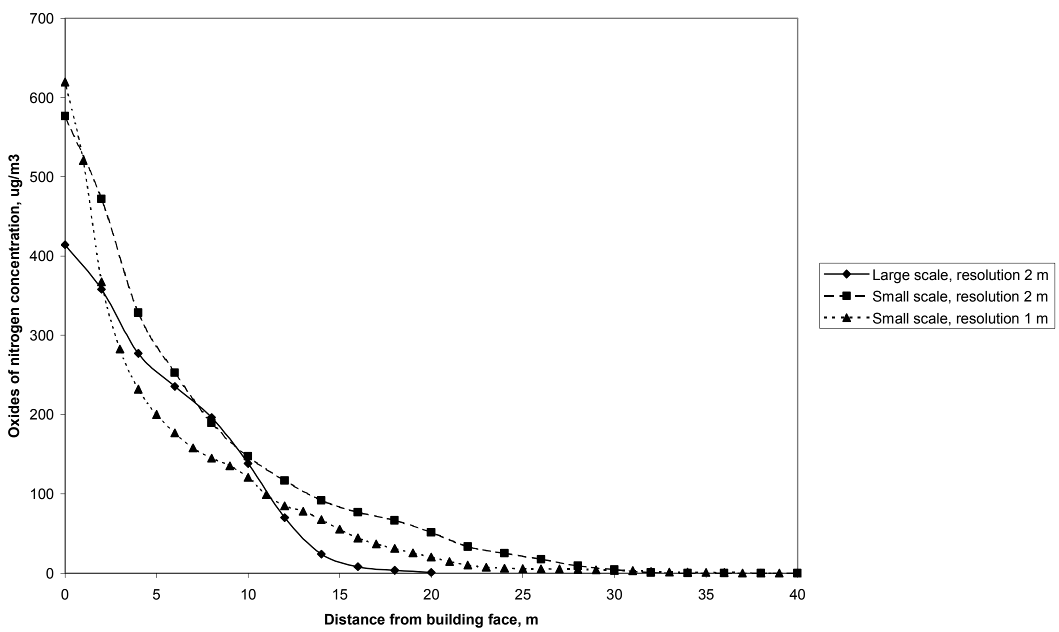

Fig. 7: Three minute average oxides of nitrogen concentrations at ground level in front of building. Comparison of results for large-scale and small-scale models and grid resolutions of 2m and 1 m. Five 0.15 MW boiler flues on upwind face of building, 10 m wind speed of 4 m/s

It is concluded that discharging multiple boilers with aggregate capacity in excess of the Clean Air Act limit of 366.4 kW through separate flues below the building roof line is likely to lead to high nitrogen dioxide concentrations on the face of the building close to the points of discharge in excess of the hourly objective for nitrogen dioxide of 200 $\mu g\ m^{-3}$. However, the extent of the area of exceedence of the hourly mean objective for nitrogen dioxide is likely to be small. Members of the public outside are unlikely to be affected.

The industrial emissions calculator was developed for local authority review and assessment and is intended as a screening tool. It aims to help identify low-level sources of oxides of nitrogen with the potential for exceeding the annual average objective for nitrogen dioxide. Further assessment of emission sources may be required where there is a risk of exceeding the objective. Consideration of Table 7 indicates that in many applications it will be possible to use modular boilers with total capacity in excess of the Clean Air Act limit of 366.4 kW without risking exceedence of the annual mean objective for nitrogen dioxide.

7 Discussion

The assessment carried out in this report indicates that the guidance provided by the CHM is adequate in most cases to prevent exceedences of the hourly objective for nitrogen dioxide. However, the margin of safety inherent in the guidance is not the same for each type of boiler. The inherent safety margin applied for conventional boilers discharging above roof level is consistent with that applied for other screening models. On the other hand the guidance provided for fan-diluted flues discharging below roof level provides only a small margin of safety. Safety margins are also reduced when the guidance is applied to condensing boiler discharges. From an industry point of view it might be desirable to have similar margins of safety applying to all boiler types: this would almost certainly lead to more stringent requirements for fan-diluted discharges below roof level and for condensing boilers.

