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Deposition of large particles from warehouse fire plumes—a small-scale wind tunnel model study

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Abstract

The report describes measurements of the deposition of large particles from a small scale wind tunnel model of a chemical warehouse fire plume. A common feature of such fires is the discharge of relatively large particles with falling speeds of the order of $m\,s^{-1}$, partly generated by mechanical damage, which can fall out of the fire plume in a different pattern to that of the gases and fine particles. These large particles may also contain toxic components, so it is desirable to know their fallout pattern. The deposition of large particles from fire plumes has therefore been modelled directly as an adjunct to earlier small scale wind tunnel experiment on gaseous plume dispersion [1] using the same experimental conditions, so that the relative behaviour of gas plume and heavy particle dispersion could be compared. As far as we are aware, this is the first experiment of this type to be carried out. There are constraints on the range of deposition conditions that can be modelled, due to scaling problems. However, it proved possible to develop a viable technique and some useful data was obtained over a range of particle and plume conditions of interest. Nonetheless, the work should be regarded mainly as a proving trial of the technique and an indicator of the significant parameters as the measurements made were too few in number (essentially of three particle deposition conditions) to provide a broad-based indication of large particle deposition.

Abbreviations: d Particle aerodynamic diameter. That is, the diameter of the sphere of unit density with the same falling speed as the particle in question; D Particle stop distance; g Gravitational acceleration; H Building height. Taken as a nominal 10 m in the present work. This is also the reference length scale for the flow used in the scaling parameters; m Mass of particles deposited per unit area; M Mass of particles discharged from source; Q Rate of discharge of tracer or particles (in the latter case $Q = M/t$); t Elapsed time of deposition experiment; U Reference windspeed, measured at height H; v_f Particle falling speed in still air; α Mean angle of fall of particle in reference windspeed, U

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Experiments were carried out for two gas plumes, buoyant and non-buoyant, both with and without a building shell around the source. Large particle concentrations near the surface proved markedly different to those for a gaseous plume, showing a much more rapid reduction in concentration with increasing distance. Both particle falling angle and particle inertia affected the particle plume dispersion, the highest concentrations at the ground occurring for the case with small falling angle and inertia, the lowest concentrations for the case with large falling angle and moderate inertia. Concentrations for the remaining condition, with large falling angle and high inertia, fell between these two, probably because the high inertia constrained the rate of lateral dispersion of the particles. Compared with the effects of particle falling angle and inertia, the effects of a building shell around the source were relatively limited. This was greatest for the non-buoyant plume where the building shell tended to act as a trap for large particles. The buoyant plume tended to carry particles beyond the building shell, so that in this case its effects were quite limited.

Keywords: Dispersion; Fires; Fire plume; Warehouse fires; Large particle dispersion; Large particle deposition

1. Introduction

Chemical warehouse fires have become a subject of concern due to a number of these events that have generated quite serious environmental problems. Following the EC SEVESO directive, large installations of this sort are subject to individual risk assessment studies and in the UK the CIMAH regulations require the submission of safety cases. In response to these needs there has been a considerable research effort on this subject, much of it sponsored by the European Commission, whose Major Technical Hazard programmes on industrial fires and fire behaviour have been reported in the proceedings of the recent workshops held on this subject [2,3].

Dispersion of the fire plume is of particular importance as it is the main route for exposure of the general populace to any toxic hazards. This has been the subject of a specific investigation [1] as part of one of the research groups in the European Commission programmes described above. This investigation used a small scale wind tunnel model to look at the dispersion of gaseous plumes discharged from burning warehouses in progressive states of degeneration.

However, besides gaseous materials, fire plumes also usually contain large quantities of particulate matter. Much of this is smoke and fume (the latter is formally defined as condensed volatilised material) from the combustion process which, even allowing for the particle agglomeration that will occur quite quickly after initial production, will be of small particle size mostly below 10 μm aerodynamic diameter. In addition to this small particulate matter, there can also be relatively large particles generated either directly by the fire (the shedding of pieces of partially burned material for example) or mechanically from the collapse of the building structure itself or structures within it partially destroyed by fire. Also, the high discharge velocities of fire plumes, up to 10 $m\,s^{-1}$ or more, allow the discharge of these large particles, with their associated high falling speeds and inertia. There have been a number of practical examples of centimetre-sized pieces of partially burned plastic and of scraps of asbestos (from the collapsing walls and roof of a building) falling out in the vicinity of industrial fires. The deposition of these large particles around the site can be an important source of contamination from the fire products.

Predicting the paths of the fine particles is relatively straightforward. Their falling speeds will be of the order of $\mathrm{cm\,s^{-1}}$ at most and their inertial scales usually of a sub-centimetre order. Thus on the scale of a fire plume their dispersion patterns would be indistinguishable from gaseous materials in the plume. Their deposition to the ground can then be fairly readily estimated assuming a deposition velocity and knowing the concentrations in the plume from gas dispersion estimates. The larger particles are more difficult to deal with. Their falling speeds can be of the order of $\mathrm{m\,s^{-1}}$ and their inertial scales of metre order. These falling speeds are comparable to windspeeds and plume rise velocities near the point of discharge and the inertial scales are comparable to those of warehouse buildings and plume depths near the source. Thus large particle paths may readily depart from those of the gaseous and small particle plumes, with enhanced deposition nearer the plume source than would be indicated by the gaseous plume behaviour.

