14th Australasian Fluid Mechanics Conference
Adelaide University, Adelaide, Australia
10-14 December 2001

Natural ventilation of a side-vented enclosure containing a source of welding fume

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Abstract

This paper presents a theoretical model of the fluid mechanics of a naturally ventilated enclosure containing a point source of buoyancy and contamination which is vented to through a single opening on a vertical wall. This represents part of an ongoing study to determine the distribution of welding fume within an enclosure and how exposure of the welder to the weld fume might be effectively controlled. The welding source generates a buoyant plume that rises and slowly fills the confined space with contaminated air. The mixing of the contaminant within the enclosure is complex due to the dense inflow through the side opening.

A mathematical model of this problem is presented which has similarities to the classic "filling box" analysis but is substantially modified to account for the exchange flow through the vent. Theoretical predictions of the critical vent area required to prevent the buoyant contaminated layer of fluid descending below the vent are presented together with a discussion of previous research by others on related problems. Results from preliminary experiments and the practical implications of our theoretical model are also discussed.

Introduction

Natural ventilation between a confined space and external ambient may be driven by external forces that may originate from either external ambient velocity (wind effects) or a temperature difference between the interior of the space and the ambient (stack effect). Ventilation's primary function is to remove contaminated air and provide fresh air to the conditioned space.

The present investigation is motivated by the need to reduce the exposure of welding operators to contaminants in welding fume. The generation of fume from industrial processes, such as welding and other hot metal processes, is due to the oxidation and condensation of the hot metal vapour from the high temperature sources. Welding fume, in particular, has been investigated in terms of fume formation rates and composition, eg Heile & Hill [5] and Voitkevich [9]. When dealing with welding processes, a fume plume of hazardous material is generated. The process of welding in an enclosed environment is considered a hazardous occupation, as concentration levels of these noxious elements can exceed the permissible exposure standards.

The introduction of natural ventilation to a confined space may reduce the contaminant levels of fumes to the welders breathing zone. However, only limited research has been carried out on determination of how the plume is distributed throughout the workspace or on the effectiveness of various ventilation strategies. The present research program involves experimental research on a full-scale welding test cell, experiments using water/saline solution scale-models, theoretical modelling based on classical plume theory and numerical modelling. The intent is to develop a comprehensive model of the behaviour of welding fume plumes so as to assist in the improvement of welding ventilation systems and the health of welders.

The problem at hand is essentially an enclosure containing a continuous source of buoyancy and contamination on the floor. The transient case is related to the research of Baines and Turner [2] who first described the sealed filling box model. Subsequently this has become a area of great interest and a number of related works such as those of Baines [1] and Worster & Huppert [10] have dealt with this issue in detail.

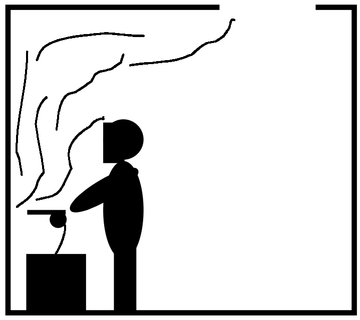

Figure 1. Schematic of welding in a confined space.

Fundamental principles of the natural ventilation of enclosures has been investigated by many researchers: eg Linden, Lane-Serff & Smeed [7], Cooper & Linden [3]. Ventilation flows may be classified into the two main types of displacement and mixing flows. Displacement ventilation utilises a denser, cooler medium of air that is adding into the space by a low opening, and warm air is extracted from a high opening, close to ceiling. This vertical displacement leads to a stably stratified environment within the enclosure. Mixing ventilation involves the addition of clean air in such a way so as to induce mixing throughout the entire space.

The Sealed Filling Box

When a buoyant thermal plume from a heat source rises within an enclosure with adiabatic walls, it entrains surrounding ambient fluid and on reaching the ceiling it spreads out to form a buoyant layer. This depth of this buoyant layer then increases with time.

