

# Deposition of Charged Powder Particles

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## 1 Introduction

The problems brought to the Study Group by Courtaulds Coatings concern the electrostatic deposition of powder paints onto an earthed metal workpiece. The process involves charging the paint particles as they pass through a 'gun'; they then travel towards the workpiece under the influence of aerodynamic and electrostatic forces. At present two types of gun are used, these are:

- the Corona gun in which particles are forced past a high voltage electrode which ionises the surrounding air and hence particles are charged by collecting ions (Paulthier Charging).
- the Tribo gun in which particles are charged in an earthed gun directly by friction.

The main differences between these two types of gun are:

- when using a corona gun the electric field is set up not only by the space-charge but also by the applied potential difference between the gun and workpiece.
- free ions constitute 99% of the charge in a corona system, whilst no free ions are present when using a tribo gun.

As the corona gun involves many more complicated physical processes, it is the tribo gun, with a single species of particle, which is considered in this report.

The main questions asked by Courtaulds were

- What factors affect deposition efficiency?
- How is deposition efficiency maximised?

The following report is organised into three main sections. Firstly, a tribo gun model is presented and non-dimensionalised, revealing that electrostatic and aerodynamic forces are in balance, whilst particle inertia and gravity may be neglected for the system in question. Then, a one-dimensional model is considered which gives vital information about the orders of magnitude of relevant quantities at the workpiece and the effect of charge saturation. Finally, a model is proposed for a narrow 'jet' of particles impinging on an earthed workpiece and it is shown that geometry is by far the most important factor affecting deposition efficiency.

## 2 A Tribo Gun Model

The motion of paint particles through the air, between the gun and workpiece, is now considered. The forces acting on the particles are the electric forces, the Stokes drag and gravity. It is assumed that the particles are small and spherical with mass  $m$ , radius  $a$  and charge  $q$ . Further, it is assumed that a continuum approach can be used to describe a dilute cloud of particles (although a particle model was also considered during the study group). A simple force balance then gives

$$m \frac{d\mathbf{v}}{dt} = -k(\mathbf{v} - \mathbf{v}_g) + q\mathbf{E} + m\mathbf{g},$$

where  $\mathbf{v}$  is velocity of the powder cloud,  $\mathbf{v}_g$  is the carrier gas velocity,  $t$  is time,  $q$  is the charge of a single particle,  $\mathbf{E}$  is the electric field and  $\mathbf{g}$  is the gravitational field. On the basis of the data given in Section (2.1) the appropriate Reynolds number for a particle is less than 1, thus justifying the use of the Stokes drag assumption  $k = 6\pi\eta_g a$ , where  $\eta_g$  is the dynamic viscosity of the carrier gas. It is also required that the number of particles is conserved and so the mass equation is

$$\frac{\partial n}{\partial t} + \nabla \cdot (n\mathbf{v}) = 0, \quad (1)$$

where  $n$  is the particle concentration. The Poisson equation for the electric field which is generated by the space-charge gives

$$\nabla \cdot (\epsilon_0 \mathbf{E}) = qn, \quad (2)$$

where  $\epsilon_0$  is the permittivity of air. The magnetic field may be neglected, and Maxwell's equations imply that there exists a potential  $\phi$  such that

$$\mathbf{E} = -\nabla\phi.$$

Finally, Euler's equations for the inviscid (the Reynolds number based on the workpiece is lengthscale is  $10^5$ ), incompressible air flow are

$$\begin{aligned} \rho \frac{d\mathbf{v}_g}{dt} &= -\nabla p + nk(\mathbf{v} - \mathbf{v}_g) + \rho\mathbf{g}, \\ \nabla \cdot \mathbf{v}_g &= 0, \end{aligned}$$

where  $\rho$  is the air density. These equations are to be solved in a region of size  $L_0$  in which the particles have an observed velocity of  $O(v_0)$  and residence time  $O(t_0)$ .