The CHM was developed to limit short-term ground level concentrations of sulphur dioxide and oxides of nitrogen. It was not intended to provide any control on annual average nitrogen dioxide concentrations., However, it does provide effective control of annual average nitrogen dioxide concentrations for conventional discharges above roof level although it does not provide effective control of the contribution from fan-diluted or modular boiler systems discharging below roof level. New guidance to local authorities (LAQM.TG(03)) will allow such sources with the potential to cause exceedence of the annual mean objective for nitrogen dioxide to be identified. The guidance requires local authorities to consider new industrial sources or sources with substantially increased emissions when carrying out their reviews and assessments. Wider application of the guidance in LAQM.TG(03) should be encouraged.

8 Conclusions

Chimney heights for conventional natural draught gas boilers determined by proper application of the third edition of the Chimney Heights Memorandum are likely to be sufficient to prevent local exceedences of the air quality objectives for nitrogen dioxide.

Application of the Memorandum for the determination of chimney heights for large condensing boilers may lead to unsatisfactory dispersion because of the low efflux velocity associated with flues for these boilers. For condensing boilers with low NO_x burners and heat inputs less than 1.5 MW the Memorandum is likely to be adequate to prevent local exceedences of the air quality objectives for nitrogen dioxide. Larger condensing boilers (of which there are currently very few) may require more detailed assessment.

Chimney heights for room-sealed boiler flues and their placement with respect to nearby buildings, ventilation inlets, opening windows etc. should be determined by direct application of the Memorandum in the same fashion as for any other flue, since the nature and quantity of the pollutants emitted in the flue gases is just the same.

Exceedence of the hourly objective for nitrogen dioxide in the vicinity is not likely for fan-diluted emissions discharging below roof level but meeting the requirements of the Memorandum. However, the margin of safety inherent in the Memorandum for fan-diluted discharges below roof level is much smaller than that applied to conventional discharges above roof level.

Exceedence of the annual mean objective for nitrogen dioxide is possible for larger fan-diluted installations discharging below roof level. The industrial emissions calculator developed for local air quality review and assessment (LAQM.TG(03)) will allow those installations requiring more detailed assessment to be identified. Use of the industrial emissions calculator should be encouraged.

In theory it is possible to install modular boilers with aggregate capacity considerably in excess of 366.4 kW without coming under the provisions of the Clean Air Act 1993 regarding chimney height determination. Localised high concentrations of nitrogen dioxide are possible on the face of buildings close to the discharge points of modular gas boilers. However, the area of potential exceedence of the hourly objective for nitrogen dioxide is very small.

There is the possibility that installations of modular boilers with large aggregate capacity could lead to potential exceedences of the annual mean objective for nitrogen dioxide. The industrial emissions calculator developed for local air quality review and assessment (LAQM.TG(03)) will allow those installations requiring more detailed assessment to be identified. Use of the industrial emissions calculator should be encouraged.

9 References

DEFRA/ Local Air Quality Management: Technical Guidance LAQM.TG(03).

D.J. Hall. Air pollution aspects of room-sealed boiler flue systems. Clean Air Volume 17, Number 3/4, 1987.

D. J. Hall and V Kukadia. Background to the new HMIP guidelines on discharging stack heights for polluting emissions. Warren Spring Laboratory, LR929 (1993).

D. J. Hall, V. Kukadia, S.Walker and G.W.Marsland. Plume dispersion from chemical warehouse fires. BRE client report CR56/95.

D. J. Hall, S.C.Walker, A.M. Spanton and V. Kukadia. Pressure and concentration patterns on building forms in .urban arrays. BRE report CR125/99.

Institution of Gas Engineers and Managers. Installation of gas appliances in industrial and commercial premises. Part 1 : Flued appliances. Utilization procedures IGE/UP/10 Part 1. Edition 2. Communication 1676, 2002.

R N Meroney. Turbulent diffusion near buildings in E Plate (ed) Engineering meteorology. Elsevier, 1982.

