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THE APPLICATION OF AN AEROFOIL ARRAY TO ENHANCE THE DISPERSION OF AN EXTENDED SURFACE-BASED POLLUTION SOURCE

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Abstract: An aerofoil generates lift by transferring vertical momentum to the unperturbed flow. For an aerofoil of finite width, this effect is conventionally described through the generation of a pair of counter-rotating trailing vortices. In this paper we model the behaviour of the swarm of vortices generated by an array of surface-mounted aerofoils and its effect on the distribution of a passive tracer released upwind of the array. As a test bed for the calculation, we use the notional trail of an exhaust plume emitted by an aircraft in its take-off roll at Heathrow. It is shown that large parts of this surface-based emission are then usefully lifted and dispersed – some elements of the plume are lifted by ten's of m by the distance of the perimeter fence. Surface concentrations immediately offsite can thus be significantly reduced.

Such an array might be of value in abating the impact of any distributed surface source of pollution – a road, runway or, indeed, landfill site – or perhaps in suppressing ground frosts.

Key words: *Local air quality, mitigation, dispersion, surface sources, airport, Heathrow***.**

INTRODUCTION

Conventionally, gaseous pollutants are released to the atmosphere though tall chimneys. For an effective emission height, *H*, peak ground-level concentrations are then reduced by a factor of $\sim H^{2}$, while long-term means may be reduced by a factor of $\sim H^{3}$. Not all emissions, however, can be so mitigated. A tall stack is clearly impossible for a motor vehicle, or for an aircraft in its take-off run. Nevertheless, we have demonstrated in a recent paper (Bennett *et al.* 2013) how aircraft emissions at the start of the take-off run can be mitigated through the installation of an array of aerodynamic baffles behind the start point. Through a combination of lift and drag, such baffles can break the Coanda effect holding the exhaust jet to the ground; add vertical momentum directly to the jet; and, by reducing its horizontal momentum, reduce the scale time before buoyancy-generated vertical momentum exceeds its initial horizontal momentum. In effect, the array serves as a 'virtual chimney'.

Such an intervention, however, is only effective against the initial blast of effluent gases as the aircraft starts to roll (albeit that these will deliver the highest ground-level concentrations). As the aircraft accelerates down the runway, it leaves a trail of pollutant gases behind it; this will typically be advected laterally by the ambient wind, giving rise to intermittently high concentrations at the boundary fence and beyond (Carslaw 2008). It is not feasible to mitigate the local impact of this trail using baffles: if we lift it bodily, where is the clean air to come from to replace it at the surface? We could enhance the vertical dispersion of the pollution by installing an array of baffles to the side of the runway; but these would have to be quite tall to ensure that their wakes should have grown to a substantial height by the time the flow reached the boundary fence. By implication, they would also have to be of robust construction, and the turbulence they generated would present a hazard to aircraft when the ambient wind blew from fence to runway. Safety is paramount in the aviation industry, so such an array is not a practical proposition.

We propose instead an array of near-horizontal circular aerofoils installed at some distance to the side of the runway at a height equal to the median height of the trailing exhaust (Figure 1). By tilting the aerofoils in the direction of the prevailing wind, they will generate lift, with pairs of trailing vortices extending downstream. Our modelling shows that these break up the trailing exhaust between segments which are advected upwards by the strong updrafts above aerofoils and segments which remain close to the ground in the weak downdrafts between aerofoils. Since the exhaust is initially ground-based, the net effect is to greatly enhance vertical dispersion, thereby mitigating long-term surface concentrations at the perimeter.

