Third International Conference on CFD in the Minerals and Process Industries
CSIRO, Melbourne, Australia
10-12 December 2003

CFD PREDICTION OF ODOUR DISPERSION AND PLUME VISIBILITY FOR ALUMINA REFINERY CALCINER STACKS

G.J. BROWN[1] and D.F. FLETCHER[2]

[1]Alcoa World Alumina Australia, PO Box161, Kwinana, WA 6167, Australia
[2] Department of Chemical Engineering, University of Sydney, NSW 2006, Australia

ABSTRACT

Computational fluid dynamics (CFD) models are developed to examine the behaviour of moisture-laden buoyant plumes emitted from Alumina refinery calciner stacks. The CFD modelling is carried out to complement traditional atmospheric dispersion modelling undertaken as part of a study to develop odour reduction strategies for Alcoa's Wagerup refinery in Western Australia.

The commercial package CFX-4.4 is used to develop a plume model which incorporates source terms for condensation, evaporation and associated heat transfer. The model is used to examine issues that cannot be assessed well with standard atmospheric dispersion models, such as the impact of condensation on plume rise and ground-level odour and the impact of ambient air addition on plume visibility.

A second model developed in the commercial package CFX-5.5 is used to examine the potential to reduce ground-level odour through the construction of a 100 m high multiflue stack. Solution-adaptive meshing is used to reduce initial model set-up time and to optimise the mesh size in regions of high concentration gradients.

The relationship between the CFD models developed and traditional atmospheric dispersion models is discussed and the paper illustrates how the different techniques can be used in a complimentary fashion to develop engineering solutions to reduce the impact of emissions from an industrial plant.

NOMENCLATURE

h_{fg}	latent heat of vaporisation
k	turbulent kinetic energy
m	mass fraction
P	pressure
S	source term in conservation equation
U	velocity
z	vertical height
ε	turbulent energy dissipation rate
ρ	density
τ	characteristic timescale

Subscripts

c	condensation
sat	saturation value
v	vapor

INTRODUCTION

Alcoa's Wagerup alumina refinery is located in a rural area approximately 130 km south of Perth in Western Australia. Prior to 1996 the refinery received only a small number of complaints about its operations (approximately 10 per annum) with these mostly related to dust from the residue storage area. However, following the installation of a liquor burning facility in 1996 Alcoa received a significant increase in complaints regarding refinery odour and this issue became the source of considerable scrutiny by the community, workforce, government and later by the media.

Alcoa put in place an aggressive program to reduce odorous emissions, starting with an initial focus on liquor burning in 1998 and culminating in a $25 million, plant-wide, program of capital works in 2002. As part of this program the potential to reduce the impacts of calcination odour through better dispersion was assessed and a 100 m high multiflue stack for three calciners and liquor burning was ultimately commissioned in June 2002 (Cox, 2002).

As part of the initial feasibility study for the multiflue stack, consulting engineers Sinclair Knight Merz (SKM) undertook modelling of odour dispersion at Wagerup refinery using the atmospheric dispersion models TAPM, Ausplume and CALPUFF (Sinclair Knight Merz, 2002). In addition, computational fluid dynamics (CFD) modelling of dispersion from the calciner stacks was undertaken. The CFD models were not intended to replace or supersede the atmospheric dispersion models, which are the tools currently accepted by regulatory authorities, but rather the two studies were seen as complimentary. The CFD study was undertaken with the objectives of helping to support the conclusions from the dispersion modelling being undertaken by SKM and enabling the assessment of issues that could not easily be investigated with the dispersion models, such as;

- The impact of condensation on plume rise and ground-level odour.
- The impact of ambient air addition on plume visibility.
- Optimal configuration of the multiflue stack in terms of exit velocities, temperature and discharge heights for different stacks.
- Detailed visualisation of plume dispersion for fixed atmospheric conditions.

MODEL DESCRIPTION

Literature Review

A literature review showed that beyond the well-known plume dispersion models there was very little available in the literature on prediction of visible water vapour clouds, despite its importance for cooling tower design and wet plumes. Clarke and Shaw (1993) produced a correlation to predict the presence of a visible cloud. Gangoiti et al (1997) and Janicke and Janicke (2000) have developed Gaussian dispersion type models that included prediction of condensation. Fisher (1997) pointed out the complexities introduced by atmospheric conditions and that criteria based on the stack exit conditions are not sufficient. No detailed CFD model of visible plume formation could be found.

Model of plume visibility (CFX-4)

Initial modelling to examine the feasibility of the multiflue stack concept, the effects of condensation on plume rise and the impacts of ambient air addition was undertaken using a model developed using the CFX-4 code (ANSYS CFX, 2003). The model included condensation and evaporation of the water phase to enable assessment of plume visibility, as well as odour dispersion. The model was based around the Reynolds Averaged Navier Stokes equations, with additional transport equations being solved for the enthalpy of the mixture, the mass fraction of water vapour, of liquid water and of the odorous gas. The following assumptions were made:

- The system reaches local thermodynamic equilibrium almost instantaneously. The implication of this is that there are sufficient nuclei present that condensation occurs as soon as the system becomes supersaturated and evaporation occurs as soon as the humidity drops below 100%. In the code, rate constants are introduced to implement this (see later).
- The air and vapour behave as ideal gases and the liquid is incompressible.
- The droplets formed are so small that they are always in mechanical and thermal equilibrium with the surroundings.
- The latent heat of vaporization is constant over the temperature range considered.
- Turbulence is modeled using the k-ε model with the buoyancy correction term included (C_3 = 1.0).

Condensation/evaporation modelling

The algorithm to determine the condensation/evaporation used the following approach. In any volume the temperature, T, density, ρ, and the mass fraction of vapour m_v are known. The thermodynamic pressure is assumed constant at 1 bar (because the pressure range in the model is typically <1% of atmospheric). From the temperature T calculate the saturation vapour pressure from an Antoine equation to obtain $P_{sat}(T)$. From the given data the vapour pressure of water is calculated using the ideal gas law. Then, if P_v is greater than P_{sat} some vapour must be condensed. The amount can be estimated by using the ideal gas law, which says the mass fractions must scale with the pressure, so that the mass to be condensed is equal to $m_v \rho(1 - P_{sat}/P_v)$ for $P_v > P_{sat}$. Therefore there needs to be a source term in the vapour mass fraction equation of the form

$$S_m = -m_v \rho (1 - P_{sat} / P_v) / \tau_c \quad (1)$$

where τ_c is a user-specified timescale for condensation. Note a finite rate is needed because of the equation formulation but it can be selected to be small enough to ensure local thermodynamic equilibrium. This term is accompanied by an additional enthalpy source term that takes the form

$$S_h = S_m \times h_{fg} \quad (2)$$

Note that this term has the effect of leaving behind the latent heat of vaporisation, which results in a temperature rise locally due to the released latent heat.