In a sealed enclosure conservation of volume dictates that the velocity of the "first front" interface at the bottom of the buoyant layer is such that the increase in volume of the layer is equal to the volume flow in the plume at the height of the first front. The volume flow, Q, and local buoyancy, G, in the plume are given by [7]:

$$Q = CB^{1/3}z^{5/3}\,, \tag{1}$$

$$G = B^{2/3}z^{-5/3}/C\,, \tag{2}$$

where B is the buoyancy flux of the source, z is the elevation and C is a constant related to the entrainment ratio, α, that is the ratio of the mean horizontal inflow velocity and the characteristic vertical velocity in the plume. Note that $C = (6\alpha/5)(9\alpha/10)^{1/3}\pi^{2/3}$ and that for the assumption of "top hat" velocity profiles $\alpha \sim 0.1$.

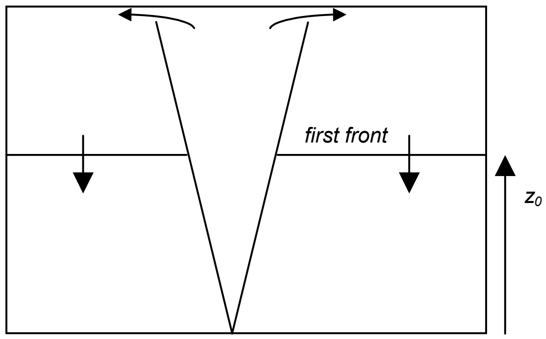

Figure 2 Turbulent buoyant plume rising into a sealed, adiabatic space generating a stratified environment.

Exchange Flow Through a Single Vertical Opening

Our consideration here is focussed on a confined space with a single opening positioned in one of the vertical walls. This is rectangular with depth, d, and width, w, and area, A. For an enclosure with no other ventilation openings the net volumetric flow through the opening will be zero. The hydrostatic pressure either side of the opening varies with height and there will be a *neutral plane* where the internal and external hydrostatic pressure will be equal as shown in figure 3. The buoyancy difference, g', across the opening is taken to be that at the neutral plane. If the flow is assumed Boussinesq then symmetry considerations dictate that the neutral plane is at the half-height of the opening, providing the opening is some distance from the ceiling or floor as discussed by Dalziel & Lane-Serff [7].

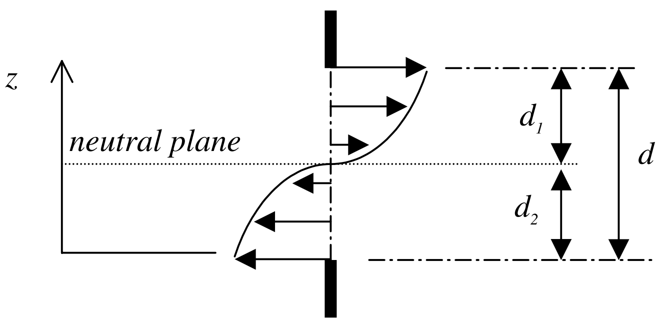

Figure 3 Schematic of natural convection across a vertical opening

Thus, $d_1 = d_2 = d$ and for an ideal flow through the vertical opening with an imposed buoyancy difference of $g' = g(\Delta\rho/\rho)$, Bernoulli's equation gives velocity, v, at any height, z, above the bottom of the opening as:

$$v = \left[2g'z\right]^{1/2} . \quad (3)$$

The volumetric flow of inflow or discharge, Q_{vent}, is therefore

$$\begin{aligned} Q_{vent} &= \int_0^{d/2} kw\left[2g'z\right]^{1/2} dz \\ &= \frac{k}{3} wd\left[g'd\right]^{1/2} \\ &= k_1 A\left[g'd\right]^{1/2} \end{aligned} . \quad (4)$$

Shaw & Whyte [8] state that the coefficient for a vertical door opening is $k = 0.65$, while Linden *et al.* [7] give the constant $k_1 = 0.25$ for a window.