### 2.1 Scalings and Nondimensionalisation

The following data is used to nondimensionalise the above model,

$$\begin{aligned} a &\sim 10^{-5}m, \quad m \sim 10^{-12}kg, \quad q \sim 10^{-15}C, \quad k \sim 10^{-9}kgs^{-1}, \\ \rho &\sim 1kgm^{-3}, \quad g \sim 10ms^{-2}, \quad \epsilon_0 \sim 10^{-11}As(Vm)^{-1}, \\ |\mathbf{x}| &\sim L_0 \sim 1m, \quad t \sim t_0 \sim 1s, \quad |\mathbf{v}| \sim v_0 \sim 1ms^{-1}, \quad |\mathbf{v}_g| \sim v_0, \\ n &\sim n_0 \sim 10^9m^{-3}, \quad |\mathbf{E}| \sim qn_0L_0/\epsilon_0 \sim 10^5Vm^{-1}, \quad \phi \sim qn_0L_0^2/\epsilon_0 \sim 10^5V. \end{aligned}$$

The scaling for the electric field is so chosen because it is generated solely by the space-charge as opposed to any applied potential difference. Scaling all quantities with these values gives the following nondimensional model:

$$\begin{aligned} \left(\frac{m}{kt_0}\right)\frac{d\mathbf{v}}{dt} &= -(\mathbf{v} - \mathbf{v}_g) + \left(\frac{q^2 n_0 L_0}{k v_0 \epsilon_0}\right)\mathbf{E} + \left(\frac{m\mathbf{g}}{k v_0}\right), \\ \left(\frac{L_0}{v_0 t_0}\right)\frac{\partial n}{\partial t} + \nabla \cdot (n\mathbf{v}) &= 0, \\ \nabla \cdot \mathbf{E} &= n, \\ \frac{d\mathbf{v}_g}{dt} &= -\nabla p + \left(\frac{k n_0 t_0}{\rho}\right)n(\mathbf{v} - \mathbf{v}_g) + \left(\frac{t_0 \mathbf{g}}{v_0}\right), \\ \nabla \cdot \mathbf{v}_g &= 0, \end{aligned}$$

where the dimensionless constants have the typical values,

$$\begin{aligned} \frac{m}{kt_0} \sim 10^{-3}, \quad B \equiv \frac{q^2 n_0 L_0}{k v_0 \epsilon_0} \sim 1, \quad \frac{m\mathbf{g}}{k v_0} \sim 10^{-2}, \\ A \equiv \frac{L_0}{v_0 t_0} \sim 1, \quad \frac{k n_0 t_0}{\rho} < 1, \quad \frac{t_0 \mathbf{g}}{v_0} \sim 10. \end{aligned}$$

In this expression the constant  $B$  expresses the ratio of electrostatic to aerodynamic forces. Hence, since  $B \sim 1$ , it is clear that these forces are in balance whilst the particle inertia and gravity may be neglected. Also, the momentum imparted to the air by the particles (the so called ion wind, see Cross (1987)) will be neglected to first order. In view of the size of  $k n_0 t_0 / \rho$ , this is not a good approximation, but it does allow for an enormous simplification and provides the first step in a possible iterative procedure. Thus finally, the non-dimensional model becomes, to leading order,

$$\mathbf{v} = \mathbf{v}_g + B\mathbf{E}, \quad (3)$$

$$\begin{aligned} A\frac{\partial n}{\partial t} + \nabla \cdot (n\mathbf{v}) &= 0, \\ \nabla \cdot \mathbf{E} &= n, \end{aligned} \quad (4)$$

where  $\mathbf{v}_g$  ( $|\mathbf{v}_g| \sim 1$ ) is assumed to be known and satisfy  $\nabla \cdot \mathbf{v}_g = 0$ .

## 2.2 Boundary Conditions

The tribo gun and workpiece are both earthed. However, it is important to note also that although the charged particles adhere to the workpiece and ‘shield’ it as the layer builds up, the potential difference across the layer is of the order  $q n_l h^2 / \epsilon_0 \sim 10^3 V$ , where  $n_l \sim 10^{15} m^{-3}$  is the particle concentration in the layer and  $h \sim 10^{-4} m$  is a typical layer thickness. This calculation results from solving Equation (2) in the layer. Hence, it becomes clear that the potential difference across the layer is negligible in comparison to the potential in the powder cloud and so the boundary potential is taken to have the constant value 0.

Another boundary condition is needed in order to close the system. The most natural one is to specify  $n$  at the gun, although there are other equally convincing candidates (such as specifying  $E$  at the gun). However, the dimensionless value of  $n$  is typically of the order  $n \sim 10^3$  near the gun, since every second  $10^{-3}kg$  of particles are passing through the gun nozzle (of cross-sectional area  $10^{-4}m^2$ ) at a velocity  $10ms^{-1}$ . It will be shown in Section (3.1) that, to leading order, we can take this boundary condition as  $n = \infty$  (the saturated limit).