In order to accommodate the fact that there is liquid present, the default calculation of the density needs to be modified. If the mass fractions of each species are known, then it is easily shown that

$$\frac{1}{\rho} = \frac{m_{air}}{\rho_{air}} + \frac{m_v}{\rho_v} + \frac{m_l}{\rho_l} \quad (3)$$

where the subscripts *air*, *v* and *l* refer to the air, vapour and liquid, respectively. For the gases the density is calculated using the ideal gas law and for the liquid a constant density is used. A similar set of source terms are coded for the reverse situation when liquid has to be evaporated. The contour of zero liquid mass fraction indicates the extent of the visible plume.

Validation of the condensation/evaporation coding was carried out by running a comparative calculation in the Aspen+ process simulation code. In this calculation, stack gases from a calciner were mixed in a 3:1 ratio with air at 12 °C, such that condensation would occur. This process was then simulated in CFX-4 using a static mixer model and the same heat and mass transfer coding described above. The resultant volumetric flow, temperature and liquid mass fraction matched closely the figures from Aspen+, hence providing confidence that the physics coded into the CFX-4 model was correct.

The wind profile

The wind profile upstream of the stacks was set using a standard logarithmic profile, given by;

$$U_z = \frac{u^*}{\kappa} \ln\left(\frac{z}{z_0} + 1\right) \quad (4)$$

where

$$u^* = \frac{\kappa}{U_{ref}} \ln\left(\frac{z_{ref}}{z_0}\right) \quad (5)$$

The turbulent kinetic energy and dissipation rate are given by

$$k = \frac{u^{*2}}{\sqrt{c_\mu}} \quad \text{and} \quad \varepsilon = \frac{u^{*3}}{\kappa z} \quad (6)$$

where the wind speed is U_{ref} at a reference height of z_{ref}, z_0 is the roughness height and z is the vertical distance from the ground. The turbulence constants c_μ and κ were set to the standard values of 0.09 and 0.41, respectively.

No attempt was made to simulate vertical temperature profiles, due to the complexities that this introduces via the need to make use of potential temperature. Thus buoyancy was included due to temperature differences between the stack gas and the surrounding air but the approaching airflow was always assumed to be stable. This approach was considered valid for the current study because field odour surveys had shown that some of the highest ground-level odour values occur under stable atmospheric conditions (Sinclair Knight Merz, 2002) and because a much wider range of atmospheric conditions (including temperature inversions which can trap the plume and cause high ground-level odour values) would be examined with the standard dispersion models.

Odour modeling

As part of the emissions reduction program at Wagerup, Alcoa undertook comprehensive sampling and chemical analysis for a large range of emissions sources within the refinery, including the calciner stacks. However, chemical analysis of refinery emissions does not usually provide enough information to determine sources of odour.

To determine the odour strength of different emissions it was necessary to use a technique called dynamic olfactometry. This involves the use of human noses, which are much more sensitive to odour than most instruments, though the results are more qualitative. One odour unit per cubic metre (OU/m^3) is defined as the level at which 50% of a properly constituted odour panel are able to detect the presence of an odour. The number of dilutions of a sample required to reach this level is thus a measure of the sample strength in OU/m^3. Using this technique the odour concentration for different emission sources across the plant was determined and it was possible to use these values as inputs to the CFD and dispersion modeling.

In the CFX-4 model an additional transport equation was solved for a non reacting scalar. This allowed the concentration at any location to be calculated relative to the given inlet concentration. As the equation is linear, this meant that the scalar field so calculated could be used to represent any of the odorous species.

Computational Domain

The computational domain in the CFX-4 simulations generally extended from approximately 200 m upstream to 2 km downstream of the stack being modelled (figure 1). The width of the area being modelled was effectively 600 m, but because only single stacks were modelled the flow was assumed to be symmetric about the stack centre-line and hence the computational domain was only half this width. As CFX-4 uses a hexahedral cell topology the stacks were also treated as being square in cross-section, but the correct discharge areas were maintained. The computational mesh size used was generally close to 110,000 elements, with element edge lengths varying from 0.8 m close to the stacks to 100 m at 2 km downstream. The calcination buildings and other refinery buildings were not included in the current study.

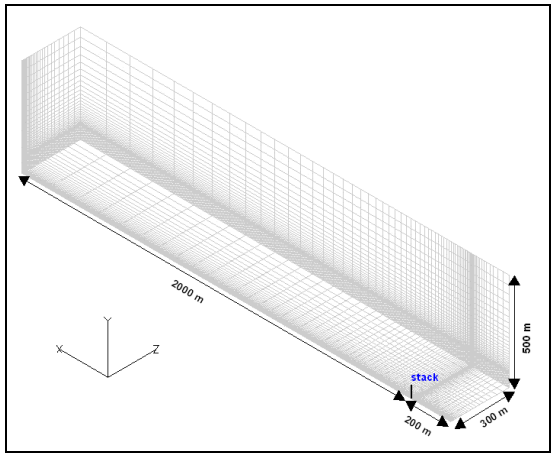

Figure 1: Computational domain for plume visibility calculations (CFX-4).

Multiple-stacks model (CFX-5)

In the second stage of the study, further modelling was undertaken to look in detail at the arrangement of individual stacks within the multiflue arrangement and to thoroughly compare the existing stacks and the proposed multiflue stack using models in which each individual stack was included separately. This modelling was undertaken using the CFX-5 code (version 5.5) as the unstructured tetrahedral meshing approach enabled models for complex geometries to be developed more quickly than in CFX-4.

Apart from the condensation/evaporation coding, the physical models used in the CFX-5 models were the same as used in the CFX-4 models described above. The condensation/evaporation coding was omitted because the intent of the CFX-5 models was to only study dispersion and results obtained with the CFX-4 models showed that the inclusion of condensation and evaporation had negligible impact on plume rise and ground-level odour.

