Sulphur Dioxide Emissions from Small Boilers - Supplementary Assistance on Stack Height Determination

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Abstract

The Air Quality Strategy (2000)[2] recognises that despite national measures to control SO_2 emissions from combustion plant, there may still be some exceedances of the 15-minute mean objective in very local areas in the immediate vicinity of small combustion plant less than 20 MW. Currently, chimney height calculations cannot be carried out easily for many of these boilers due to a number of limitations in the available methods.

At the request of the Department of the Environment, Transport and the Regions (DETR), Stanger Science and Environment (SSE) have produced supplementary technical assistance for estimating the minimum permissible chimney height for small boilers emitting SO_2. This simple, screening tool is in the form of an EXCEL spreadsheet, and is available on the SSE website (www.stanger.co.uk/airqual/modelhlp/helpline.htm).

1.   Background to the Study

The Government and the devolved administrations have adopted a 15-minute mean of 266 μg m^{-3} as an air quality standard for sulphur dioxide (SO_2), with the objective for the standard to be achieved as the 99.9[th] percentile (equivalent to no more than 35 exceedances per year) by the end of year 2005. Less stringent 1-hour mean and 24-hour mean objectives have also been adopted, which are to be achieved by the end of 2004.

Many small boilers (i.e. those less than 20 MW) are not regulated by local authorities, as they do not come within Part B of the Environment Act 1990; these are subject to control under the Clean Air Act 1993 Section 15. Even some boilers which are regulated under local authority air pollution control (LAAPC) cannot be adequately assessed for their air quality impact, due to the limitations of available methods for stack height determination.

The screening techniques which are currently available, and their shortcomings with respect to stack height determination for small boilers, are described below.

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[1] Currently at Entec UK, 17, Angel Court, City Rd, London EC1V 2SH
[2] The Air Quality Strategy for England, Scotland, Wales and Northern Ireland, January 2000, DETR.

1.1 Third Memorandum on Chimney Heights[3]

The Chimney Heights Memorandum provides guidance for local authorities and industry on calculating the minimum stack height of fuel burning plant with gross heat input of between 0.15 - 150 MW. This method was formulated under the former Clean Air Act 1956, prior to the implementation of the AQS air quality objective for SO_2.

The guidance in the Chimney Heights Memorandum was based on an assessment criterion of 452 $\mu g \; m^{-3}$ averaged over a time period of a nominal 3 minutes[4]. There is no straightforward comparison of this against the 15-minute mean AQS objective of 266 $\mu g \; m^{-3}$, expressed as a 99.9[th] percentile. Therefore, a calculated stack height using the Chimney Heights Memorandum may not be sufficient in all cases to guarantee compliance with the most stringent, 15-minute mean air quality criterion.

The Chimney Heights Memorandum cannot be used to determine the stack height of emissions with an efflux velocity of less than 6 m s^{-1}; it does not take account of the actual efflux velocity for the plant. Background levels of SO_2 are treated simply in five categories (ranging from 'undeveloped area' to 'large city'), and more importantly, do not include projections of the much lower SO_2 background concentrations in year 2005 compared to the 1980s.

1.2 D1[5]

The D1 method calculates stack heights using the 98th percentile envelope of worst case meteorological conditions. This could be inadequate for assessing the 99.9[th] percentile concentrations required for SO_2, which can depend on more extreme weather conditions. Moreover, the D1 method cannot be used with efflux velocities of less than 10 m s^{-1}. The method is based upon a time-averaged concentration of 15 - 30 minutes.

An analysis carried out in 1995 used the database of dispersion calculations which comprised the D1 method, to consider the probability of exceedance of an air quality standard for SO_2 of 266 μg m^{-3} as a 100th percentile[6]. The study concluded that the largest possible exceedances are from small boiler plant of around 1 MW capacity and below.

1.3 Guidance on Stationary Sources (GSS)[7]

In common with many screening models, the GSS will calculate the maximum ground level SO_2 concentration (expressed as the 99.9[th] percentile of 15-minute means), if the user defines the stack height and other relevant emission parameters. Therefore, the method is the reverse of what is

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[3] '*Chimney Heights – Third Edition of the 1956 Clean Air Act Memorandum*', 1981, The Stationery Office
[4] 'Approximate Estimates of the Frequencies of Exceedance of the New EPAQS Short Term Air Quality Standard for Sulphur Dioxide due to Local Stack Discharges', November 1995, BRE Report CR 223/95, DETR
[5] '*D1 – Technical Guidance Note (Dispersion) D1 – Guidelines on Discharge Stack Heights for Polluting Emissions*', HMIP 1993, The Stationery Office
[6] 'Approximate Estimates of the Frequencies of Exceedance of the New EPAQS Short Term Air Quality Standard for Sulphur Dioxide due to Local Stack Discharges', November 1995, BRE Report CR 223/95, DETR
[7] Guidance for Estimating the Air Quality Impact of Stationary Sources', The Environment Agency, GN24, November 1998

required for a chimney height calculation, and could require a large number of re-iterative modelling runs to be used as a deterministic tool for stack heights.