### 3 Preliminaries

#### 3.1 Integration Along Particle Paths

Since the air flow is incompressible (i.e.  $\nabla \cdot \mathbf{v}_g = 0$ ), we have

$$\nabla \cdot \mathbf{v} = B \nabla \cdot \mathbf{E} = Bn.$$

Hence,

$$\mathbf{v} \cdot \nabla n = -n \nabla \cdot \mathbf{v} = -Bn^2, \quad (5)$$

or equivalently,

$$\mathbf{v} \cdot \nabla(1/n) = B.$$

This equation has far-reaching consequences, namely that

1)  $1/n(s) = 1/n(s=0) + B(t - t_0)$  along particle paths,  $s$  being arc length and  $t - t_0$  the time of the particle motion.

2)  $n$  decreases along particle paths.

From 1) we see that as  $n(s=0)$  increases, the value of  $n(s)$  approaches a well defined (saturated) limit which is given when  $n(0) = \infty$ . This is due to the formation of a space-charge cloud close to the gun. For small  $n(0)$  the value of  $n(s)$  (and hence the number of particles close to the workpiece) increases as  $n(0)$  increases. However for larger values of  $n(0)$ , the value of  $n(s)$  saturates and the efficiency of the process is not improved by increasing  $n(0)$ . For the problem considered saturation occurs at about  $n(0) = 0$ .

In particular, the one-dimensional case reduces to

$$v = 1 + BE, \quad (nv)_y = 0, \quad E_y = n,$$

where we recall the dimensional air velocity is taken to be  $v_0$ , the gun is at  $y = 1$  and the workpiece is at  $y = 0$  (see figure 4.1 for the coordinate definition). For the saturated problem appropriate boundary and integral conditions are

$$\int_0^1 E dx = 0, \quad n(y=1) = \infty.$$

This system has the solution

$$\begin{aligned} E &= (-2 + 3\sqrt{1-y})/2B, \\ n &= 3/4B\sqrt{1-y}. \end{aligned} \quad (6)$$

This gives  $n(y=0) = 3/4B$ . This value is used as data in Section (4).

### 3.2 Potential Air Flow

If it is now further assumed that the air flow is also irrotational, so that the air flow has a scalar potential, say  $\mathbf{v}_g = \nabla\Phi$  where  $\Phi$  is known, then by defining  $\Omega = \phi + \Phi$ , the above model results in the familiar space-charge equation for  $\Omega$ ,

$$\nabla \cdot (\nabla\Omega\Delta\Omega) = 0,$$

with boundary conditions which depend on  $\Phi$ . There is an extensive literature concerning the solution of this equation and hence this system can be solved (at least numerically) as long as  $\Phi$  is known (see Budd and Wheeler (1988) (1991) and Hare and Hill (1991)). In particular it would be desirable to analyse a two-dimensional needle plane geometry with a superimposed stagnation air flow.

## 4 Particle Deposition Efficiency

The problem of a two-dimensional inviscid ‘jet’ impinging on an infinite flat plate has been considered by Milne-Thomson (1968, p.291). At the centre of the workpiece the one-dimensional solution (6) can be used to describe the deposition. Hence, in this section the region far from the jet, typically at a distance  $\alpha L_0$  (where  $\alpha \sim 1$ ), where particles flow in a thin layer will be considered (see figures 4.1 and 4.2).

As typical jets have width  $2\delta L_0 \sim 20\text{cm}$  ( $\delta \ll 1$ ), it is clear by mass conservation that the thin layer will have width  $\delta L_0$ . It is assumed that in the thin layer the air velocity is parallel to the workpiece and has constant value  $v_0$  (outside a narrower viscous boundary layer of width  $L_0/Re_{air}^{1/2} \sim 1\text{cm}$ ). If we now scale  $y \sim \delta$  in the layer, then by (4) we must also scale  $E \sim \delta$  (and so  $\phi \sim \delta^2$ ). Hence, Equations (3)–(4) are reduced, to leading order, to

$$\begin{aligned} v &= BE, \quad u = 1, \\ \frac{\partial(nu)}{\partial x} + \frac{\partial(nv)}{\partial y} &= 0, \\ E_y &= n, \end{aligned}$$

where  $E$  is the component of  $\mathbf{E}$  perpendicular to the workpiece and  $\mathbf{v} = (u, v)^T$ . Thus equivalently, we have