Appendix 1: FDS3 model verification for small emission sources

Introduction

The FDS3 large eddy simulation model has been extensively validated by the model developers, the US National Institute of Standards and Technology. However, the developers recommend that the model performance is verified by comparison with relevant experiments. Relevant experiments have been carried out by Hall et al (1995, 1999): this Appendix compares model predictions with the results from selected wind tunnel experiments.

Velocity and turbulence profiles

Preliminary numerical experiments were carried out to determine the velocity and turbulence profiles in the model domain. During most of the experiments additional turbulence is provided by the modelled obstacles and so the turbulence levels determined in the preliminary experiment may not be representative of the actual turbulence levels when modelled obstacles are present. Nevertheless, it useful to show that levels of "background" turbulence are representative of atmospheric conditions at least to a first order of approximation. For this preliminary assessment, 12 m square, 4 m high roughness elements were placed at 24 m intervals on a rectangular grid covering the model domain. Fig. A1 shows the velocity profile at the upwind and downwind edges of the modelled domain and the midpoint. Fig. A2 shows the turbulent kinetic energy ($(u'^2+v'^2+w'^2)/2$) at various heights at the midpoint of the modelled domain. Fig. A3 shows the autocorrelation coefficient for the vertical velocity at various heights at the midpoint of the model domain.