The GSS model cannot be applied under the following circumstances, which present limitations for assessing the impact of small combustion plant:

- stacks lower than 20 m;
- stacks with adjacent, significant buildings (i.e. of height at least a third of the stack height);
- stack exit velocities lower than 10 m s^{-1} or greater than 25 m s^{-1}. (The results presented in the GSS are based on modelling carried out only for an efflux velocity of 15 m s^{-1}).

It is noteworthy that the GSS method uses statistically-grouped meteorological data (covering a period of 10 years), rather than hourly sequential readings. This approach takes into account variability in meteorology over the years, but data in this format has the potential for under-predicting ground level pollutant concentrations.

The GSS used ADMS Version 2.02.3. There may be differences in the results for certain scenarios compared against the more recent ADMS Version 3, which has been used in compiling this Supplementary Assistance. However, it was considered important to use the most up-to-date version of the dispersion model.

1.4 ADMS-Screen[8]

This is a computerised dispersion model, available under licence from a commercial supplier. In common with most dispersion models, it will calculate the maximum ground level SO_2 concentration (expressed as the 99.9th percentile of 15-minute means), if the user defines the stack height and other relevant emission parameters. Therefore, the method is the reverse of what is required for a chimney height calculation, and could require a large number of re-iterative modelling runs to be used as a deterministic tool for stack height.

Although it is relatively simple for a computerised dispersion model, the user still needs some basic knowledge of atmospheric dispersion to understand the input data requests.

2. Role of Supplementary Assistance

A need arose for a simple screening tool with which to estimate the minimum permissible stack height for small boilers emitting SO_2, which would ensure compliance with the 15-minute mean air quality objective. The Supplementary Assistance which has been developed:

- is simple to use. It would be reasonable to assume that most lay-people are now comfortable with the use of an EXCEL spreadsheet, in preference to a paper-based method e.g. looking up nomograms or graphs in a handbook;
- focuses only on the range of emission parameters which are encountered for small boilers. However, care has been taken to ensure that the method encompasses the full range of operating parameters for such processes;
- is based on modelling for SO_2, for compliance against the most stringent AQS objective i.e. the 99.9th percentile of 15-minute means;

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[8] ADMS-Screen 3 User Guide, April 2000, CERC Ltd, Cambridge

- is consistent with the Guidance on Stationary Sources, and other Technical Guidance already issued by the DETR[9]. Pertinent assumptions which have been made to ensure this consistency are listed in Section 4.

3.   Structure of Supplementary Assistance

The Supplementary Guidance Assistance spreadsheet comprises a summary of the results of a large number of ADMS (Version 3) dispersion modelling runs specifically for SO_2 emissions. The spreadsheet asks the user to define only four parameters, as follows:

- stack internal diameter (m);
- stack volumetric flow rate ($m^3 s^{-1}$);
- background annual mean SO_2 concentration ($\mu g\ m^{-3}$);
- SO_2 emission rate ($g\ s^{-1}$).

The minimum permissible stack height (with and without building wake effects) is automatically displayed. The ranges and combinations of emission parameters which have been modelled in compiling the Supplementary Assistance method are shown in Table 1.

Functioning of Spreadsheet

The spreadsheet is available on the Modelling Helpline Website[10]. Upon downloading the spreadsheet via the internet and opening it from the user's local disk drive, the user is faced with an instruction sheet explaining what the model can be used for, how the operator can proceed with entering stack and site parameters, and how to interpret the results. Users who do not have access to the Internet can request a copy of the spreadsheet on floppy disk.

When the user is satisfied with this preliminary information, he is invited to click on the tab at the bottom of the screen and proceed to the next sheet where the input data are defined. At the bottom of this page, the results are displayed.