$$(E_x + BEE_y)_y = 0.$$

Integration then yields

$$E_x + BEE_y = f(x), \tag{7}$$

where  $f(x)$  is an arbitrary function determined by consideration of the far field behaviour. If we now consider the outer problem in the region above the line  $y = \delta$  in figure 4.2, then continuity of  $\phi$  gives that  $\phi \sim \delta^2$  outside the layer. Hence, by solving  $\Delta\phi = 0$  in the outer region with boundary conditions  $\phi \sim \delta^2$  it becomes

clear that  $E \sim \delta^2$  also. Thus  $E = 0$  is the appropriate matching condition on  $y = 1$ , giving  $f \equiv 0$ . It now becomes apparent that the device is working efficiently as the advection and electric field terms in Equation (7) are in balance. That is, particles spread over the whole of the workpiece.

Now  $E_y = n$ , and hence using Equation (6), on  $y = 0$  in the layer,

$$E_y = n \simeq 3/4B,$$

or equivalently,

$$E = 3(y - 1)/4B. \quad (8)$$

Clearly, this is not the correct boundary data for the problem and strictly we should match with the fully two-dimensional region where the jet hits the workpiece. However, this is not a straightforward problem and will have to be done numerically, when times permits. Thus, using (8), the solution is

$$E = y/B(x + 4/3).$$

Now, efficiency  $\Upsilon$  is defined to be the proportion of particles deposited compared to the number of particles arriving at the centre of the workpiece. That is,

$$\Upsilon = \frac{N(x = 0) - N(x = \alpha)}{N(x = 0)},$$

where  $N(x) = \int_0^1 n(x, y)dy$  is the integrated concentration of particles contained in the section of the layer at  $x$ . However,

$$N(x) = \int_0^1 E_y(x, y)dy = E(x, 0),$$

and so

$$\Upsilon = \frac{H_0}{H_0 + 4L_0/3}. \quad (9)$$

Hence finally, this yields the key result that more particles are deposited if the gun is held closer to the work piece. However deposition efficiency can only be weakly dependent on other factors such as particle size, flow rate etc, as these terms do not even enter into the lowest order formula (9).

## 5 Discussion

### 5.1 Turbulence

In this report, viscous effects have been neglected completely. However, it should be noted that there are two regions in which turbulence plays a major role, namely in the shear layers at the nozzle of the gun and at the edges of the workpiece. In fact, some authors (see Hughes (1984)) claim that turbulence is as important as electrostatic effects for achieving good 'wrap-around' deposition.

## 5.2 Coating Recesses

For a convex geometry, the electrostatic force assists with particle movement and deposition. However, the situation is reversed when coating recesses, as most electric field lines terminate outside the recess (see Figure 5.1) resulting in minimal penetration of particles to the inside surfaces of the workpiece. This is commonly known as the Faraday Cage effect. For this reason, tribo guns are generally more efficient at coating recesses than corona guns, which have a large electric field generated by the potential difference between the gun and workpiece superimposed onto the space-charge field.

It is clear that the only way to coat recesses is to use aerodynamic forces. Once sufficiently far into recesses particles will be attracted to the workpiece by the electrostatic force. As the only possible air flow in a recess (if the particles are not to be blown off the workpiece) is a recirculating cell (see Figure 5.2), this clearly limits the aspect ratio of recesses which can be coated.

## 5.3 Suggestions

The most obvious suggestion to improve deposition efficiency is to hold the gun closer to the workpiece, although clearly there is a point when the jet starts to actually blow the particles off the workpiece. Also, it is pointless feeding so many particles into the system as it does not significantly increase the number of particles at the workpiece but does increase the number of particles in the space-charge cloud. Finally, it is generally felt that charging the booth with the same polarity as the particles would increase deposition efficiency, as particles would remain airborne for longer. However, this would most certainly be detrimental when coating recesses.