The size of the computational domain used in the CFX-5 simulations was generally similar to that used in the CFX-4 models (see figure 1), although a symmetry plane was not used because multiple stacks were being modelled in each simulation. Some of the models were also extended to 4 km downstream to provide additional information. In the CFX-5 simulations an initial computational mesh was created with element sizes ranging from 40 m at 2 km to 5 m near the stacks. However, during the simulations solution-adaptive meshing was used to automatically refine the grid in areas of high gradients in odour concentration. This resulted in element sizes near the stack tips as low as 0.5 m and final mesh sizes of close to 3.5 million elements (figures 2 & 3).

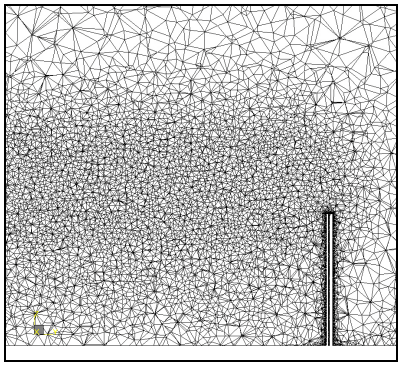

Figure 2: CFX-5 mesh prior to mesh adaption.

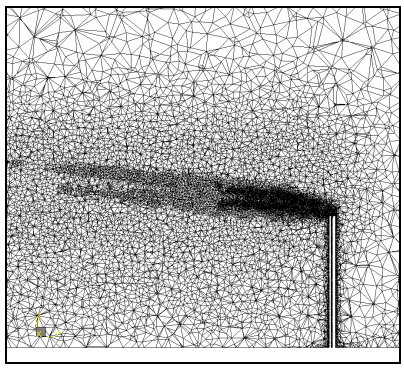

Figure 3: CFX-5 mesh after mesh adaption using odour concentration gradients.

Relationship between atmospheric dispersion models and CFD

In parallel with the CFD modelling, Sinclair Knight Merz undertook modelling of odour dispersion at the Wagerup refinery using the atmospheric dispersion models TAPM, Ausplume and CALPUFF (Sinclair Knight Merz, 2002). It is important to distinguish between these models.

Ausplume is a semi-empirical/analytic model based on the Gaussian plume approach and is accepted by all Australian regulatory authorities for pollutant dispersion modelling. CALPUFF is the preferred model of the US Environmental Protection Agency (EPA) for long-range dispersion modelling and uses a Lagrangian approach to track the continuous release of a series of puffs. This approach is more advanced than the Gaussian plume approach in that it allows spatial variations in wind and turbulence fields to be taken into account (D'Abreton, 2003). In both of these approaches the meteorological data required by the models is derived from either local observations (e.g. wind speed, wind direction and cloud data at a measuring station) and/or from other models, such as TAPM.

TAPM (The Air Pollution Model) differs considerably from these two approaches. It solves a discretised form of the Navier Stokes equations on an Eulerian grid and hence the fundamentals are the same as a commercial CFD code, such as CFX. However, there are significant differences between TAPM and the CFD models used in this study (Hurley, 2002 and Fletcher, 2002). For example;

1. TAPM has been highly customised for atmospheric dispersion modelling. It includes parameterisations for cloud/rain micro-physical processes, turbulence closure, urban/vegetative canopy and soil, and radiative fluxes which are not available as default options in commercial CFD packages. TAPM is also able to predict the meteorology for the region of interest, whereas parameters such as wind speed, wind direction and turbulence levels are inputs to the CFD model.
2. The TAPM simulations cover a much larger area of land, and larger mesh elements are used than in the CFD modelling described in this paper (The outer meteorological grid in the TAPM simulations covers an area of 400 km × 400 km and the smallest mesh elements on the pollution grid have an edge length of 300 m. In contrast, the grid in the CFD modelling has a maximum extent of 4 km with mesh elements being as small as 0.5 m close to the stacks.)
3. The TAPM simulations are transient, with simulations being conducted for pollutant dispersion over periods of 1-2 days up to potentially 1 year or longer. In contrast, the CFD modelling presented here is steady-state and presents the time-averaged flow with emission rates, wind direction and wind speed held constant.
4. The actual geometry of the stacks is not modelled in TAPM and initial plume rise is determined through a simplified momentum balance. Air flows around buildings close to the stacks are also not modelled in detail and their impacts are accounted for using a semi-empirical approach. In contrast, the CFD models include the geometry of the individual stacks and predict the initial rise and dispersion of the plume from solution of the governing flow equations. Buildings were not included in the CFD models in the current study, but could be included.

Based on the above differences, the CFD models developed in this study are obviously best suited to examining dispersion and visualising the flow field immediately downstream of the stacks under steady-state conditions, whereas the dispersion models, such as TAPM, are better suited to predictions over longer ranges and longer time periods. As such, the intention of the current study was primarily to use the CFD models to examine issues that could not easily be examined with the other models. This included issues such as the impact of condensation and ambient air addition on plume visibility and ground-level odour, and detailed design of the multiflue stack. It was also obviously of interest to see whether the CFD models would support conclusions drawn from the dispersion models regarding potential odour reductions with the multiflue stack, but any agreement was expected to only be qualitative due to the differences discussed above.

RESULTS

Effect of condensation on plume rise

Prior to the start of the study there was concern that the high moisture content of the calciner plumes (typically 50% v/v), and the resulting condensation that occurs under some atmospheric conditions, may affect the buoyancy and ultimately dispersion of the plumes. This was studied by running the CFX-4 model described above for several stacks under a range of atmospheric conditions.

Indicative results for calciner 1 are shown in figures 4 & 5 below. The model was run with a wind speed of 4 m/s at a height of 10 m for three atmospheric conditions. Condensation in the plume occurs under the first condition

(15 °C, 70% relative humidity) but not under the other two conditions. The plots show that the presence of condensation has a negligible impact on plume rise and hence ground-level odour downstream of the stack.