Enclosure Ventilated by a Side Opening

The geometry applicable to welding in a confined space with a single opening in a vertical wall is shown schematically in figure 4. The focus of the present work is to determine the critical area of the vent, A_{crit}, required to prevent the depth of the buoyant, contaminated layer increasing such that the layer is significantly below the vent. Following the work of Linden *et al.* [7] one may reasonably assume, under steady state conditions, that the buoyant layer is fully mixed, rather than stratified as in the transient sealed, filling box problem. Under these conditions it is also reasonable to model the incoming flow through the vent as not mixing with the outgoing contaminated air. The plume flow rate through the interface at $z = h$ must then equal the exchange flow rate through the opening.

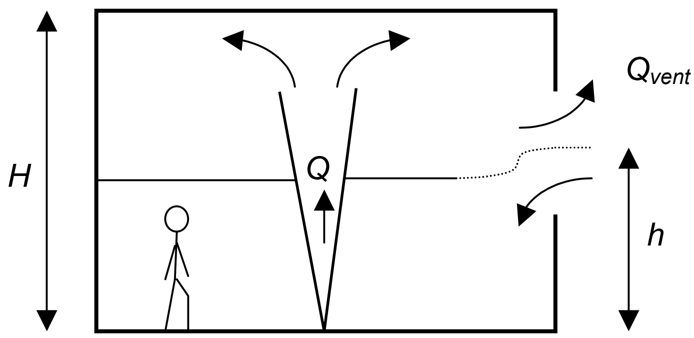

Figure 4 Enclosure with a point source of buoyancy and a vertical opening at a height h above floor illustrating flow with the *critical* vent area, A_{crit}, required to ensure buoyant layer remains above opening

Thus,

$$\begin{aligned} Q_{vent} &= Q_{z=h} \\ &= k_1 A_{crit}\left(g'd\right)^{1/2} \\ &= CB^{1/3}h^{5/3} \end{aligned} . \quad (5)$$

Since the buoyant layer is fed by the plume:

$$g' = G_{z=h} = B^{2/3}h^{-5/3} / C .$$

For an opening with aspect ratio $\gamma = d/w$ then:

$$A_{crit} = \frac{C^{6/5}}{\gamma^{1/5}k_1^{4/5}} h^2 . \quad (6)$$

It is interesting to note that the critical vent area is *not* a function of the *strength* of the source of buoyancy in the enclosure. This is to be expected from dimensional arguments and is consistent with other models of buoyancy-driven natural ventilation situations [7].

The ventilation volume flow rate is an important parameter and can be determined simply from (5).

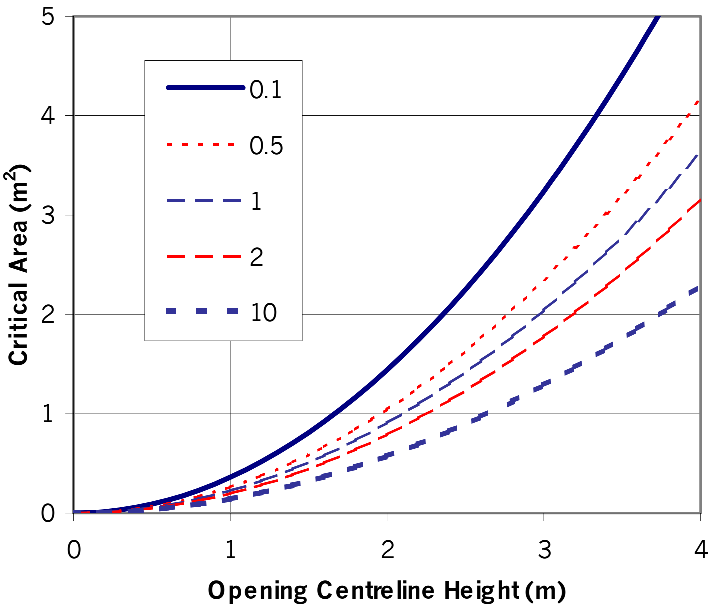

Figure 5. Plot of the critical vent area required to maintain the buoyant, contaminated layer above the mid-height of the enclosure opening with vent aspect ratio, γ, taking values of 0.1, 0.5, 1, 2 and 10.

