Computational Fluid Dynamics (CFD) Modelling of Carbon Monoxide Dispersion within a Badger Sett
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Executive summary

(1) This report details the findings of a programme of work for the Department for Environment, Food and Rural Affairs (Defra) under order/contract reference N1JL280505. The report details the findings of a Computational Fluid Dynamics (CFD) model of a sub-section of an excavated badger sett [1].

(2) This report is the second of two presented to Defra during Autumn 2005. The first [2] examined the factors which might affect CO dispersion in idealised geometries. These simplified geometries were used to examine factors such as soil porosity, blind tunnel ends and branching. This current report examines a more realistic sett structure, and builds upon the fundamental research undertaken previously [2].

(3) Of specific interest was the dispersion of carbon monoxide (CO) gas, and its subsequent penetration to deeper parts of the sett. The CO was assumed to be generated by a de-tuned petrol engine, without a catalytic converter, delivering a flow rate of 900 litres per minute with 2% (by volume) CO content. A constant wind profile of 4ms\(^{-1}\) was applied to the model, and a specific delivery strategy was applied to the modelling relating to the entrances through which CO was delivered, and appropriate times to block other entrances.

(4) The concentration of carbon monoxide was monitored in sett chambers, blind tunnels and at the openings, with specific reference to a concentration of 1% CO by volume, sustained for 1 hour for a definite humane termination.

(5) The report concluded that for the conditions described in the modelling:

- Only one chamber reached and sustained a concentration of greater than 1% CO by volume. The concentration was only maintained for approximately 30 minutes, whilst the CO generator inlet was running continuously.
- Carbon monoxide did not penetrate any wall ends (i.e. blind tunnel ends) at any point during the CFD model running time.
- The concentration of carbon monoxide exiting the openings did not reach 1%.
- External wind direction and conditions had a significant effect on the dispersion of CO within the sett.

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1 Introduction

This report details the findings of a programme of work for the Department for Environment, Food and Rural Affairs (Defra). The work was carried out between August 2005 and November 2005. The programme of work was carried out to assess dispersion of carbon monoxide (CO) gas within a three dimensional representation of a previously excavated badger sett [1]. Of specific interest was the penetration of carbon monoxide to deeper parts of the sett, and whether or not the nominal concentration of 1% (by volume) of carbon monoxide was obtained and consequently maintained for longer than 1 hour.

This report is the second of two presented to Defra during Autumn 2005. The first [2] examined the factors which might affect CO dispersion in idealised geometries. These simplified geometries were used to examine factors such as soil porosity, blind tunnel ends and branching. This current report examines a more realistic sett structure, and builds upon the fundamental research undertaken previously [2].
2 Computational Fluid Dynamics Model

2.1 Background

Computational Fluid Dynamics (CFD) was used to examine the airflows and CO dispersion within a badger sett. CFD is a powerful computer modelling tool that is capable of modelling complicated aspects of fluid (liquid or gas) flow. CFD solves the fundamental equations of fluid flow, and is capable of modelling the complex effects of turbulence, heat transfer, material transport and chemical reactions.

2.2 Summary of the Assumptions Used in the CFD Modelling

Due to the extremely complicated nature of the sett, a number of assumptions were made in the creation of the model. These assumptions were required to allow the CFD model to be constructed and run in an appropriate time frame (days rather than months). These assumptions are detailed below.

2.2.1 Assumptions in the Geometry

- Tunnel entrances opened flush with the ground.
- Tunnels and chambers were assumed to have a uniform diameter.
- Several curved tunnels were assumed to be straight.

2.2.2 Assumptions in the CFD Model

- Soil porosity 43%.
- Loss of CO was determined by the concentration of CO in the cell nearest the wall.
- The flux of CO across the tunnel walls was in one direction only – out of the tunnels into the soil.

2.3 Badger Sett Geometry

APPENDIX B A section of a previously excavated badger sett [1] was modelled, as representative of a typical badger sett, using CFD. The section of sett modelled is shown in Figure 1. The top area between the two hashed lines represents the slope in which part of the sett was constructed.
1. Figure 1 - Section of excavated sett from which the CFD geometry was created [1]. The area between the two hashed lines indicates the sloping area of the bank into which the sett was constructed. The figure represent the depth (in cm) below ground level.