The functioning of the spreadsheet and the calculation procedures take place on additional, hidden and protected worksheets within the workbook. These cross-reference the parameters input by the user and undertake all the necessary calculations. Within the input sheet, all cells (with the exception of those into which the user is required to enter information), are locked and password protected.

Considering only the scenario without building wake effects, the model results for the 4 values for the stack diameter are collated independently (Charts A, B, C, and D). For each Chart, 8 different graphs were constructed (A1, A2, A3….etc) of concentration ('ug m^{-3} for unit emission rate' on x axis) versus 'stack height' (on y axis), depending on the value for the volumetric flow rate (V) (see examples in Figures 1 - 8). Each of these 8 graphs have 15 data points (as 15 stack heights were modelled). The EXCEL spreadsheet computes the mathematical functions for these graphs, to be able to interpolate a stack height from each graph for the required ground level concentration. Finally, the whole procedure is repeated for the model results which include building wake effects.

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[9] LAQM.TG3(00): *'Review and Assessment: Selection and Use of Dispersion Models'*, May 2000
 LAQM.TG4(00): *'Review and Assessment: Pollutant Specific Guidance'*, May 2000
[10] www.stanger.co.uk/airqual/modelhlp/helpline.htm

4.   Simplifications in the Supplementary Assistance

A number of assumption have been made in the modelling, but care was taken to ensure consistency with other DETR guidance.

4.1   Short Averaging Period

A factor of 1.34 was assumed to convert the 99.9[th] percentile of 1-hour mean concentrations predicted by the ADMS-3 model to the 99.9[th] percentile of 15-minute means (as advocated in LAQM.TG4(00)). The GSS also uses this factor of 1.34. The higher factor of 2 would not be relevant as it is more applicable to tall stacks, whereas small combustion plant usually have quite short stacks.

4.2   Meteorology

Meteorological data from Elmdon (Birmingham Airport) only was used in the modelling runs, in contrast with the GSS which employs two additional meteorological datasets.   Although there is variability between different regions of the country, the uncertainty in the results of the method (due to the use of only a single meteorological data site) is likely to be smaller than the effects of some of the other simplifying assumptions e.g. simplification of the building dimensions.   Elmdon represents mainland Britain, not influenced by coastal or significant terrain features.

One year of sequential hourly readings were used, for year 1998. This represents the most significant departure from the approach adopted in the GSS, which uses 10-year statistical meteorological dataset. A sensitivity analysis for four sequential datasets showed that 1998 was the worst year, giving a value for the maximum 99.9th percentile concentration 14% higher than 1996, and 21% higher than a 10-year statistical dataset.

4.3   Background SO_2

The method gives, as a final result, the minimum stack height which will ensure compliance in year 2005, not the existing year. This is more meaningful for the purposes of local air quality management and comparison against the AQS objectives. For this reason, the user needs to define the local annual mean background concentration[11] of SO_2 for 2005 (the method takes a value of twice the annual mean to represent the background concentration, for adding on to the predicted 99.9[th] percentile of 15-minute means, as advocated in LAQM.TG4(00)). Moreover, the Supplementary Assistance does not itself allow for any emission reduction from the plant in future years; the user must define the SO_2 emission rate for year 2005.

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[11] derived from local monitoring data at locations relevant to public exposure, or the DETR Air Quality Archive (http://www.aeat.co.uk/netcen/airqual)

4.4   Building Effects

For each scenario, the modelling was repeated with the inclusion of a single, worst-case building. This was assumed to be perfect cube, with the stack protruding 3 m above the roof. This is similar to the approach adopted in a previous study[12] into exceedances of the 15-minute mean AQS objective for SO_2. In both the Chimney Height Memorandum and the D1 method, there is the minimum requirement that a chimney should terminate at least 3 m above the level of any adjacent area to which there is general access (i.e. ground level, roof areas or adjacent opening windows).

The modelling was then repeated again with the roof of the cuboid set 6 m below stack top. It is rare for a building close to a boiler stack to be higher than 40 m. For chimneys up to 40 m, the user is therefore provided with three values for a minimum permissible stack height:

- in the absence of any nearby building;
- with a building 3 m below stack top;
- with a building 6 m below stack top.

For chimneys exceeding 40 m, the user is provided with only two values for a minimum permissible stack height: in the absence of a building and with a building of dimensions 40 m.

4.5   Exit temperature

A constant exit temperature of $250^{o}C$ was assumed for all the model runs. Sensitivity analyses carried out for a previous study[13] have shown that under convective atmospheric conditions (i.e. those which give rise to the highest 99.9[th] percentile concentrations), changes in release temperature in the range $100^{o}C – 250^{o}C$ make very little difference to ground level concentrations.