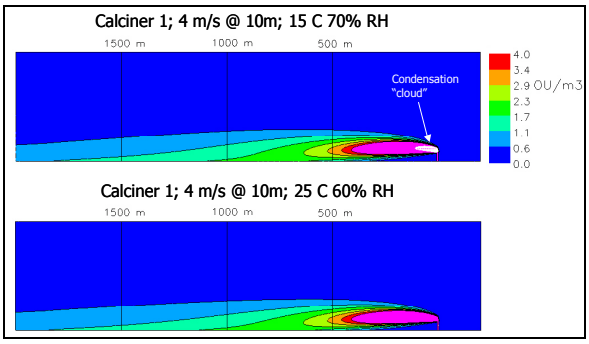

Figure 4: Odour contours and plume visibility for two atmospheric conditions (CFX-4 model).

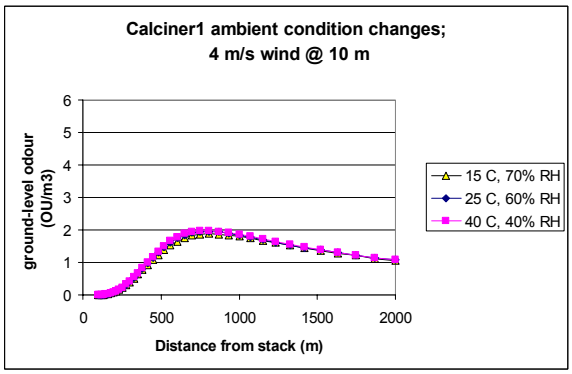

Figure 5: Ground-level odour variation with different atmospheric conditions (CFX-4 model).

Investigation of ambient air addition

As discussed above, the high moisture content of the calciner plumes causes a condensation cloud to form immediately downstream of the stack tips under some atmospheric conditions. Unfortunately, this condensation can be mistaken for smoke and creates the appearance of pollution. As part of the CFD study, the potential to reduce or eliminate this condensation cloud through the addition of ambient air to the stacks was therefore investigated. It was also of interest to determine whether ambient air addition would have any impact on ground-level odour.

Initial simulations were conducted with the CFX-4 model discussed above to look at the impact of 1:1 dilution (i.e. adding sufficient ambient air to double the calciner discharge flow rate) for calciner 1. Note that the stack discharge diameter was increased in the dilution case to maintain the same discharge velocity.

As shown in figures 6 and 7, the CFD results showed no impact on the size of the visible plume and very minor changes to ground-level odour as a result of the dilution. This latter result was consistent with atmospheric dispersion modelling results from Sinclair Knight Merz which showed only minor changes in ground-level odour with 3:1 dilution (Sinclair Knight Merz, 2002).

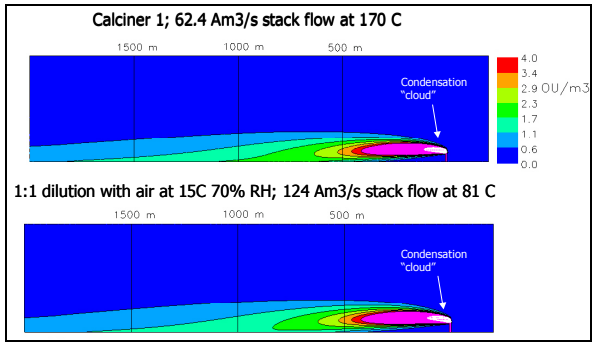

Figure 6: Odour contours and plume visibility for ambient air addition to calciner 1 (CFX-4 model).

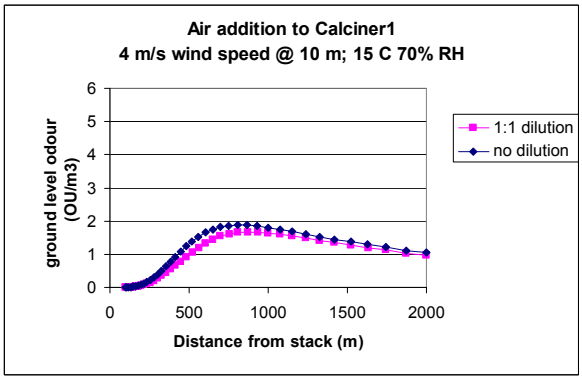

Figure 7: Ground-level odour variation for ambient air addition to calciner 1 (CFX-4 model).

After examination of the above results, a decision was made to examine a single case in more detail to look at the sensitivity of the predictions to the computational mesh density near the stack and assumptions in the models regarding the rate constants for condensation and evaporation. The scenario studied was the addition of 200 tonnes per hour (TPH) of ambient air to calciner 4, which would increase the stack flow rate by approximately 50%. This was considered to be at the upper end of air addition rates that could be practically achieved on the plant if an air addition system was installed.

Several simulations were conducted to look at the effect of the assumed rate constants for condensation and evaporation and it was concluded that to highlight any non-equilibrium effects a fast rate (0.1 s) should be set for condensation and a slow rate (10 s) set for evaporation (in previous simulations a value of 1 s had been used for both processes). The selection of these new rates was also based on the observation that condensation would be almost instantaneous due to the dust particles available to act as nucleation sites, but that there would be a finite rate associated with the evaporation process.

To increase the resolution of the flow around the stack the computational domain was reduced to cover only the first 300 m downstream of the stack (this was 2000 m in previous simulations) but the same number of mesh elements was retained. The wind speed in the simulations was also set at a lower value of 2 m/s @ 10 m height (4 m/s had been used in the previous air addition simulations) as model runs showed that the size of the visible plume was greater under light winds due to the reduced rate of mixing with the atmosphere.

Using these new model settings, simulations were conducted with and without 200 TPH ambient air addition at 15 and 18 °C (60% RH). At 15 °C the model predicted the formation of a visible plume but the extent of the plume was not reduced through ambient air addition (figure 8). At 18 °C the model did not predict the formation of a visible plume either with or without ambient air addition.

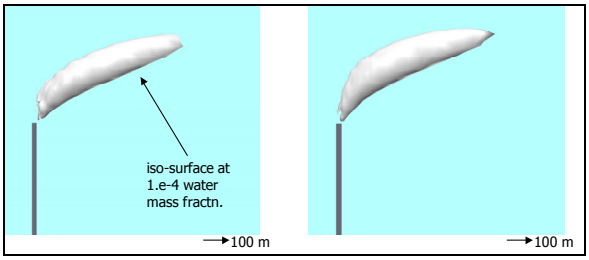

Figure 8: Calciner 4 visible plume with no ambient air addition (left) and with 200 TPH ambient air addition (right) at 15 °C.