APPENDIX C The tunnels were assumed to be cylinders of diameter 0.3m, and were located at appropriate depths found in the excavated sett [1]. Sett chambers were taken to be spheres of diameter 0.5m. Some of the geometry was simplified in order to facilitate geometry creation and meshing, necessary for successful solution and convergence of the CFD model. A plan view of the CFD representation is shown in Figure 2.
2. Figure 2 - Plan view of the CFD geometry.

APPENDIX D  The sett was modelled according to the excavation findings in [1], and therefore part of it was built into a bank (8m, elevation 17°), and part of it under flat ground. This is shown in Figure 3, where the blue circles represent the sett entrances. The report [1] also stated that west to east was from the top of the slope to the bottom of the slope, as shown in Figure 3.
3. Figure 3 - Ground level and sett entrances.

2.3.1 Summary of Sett Geometry Characteristics

APPENDIX E  The CFD model of the sett had the following characteristics:

- 20 open entrances/ exits.
- 13 nesting chambers.
- The volume of each nesting chamber was assumed to be 50% occupied by bedding material/badger.
- 10 blind ends.

2.3.2 Loss through the Tunnel Walls

(7) Previous work [2] assessed the effect of soil porosity on the concentration of carbon monoxide within open and blind tunnels, and the amount lost from the tunnels into the surrounding soil. An equation (1) for the rate of loss of carbon monoxide through the tunnel walls was derived, and applied to the CFD model in this study. The flux across the wall (kg m$^{-2}$ s$^{-1}$) is expressed as a function of the deposition velocity calculated from previous work ($V_{dep} = 3.602 \times 10^{-4}$ m s$^{-1}$) multiplied by the concentration of carbon monoxide at the wall (kg m$^{-3}$). This figure was calculated for a soil porosity of 43% which is typical for a sandy loam soil [3] which Defra confirmed would be a typical soil in which a sett might be built.

\[ Flux = V_{dep} \times Concentration \]

5. Equation 1 - Equation for the flux of carbon monoxide through the tunnel walls into the soil.
(8) To represent the diffusion of CO through the tunnel walls, a fine boundary layer mesh was applied to the model. The sink term shown in Equation 1 was applied to the cells immediately next to the wall to remove CO from the tunnels.

2.3.3 Sett Chambers

(9) The sett chambers were assumed to be half filled with fibrous material. In the simulation, the bottom half of the chamber was modelled as a porous region. The resistance coefficients were calculated [4] assuming a void fraction of 0.2 and a particle diameter of 5 mm.

2.4 CFD Model Characteristics

APPENDIX F The CFD model had the following characteristics:

- Total geometry size: 35m (x direction) x 9.7m (y direction) x 30m (z direction)
- Total tunnel and chamber volume: 130m$^3$ (equates to total tunnel length of approximately 170m).
- Solver: 3D, segregated
- Turbulence Model: k-ε, RNG with standard wall functions.
- Boundary layer mesh: Initial cell depth 0.005m; 2 cells in boundary layer, growth rate 1.2.
- Tetrahedral and hexahedral mesh applied as appropriate.
- Number of cells: $1.012 \times 10^6$
- Typical cell size 0.05m.

2.5 Environmental Conditions

F-1 The wind was assumed to be blowing from west to east (west being top of the bank, east at the bottom of the bank), with a speed of 4 ms$^{-1}$, measured at 10 m above ground using an external wind profile [5]. During the introduction of gas, a constant airflow was maintained across the site.

F-2 As the air flows down the bank it loses speed. This results in a recovery of static pressure. The openings at the bottom of the bank therefore have a higher pressure than those at the top. This pressure gradient resulted in a flow of air through the tunnel network from the bottom of the bank to the top. These features are shown in Figures 4 to 6. Every time an opening was closed, the CFD model resolved the change to the natural ventilation of the tunnel system.
6. Figure 4 - Change in static pressure as the air decelerates down the bank.