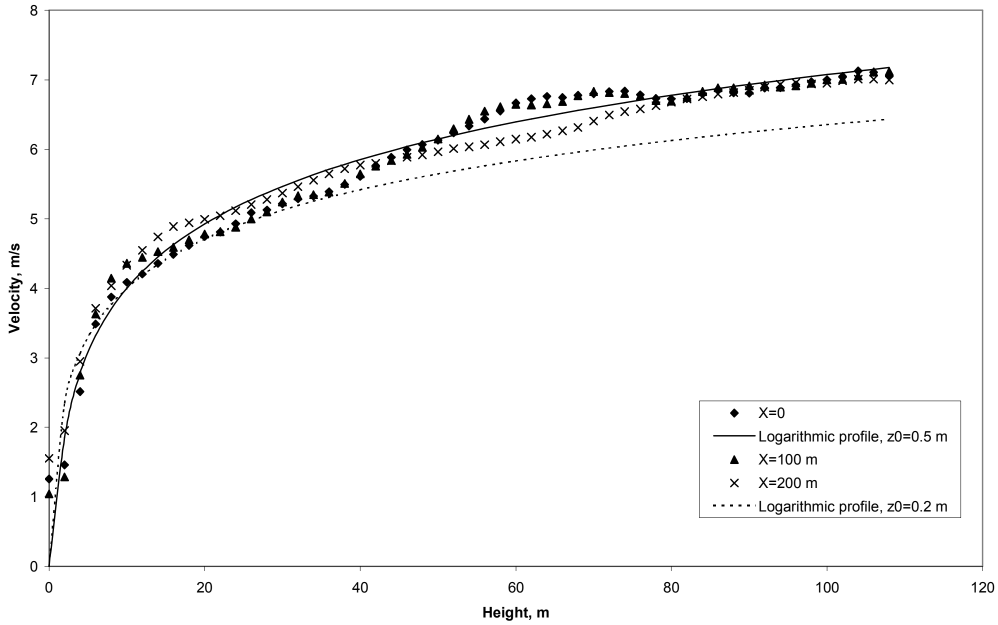

Fig. A1: Velocity profile

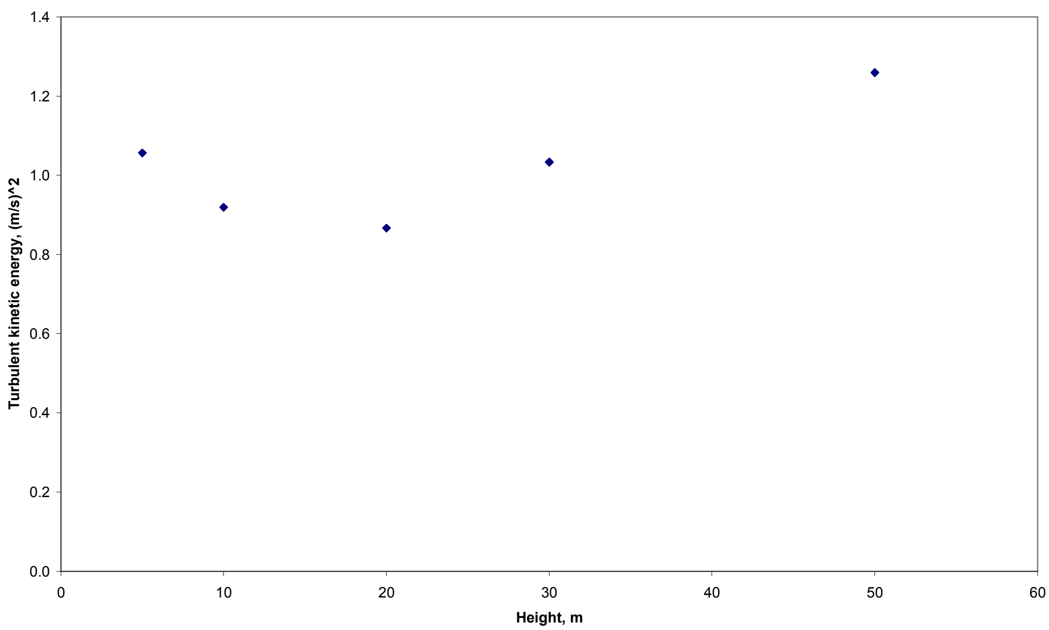

Fig. A2: Turbulent kinetic energy

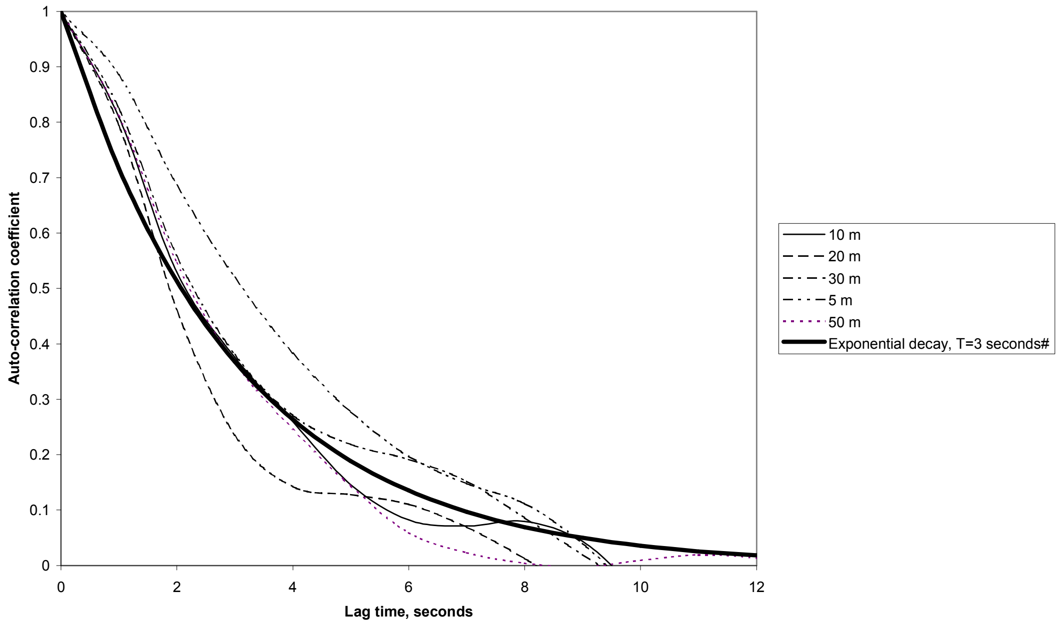

Fig. A3: Autocorrelation coefficient for vertical velocity component.

The measured velocity profile approximates to a logarithmic velocity profile with surface roughness in the range 0.2-1 m, characteristic of the suburban/built up areas where most industrial gas boilers are installed. The turbulent kinetic energy is characteristic of the surface boundary layer with surface roughness of approximately 0.2 m.