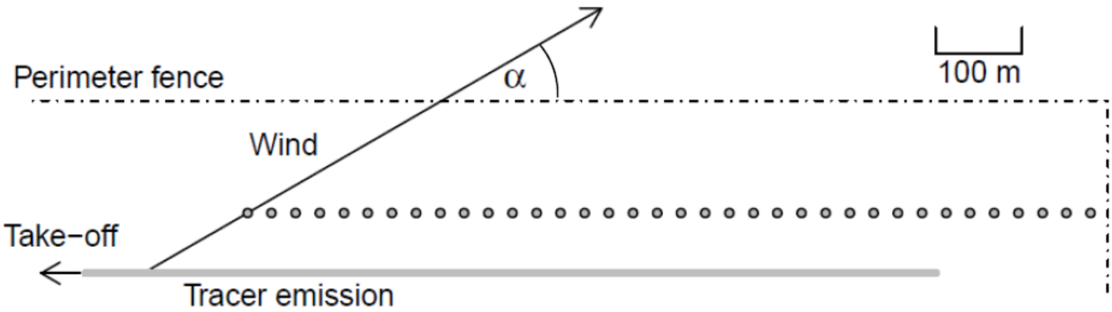

Figure 1. Schematic arrangement of possible arrangement of aerodynamic plates in relation to the take-off roll of an aircraft. For illustration, the plates are of diameter 10 m and spacing 28 m; the line of plates is at 70 m from the runway and the perimeter fence at 200 m.

THEORY

The lift generated by a long two-dimensional aerofoil is given by

$$F_L = \tfrac{1}{2}\, C_L\, \rho\, A u^2 \quad , \tag{1}$$

where A is the wing area, ρ the density of the air and u the air speed. A potential flow calculation for a flat plate shows that the lift coefficient, $C_L = 2\pi\alpha$ for a small angle of attack, α. The flow stalls for angles of attack greater than ~10^o, and it transpires that the maximum lift coefficient of $C_L \approx 0.88$ occurs for $\alpha \approx 9^o$ (Fage and Johansen 1927). It is this lift coefficient which we will use in subsequent calculations, although we note that with a properly designed aerofoil a lift coefficient of >1.5 would be possible.

In practice, no aerofoil is infinitely long and some lift is lost through induced drag at the ends of the wing. This loss is minimized for an elliptical aerofoil, which has unit efficiency. In this case, the lift is given by

$$F_{Le} = (\pi/8)\, C_L\, \rho\, W B u^2 \quad , \tag{2}$$

where W is the cross-flow width of the aerofoil and B is its chord length. Trailing vortices of circulation $\pm\,\Gamma$, defined as

$$\Gamma = 2\pi\, r\, u_t \quad , \tag{3}$$

where u_t is the tangential velocity at a radius r from the vortex core, are released from the two ends of the aerofoil. In an inviscid fluid, this circulation is conserved as the air is advected downwind. According to Zhukovski's circulation theorem, we then have

$$F_{Le} = \rho\, \Gamma\, W u \quad . \tag{4}$$

From equations (2) and (4) we have

$$\Gamma = (\pi/8)\, C_L\, B\, u \tag{5}$$

and hence from equations (3) and (5)

$$u_t = {}^{1}/_{16}\, C_L\, B\, u/r \quad . \tag{6}$$

We can use equation (6) to model the advection of a passive tracer downwind. Taking coordinates x,y,z as being respectively downwind, cross-wind and vertical distances relative to the vortex core, so that $r^2 = y^2 + z^2$, we have

$$\Delta y\, /\Delta x = {}^{1}/_{16}\, C_L\, B\, z/r^2 \quad , \tag{7}$$

and

$$\Delta z\, /\Delta x = -\, {}^{1}/_{16}\, C_L\, B\, y/r^2 \quad . \tag{8}$$

It should thus be straightforward to step downstream in increments of some small value for Δx in order to follow the trajectories of tracer particles in the circulation of all the vortices and of each vortex core in the circulation of all the others. We see that the effect of the aerofoils on the downstream flow is purely geometric. The wind speed does not enter.

Three points should be noted. Firstly, since we envisage aerofoils mounted at a modest height, H from the ground, the interaction of their trailing vortices with the surface must be taken into account. This is most simply effected by adding equal and opposite vortices as image terms beneath the ground surface. In the y-z plane, the flow downstream from a given aerofoil would thus be modelled using four vortices: two with circulation Γ from starting points ($W/2$, H) and ($-W/2$, $-H$), and two with circulation $-\Gamma$ from starting points ($-W/2$, H) and ($W/2$, $-H$). Secondly, it is evident that the tangential velocity would become unphysically large as $r \rightarrow 0$. Somewhat arbitrarily, we have therefore treated the vortex cores as rigid rotating cylinders for $r < 6$ cm. Finally, with multiple interacting vortices and given moderate advection distances, the flow becomes chaotic. Great care is thus required with the numerics if physically realistic solutions are to be achieved; it is a cause for suspicion if tracer is advected to beneath the ground! All calculations were carried out in 8-byte precision, with consistent precision being retained by adding increments in rank order at each step, the smallest being summed first.