7. Figure 5 - Change in air velocity (m/s) down the bank.
2.6 Strategy for Carbon Monoxide Delivery

F-3 Defra provided Dstl with the strategy typically employed for carbon monoxide delivery to a sett. This is outlined below.

2.6.1 Delivery Method

F-4 The carbon monoxide was assumed to be delivered using a detuned (no catalytic converter) petrol engine, with a flow rate of 900 litres per minute (lpm) and contain 2% CO by volume (provided by Defra). Material was introduced to tunnels through a pipe of diameter 0.05m, which was located 0.5m into the tunnel. A user-defined-function (UDF) was used to automatically adjust the location of the gas release when required.

2.6.2 Delivery Strategy

F-5 The following strategy (supplied by Defra) was used in the CFD model.

- Gas was initially fed into the network, via a pipe introduced into the most westerly opening, as the wind was blowing from the west.

- Once gas was observed exiting from a tunnel opening, that opening was immediately blocked (creating a blind tunnel end).

- When no gas was observed at any entrances, gas was delivered for a further 20 minutes.

- After 20 minutes, the entrance through which the gas was being introduced was closed.

- Introduction of gas was moved to the next most westerly unblocked opening, applying the same conditions on tunnel closing as previously.

- This process was repeated until all the entrances had been blocked.
The CFD calculation was then continued for a further hour of real time.

2.7 Carbon Monoxide Concentration

APPENDIX G  Defra provided Dstl with a nominal threshold concentration of CO of 1% (by volume) for at least one hour which is required for the humane culling of a badger. The modelling in this study is reported with specific reference to this concentration.

2.7.1 Carbon Monoxide Concentration at Entrances/Exits

APPENDIX H  CO concentration was monitored using a UDF at each opening. When the average mass fraction reached 0.00275 a UDF triggered the appropriate opening to close. The value 0.00275 represents a best guess at CO mass fraction associated with a dilution of the gas that might be visible. (CO itself is colourless, however, the gas being pumped into the tunnel would contain many fine particulates which are visible). A CO concentration within a pipe representative of a tunnel opening has been simulated (see Figure 7). This represents a well mixed, naturally ventilated pipe and a particulate exhaust gas. The tunnel entrances were both modelled as open, and therefore the flow from the exhaust would draw clean air into the tunnel (from right of figure) which would dilute the CO present. The air exiting the tunnel (left of diagram) is fully mixed, and has an average mass fraction of 0.0055215. The value (CO mass fraction 0.00275) chosen is to trigger closing the exit was taken to be (arbitrarily) 50% of the average CO concentration at the exit of this test.

9. Figure 7 - Calculation of well-mixed mass fraction of CO in a pipe downstream of the introduction point.
2.7.2 Simulation Run Time

APPENDIX J The modelling strategy for this simulation was refined to complete the calculation in the time scale allocated to the project. In order to speed up the simulation time the transport of CO was de-coupled from the airflow calculations. Each time a gas injection point was moved or an opening closed, the CO distribution was frozen by turning off the transport equation. The airflow, including the influence of the injected gas jet, was then solved in a steady frame of reference. An example of a flow pattern induced at a branching point as a result of a gas injection is shown in Figure 8. Once the steady flow was converged, the flow field was assumed to remain unchanged until the next event. The CO was then allowed to progress with time through the tunnel network.

APPENDIX K Adopting this strategy allowed the calculation time to be reduced from months to a few days. It was possible to make this assumption, as the transport of CO takes significantly longer to move through the tunnels than the time for the tunnel flow field to adjust to the changing natural ventilation and gas injection.

APPENDIX L

10. Figure 8 - Flow patterns induced in a branch as a result of a gas injection.

![Flow pattern](image-url)
3 Results and Discussion

APPENDIX M Figures 9, 10 and 11 show a plan view of the tunnel network in which the openings, chambers and tunnel dead ends have been labelled respectively. Figures 12 to 32 show the progress of the CO into the tunnel network as each event (closure of an opening) takes place and an arrow on the figure points to the opening that has just been closed. Included with each CO concentration map is a graph of the mass averaged concentration on the opening that has just been closed.