Experiments

Experiments have been undertaken using the saline solution scale modelling technique in an acrylic enclosure measuring 25 x 25 x 25cm internally. The latter was suspended in a larger tank of fresh water and illuminated with a shadowgraph. The buoyancy source was implemented by injecting saline solution at the top of the box. Experiments carried out to date have confirmed the validity of the theory for prediction of the critical vent area required to maintain the buoyant layer above the mid-height of the vent (located at the enclosure half-height, $H/2$).

Figure 6 shows an experiment with a vent area somewhat less than the critical vent area, A_{crit}. The exchange flow through the opening is clearly visible and the disturbances in the upper layer indicate that there is a degree of mixing between the buoyant lower layer and the ambient during the exchange process.

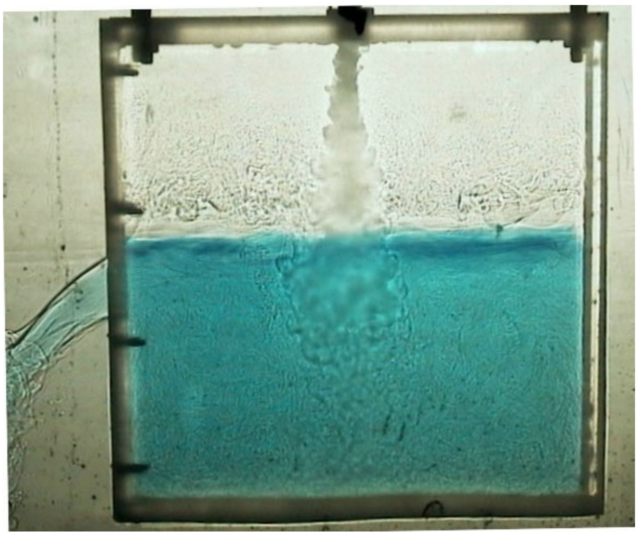

Figure 6. Shadowgraph of steady state experiment with single, square opening ($\gamma = 1$) in the left hand sidewall of the enclosure $A_{vent}/A_{crit} = 0.79$.

Linden et al. [7] developed a theoretical model of the case where $A_{vent}/A_{crit} << 1$ and deduced that in the steady state a flow must develop whereby the incoming ambient fluid generates a plume that flows downwards (in the case of a positive source of buoyancy) and establishes a fully mixed layer of fluid in the bottom of the enclosure as shown schematically in figure 7. For the case of a single source and a single opening, the height of the interface, h, between the upper and lower layers is then simply half the height of the ventilation opening above the floor. However, in the flow regime shown in figure 7 this will not occur for $A_{vent}/A_{crit} \sim 1$ as demonstrated by our results shown in figure 6.

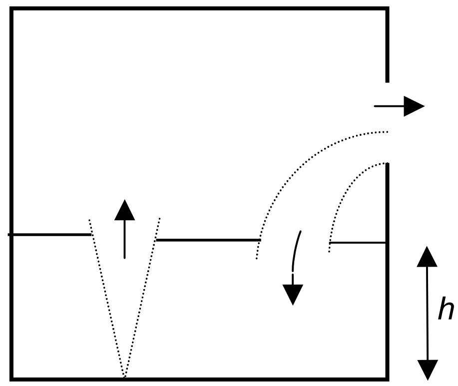

Figure 7. Schematic of flow modelled by Linden *et al.* [7] for $A_{vent}/A_{crit} << 1$ where exchange flow through opening generates a descending plume that feeds a mixed layer in the bottom of the enclosure.

The discussion above relates only to steady state flows, however, some important effects occur under transient conditions. For example, if the flow regime of figure 4 has reached steady state and the strength of the buoyancy source is subsequently reduced, then a transient three-layer structure will form whereby the plume lays down a layer of fluid of intermediate density. The thickness of this layer then grows with time as the plume entrains fluid from the original buoyant layer and eventually this layer is completely subsumed and a new steady state is reached. An experiment illustrating this transient situation is shown in figure 8.