The conventional procedure for dealing with large particle deposition is with a modified gaussian plume model, either a ‘‘tilted plume’’ model in which the plume path is modified by the falling angle of the particles, or by a plume depletion model in which an assumed deposition from the plume to the ground is accounted for by reducing the plume source strength to account for the loss to the ground. Both types of model are quite approximate and neither accounts for particle inertia. There is a discussion by Underwood [4] of these and other plume deposition models. In the present case the reliability of this type of model is additionally uncertain as the plume behaviour is complex. The highly buoyant plumes often produced by fires contain strongly recirculating internal flows and there is additionally a complex interaction with the downwash field of the warehouse building from which the plume rises. Both features of a warehouse fire plume can affect the deposition of large particles.

In order to examine large particle deposition from fire plumes more directly, an attempt was made to model this experimentally by injecting suitably scaled particles into the plume in the wind tunnel model used for the gas dispersion experiments described earlier [1]. As far as the authors are aware an experiment of this type has not been carried out previously. There are, however, wind tunnel experiments on scaled particle behaviour made for other purposes which use similar principles, for example on snow drifting and on wind-raised dust. An example of the latter are experiments by Braaten [5] on particle re-entrainment from a bed. These show some similarities to the experimental techniques used here, though this work was not available to the authors at the time.

The experiments were carried out under conditions of some difficulty during the last few weeks before the closure of the Warren Spring Laboratory, where the initial work was done. Thus it was not possible to refine the experimental technique or the scaling in any way or to resolve a number of practical difficulties that arose in its course. However, it proved possible to obtain some useful results, and these are described here.

The experimental programme used the same equipment as for the work on gaseous plume dispersion, described in [1]. The details of this work are not therefore repeated here, where only the particle-related aspects of the experiment are described.

2. Scaling

In a scaled model of a dispersing plume it is necessary that the turbulence characteristics of the plume, the approaching wind flow and the buoyancy and momentum in the plume discharge are correctly modelled in order to obtain the correct gaseous dispersion characteristics. This was done in the earlier work. If it is then desired to model the dispersing behaviour of discharged particles then both the particle falling speeds and their inertia must be correctly modelled in addition.

The particle falling speed, v_f, is scaled with respect to the reference windspeed, U, so that we require

$$\frac{v_f}{U} = \text{const} \tag{1}$$

between model and full scale. This essentially sets the mean angle of fall, α ($= \tan^{-1}(v_f/U)$), of the particle in the flow.

The particle inertia also has to be scaled, so that its rate of response to changes in flow pattern (either in the mean flow field or due to turbulence) is in the same proportion in the model as in the full scale. There are a number of ways of considering this. One is by way of the stop distance, D, which indicates the length scale of particle motions due to inertia when there is a step change in the local windspeed.

In the Stokes flow regime, D is defined as,

$$D = \frac{v_f U}{g} \tag{2}$$

and its scaling with respect to the flow is via some suitable length scale. In the present work the length scale used was the building height, H, so we require that

$$\frac{D}{H} = \text{const} \tag{3}$$

between model and full scale. Alternatively, Eq. (1) and Eq. (2) can be substituted into Eq. (3), to give

$$\frac{D}{H} = \frac{U^2 \alpha}{gH} \tag{4}$$

The ratio D/H is effectively a Stokes number for the flow.

Though the relative values of α and D/H tend to rise and fall together, it is possible to have relatively large values of D/H and small values of α (at high windspeeds) and the converse (at low windspeeds).

In practice, the Stokes flow regime is valid for viscous flows and for particle sizes up to about 50 μm aerodynamic diameter with engineering accuracy. Beyond this there are accumulating errors in the assumption. For example, in the Stokes flow regime the particle falling speed, v_f, is proportional to d^2 (where d is the particle aerodynamic diameter), while for larger particles the falling speed is more nearly proportional to d.

In the present work it has been assumed that the Stokes flow approximation applies also to large particles. This allows for simpler scaling rules and it is easier to understand their relationship to the rest of the model scaling. It was also impracticable to consider the more complex analysis for fully correct scaling within the severe constraints of the programme. For larger particles outside the Stokes regime the falling speeds and inertial effects are reduced relative to the Stokes flow assumption. The errors in this assumption for the larger particles under consideration here are of the order of a factor of two in the assumed deposition velocity. For a preliminary experiment, where order of magnitude changes in particle deposition rate might be expected, this level of error was considered acceptable.

There are three broad divisions of particle inertial behaviour in this type of discharge. These are

D/H Large ($D/H > 10$)	''Ballistic'' particles driven by inertia. Wind effects of minimal significance.
D/H Moderate ($0.01 < D/H < 10$)	Both particle inertia and wind effects important.
D/H Small ($D/H < 0.01$)	Inertia unimportant. Particle motion controlled by wind effects with dispersion patterns identical to that of gases.

It is the intermediate state, in which both particle inertia and wind effects are important, that is of concern here. This has to be considered in combination with the particle angle of fall, v_f/U. Values of v_f/U in excess of about 0.01 can affect the plume path of the particles.