4.6   Surface Roughness

A surface roughness of 1 m representative of urban topography was assumed in the ADMS-3 model runs. This ensures a conservative approach for the calculation of the stack heights, based on sensitivity analyses carried out in a previous study[14].

4.7   Variable emissions

The actual SO_2 emission rate (for year 2005) should be provided to the spreadsheet by the user, rather than the maximum emission rate for the plant. If there are known hourly, daily or seasonal variations in emission rate, a sensible approach (to ensure that stack heights are not grossly over-predicted) would be to use the hourly emission rate (expressed as $g\ s^{-1}$) averaged over the worst 24-

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[12] Adam, H.S. and Carruthers, D.J. (October 1997), 'Short-term Ambient Concentrations of Sulphur Dioxide in the Vicinity of Small Boilers in the UK', Cambridge Environmental Research Consultants Ltd, Report to the Department of the Environment.

[13] Adam, H.S. and Carruthers, D.J. (October 1997), 'Short-term Ambient Concentrations of Sulphur Dioxide in the Vicinity of Small Boilers in the UK', Cambridge Environmental Research Consultants Ltd, Report to the Department of the Environment.

[14] Adam, H.S. and Carruthers, D.J. (October 1997), 'Short-term Ambient Concentrations of Sulphur Dioxide in the Vicinity of Small Boilers in the UK', Cambridge Environmental Research Consultants Ltd, Report to the Department of the Environment.

hour cycle likely during the year, i.e. the worst day in the year would be taken into account, but not the worst hour in the year.

4.8   Geographical extent of investigation

The ADMS-3 model runs identify the highest predicted SO_2 concentration within a 3 km radius of the stack; however, the Supplementary Assistance will not give an indication of the area over which exceedances of the 15-minute mean objective occur. Due to the short stacks generally associated with small boilers, the maximum 99.9[th] percentile concentrations are unlikely to occur at greater distances from the stack.

5.   Limitations of Supplementary Guidance

In common with all screening tools, the results generated by the Supplementary Assistance spreadsheet are subject to certain caveats, which include the following:

- The Supplementary Assistance does not make any attempt to account for local topographical features. This level of detail warrants the use of complex dispersion models and would be outside the scope of a screening tool;
- The method is not able to assess the combined impact of more than one boiler in close proximity. The method is applicable to single stacks only, and the contribution of other sources in the vicinity must be accounted for by means of the background SO_2 concentrations;
- For the purpose of assessing relevant exposure, exceedances of the 15-minute mean objective are cause for concern only if they occur at non-occupational, near ground level outdoor locations, where members of the public might be exposed over a period of at least 15 minutes. The Supplementary Assistance is very conservative in the sense that a chimney height is calculated by the method which will ensure that the objective is met at **all** locations, which may in specific cases, fall within the site boundary, or at off-site locations where there is no potential for exposure to the public.

6.   Comparison of Supplementary Assistance against other Methods

Five methods were used to calculate the minimum permissible stack height for test cases without building wake effects (Test Cases 1): the Supplementary Assistance spreadsheet, ADMS-3 (re-iterative model runs), GSS, D1 and Chimney Heights Memorandum. Care was taken to choose input data which are within the permitted ranges of all the calculation methods, as well being applicable to small boilers. The input data used are shown in Table 2.

The results of the five methods are shown in Table 3. The Supplementary Assistance method and ADMS-3 calculate very similar stack heights, and higher than from the other methods. The Supplementary Assistance method gives the most conservative result. The GSS indicates stack heights a little lower than ADMS-3, as a result of its use of statistical meteorological data rather than sequential hourly data for a worst-case year (1998). The CHM shows closer agreement to the GSS for the lower stack heights. The D1 method gives the lowest stack height, a feature which is consistent with its use of the 98th percentile envelope of meteorological conditions, which would not be sufficient to ensure compliance against an air quality objective expressed in terms of the 99.9[th] percentile.

Four methods were used to calculate the minimum permissible stack height (for compliance against 15-minute mean objective for SO_2) with building wake effects (Test Cases 2): the Supplementary Assistance spreadsheet, ADMS-3, D1 and Chimney Heights Memorandum. Again, care was taken to choose input data which are within the permitted ranges of all the calculation methods. The input data are shown in Table 4, and the results in Table 5.