APPENDIX N Table 1 summarises the order of events experienced by the tunnel network. The gas injection location is moved only five times before all the openings are closed. However, because of the tunnel geometry, only the first three positions result in a flow of CO gas into the network. Openings 5, 1 and 8, respectively are the opening locations through which CO gas is introduced. In each case, shortly after starting the introduction of CO, the downstream openings are quickly closed before a near equilibrium is achieved. The equilibrium point for the first two locations is a balanced state of mixing between the gas being introduced and the clean air drawn through the network due to natural convection. For the third location most of the openings are closed and the momentum of the injected gas itself is driving the flow in the tunnels. In this case, the equilibrium position is due to the gas finding the path of least resistance through the network with a large proportion of the network having little or no flow through it. The three locations are reasonably well positioned and each resulting equilibrium state, held for 20 minutes, actually covers a good proportion of the north, middle and southerly parts of the tunnel network. Figures 17, 26 and 29 show the concentration contour maps of the three equilibrium states. These figures correspond to events 6, 15 and 18. If the tunnel system to the east of opening 19, which experiences virtually no exposure to CO, is ignored, the area associated with chambers 10 and 11 experiences the least exposure to CO gas.

APPENDIX O Figures 33 and 34 show the profiles of CO concentration recorded at each of the chambers. All but one of the chambers has an exposure to the gas. However, chambers 3 and 5 have the longest exposure as they happen to be located such that for each of the 3 main gaseous injection locations a flow of gas has been drawn one way or the other way through them. The highest level of exposure was experienced by chamber 7 during the third gaseous injection located in opening 8. Chamber 7 is directly downstream of this location and experiences around 30 minutes of 1.1% concentration of CO. Figure 35 shows that the CO concentration at wall end 1 remained zero for the duration of the simulation. This is typical of the concentration at all the wall ends.

APPENDIX P The simulation has shown that gas can be made to penetrate the sett tunnel network. However, the desired concentration of CO of 1% throughout the network for 1 hour was not achieved. For this network example, working from the most westerly opening meant that the gas flow being introduced had to work against the natural flow in the network. At tunnel dead ends, the penetration of gas dropped to very low quantities. In addition to this, the surface diffusion that was applied caused the CO that had penetrated the tunnels to quickly dissipate out through the walls.
11. Figure 9 - Plan view of the tunnel network showing the naming convention applied to the openings. Coloured spheres represent chambers.
12. Figure 10 - Plan view of the tunnel network showing the naming convention applied to the subterranean chambers (coloured).

13. Figure 11 - Plan view of the tunnel network showing the naming convention applied to the tunnel dead ends.
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<td>Closed opening 13</td>
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</tr>
<tr>
<td>06</td>
<td>Closed opening 04</td>
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<td>After 20 minutes without an event, the gas introduction point is moved from opening 4 to opening 1.</td>
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<td>Closed opening 09</td>
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<td>After 20 minutes without an event, the gas introduction point is moved from opening 1 to opening 8.</td>
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<td>16</td>
<td>Closed opening 15</td>
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<td>17</td>
<td>Closed opening 18</td>
<td>2646</td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>Closed opening 08</td>
<td>3848</td>
<td>After 20 minutes without an event, the gas introduction point is moved from opening 8 to opening 19.</td>
</tr>
<tr>
<td>19</td>
<td>Closed opening 19</td>
<td>3854</td>
<td>All the openings to the west have been closed causing the gas to flow back out of opening 19. Introduction point moved to opening 20.</td>
</tr>
<tr>
<td>20</td>
<td>Closed opening 20</td>
<td>3856</td>
<td>Reverse flow from opening 20 consequently this last opening is closed - begin diffusion calc.</td>
</tr>
<tr>
<td>21</td>
<td>End of diffusion calc</td>
<td>7653</td>
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</tr>
</tbody>
</table>