The relationship between particle behaviour, windspeed and the types of flow regime that can occur in the present case is shown in Fig. 1. This is a plot of particle falling angle, as a slope, v_f/U ($= \alpha$ for small angles), against windspeed. There are two sets of lines on the plot. The broken lines are for constant values of particle falling speed, from 10 $m\,s^{-1}$ down to 0.1 $m\,s^{-1}$. The bottom left hand corner of the plot corresponds to a particle falling speed of 0.01 $m\,s^{-1}$, below which particle falling angle is largely irrelevant. The solid lines are for constant values of D/H, assuming a Stokes law relationship, and range from values of 10 down to 0.001. If the correct relationship for large particles were applied, the lines of constant D/H would curve upwards at their right hand end. There are also shaded areas on the figure which set the boundaries of interest for the problem. The shaded area in the lower left hand part of the plot corresponds to values of D/H around 0.01 and below, for which particle inertia is unimportant and dispersion is as a gas. However, the effects of particle falling angle, v_f/U, in this region are significant and must still be considered. The shaded area in the upper right hand part of the plot is for particle falling speeds in excess of the probable discharge velocity of the fire plume, so that they cannot be ejected. This has been set at a nominal value of 10 $m\,s^{-1}$, derived from the earlier work on gaseous plume dispersion. The third shaded area, on the right hand side of the plot, corresponds to windspeeds beyond 20 $m\,s^{-1}$, the nominal 98 percentile UK windspeed which is unlikely to be exceeded.

The main area of interest for a particle deposition experiment lies in the unshaded region of the plot, for both particle falling angle and inertia, and in the lower left shaded region in addition for particle falling angle only. This covers a range of values of D/H

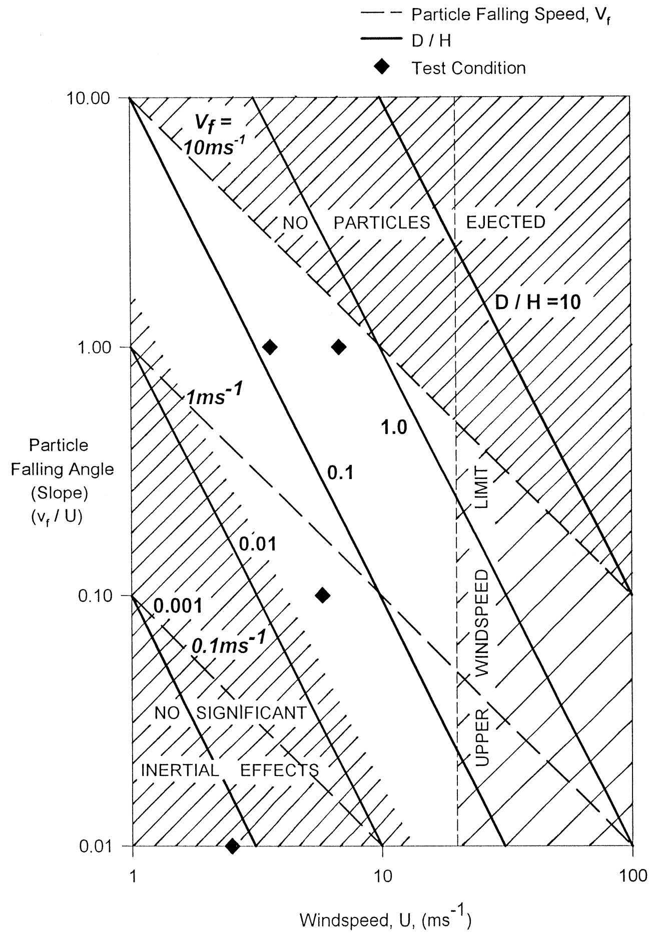

Fig. 1. Relationship between particle behaviour, windspeed and the types of flow regime.

between 0.01 and 1, the whole range of particle falling angles and windspeeds, and a range of particle falling speeds between 0.1 and 10 $m\,s^{-1}$ (equivalent to particles with aerodynamic diameters between about 300 and 3000 μm).

In setting up an experiment, it can be seen from Eq. (4) that once a value of α has been chosen then U^2/H has to remain constant between model and full scales, so that the model windspeed has to reduce as the square root of the scale. This is the same as conventional Froude number scaling for gravity-driven flows. In fixing this there is then only one particle falling speed, and by inference a single particle aerodynamic diameter, which will provide the correct values of α and D/H. There is an additional constraint in achieving this in a model involving a buoyant plume, as here, which is that there are also wind speed requirements for scaling the plume behaviour, following the scaling principle laid out in section 4.2 of the earlier work. However, since the buoyant plume scaling also involves a reduction of windspeed with model scale, it is possible to marry the two scaling requirements within some limits.

The present work used values of the same plume buoyancy and discharge momentum parameters that had been used for the gaseous dispersion experiment. However, the model windspeeds were adjusted in order to match the required particle falling angle and inertia and the buoyancy and momentum in the plume discharge were modified as appropriate. The model windspeeds were fixed by what particles were readily available from other work within the research group (whose other major interest was in a variety of dust and aerosol related pollution problems). Despite this constraint it proved possible to match a number of combinations of model test conditions and particle sizes that could be usefully used. The four test conditions that were eventually used in the experiments, described in detail in the next section, are plotted as diamonds on Fig. 1. They cover three values of v_f/U, 1, 0.1 and 0.01, and full scale equivalent windspeeds of 5–10 $m s^{-1}$. The condition for the smallest value of v_f/U fell inside the region where no significant inertial effects were expected. This was done deliberately to see what result occurred in these conditions.