The autocorrelation coefficient for the vertical velocity corresponds approximately with an exponential decay with time constant of 3 seconds. The peak in the nF(n) spectrum of the vertical velocity is thus likely to occur at a frequency of about 1/3 s^{-1} corresponding to a wavelength of 12 m for a wind speed of 4 m s^{-1}. This value may be compared with wavelengths measured in the atmosphere of around 50 m at 10 m height above the ground.

9.1.1 Horizontal and vertical plume spread

A further preliminary numerical experiment was carried out to determine the horizontal and vertical plume spreads. A point source discharge was introduced into the model domain 20 m above the ground and 50 m from the upwind edge of the model domain. Mean concentrations were then calculated on a vertical plane across the model domain 100 m downwind of the source. The horizontal concentration profile was approximately Gaussian, with a lateral dispersion coefficient of 14 m. This value may be compared with a value of 8 m given by Clarke(1979) and a value of 17 m provided for these conditions by the well-established dispersion model ADMS3.1.

The modelled vertical concentration profile is shown in Fig.A4 . Also shown is the Gaussian concentration profile (including ground level reflection) for a vertical dispersion coefficient of 9 m (c.f. Clarke 1979- 7 m and ADMS3.1- 9 m).

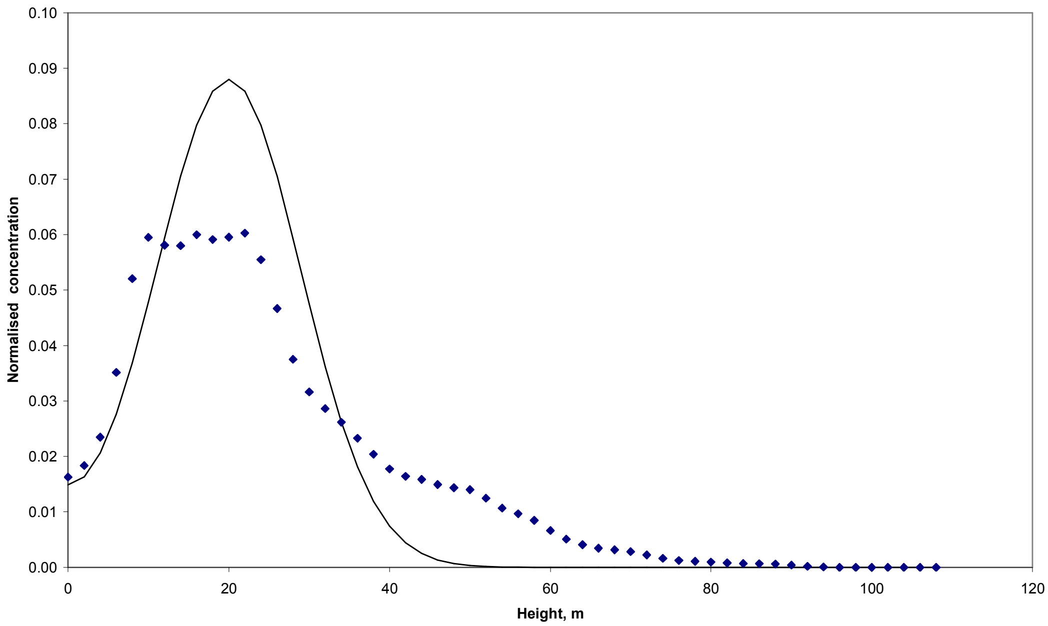

Fig.A4: Vertical plume spread

Momentum source from a large building

Hall et al (1995) have carried out wind tunnel experiments to assess the ambient concentration of pollutants released through holes in the roof of warehouse buildings of various shapes and sizes. Fig A5 compares the model predictions for a single 2 m diameter momentum source in the roof of a warehouse building with dimensions 100 m x 30 m x 10 m high to the eaves. The momentum flux parameter (M/U^2L^2) was 0.1. These discharge conditions correspond approximately to those of the 5.5 MW fan diluted boiler considered in this report.