14. Table 1 - Series of events that occurred as a result of the prescribed operating strategy.
15. Figure 12 - Concentration Map and CO profile at opening 11 recorded when event 1, the closing of opening 11, occurred.
16. Figure 13 - Concentration Map and CO profile at opening 5 recorded when event 2, the closing of opening 5, occurred.
Figure 14 - Concentration Map and CO profile at opening 14 recorded when event 3, the closing of opening 14, occurred.
18. Figure 15 - Concentration Map and CO profile at opening 13 recorded when event 4, the closing of opening 13, occurred.
19. Figure 16 - Concentration Map and CO profile at opening 12 recorded when event 5, the closing of opening 12, occurred.
Figure 17 - Concentration Map and CO profile at opening 4 recorded when event 6, the closing of opening 4, occurred.
21. Figure 18 - Concentration Map and CO profile at opening 9 recorded when event 7, the closing of opening 9, occurred.
22. Figure 19 - Concentration Map and CO profile at opening 6 recorded when event 8, the closing of opening 6, occurred.
Figure 20 - Concentration Map and CO profile at opening 2 recorded when event 9, the closing of opening 2, occurred.
Figure 21 - Concentration Map and CO profile at opening 10 recorded when event 10, the closing of opening 10, occurred.
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26. Figure 23 - Concentration Map and CO profile at opening 7 recorded when event 12, the closing of opening 7, occurred.
Figure 24 - Concentration Map and CO profile at opening 16 recorded when event 13, the closing of opening 16, occurred.
Figure 25 - Concentration Map and CO profile at opening 17 recorded when event 14, the closing of opening 17, occurred.
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31. Figure 28 - Concentration Map and CO profile at opening 18 recorded when event 17, the closing of opening 18, occurred.
Figure 29 - Concentration Map and CO profile at opening 8 recorded when event 18, the closing of opening 8, occurred.

32. Figure 29 - Concentration Map and CO profile at opening 8 recorded when event 18, the closing of opening 8, occurred.
Figure 30 - Concentration Map and CO profile at opening 19 recorded when event 19, the closing of opening 19, occurred.
Figure 31 - Concentration Map and CO profile at opening 20 recorded when event 20, the closing of opening 20, occurred.
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Conclusions

The CFD modelling detailed in this report supports the following conclusions:

- Chamber 7 was the only chamber which reached and sustained a concentration of greater than 1% by volume of CO as shown in Figure 36. The concentration was only maintained for approximately 30 minutes, whilst the CO generator inlet was running continuously at opening 8.

![Graph showing concentration of CO in different chambers over time](chart.png)

- Carbon monoxide did not penetrate to any of the wall ends i.e. blind tunnel ends, at any point during the CFD model running time. This is consistent with the findings of the first report provided to Defra [2].

- The concentration of carbon monoxide exiting the openings did not reach 1%.

- External wind direction had a significant effect on the dispersion of material within the sett.

(10)

39. Figure 36 - Concentration of CO (% by volume) in the chambers for the duration of the model run.

(11)
5 Recommendations

It is recommended that the following further work be carried out:

- Modelling: Re-run the CFD model with the wind blowing in the opposite direction (east to west) to assess the effect on dispersion within the tunnel system. Retain all of the other model characteristics.

- Experimental Work: Carry out experimental trials to assess the dispersion of carbon monoxide within simplified tunnel geometries (without badgers) in order to reduce and validate the assumptions used in the current model creation.
6 List of references


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| 13. Abstract (A brief (approximately 150 words) factual summary of the report) | A CFD assessment of the dispersion of carbon monoxide within a section of a badger sett. The CFD model included external wind conditions and loss of CO through the tunnel walls. A defined strategy of gas introduction was followed, and the concentration of carbon monoxide in the sleeping chambers and blind ends was monitored for the duration of the model run. The concentration was referenced to the specified concentration of 1% by volume supplied by the report’s sponsor, Defra. The report concluded that only one chamber achieved a concentration of CO of 1%. However, this was only sustained whilst the generator was running at a nearby entrance. CO did not penetrate any of the wall ends, and external wind conditions had a significant effect on dispersion within the tunnels. |
| 14. Abstract Protective Marking including any Caveats | UNCLASSIFIED |
| 15. Keywords/Descriptors (Authors may provide terms or short phrases which identify concisely the technical concepts, platforms, systems etc. covered in the report.) | Computational Fluid Dynamics, CFD, dispersion, carbon monoxide, badger, sett |
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