3. Details of experiment

Deposition experiments were carried out for four test conditions. These were two plume discharge buoyancies, S2 and W2 (the details of which can be found in [1]), in combination with two building arrangements, with and without the small building shell in a wind direction of 90° (Fig. 2). With the four particle test conditions this provided a total of sixteen data sets. Buoyancy condition S2 was a neutrally buoyant plume.

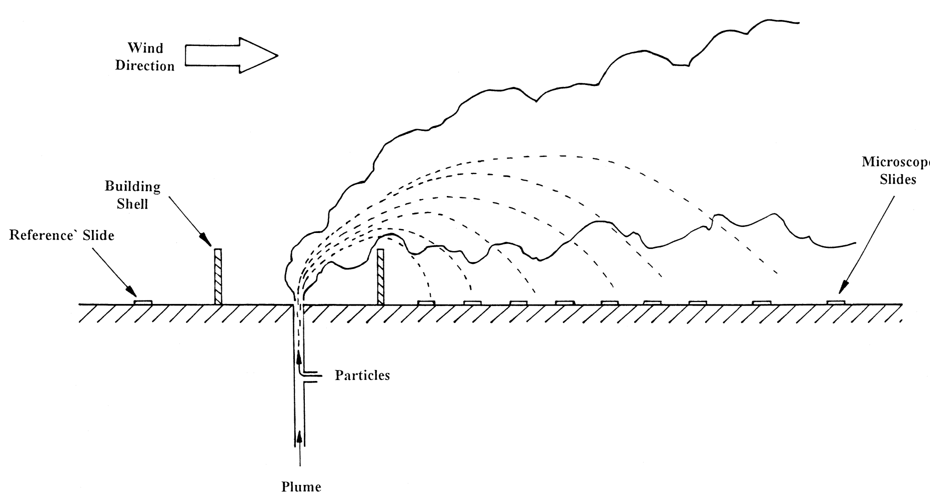

Fig. 2. Sketch of deposition experiment in wind tunnel.

Condition W2 was a moderately buoyant plume just starting to clear the ground and showing a marked reduction in ground level plume concentrations. Both conditions had a small discharge momentum. This was required for practical reasons as fluidising the particles into the plume gas stream needed a flow of air which appeared as additional plume discharge momentum. The gas source was flush with the ground, of 26 mm i.d.

Two types of particle were used, ballotini (spherical glass beads) and aloxite (aluminium oxide abrasive particles). Both types of particle are available in large quantities and had been previously used in dust and aerosol experiments within the group (see, for example [6,7]), so that their characteristics were well known. The ballotini are highly spherical and of consistent density, they were sieved within small size bands for experimental purposes. The aloxite is used in large quantities for grinding optical lenses, etc. and is available in quantity within tight size bands, sized by an elutriation process which effectively sorts them by falling speed.

The ballotini sizes used were of 62 and 105 μm nominal diameter (actually in the ranges 54–69 and 95–108 μm) which corresponds to aerodynamic diameters, d, of 108 and 183 μm respectively, allowing for the specific gravity of the glass of 3.0. The aloxite sizes used were nominally 4 and 21 μm equivalent spheres, corresponding to aerodynamic diameters of 8 and 42 μm respectively (the specific gravity of aloxite is 4). Size distributions of the two sizes of aloxite particle used, measured by a liquid sedimentation technique (a sedigraph), are shown in Fig. 3. It can be seen that for the smaller size (4 μm) aloxite the 10 and 90 percentile bands of the distribution were within a factor of two of the nominal size, while for the larger size (21 μm) the 10 and 90 percentile bands were within about 30–50% of the nominal size. We were unable to size the ballotini specifically for the present experiment and took the size range as quoted for previous samples put through the same sieves. Fig. 4 shows photographs of samples of the four types of particle, as deposited on the slides during the experiments. All photographs are at the same magnification. The photograph of the smallest particle size, the 4 μm aloxite, shows both individual particles and agglomerated clusters deposited on the slide. It was apparent in this case that the agglomerated clusters carried a significant, but not readily quantifiable, proportion of the discharged particle mass. Because of this it was eventually decided that data from this particle size could not be used reliably.

Table 1 shows the four particle sizes, the values of falling angle and D/H for the test conditions and the wind tunnel reference windspeeds required to achieve them. Also shown are the effective full scale heat releases and windspeeds corresponding to the test conditions. In the earlier gaseous dispersion experiment the release conditions, such as condition W used here, corresponded to a range of heat releases and windspeeds. In the present work, since the windspeed was effectively fixed by the particle scaling requirements, the heat release in the plume was also effectively fixed for this release condition.