The overwhelming conclusion from the modelling results was that the addition of small volumes of ambient dilution air would be of no practical benefit in terms of reducing plume visibility and would have little effect on ground-level odour.

Initial multiflue stack predictions

Initial assessment of the proposed multiflue stack for calcination was undertaken using the CFX-4 model. At this stage of the study it was envisaged that the multiflue stack would replace the existing stacks for calciners 1, 2 and 3 and it was assumed that it would be possible to locate the individual stacks in the multiflue arrangement in close enough proximity that they would essentially act as a single stack. As such, in the CFX-4 model the multiflue arrangement was treated as a single, large diameter stack with a discharge area close to 3× that of calciner 1, such that the discharge velocity would be similar to the existing stacks.

Simulations were run for 60 m and 100 m high multiflue stacks at wind speeds of 2, 4 and 8 m/s (at 10 m height). Results from these simulations were compared with predictions for calciner 1 and, in order to gain some indication of how the multiflue stack would compare with the existing calciner 1, 2 and 3 stacks, the multiflue results were also compared to the results for calciner 1 multiplied by a factor of 3×. This latter comparison was justified on the basis that the existing calciner 1, 2 and 3 stacks had similar emission rates and were located in close proximity. However, it was acknowledged that the comparison would only be indicative because the centre-lines of the existing plumes would not be completely coincident and it is possible that their close proximity might result in enhanced buoyancy that would not be captured through the simulation of an individual stack.

In figures 9, 10 & 11 the 60 m and 100 m multiflue stacks are compared against 3×calciner 1 using graphs of ground-level odour on the plume centre-lines.

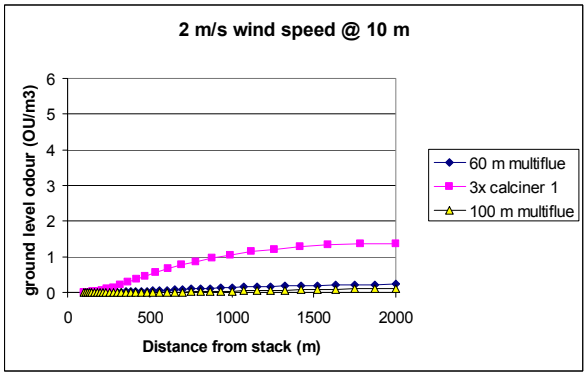

Figure 9: Ground-level odour with 2 m/s wind.

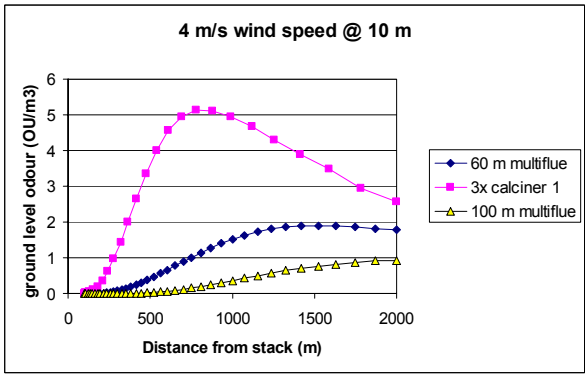

Figure 10: Ground-level odour with 4 m/s wind.

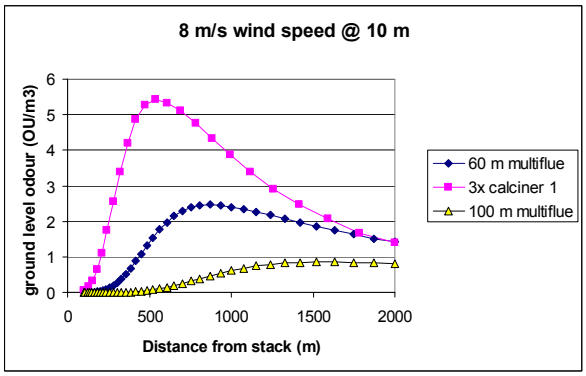

Figure 11: Ground-level odour with 8 m/s wind.

The results show that at 2 m/s significant plume rise is achieved in all cases, leading to low ground-level odour values. This is because the slow rate of mixing with the atmosphere allows the plume to stay hotter (and hence more buoyant) than the surrounding air for a significant distance. As wind speed increases, plume rise is reduced in all cases due to faster mixing and reduced buoyancy and the plume "hits" the ground closer to the stack. However, it is interesting to note that the predicted ground-level odour values at 2 km are actually slightly lower in the 8 m/s cases than in the 4 m/s cases and this trend would be expected to increase at higher wind speeds. This is because the higher wind speeds lead to faster dilution of the stack emissions. This leads to the conclusion that the highest odour values at distances of 1500 – 2000 m would be expected at moderate (approx. 4 m/s wind speeds) and this is in fact consistent with the conclusions from an assessment of community odour

complaints undertaken for April, May and June 2001 (Sinclair Knight Merz, 2002).

Comparison of the different stack scenarios shows significant odour reductions under all wind speeds and at all downstream distances for the 100 m multiflue stack compared with the existing stacks. The 60 m multiflue stack also showed significant odour reductions at low to moderate wind speeds but the results suggest that at high wind speeds the 60 m stack may not have given significant reductions at distances around 2 km from the refinery (close to the location of the nearest neighbours).

These predictions and results obtained with the dispersion model TAPM at the same time provided a strong conclusion that significant odour reductions could be achieved through the use of a 100 m high multiflue stack for calcination. The impact of a multiflue stack on the odour signature from the full refinery over longer time periods was then examined by Sinclair Knight Merz using the CALPUFF dispersion model and a decision was made to undertake further CFD modelling to optimise the exact layout of the individual stacks in the proposed multiflue arrangement.

Full 3-D model development

Fully 3-d models were developed for both the existing calciner stacks and the proposed multiflue arrangement using CFX-5.

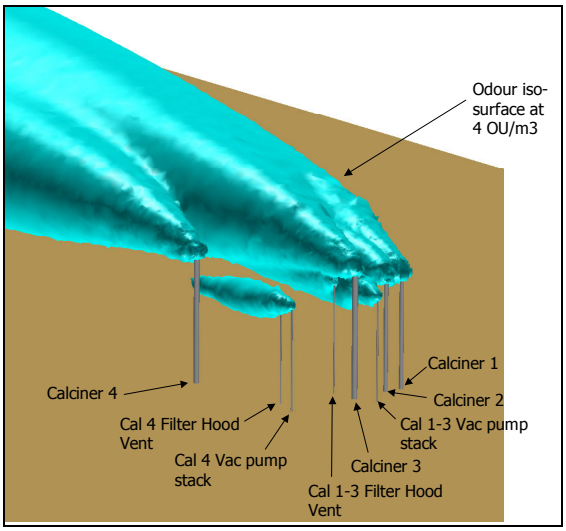

Figure 12: Layout of existing stacks (CFX-5 model).