SIMULATIONS

Figure 1 gives a schematic representation of how an array of aerofoils might be distributed along a runway, loosely based on the North runway at London Heathrow. It is assumed that aircraft take off westwards into a headwind making an angle α to the runway.

From equations (7) and (8), we want B to be as large as possible. We also want to fit in as many aerofoils as possible, so W should be small. Pragmatically, therefore, we chose $W = B = 10$ m as the basis for our calculations. The 'aerofoils' were thus simple circular plates inclined towards the SW at 9^o to the horizontal, having an inter-centre spacing of 28 m: this was a compromise between maximizing the number of plates and having them far enough apart so that their trailing vortices would not interfere with one another. If this happens, the flow becomes chaotic; the detailed results are then extremely sensitive to the driving parameters, but in general terms it could be seen that, although occasionally the tracer might be lifted to a substantial height (> 30 m), more commonly it was stirred rather than lifted.

The heights of the plate centres were set at $H = 2.5$ m since, to be effective, they must be installed at a height above ground comparable to the height of the pollution source: they have little effect on the flow at greater heights. As discussed in Bennett *et al.* (2013), the initial exhaust jet from an airliner is relatively shallow, being held to the surface by the Coanda effect. As the take-off roll proceeds, the aerodynamics of flow around the airframe start to affect the dispersion of the exhaust (Bennett *et al.* 2010), again forcing the emissions towards the surface but creating a deeper head where the outward exhaust flow meets the undisturbed air. We will not attempt to model these complications here but will simply treat the exhaust plume as a passive trail of tracer uniformly distributed from the ground up to a height of 5 m. This will then be advected downwind across the rows of aerodynamic plates and towards the perimeter. Pragmatically, also, we note that the wingspan of the largest airliner currently in service is 80 m; we have therefore placed the first line of plates at 70 m from the runway centreline (the closer the better).

Figure 2, then, illustrates the dispersion of this tracer at the distance of the boundary fence for a wind direction of $\alpha = 45^o$. The tracer is here represented as coloured points starting at heights of 0.5, 1.5, 2.5, 3.5 and 4.5 m and spaced at 1 m intervals along the runway centreline. For the sake of clarity, we have continued the initial tracer emission to 50 m beyond the upwind point of the westernmost plate. The tracer distribution beyond the influence of the plates is thus clear. We see that the plates have split the tracer between a shallow layer close to the ground and a diffuse layer between heights of 5 m and 21 m.

Note that we have assumed in these calculations that the plates are tilted precisely in the direction of the ambient wind. For such a crude aerofoil as a circular tilted plate, this is probably not a critical assumption. Since the tilt of 9^o is close to that giving the maximum lift, the lift imposed on a modestly off-axis wind is unlikely to be significantly different.