A sketch of the experimental layout is shown in Fig. 2. Particles were injected into the vertical part of the gas feed line as close to discharge point into the wind tunnel as possible and their deposition on the ground monitored by collecting them on sticky microscope slides laid out downstream in an array along the plume centreline. A single slide placed upstream of the source acted as a system check. Unless there were significant quantities of particulate already in the flow, some accident in handling the

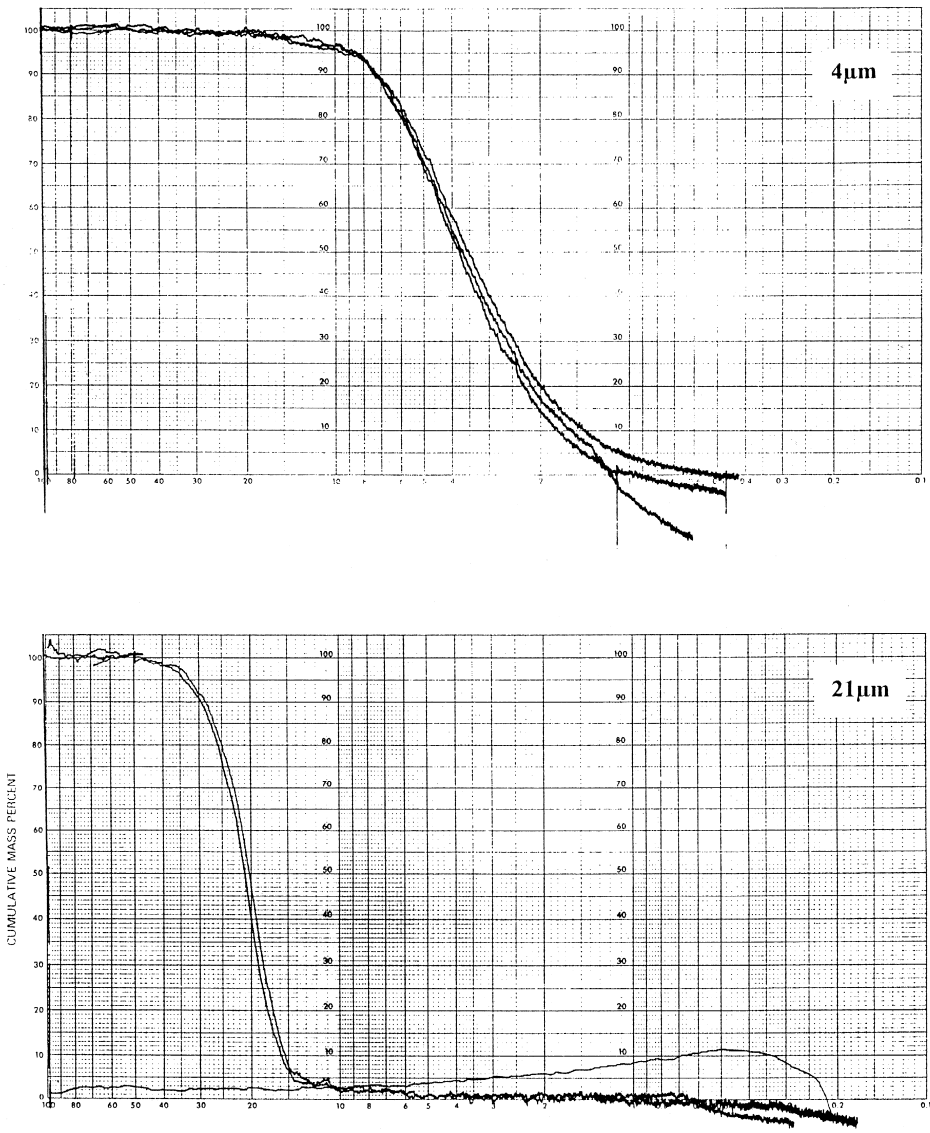

Fig. 3. Size distributions of aloxite particles used in experiments.

particles, the sticky slides or in the running of the experiment, this slide was expected to show a negligible particle count compared with the others. It did so in all cases.

The particles were injected into the plume gas stream over a period of about 10 min after being fluidised by a separate airflow. It was important that the particles were completely deagglomerated in this process as only single particles would have the correct aerodynamic behaviour. The ballotini deagglomerated fairly readily in a small

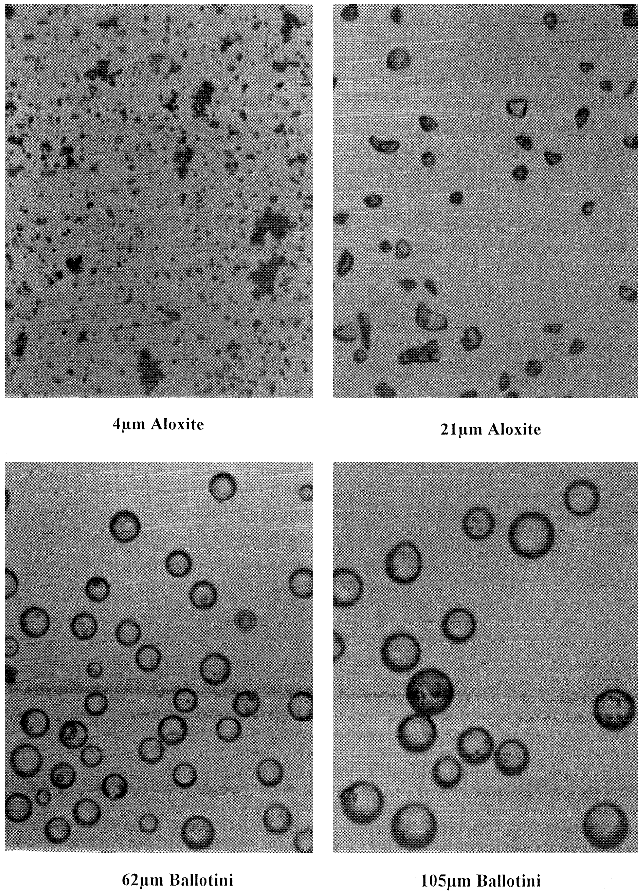

Fig. 4. Photographs of the four particle sizes and types used in the experiments.