The stack layout for the "current" calcination model is shown in figure 12 and included the stacks for calciners 1, 2, 3 & 4 and associated smaller stacks. The model did not include the liquor burning stack. The proposed multiflue stack at this point in the study included three, 100 m high stacks for calciners 1, 2 & 3 in a triangular arrangement with another stack centred between these three (referred to as the "cold" stack due to its lower temperature) which would take the combined flow which had previously gone to the calciner 1-3 filter hood and vacuum pump stacks. Calciner 4 and its associated minor stacks would be unchanged. The stack layout for the multiflue model is shown in figure 13.

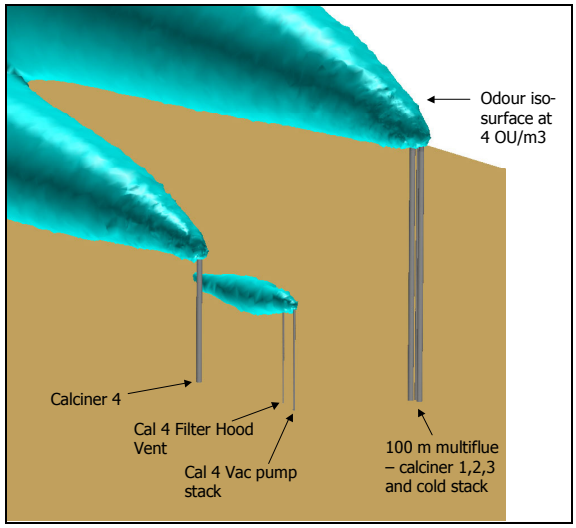

Figure 13: Layout of multiflue stack (CFX-5 model)

Simulations were run for each of these scenarios using wind conditions of 4 m/s @ 10 m height with ambient conditions of 15 °C, 70% relative humidity. The simulations were run using solution-adaptive meshing based on odour gradients and were run initially for distances of 2 km downstream. Comparison of the results showed some differences to the earlier CFX-4 results (see later discussion) but still confirmed that significant odour reductions could be achieved using the multiflue stack and hence that further development and design of this concept was warranted. Importantly, the results also showed that the individual plumes in the multiflue arrangement would rapidly combine into a single plume with enhanced buoyancy, as at this point in the study the stack spacings in the proposed multiflue design were based entirely on empirical correlations.

Incorporation of "cold" stack and liquor burning into multiflue

As discussed above, the initial multiflue design included a stack (to be placed between the three calciner stacks) which would take the combined flow from the calciner 1-3 filter hoods and vacuum pumps. This stack was referred to as the "cold" stack because the discharge temperature of 70 °C was significantly lower than the calciner stacks, which were typically in the range 145 – 180 °C. In the initial simulations the cold stack diameter used resulted in a discharge velocity of approximately 20 m/s (similar to the discharge velocities from the calciner stacks). However, the pressure drop across this stack was considered to be too large and hence the model was also used to look at the impact of using a larger diameter stack with a discharge velocity of closer to 4 m/s.

In addition to the above, the potential to incorporate the liquor burning stack into the multiflue arrangement (using a fifth stack on the outside of the existing four stack bundle) was also examined. Initially a discharge temperature of 70 °C was assumed for the stack based on the existing liquor burning flow sheet. However, a 200 °C discharge temperature was also examined, based on the potential to alter the liquor burning flow sheet if the higher discharge temperature was warranted as a result of better dispersion.

As a result of the above requirements, three separate simulations were run using combinations of the different configurations;

1. No liquor burning stack; 20 m/s cold stack
2. 70 °C liquor burning stack; 4 m/s cold stack
3. 200 °C liquor burning stack; 4 m/s cold stack

Figure 14 looks in detail at mixing and entrainment of the different plumes immediately downstream of the stacks for cases 1 and 2 using streamlines.

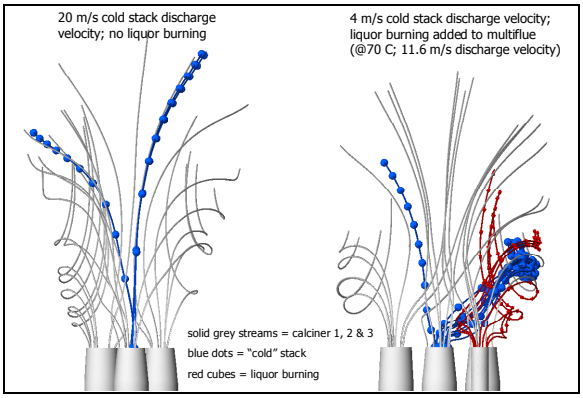

Figure 14: Initial plume mixing for cases 1 & 2.

The figure shows that the lower discharge velocity for the cold stack in the second multiflue scenario appears to hinder initial entrainment into the main plume. This also appears to be true for the liquor burning stack due to its lower temperature and discharge velocity compared with the calciner stacks. The liquor burning plume in the second case (and to some extent the cold stack plume) also appears to be entrained predominantly into the right hand side of the plume (as viewed from upwind of the stacks). Further examination of the results, however, showed that the cold stack and liquor burning plumes in the second case are progressively dispersed within the overall multiflue plume further downstream of the stacks and, as a result, plots of ground-level odour on the plume centre-lines for the two cases show negligible difference (figure 15). However, based on the above results the final design of the multiflue stack installed at Wagerup included a tip nozzle on the cold stack to increase the discharge velocity to close to 20 m/s, whilst at the same time giving overall lower pressure drop compared with a smaller diameter stack.

Results for case 3, with a 200 °C liquor burning discharge temperature, showed minor improvements in initial entrainment of the liquor burning plume compared with a 70 °C discharge temperature, but plots of ground-level odour on the plume centre-line again showed negligible change (figure 15). As a result, the liquor burning stack was included in the final multiflue design but the concept of using a high discharge temperature was not pursued further due to the significant flow sheet required and the negligible benefit.

