Design Parameters for Push-Pull Ventilation of Open Surface Tanks

Robinson M, Ingham D B
Department of Applied Mathematics, University of Leeds, Leeds, U.K.

Introduction

Side push-pull ventilation, shown schematically in Figure 1, is often the best option for open surface tanks where overhead access is required; see for example (1). There has been much work on the system in the last 50 years, but little agreement over the important design parameters either in terms of what are the relevant parameters, or what values they should take. In this paper we draw on earlier work by the same authors (2) which showed that the flow field over the majority of the tank surface can be represented by a simple set of formulae which represent a wall jet to devise recommendations for the design parameters for the push-pull system. This hypothetical wall jet gives a flow pattern which is approximately similar to the real offset jet case providing it has initial momentum j_i and nozzle height b_i which are related to the offset jet's momentum and nozzle height, j_i and b_i, as given in Figure 2.

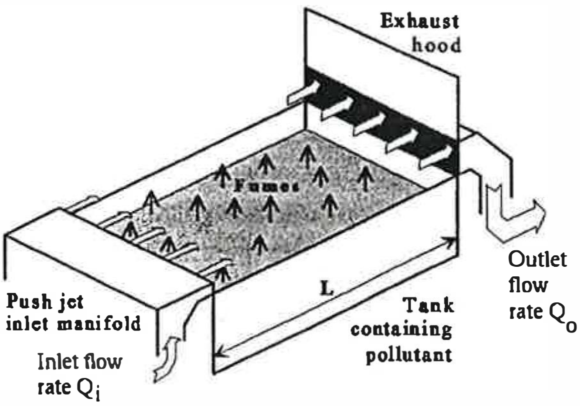

Figure 1. Side push-pull ventilation

The Wall Jet

The most straightforward representation of a wall jet is given by a combination of (3) and (4), which together show that the wall jet can be represented by

$$\frac{u}{u_m} = U(\eta) = B_1 \eta^d \operatorname{erfc}(B_2 \eta),$$

$$b = \frac{\bar{x}}{\sigma} = \frac{x+\varepsilon}{\sigma}, \qquad u_m = x^{-c} \varphi \sqrt{j_i/\rho} \quad (1)$$

where u is the horizontal component of the fluid velocity, b is the jet width, defined to be the perpendicular distance from the surface of the tank to the point where the velocity is half the local maximum, u_m, and the velocity is decreasing with increasing distance, j_i is the initial kinematic momentum

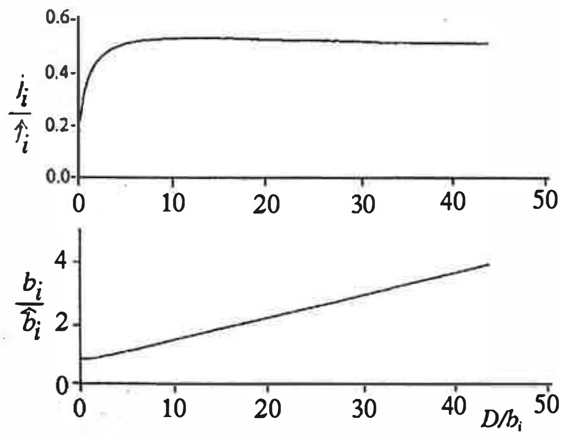

Figure 2. The variation of j_i/j_i and b_i/b_i as a function of D/b_i

of the jet per unit width of tank, ρ is the fluid density, x is the horizontal distance from the jet nozzle and $\bar{x}$ is the horizontal distance from a hypothetical jet origin, and the similarity variable η is given by $\eta = y/b$ where y is the perpendicular distance from the tank surface. The other symbols, B_1, B_2, σ, φ, ε, m, c and d are empirical constants which take can take the 'Original' or 'Modified' values given in table 1. Together with these values, we refer to equations (1) as the Original or Modified Verhoff formulae.

Table 1. The values of the constants in the Verhoff formulae.

Constant	Original Verhoff	Modified Verhoff
B_1	1.48	1.28
B_2	0.68	0.61
σ	13.7	9.68
φ	3.98	3.86
ε	$10b_i$	0
M	1	1
c	½	0.509
D	1/7	1/13

It is worth noting here that the only parameter within the control of the designer in equations (1) is the initial momentum of the jet, j_i. The same is true of the equations which can be derived for the free jet. This suggests that it is the initial momentum which determines the nature of the fluid flow, and hence the effectiveness of the ventilation system, rather than the flow rate, fluid velocity or jet nozzle height directly.