gas flow of a few $\mathrm{l\,m^{-1}}$. They were previously washed in a weak solution of detergent, which leaves a surface coating to conduct away any static charge, which together with their natural mobility allows them to separate easily in a gas flow. The requisite weight of particles was placed in a small glass tube with a gas feed at the bottom and the outlet in the main gas line into the wind tunnel. Diverting some of the normal gas feed for the plume through the tube fluidised the ballotini, which then fed readily through the gas line and into the tunnel.

The aloxite proved more troublesome, it does not deagglomerate readily and usually requires a relatively high pressure air jet to achieve this. In the present experiments there were limits to the amount of air that could be fed into the gas stream as this affected the total gas discharge in the plume. The procedure finally used was a small home-made nebuliser, made from two small bore tubes of about 0.5 mm i.d. with the ends set at 90°. An air jet through one line generates a sufficiently low pressure in the other to suck material through it, which is further broken up in the high energy turbulent flow from

Table 1
Wind tunnel operating conditions, particle types and sizes used in deposition experiments

v_f / U	D/H	Tunnel windspeed ($m s^{-1}$)	Particle type	Actual particle diameter (μm)	Particle aerodynamic diameter (μm)	v_f ($cm s^{-1}$)	Equivalent full scale windspeed and heat release[a]	
							($m s^{-1}$)	(MW)
0.01	0.0006	0.2	Aloxite	4	8	0.2	2.5	0.7
0.1	0.04	0.5	Aloxite	21	42	5.1	6	8
1	0.1	0.3	Ballotini	62	108	28	3.6	1.8
1	0.6	0.6	Ballotini	105	183	60	7.3	20

[a] For buoyancy condition W2.

the jet. In the present case, the pressure that could be applied to the jet was limited by the airflow produced, which became part of the gas stream in the plume. Particles were picked up through the suction tube from a small supply which was weighed before and after a run. It proved possible to deagglomerate the larger size of aloxite with this technique, but only to partially deagglomerate the smaller size. Since the smaller size of aloxite had a relatively low falling speed, the deposition on to the collecting slides was mainly of agglomerated material, which had a higher falling speed. Some further experiments were carried out using particles injected in liquid suspension, but it was not possible to develop this technique or to further improve the aloxite suspension process within the very limited time scales of the experiment. In the end, the results for these small particles were not used, as they did not seem sufficiently reliable.

The particle collecting slides were standard microscope slides, 60×20 mm, coated with a thin sticky layer of petroleum jelly. This was initially dissolved in xylene and one surface of the slide wetted with the solution by laying it on the liquid surface, draining off the surplus and allowing the solvent to evaporate. A fair degree of cleanliness was required in this process to avoid any other particulate contaminating the solution. These proved very effective collectors and particles remained fixed to the slides, with no apparent loss, after eighteen months.

The experimental procedure was quite simple. Clean sticky slides were laid out downwind of the source, with a single slide just upwind as a system check. The tunnel was started and the gas plume set up. Particles were then fed into the gas plume feed line about 30 cm below the tunnel floor, with a straight vertical run up to the plume discharge point set in the tunnel floor. The particle feed period was 10–20 min. For ballotini, a fixed weight of material, preweighed, was fed into the tunnel. For aloxite, material was fed into the tunnel via the nebuliser feed device for about 15 min from a small container of particles, which was weighed before and after a run to determine the injected weight.

The deposited mass on the slides was found by counting the particle density on the slides, averaging counts over six separate areas on each slide, and multiplying by a particle mass estimated from the mean diameter and density. Close to the source, the deposition rate was so high that particles occasionally piled up on the slide, so that counting a single layer was no longer reliable. Particle counts were still made, on these slides, but they were also weighed to try and find the deposited mass directly.

4. Results and discussion

The main point of interest in the particle deposition data is the deposition rate relative to that resulting from the assumption that the particle dispersion is similar to a gas. Gaseous dispersion data was available from the earlier work, and for comparison values of particle concentration just above the ground have been estimated from the deposition data. The procedure for doing this is outlined below. It is assumed that the process of discharge and deposition of particles takes place over a time, t.

The rate of particle deposition is assumed to be due entirely to gravitational settling, so that

$$\text{Rate of Deposition} = C v_f \tag{5}$$

where C is the ambient concentration of particles close to the surface.

The mass of particulate per unit area, m, deposited at the surface is the product of rate of deposition and time, that is

$$m = C v_f t \tag{6}$$

If a mass, M, of particles is discharged from the source over the same time, then the rate of discharge, Q, is simply,

$$Q = \frac{M}{t} \tag{7}$$

The dimensionless concentration, K, for gaseous dispersion used in the earlier work is defined as

$$K = \frac{CUH^2}{Q} \tag{8}$$

where H is the building height (taken as 10 m nominal).