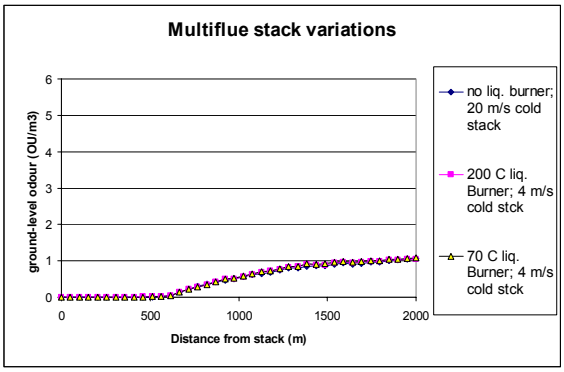

Figure 15: Odour contours for different multiflue stack scenarios.

Comparison of final multiflue design and current stacks

Simulations were run for the final multiflue configuration (incorporating the liquor burning stack) and the existing stacks using the CFX-5 models with the computational domains extended to 4 km downstream. Solution-adaptive meshing based on odour gradients was again used and the wind was set to 4 m/s @ 10 m height. Results for these simulations are presented below in figures 16 and 17. Note that the odour contours have been plotted on the centre-line of the combined plume from all stacks in each case and have only been plotted over the first 2 km for clarity.

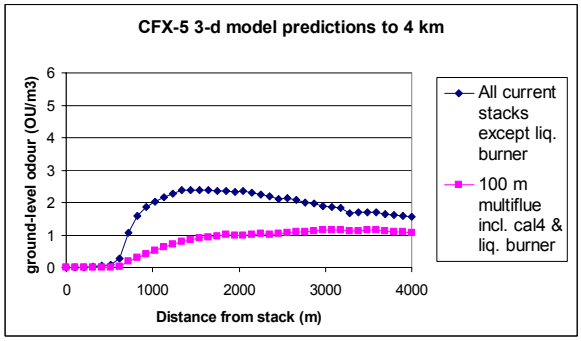

Figure 16: Ground-level odour for current and multiflue stacks.

Comparison of figure 16 with the earlier CFX-4 results in figure 10 shows similar predictions for the multiflue stack, but a significant change in the predictions for the current stacks. This was, however, expected given that the existing stacks are not coincident as had been assumed for the purposes of making a preliminary comparison in the earlier CFX-4 work (see previous discussion). The key outcome is that the CFX-5 results, which are considered more accurate, still show a significant reduction in ground-level odour with the multiflue stack (57% at 2 km). The predicted odour levels and potential reductions are also in good qualitative agreement with predictions made for the calciner stacks using the TAPM dispersion model under similar atmospheric conditions (TAPM predictions for 12-13 August 2001 show a reduction in 3-minute 99.9 percentile values from 3.3 to 1.1 OU/m^3 (67%) at 2 km using a 100 m multiflue stack) (Sinclair Knight Merz, 2002). This level of agreement exceeded the initial expectations for the modelling.

A further important aspect of the CFD results is that the contour plots (figure 17) helped to allay concerns that the taller stacks might spread the odour over a wider area or that the plume would touch down to ground at high concentrations at greater distances from the refinery. Figure 19 clearly shows that the zone of high odour (>4 OU/m^3) reduces in size and extends less distance away from the stacks due to greater dilution in the multiflue case. As such, contour plots such as these were at times used in discussions with community groups to explain the multiflue concept.

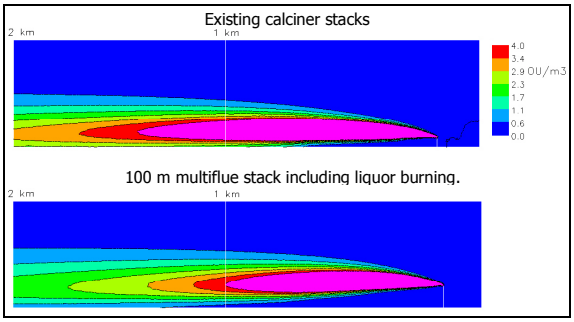

Figure 17: Odour contours for current and multiflue stacks to 2 km (CFX-5 models).

The CFD and TAPM results provided a significant level of confidence for Alcoa to proceed with construction of the multiflue stack. Further confidence was provided by results obtained using the CALPUFF dispersion model, which was used by Sinclair Knight Merz to examine the effect of all of the proposed odour reduction projects (including the multiflue stack project) on the odour signature from the total refinery over a full year of operation (Sinclair Knight Merz, 2002). Predicted odour contours from the CALPUFF modelling are shown in figures 18 and 19 below.

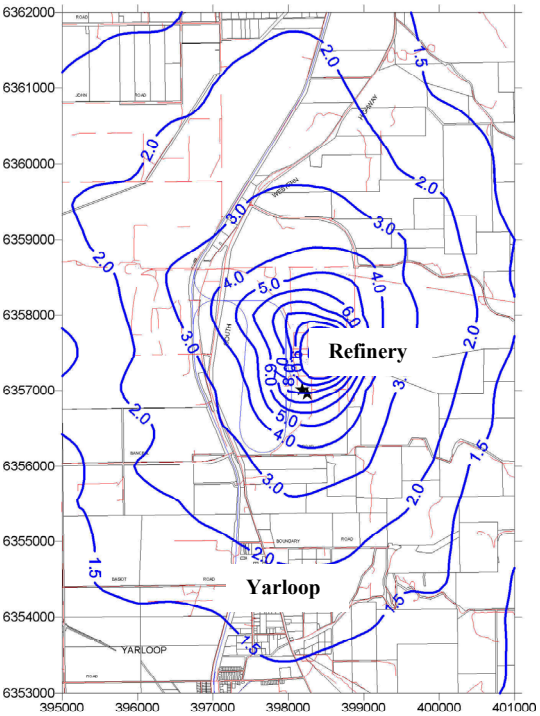

Figure 18: Predicted 3-minute, 99.5 percentile ground-level odour values before implementation of 2002 projects