The Movement of Pollutant

Having established that the fluid flow patterns can be reasonably modelled using just the effects of a wall jet, we look to solve the concentration equation based on the usual assumption that the diffusion coefficient Γ can be approximated by $\Gamma = \mu_e / 0.7$. By examining both analytical and numerical results for the wall jet we have found that the effective kinematic viscosity can be given by

$$\nu_e = -\frac{\phi^* c}{\sigma^2} x^n h(\eta) \quad \text{where } h = \begin{cases} E\eta^{1-d}\left(1-(\eta/\eta_0)\right) & 0 \le \eta < (\eta_0 - \delta) \\ E(\eta_0 - \delta)^{1-d}\left(1-((\eta_0-\delta)/\eta_0)\right) & \eta \ge (\eta_0 - \delta) \end{cases} \tag{2}$$

where $\phi^* = \sqrt{j_i/\rho}$ and E, η_0 and δ are constants whose values can be readily determined but the derivation of which we shall not detail here.

We are now in a position to solve the concentration equation, which can be simplified in the same manner as the Navier-Stokes equations, to derive a boundary-layer approximation, namely

$$u\frac{\partial C}{\partial x} + v\frac{\partial C}{\partial y} = \frac{\partial}{\partial y}\left(\frac{\Gamma}{\rho}\frac{\partial C}{\partial y}\right) \tag{3}$$

where C is the mass fraction of the pollutant. By writing $\hat{U} = f'(\eta)$ and using equation (2) to determine the diffusion coefficient, we can reduce equation (3) to the ordinary differential equation $C'' = [0.7(1-c)f/c - h]C'/h$ where prime denotes differentiation with respect to η. The boundary conditions are to let the concentration be unity on the tank surface and zero far from the tank surface. Along with the boundary-layer approximation to the Navier-Stokes equations, we now have a fifth order system which can be solved using a standard NAG library routine and the results for the concentration are shown in Figure 3, along with numerical results obtained from the CFD package FLUENT, and there is reasonable agreement between the two.

The above approach works well for a neutrally buoyant pollutant. In the case of a buoyant pollutant, we assume that the governing equation becomes

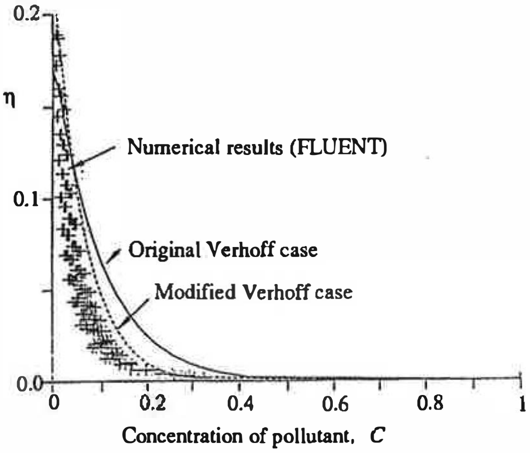

Figure 3. Concentration as a function of η.

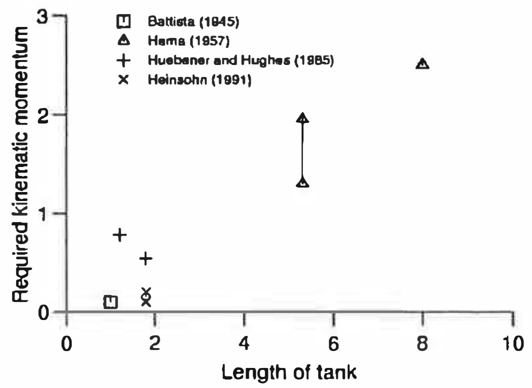

Figure 4. Required kinematic momentum as a function of tank length

$$u\frac{\partial C}{\partial x}+\left(v+v_g\right)\frac{\partial C}{\partial y}=\frac{\partial}{\partial y}\left(\frac{\Gamma}{\rho}\frac{\partial C}{\partial y}\right) \tag{4}$$

where v_g is an empirical velocity related to the buoyancy of the pollutant in air. We further assume that the overall fluid flow pattern is unaffected by the minor quantity of the buoyant pollutant. On substituting for u, v and Γ in equation (4), the resulting PDE is solved numerically to find the concentration at any position.