For the particle deposition experiments an equivalent value of K close to the surface can be found by substituting C and Q from Eq. (6) and Eq. (7) respectively into Eq. (8). This yields,

$$K = \frac{m}{M} \cdot \frac{UH^2}{v_f} \tag{9}$$

Note that the time, t, of the experiment disappears from the expression for K, so that the time of discharge is not important. Only the discharged and deposited masses of particles need be known.

Values of K were determined using Eq. (9). Values of m were found from the counts or weights of deposits on the slides. Values of M were known directly from the experiment by weighing. Values of v_f were known from the particle characteristics. The building height, H, in the model was as in the previous experiments (6.7 cm) and modified windspeeds were as given in Table 1.

Figs. 5 and 6 show the basic data obtained from the experiments. Data for the three largest particle sizes only are shown. The reliability of data for the smallest particle size

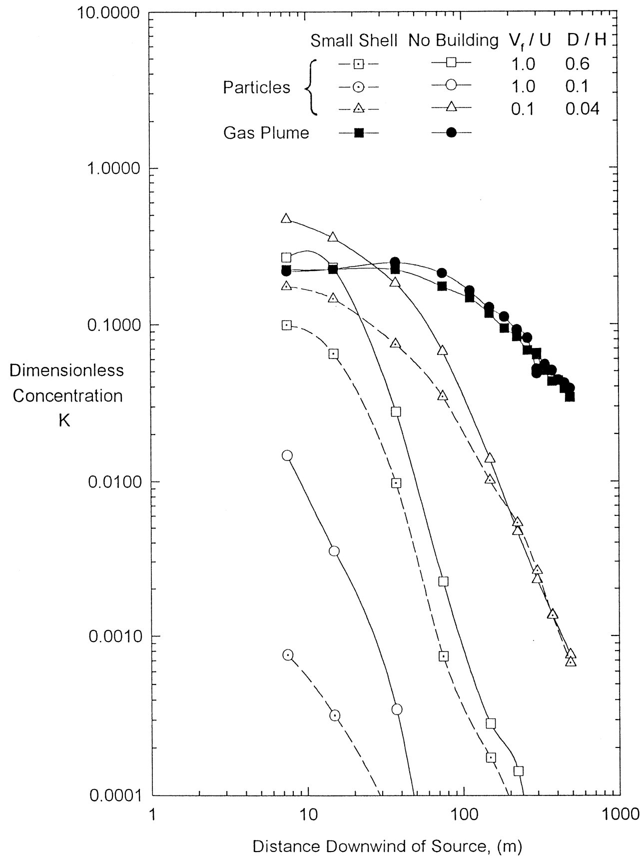

Fig. 5. Estimated particle concentrations close to the ground for discharges from the non-buoyant plume, condition S2. $M/U^2L^2 = 0.1$.

was felt to be uncertain due to partial agglomeration as described earlier. Fig. 5 shows results for plume condition S2, with no discharge buoyancy, both with and without the building shell. Fig. 6 shows results for plume condition W2, with a significant discharge buoyancy. The solid data points on each figure are for the ground level concentrations of the gaseous plume, from the earlier work.

The two figures show particle concentrations close to the surface that were quite different to the gas concentrations from the earlier work. All the experimental conditions in both figures show particle concentrations falling much more rapidly with distance than with the gas plume. Also, with the buoyant plume, in Fig. 6, concentrations near the source were well above levels for the gas plume. Close to the source, the particle concentrations also appeared to level off or show maxima in most of the test conditions. However, this is also the region where the collecting slides became overloaded and were weighed and it is possible that these concentrations are underestimates.

The most marked differences in the data are between the different particle types and between gases and particles. The two particle sizes with the same value of v_f/U (1.0)

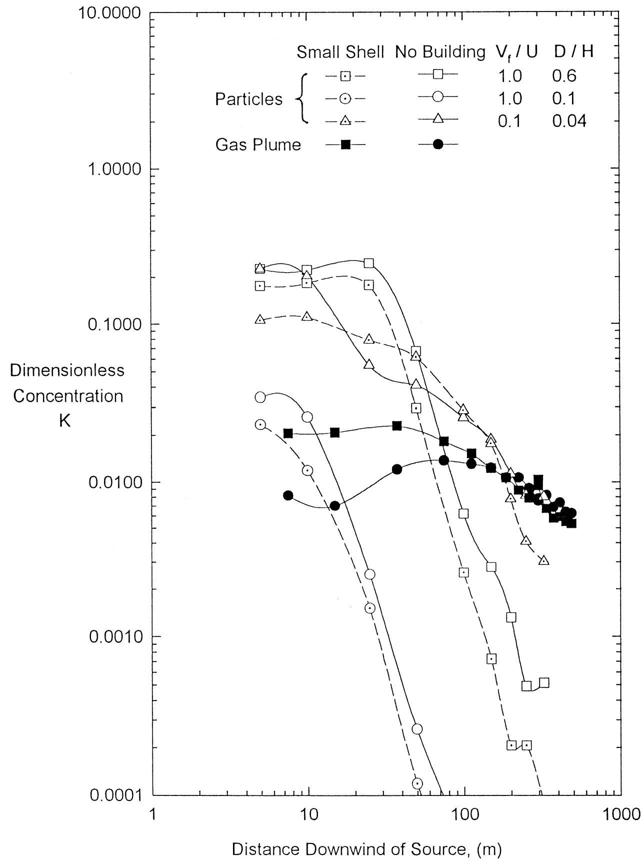

Fig. 6. Estimated particle concentrations close to the ground for discharges from the buoyant plume, condition W2. $M/U^2L^2 = 0.1$, $F/U^3L = 0.1$.