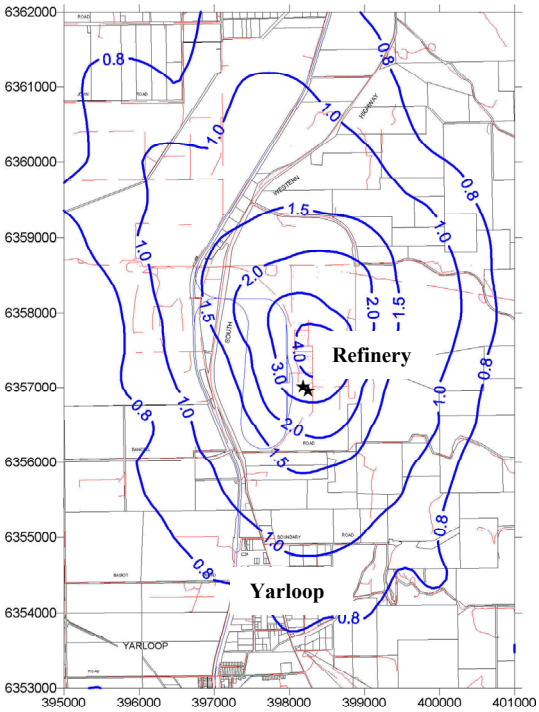

Figure 19: Predicted 3-minute, 99.5 percentile ground-level odour values after implementation of 2002 projects

Project implementation

Based on preliminary results from the CFD and dispersion modelling, detailed design for the multiflue stack commenced in February 2002. By this point a deadline of 30 June 2002 for the implementation of the planned emission reduction projects had been set by the government. This required the coordination of an innovative and parallel design, fabrication and installation effort. For example, CFD modelling to finalise the exact multiflue design was still being conducted in March only days before the fabrication contract was let. The multiflue stack was ultimately completed on time and within budget on 26th June 2002. Other major emissions reduction projects, such as non-condensable gas destruction in the powerhouse boilers, were also completed on target prior to the June 30th deadline.

Figure 20: Multiflue stack at Wagerup refinery.

Since the implementation of these projects in June 2002 there has been a dramatic decline in total community complaints and complaints from the local Yarloop

community (located south of the refinery) during northerly winds (figure 21) (Alcoa of Australia, 2003). Wagerup is now widely regarded as a benchmark refinery with regard to emissions and further emissions reductions activities are still being pursued.

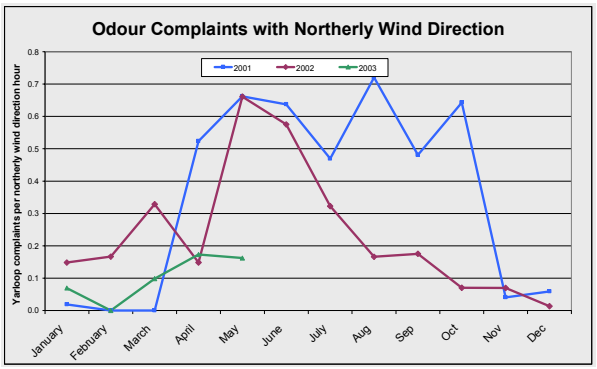

Figure 21: Odour complaints history

CONCLUSION

CFD modelling of odour dispersion and plume visibility for calciner stacks at Alcoa's Wagerup alumina refinery has been undertaken to compliment traditional atmospheric dispersion modelling as an integral part of a major program to reduce refinery emissions.

A CFD model based upon the commercial code CFX-4 has been developed which is able to predict the formation of a "condensation cloud" immediately downstream of the discharge from the moisture-laden calciner stacks. Results obtained with the model have shown that the formation of this cloud does not have any significant impact on ground-level odour. The results have also shown that the formation of the cloud cannot be prevented through the addition of practical levels of ambient air to the stacks prior to release, thus preventing the expenditure of further engineering effort on a concept which would not have been successful.

A further fully 3-D model developed using the CFX-5 code has been used to optimise the design of a proposed 100 m multiflue calcination stack and to compare odour dispersion to the existing stacks. The results obtained were in good qualitative agreement with results obtained using traditional atmospheric dispersion models and showed the potential to significantly reduce ground-level odour through the construction of the multiflue stack. Subsequent construction of the multiflue stack at Wagerup refinery, and the implementation of other emission reduction projects, has seen a significant reduction in community complaints related to odour.

These results demonstrate how CFD techniques and traditional dispersion modelling can be used in a complimentary fashion to develop engineering solutions to reduce the impact of emissions from an industrial plant.

ACKNOWLEDGEMENTS

The authors would like to acknowledge B. Maley, P. Coffey and S. Cox at Alcoa for their input to, and ongoing review of, the modelling described in this paper. The authors would also like to acknowledge Dr O. Pitts at Sinclair Knight Merz who primarily undertook the odour dispersion modelling using Ausplume, TAPM and CALPUFF.

REFERENCES

ALCOA OF AUSTRALIA, (2003), "Wagerup emissions reduction program", Institution of Engineers Australia Engineering Excellence Awards submission, June.

ANSYS CFX, (2003), See www.ansys.com/cfx.

CLARKE, A.G. and SHAW, C.L., (1993), "Evaluation of plume visibility", *Trans. IChemE, Part B*, 71, 203-207.

COX, S., (2002), "Odour emission reduction case study at Alcoa's Wagerup Alumina Refinery", *Proc. Alumina Quality Workshop*, Brisbane, Australia, September 8-13.

D'ABRETON, P., (2003), "Modelling best practice guidance for the Australian alumina industry", Report prepared for the Alumina industry air emissions forum, August 28.

FISHER, B.E.A., (1997), "Predicting cooling tower plume dispersion", *Trans. IMechE, Part A, Journal of Power and Energy*, **211**, 291-297.

FLETCHER, D.F., (2002), "Comments on the TAPM Air Pollution Model and its Relationship to CFD Modelling", Memo prepared for Alcoa, November 17.

GANGOITI, G. et al. (1997), "Rise of moist plumes from tall stacks in turbulent and stratified atmospheres", *Atmosphere and Environment*, **31**, 253-269.

HURLEY, P., (2002), "The air pollution model (TAPM) version 2. Part 1, Technical description", CSIRO Atmospheric Research Technical Paper No.55.

JANICKE, U. and JANICKE, L., (2000), "A three-dimensional plume rise model for dry and wet plumes", *Atmosphere and Environment*, **35**, 877-890.

SINCLAIR KNIGHT MERZ, (2002), "Wagerup Refinery Odour Assessment", Final consultant's report to Alcoa, February.