## 6 References

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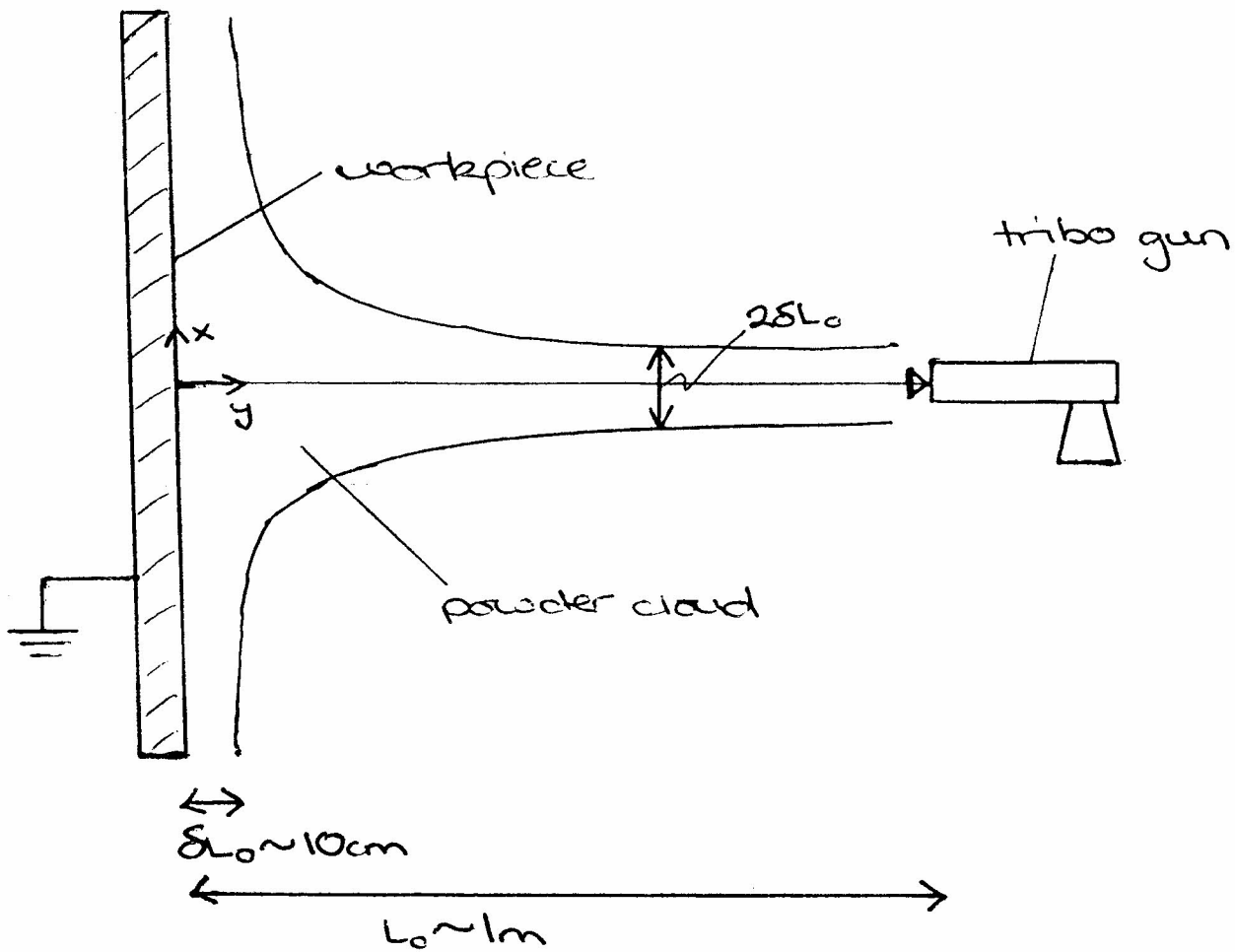


Figure 4.1 : A typical gun-to-workpiece configuration.