but different values of D/H (0.1 and 0.6 respectively) show differences in concentration close to the surface of around an order of magnitude, the particles with the highest value of D/H having the highest concentrations. It is of interest that particle inertia should have such a substantial effect on dispersion behaviour. The particle size with the smallest value of v_f/U (0.1) and small inertia ($D/H = 0.04$) showed generally higher concentrations close to the surface than for the other two sizes and a slower reduction with increasing distance from the source. Compared with the two larger particle sizes, the concentrations for this particle size showed some trends back towards the values of the gas plume measurements, though there remained significant differences.

The effect of the building shell in nearly all conditions was to reduce particle concentrations near the ground. The reduction was markedly smaller for the buoyant plume results of Fig. 6, probably because the building shell was more effective in blocking the particle paths with the neutrally buoyant plume. The buoyant plume nearly passed clear of the building shell and would have been more effective in carrying particles with it. It was observed during the experiment that with the neutrally buoyant plume the building shell trapped quite large numbers of particles and this must have significantly depleted the plume particle content close to the source.

Though the buoyant gas plume appeared to be able to lift the particles with it, their rate of rise was clearly less than that of the gases, so that particle concentrations near the source did not show such a marked reduction with increased plume buoyancy as the gases. This is a predictable conclusion in principle, though the degree of the variation is not predictable in such a complex flow.

There are a number of interacting features of the dispersion and deposition process in the model, which affect the resultant concentration pattern. High values of v_f/U produce plumes closer to the ground with higher deposition rates. However, high deposition rates deplete the plume, so lowering concentrations further downwind. High values of D/H reduce the rate of lateral dispersion in the plume, leading to narrower, more highly concentrated particle plumes compared with gas plumes. Thus increasing values of v_f/U and D/H should both lead to higher plume concentrations near the ground, but also to higher deposition and depletion rates.

It is not possible to deconvolve these different facets of large particle deposition from fire plumes with the few measurements reported here. However, it is quite clear that their effects are significant and that both particle falling angle and inertia affect the resultant plume concentration patterns. Particle inertia is not accounted for at all in simple plume deposition models.

In addition to weighing deposited particles, it was found that the particle motions could also be observed as a form of flow visualisation in strong, well directed lighting. Particles could be seen travelling with the plume and depositing on the ground with trajectories consistent with their falling angles and inertia. Thus the largest particles could be seen travelling on rapidly falling trajectories close to the source with only limited effects due to the airflow, while the smaller sizes travelled significant distances before falling out. Observation of the smallest particle size, 4 μm Aloxite, was especially impressive. The particle discharge produced a visible plume with the same appearance as oil smoke and because of their low falling speed the particles filled the whole region of the plume along the length of the wind tunnel. The presence of agglomerated material could also be observed in this case, as brighter particles falling relatively rapidly out of the plume.

Because of the short time and very difficult conditions under which the work described here was carried out, it was not possible to fully develop the experimental technique, to resolve a more rigorous scaling procedure or to investigate large particle deposition with any thoroughness. It must therefore be regarded as a proving trial of the technique and a brief investigation as to the relative importance of different facets of particle behaviour to the deposition process. However, the experiments show that it does seem to be possible to scale and carry out a large particle deposition experiment using a small scale wind tunnel model. It also appears that the deposition behaviour of large particles is complex and that particle falling angle and inertia are both important to the particle plume behaviour. The experimental technique seems in principle to be fairly effective as the plots of Figs. 5 and 6 show quite well behaved data. The least well resolved part of the technique, which caused the most difficulty in practice, was that of injecting monodisperse particles into the plume gas stream. However, with some further development these difficulties would almost certainly be resolvable.

5. Conclusions

1. It has proved possible to scale and operate an experiment on large particle deposition from fire plumes using a small scale wind tunnel model.

2. The particle deposition behaviour is complex and is affected by both the particle falling angle and the particle inertia, as well as by building downwash effects.

3. The limited data presented here show a much more rapid reduction of particle concentration at the surface with increasing distance from the source compared with a gaseous plume. Highest concentrations occurred with the particles with low falling speed and inertia, lowest concentrations with the particles with high falling speed and moderate inertia. The particles with high falling speed and high inertia produced concentrations between the other two.

4. The effect of the building shell on particle concentrations near the surface was relatively limited with the buoyant plume. With the neutrally buoyant plume the building shell reduced particle concentrations near the surface, partly by acting as a trap, retaining large particles within the building shell.

5. Though the present work has indicated the importance of both particle falling angle and inertia, it must be considered as of a preliminary nature. It is too limited in extent to provide a broad-based indication of particle behaviour.

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