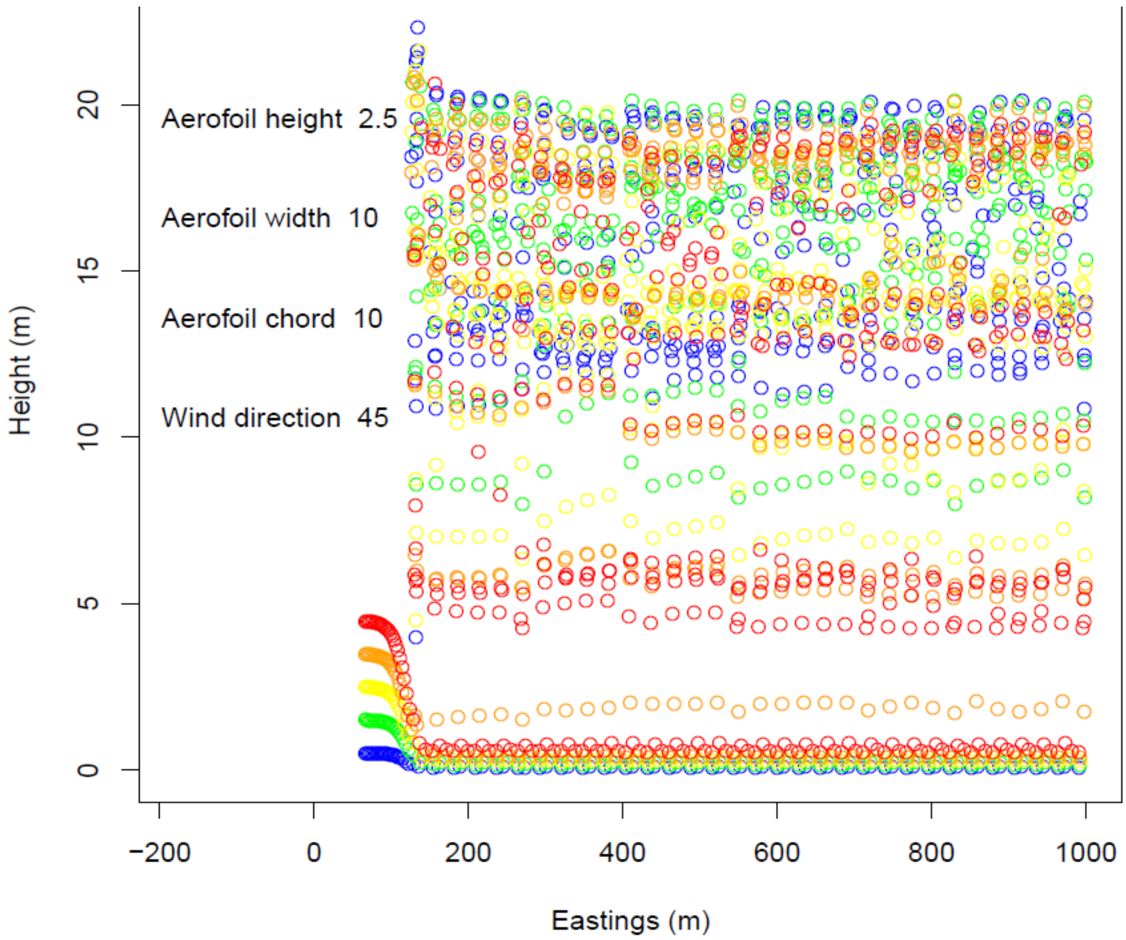

Figure 2. Height of tracer points as they advect across the boundary fence at Northings = 130 m. Eastings are relative to the first plate. Plate spacing is 28 m and α = 45°.

EFFECT ON SURFACE CONCENTRATIONS

Lifting the effective height of the source is clearly helpful; some modelling is required, however, to indicate whether the reduction in surface concentrations might be practically useful.

Conventionally, the surface concentration beneath a plume may be deemed to be proportional to the Gaussian expression

$$\frac{1}{\Delta z} = \sqrt{\frac{2}{\pi}}\ \frac{1}{\sigma_z}\ \exp\left\{-\frac{1}{2}\ \frac{h^2}{{\sigma_z}^2}\right\}, \tag{9}$$

where h is the plume centreline height and σ_z its vertical standard deviation. Carslaw *et al.*'s results for Heathrow imply that $\Delta z \approx 95$ m close to the airfield perimeter. (This is of course a mean value over many different meteorological conditions; for small α, the fetch – and hence Δz – is greater.) It follows that

$$\frac{1}{\chi}\ \frac{\partial \chi}{\partial h} = \frac{\partial}{\partial h}\ln(\chi) = -\ \frac{1}{\sigma_z}\ \frac{h}{\sigma_z} = -\ \frac{1}{\sigma_z}\ \sqrt{2\ln\frac{2\ \Delta z}{\pi\ \sigma_z}}. \tag{10}$$