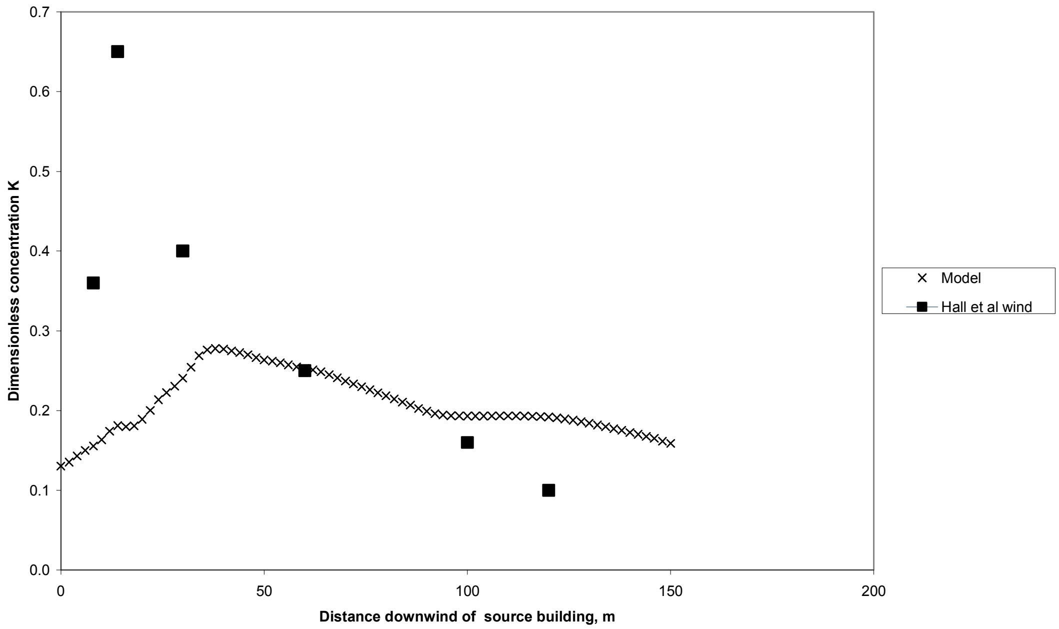

Fig. A5: Comparison of model predictions and wind tunnel studies carried out by Hall et al 1995 of a large warehouse building (100 m x 30 m x 10 m) with single 2 m diameter discharge in the roof with momentum flux parameter=0.1. Large-scale model with grid resolution 2 m.

Ground level source in front of a rectangular building

Hall et al (1999) have carried out wind tunnel experiments to assess the ambient concentration of pollutants released at ground level in front of buildings. Fig. compares the model predictions and wind tunnel measurements of the concentration on the windward face of a 40 m x 10 m x10 m building for a non-buoyant low-momentum source 10 m in front of the building.

Hall et al (1999) also measured the concentrations on the face of buildings in arrays of buildings in a wind tunnel. Fig. A7 shows such an array of buildings as modelled using FDS3. The buildings are each 40 m x 10 m x 10m with an overall building density of 44 %. The emission source was located midway between two buildings. Fig. A8 compares the concentration on the face of the building immediately downwind of the source predicted by the FDS3 model with the wind tunnel measurement.