When building wake effects are included in the calculations, all four methods gives very similar results. This is a surprising departure from the comparison described above, which excluded building wake effects. The D1 and CHM have identical procedures for correcting the initial calculated stack height to take into account nearby buildings; this correction procedure accounts for the taller stacks calculated by these methods when buildings are included.

Acknowledgements

Table 1: Model Input Data for Compilation of Supplementary Assistance Method

Parameter	Values modelled	
Stack heights (m)	10 to 80, in steps of 5 m	The method gives a result for a minimum permissible stack height as an integer interpolated between modelled 5 m intervals
Exit temperature (^{o}C)	250 (fixed)	
Volumetric flow rate (m^3 s^{-1})	2.5 to 20, in steps of 2.5 m^3 s^{-1}	8 values modelled. The spreadsheet rounds down to the nearest 2.5 m^3 s^{-1} step modelled.
Diameter (m)	0.5 to 2, in steps of 0.5 m	4 values modelled (Charts A, B, C and D). The spreadsheet rounds up to the nearest 0.5 m step modelled.
SO_2 emission rate (g s^{-1})	1	Nominal value, which is pro-rated later in spreadsheet

Table 2: Input Data for Comparison Runs: Test Cases 1 (no building wake effects)

Parameter	Value	
Meteorological data	1998 for ADMS3 and Supplementary Assistance	
Buildings	No	
SO_2 emission rate (g s^{-1})	10, 5, 2, 1	
Stack diameter (m)	0.5	
Exit temperature (^{o}C)	250	D1, GSS and Chimney Heights Memorandum require user to calculate efflux heat Q. This has value of 0.466 MW.
Volumetric flow rate (m^3 s^{-1})	2.945	GSS and D1 require user to calculate efflux momentum M. This has value of 23.904 $m^4 s^{-2}$.
Annual mean background SO_2 concentrations (ug m^{-3})	5	Typical value for an urban area for year 2005.

Table 3: Minimum Permissible Stack Heights Calculated by Various Methods for Test Cases 1 (no building wake effects)

Method	Estimated Stack Height (m)			
SO$_2$ Emission rate	10	5	2	1
Supplementary Assistance	48	27	13	<10
ADMS3	48	25	11	10
GSS	38[15]	24[16]	<20[17]	<20[18]
D1	16	11	7	5
Chimney Heights Memorandum	22 – 26	19 - 23	12 – 20	8 – 14

Table 4: Input Data for Comparison Runs: Test Cases 2 (with building wake effects)

Parameter	Value
Meteorological data	1998 for ADMS3 and Supplementary Assistance
Buildings heights (m)	14 – 27
SO$_2$ emission rate (g s^{-1})	0.7 – 2.1
Stack diameter (m)	0.5
Exit temperature (^{o}C)	250
Volumetric flow rate (m^3 s^{-1})	2.945
Annual mean background SO$_2$ concentrations (ug m^{-3})	5

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[15] Interpolated between contours on look-up graphs
[16] Interpolated between contours on look-up graphs
[17] outside range of GSS method
[18] outside range of GSS method

Table 3: Minimum Permissible Stack Heights Calculated by Various Methods for Test Cases 2 (with building wake effects)

Method	Estimated Stack Height (m)					
SO$_2$ Emission rate	2.1	1.6	1.6	1.1	0.8	0.7
Building height (m)	27	17	29	22	17	14
Supplementary Assistance	33	23	32	25	20	17
ADMS3	32	23	32	25	20	17
D1(with building correction)	38	27	40	30	24	20
D1 (without building correction)	7	6	6	5	5	4
Chimney Heights Memorandum (with building correction)	34 – 40	23 – 28	35 – 40	27 – 31	22 – 25	18 – 21
Chimney Heights Memorandum (without building correction)	12 – 21	11 – 18	11 – 18	9 – 15	8 – 13	1 – 4

Figure 1
D = 0.5 m, V = 2.5 m³ s⁻¹

Figure 5
D = 0.5 m, V = 12.5 m⁻³ s⁻¹

Figure 2
D = 0.5 m, V = 5 m³ s⁻¹

Figure 6
D = 0.5 m, V = 15 m⁻³ s⁻¹

D = 0.5 m, V = 7.5 m⁻³ s⁻¹

D = 0.5 m, V = 17.5 m⁻³ s⁻¹

Figure 4
D = 0.5 m, V = 10 m⁻³ s⁻¹

Figure 8
D = 0.5 m, V = 20 m⁻³ s⁻¹