We can thus readily calculate the percentage decrease in surface concentration at the Heathrow perimeter for each 1 m increase in plume centreline height as a function of the vertical plume standard deviation. Over the relevant wind directions, Carslaw *et al.*'s monitor was downwind of the terminal buildings. Light winds were of marginal relevance since the longer travel time then permitted the emissions to rise buoyantly (Department for Transport, 2005). We may therefore take the dispersion conditions as being urban and category D. For $\alpha = 45^o$, we have a fetch of 282 m to the perimeter. Using then the formulae for Pasquill-Gifford plume spreads recommended by Griffiths (1994), we see that $\sigma_z \approx 38$ m and $(\partial\chi/\partial h)/\chi \approx -2.5\%$ m^{-1}. For a mean vertical plume displacement of 9.5 m (Figure 2), this implies a reduction in ground-level concentrations at the perimeter by 24%. More would be delivered by a better aerofoil.

The commonest wind direction sector at Heathrow is that for $\alpha = 60^o$, followed by that for $\alpha = 30^o$ (Meteorological Office 2014). In fact, the percentage mitigation should be relatively insensitive to α between these values. Considering equation 10, we may take it that h/σ_z depends only weakly on fetch. For small α, meanwhile, the fetch to the perimeter is greater, so both σ_z and the uplift from the plates should be greater, largely cancelling out any variation in their ratio. The mitigation is enhanced for small α by the reduced cross-wind separation between plates, but this effect collapses when the separation is small enough for the trailing vortices to overlap. (In this case, this occurs for $\alpha < 24^o$).

DISCUSSION

Our simple modelling has suggested that a relatively crude intervention should be capable of reducing immediately off-site concentrations near a runway by up to 25%. Clearly, more sophisticated modelling (CFD plus wind tunnel modelling) would be required before any such system could be installed at a commercial airport. Significant technical issues that we have scarcely touched on in this paper are the disruption to the trailing vortices engendered by ambient turbulence within the airfield boundary layer and the initial dispersion engendered by flow around the airframe.

Before a full-scale trial could be carried out, there would be serious issues – besides cost – of regulation and safety which would have to be addressed; the authorities would also be interested in the possible impact of such an installation on the propagation of aircraft engine noise off-site.

We have set up this modelling within the context of assisting the dispersion of the surface emissions of an aircraft on take-off. The principle, however, is equally applicable to any distributed surface source of pollution, e.g. a landfill or a motorway. The intervention would indeed be much more effective at a rural site than at Heathrow since the unperturbed vertical dispersion rates would be much smaller. An interesting possible application would be for the dispersion of radiation frosts at night – these are an important cause of agricultural losses.

REFERENCES

Bennett, M, S. Christie, A. Graham and D. Raper, 2010: Lidar observations of aircraft exhaust plumes. *J. Atmospheric and Oceanic Technology,* **10,** 1638-1651. DOI: 10.1175/2010JTECHA1412.1.

Bennett, M, S.M. Christie, A. Graham, K.P. Garry, S. Velikov, D.I. Poll, M.G. Smith, M.I. Mead, O.A.M. Popoola, G. Stewart and R.L. Jones, 2013: Abatement of an aircraft exhaust plume using aerodynamic baffles. *Environ. Sci & Technol.* **47,** 2346–2352. DOI: 10.1021/es303586x.

Carslaw, D.C, K. Ropkins, D. Laxen, S. Moorcroft, B. Marner and M.L. Williams, 2008: Near-field commercial aircraft contribution to nitrogen oxides by engine, aircraft type, and airline by individual plume sampling. *Environ. Sci. & Technol.,* **42,** 1871–1876.

Department for Transport, 2006: Project for the Sustainable Development of Heathrow, Chapter 2. Dept. for Transport, London SW1P 4DR, UK.

Fage, A. and F.C. Johansen, 1927: On the flow of air behind an inclined flat plate of infinite span. *Proc. Roy. Soc. Lond. A,* **116,** 170-197.

Griffiths, R.F, 1994: Errors in the use of the Briggs parameterization for atmospheric dispersion coefficients. *Atmos. Environ.,* **28**, 2861-2865.

Meteorological Office, 2014: Southern England: Climate. http://www.metoffice.gov.uk/climate/uk/so/print.html (Accessed 11 June 2014).