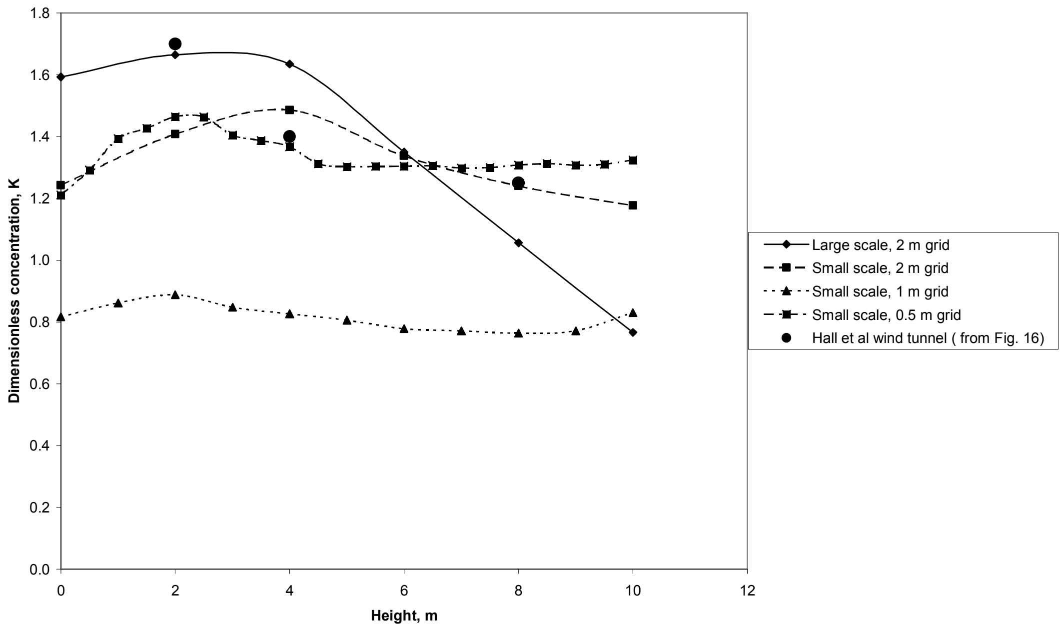

Fig. A6: Comparison of model predictions and wind tunnel studies carried out by Hall et al 1999 of a 4:1 building (40 m x 10 m x 10 m) with single discharge 10 m from the upwind wall. Large scale model with grid resolution 2 m and small-scale model with resolution 2 m, 1 m and 0.5 m.

Fig. A7: Modelled array of buildings

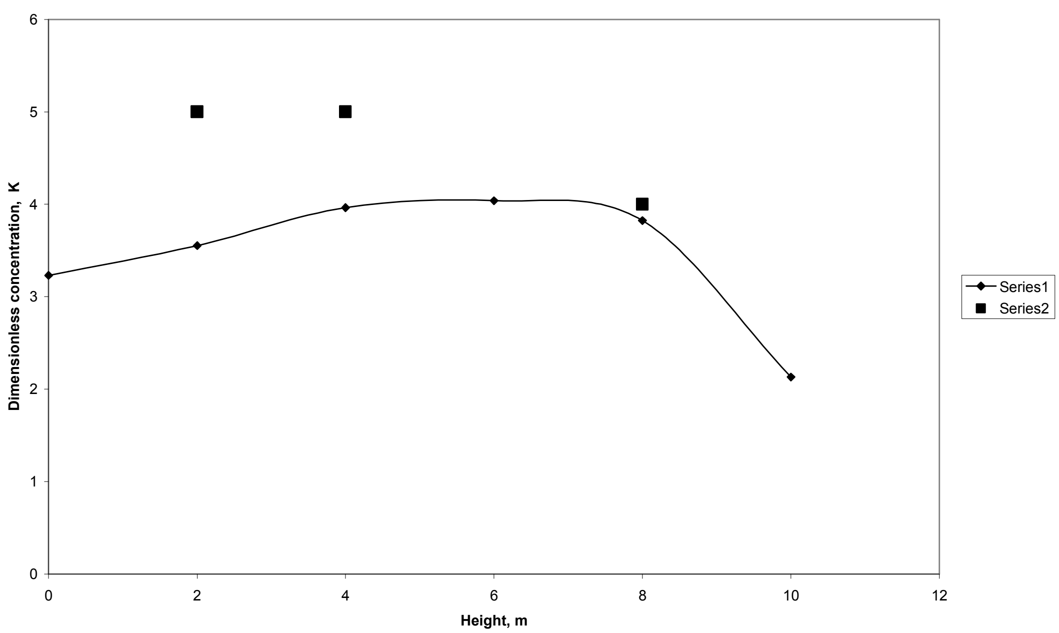

Fig. A8: Comparison of model predictions and wind tunnel studies carried out by Hall et al 1999 of an array of 4:1 buildings (40 m x 10 m x 10 m, 44% building density –see Fig. A7) with single discharge between buildings. Large-scale model with grid resolution 2 m