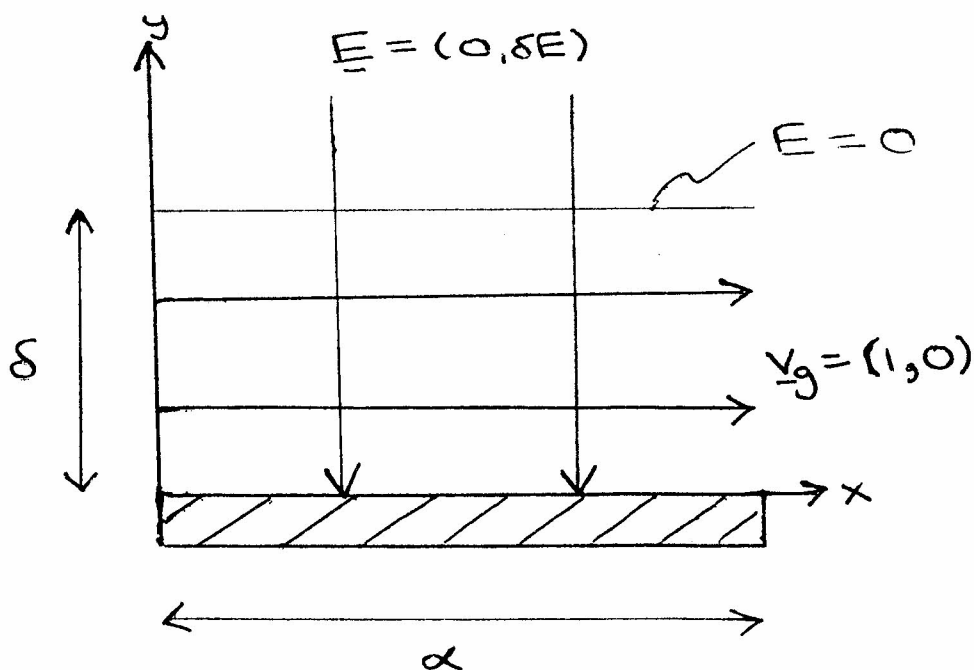


Figure 4.2 : A typical configuration in the thin particle layer

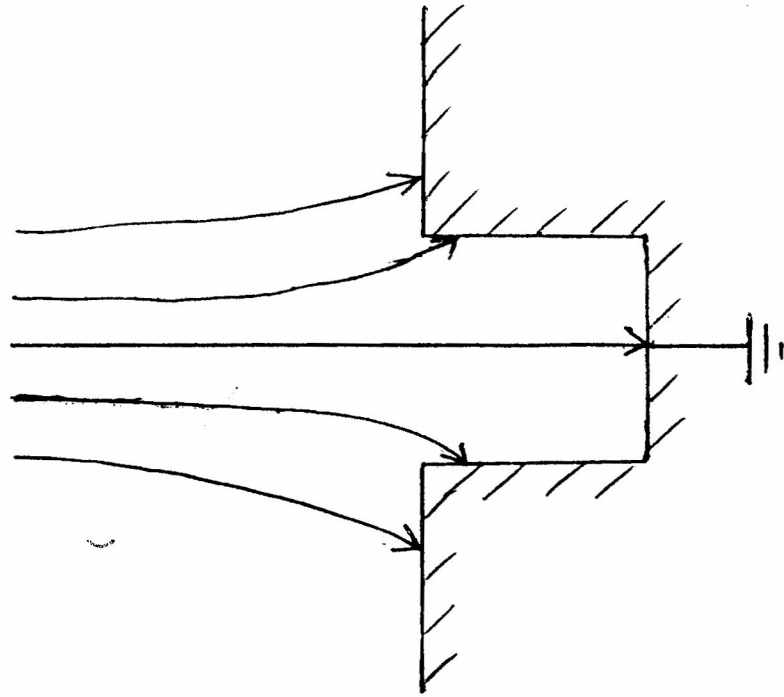


Figure 5.1: Field Lines at a workpiece recess.

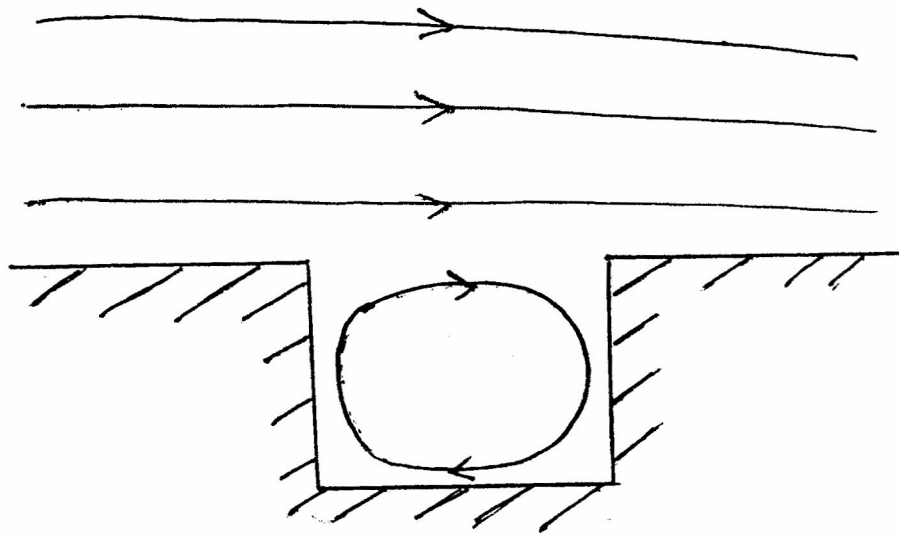


Figure 5.2: Air flow in a recirculating cell.