Recommendations for the Design of Push-Pull Systems

Capture Velocity Criterion

Guidelines from the ACGIH (5) give a minimum 'capture velocity', V_{cap}, which must be induced to move a pollutant towards an exhaust. The value depends on the industrial process and the local conditions and ranges from 0.25 to 1.02 ms^{-1} for open surface tanks. In the wall jet model, the maximum velocity in the plane x constant is given by $u_m = \varphi x^{-c}\sqrt{j_i/\rho}$, where c is approximately one half, so we know the lowest value will be at $x = L$ and therefore we require $j_i/\rho \geq \left(V_{cap}/\varphi\right)L^{2c}$. This gives the required minimum value for the momentum of the equivalent wall jet; we must recall the relationship shown in Figure 2 to determined the required momentum of the offset jet in the push-pull system. The biggest drawback to this approach is that the only inclusion of the pollutant buoyancy is in the choice of the appropriate value for V_{cap}, and this is necessarily subjective. However, it is worth noting that since $c \approx 1/2$ we have shown that the required minimum initial momentum is approximately

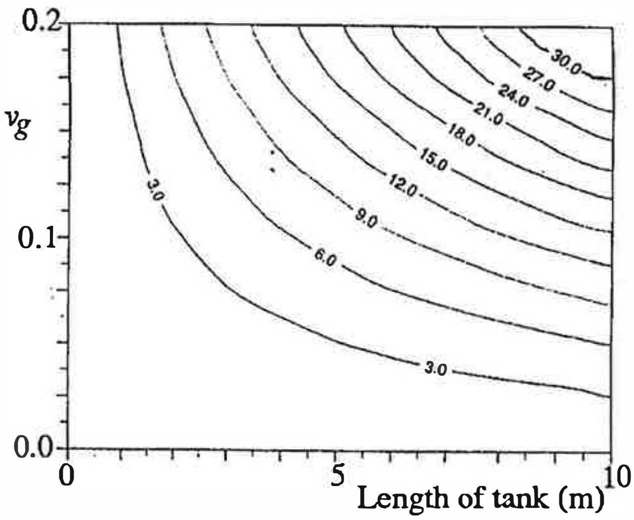

Figure 5. Recommended kinematic momentum when C_{crit} = 0.1 and cross draughts are 0.5ms^{-1}.

proportional to the length of the tank and if we take the recommendations from those researchers who give enough information to calculate the initial momentum we find that their recommendations are approximately consistent with each other and with this hypothesis, as shown in Figure 4.

Critical Contour Criterion

For this criterion, we seek to ensure that when the velocity falls below some critical value, V_{crit}, the concentration must be below some allowable value, C_{crit}, which depends on the pollutant. To demonstrate this, the critical velocity is taken to be the maximum of the buoyancy velocity v_g and the typical cross draughts. Using the solution of equation (4) we can thus determine the required initial momentum to satisfy these requirements. Figure 5 shows the required momentum as a function of the buoyancy velocity and the tank length when $C_{crit} = 0.1$ and cross draughts are assumed equal to $0.5 ms^{-1}$. The equivalent figures for alternative values of critical concentration and cross draughts are readily determined by solving equation (4).

Other Design Parameters

The outlet flow rate can be determined in the manner described in (5) to be $q_o = SF\, 0.316\left(\left(L + 10b_i\right)/\sqrt{L}\right)\sqrt{j_i/\rho}$, where SF is a safety factor and we have used the Original Verhoff formulae to determine the nature of the wall jet. This analysis does not specify the values of the jet nozzle height or inlet velocity, except insofar as these affect the initial momentum.

Conclusions

Even with modern CFD packages, achieving accurate results for a full numerical model of the push-pull system is time consuming because of the very fine grid required close to the jet nozzle and close to the surface of the tank. With the techniques described in this paper, it is possible (a) to show that the initial jet momentum is the critical parameter, and that the required value is approximately proportional to the tank length, and (b) to determine first estimates of the required value of the momentum for a given system. It is then recommended that a designer would conduct full numerical testing of the system to make final adjustments, and when the system is installed, it is important to allow for some adjustment of the operating parameters following in-situ testing of the ventilation system.

References

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