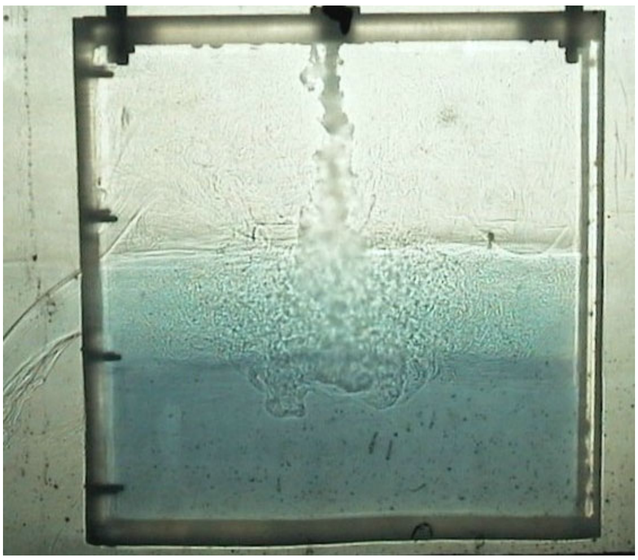

Figure 8. Shadowgraph of the ventilated enclosure of figure 6 in a transient state following a substantial reduction in the strength of the buoyancy source.

Practical Application of Theory to a Welding Enclosure

Arc welding generates significant heat that is used for fusion bonding of metal joints. A significant proportion of the total energy input to the arc results in heating of the air, which forms the convective plume. Jin [6] states that approximately 7-20% of the power input generated by the GMAW process is transmitted to the fume plume. The power input to the process, q_{elec}, is simply the product of voltage, V, and current, I. Using the above efficiency one may estimate the buoyancy flux of the welding plume, B, since at normal room temperature and pressure:

$$B = QG = \frac{g\beta q}{\rho c_p} \approx 0.0281 q_{source} \quad , \qquad (7)$$

where q_{source} is the heat input to the plume in kilowatts.

To illustrate the type of flows that might be expected in a naturally ventilated confined welding space driven only by the thermal input from the welding process, consider an enclosure 5 x 5m in plan with the centre line of a single opening in one wall located 2m above the floor. A typical convective heat input to the plume would be ~ 1kW (ie q_{elec} ~ 7 kW).

It should be noted that the analysis above does *not* include the important effects of radiation exchange and non-adiabatic walls that apply in a real situation.

γ	A_{crit}	d	w	q_{source}	Q	ACH
	(m^2)	(m)	(m)	(kW)	(m^3/s)	(hr^{-1})
0.5	0.93	0.68	1.36	0.50	0.080	3.86
0.5	0.93	0.68	1.36	1.01	0.101	4.86
1	0.81	0.90	0.90	0.50	0.080	3.86
1	0.81	0.90	0.90	1.01	0.101	4.86
2	0.70	1.19	0.59	0.50	0.080	3.86
2	0.70	1.19	0.59	1.01	0.101	4.86

Table 1. Required critical area of a single vertical opening, A_{crit}, in a confined space as a function of aspect ratio, γ, for opening centreline height h = 1. Also shown is the dependence of the ventilation flow rate as a function of heat input to the plume, q_{source}, expressed as volume flowrate, Q, and air change rate per hour, ACH, for a room measuring 5 x 5 x 3m.

From these results we conclude that the critical vent area is dependent only on opening height from the floor and the vent aspect ratio. For the practical case examined here, it would appear that the natural ventilation flow driven only by the heat input to the plume provides air exchange with the ambient of ~4 air changes per hour (ACH).

Conclusions

This paper reports on work in progress to investigate natural ventilation of an enclosure with a single opening on a vertical wall and which contains a source of buoyancy/contamination on the floor. A theoretical model has been developed to predict the minimum vent area required to maintain ventilation flow so that the contaminated, buoyant layer of air within the enclosure does not extend below the vent centre line.

This critical vent area is found to depend only on the height of the vent above the floor and the vent aspect ratio. The ventilation flow rate is dependent on the strength of the buoyancy source. Experimental results have confirmed this theory and provided insight into transient effects arising from changing to the strength of the buoyancy source with time.

Acknowledgments

The authors would like to acknowledge financial support from the Australian Research Council for the APA(I) award to the first author. They are also grateful to N. Eager for assistance with the experiments.

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