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EXPOSURE MODELS FOR CONTAMINANT CONTROL DECISIONS INVOLVING VENTILATION

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ABSTRACT

This paper discusses two complementary techniques for modeling human exposures to airborne contaminants with a focus on control decisions involving ventilation. Particular attention is given to: (1) the use of empirical-conceptual models with dimensional analysis and (2) computational fluid dynamic simulations. Both techniques provide valuable information. An empirical -conceptual model is formulated with dimensional analysis for a spray painting operation. Parameter estimates are obtained from wind tunnel studies to develop specific equations for worker exposure as a function of nozzle air pressure, mass over-spray generation rate, paint viscosity, booth air velocity, worker orientation to the air flow and object, and worker size. Field data confirm the model and illustrate its utility. Eight workers were sampled for a total 55 spraying tasks involving conventional air atomization applications conducted in spray booths. The model predictions provided a nearly unbiased estimator with 71% of the measured exposures within a factor of 3 of the predictions, and 40% within the measurement uncertainty of the methods employed. Transport processes related to the interaction of the spray-gun, the worker position, and the spray-booth air flows are examined with the computational fluid dynamic simulations and corroborated with flow visualizations. Steady state solutions of the Navier-Stokes equations employing k-e turbulence models and particle tracking are presented. The simulations confirm the flows observed experimentally and identify the recirculation zones responsible for exposure. The model is used to speculate on optimization of control decisions as well as the limits of control achievable subject to real-world constraints.

INTRODUCTION

An important deficiency in the design of industrial ventilation for contaminant control is our inability to estimate worker exposure prior to system installation. This shortcoming means that the industrial hygiene engineer is uncertain if the proposed design will reduce exposure below the target level, or conversely, if it does so; is the flow excessive and needlessly expensive. This situation could be remedied by models, capable of predicting exposure as a function of the relevant variables.

Different exposure modeling techniques are available with varying degrees of applicability and complexity. Ultimately the model must relate contaminant concentration to the significant determinants in a quantitative fashion such that rational control decisions can be made. Concentration depends upon the contaminant generation rate and the air velocity field transporting it to the worker. The problem is one of applied fluid mechanics and as such there are three fundamental techniques available: control volume analysis, dimensional analysis with empirical parameter estimation, and differential analysis (computational fluid dynamics). For an interesting discussion of these three techniques the reader is referred to Fluid Mechanics (White 1986).

Each of these tools has seen application in the area of industrial ventilation for contaminant control. The dilution ventilation equations, commonly employed to estimate average room concentration, result from a control volume analysis. The velocity contours of local exhaust hoods are an example of dimensional analysis with empirical parameter estimation, and recent papers using computational fluid dynamics, (CFD) to predict room air flow patterns are becoming more common. However, with the exception of the dilution ventilation equations there are few models to actually predict exposure, and it is generally acknowledged that they will not provide useful estimates for any but the simplest of cases.

This paper examines empirical-conceptual modeling used in conjunction with dimensional analysis to predict worker exposure to spray paint mists, and also some simple CFD simulations to support the observations and conclusions of that model. The combination of CFD with dimensional analysis and scale model experiments is a powerful tool in many engineering disciplines and has the potential to become one in contaminant control ventilation as well.

MODELING

All models begin with an abstraction of the real-world situation to a simpler approximation which permits the essence of the problem to be addressed. The ultimate success of the effort depends upon the objective of the model and how well the initial abstraction preserves the dynamics governing this objective. A successful model is the simplest one that achieves its desired objective. In constructing an exposure model which will facilitate control interventions, it is important to develop a quantitative prediction of exposure as a function of the significant determinants that one has control over.

The physics governing the transport of airborne contaminants and hence worker exposure are reasonably well defined by the Navier-Stokes equations and the general transport equations of fluid mechanics. CFD simulations are an attempt to approximate solutions to these equations numerically. With appropriate geometry, boundary conditions, and/or initial conditions the problem of exposure and control decisions is, at least theoretically, completely determined. In practice computational limitations such as memory, time, and an incomplete knowledge of turbulence and boundary conditions, prevent anything but the simplest of simulations from being run. Despite this, CFD is appealing in its generality and promise to address a broad range of contaminant control problems.

As with most engineering disciplines that employ CFD as a tool in analysis and design; it is a complement to carefully controlled laboratory experiments used in conjunction with dimensional analysis. Dimensional analysis is important for one very fundamental reason. If a mathematical relationship exists among a group of variables then dimensional analysis will identify the dimensionless groups of those variables that form the functional relationship. This formulation is more efficient and provides an economy in the experimental design needed to determine that relationship. Dimensional analysis does not specify the mathematical relationship but provides an important step in its determination.

In either case the beginning step is to create the initial abstraction of reality that will maintain essential process dynamics and form the basis for either the CFD simulation or the dimensional analysis and experiments. This initial step we will call the conceptual model, and it is the point at which much of ones experience and understanding of the process is used to construct the abstraction. It is here that the essential features which contribute to exposure must be included, and extraneous material minimized. Here the term exposure refers to the time weighted average concentration for an individual engaged in a specific task. It is assumed that complete exposures may be obtained by summing over tasks, time, and ultimately individuals if population statistics are desired.

AN ILLUSTRATION: SPRAY PAINTING

Dimensional Analysis

To be successful the conceptual model must address the contaminant generation rate and the air velocity field. Most factors which influence concentration and hence exposure, can be incorporated into these two variables. In the spray painting example used here we wish to incorporate certain aspects of the spraying process but not all of the complex detail. A conceptual model for the total mass exposure (i.e., solvent and particle) for a painter spraying a flat plate in a spray-booth has been presented in Carlton and Flynn[2]. A stationary worker and spray-gun were used in the original model and two worker orientations to the plate were employed, one with the worker's back to the flow the second orientation side on to the flow, see Figure 1. Additional factors considered in the derivation of the model are: (1) the nozzle air pressure, P_n ; (2) the paint mass flow rate, m_l (3) the air mass flow rate, m_a, (4) the overspray mass generation rate, m_o; (3) the paint viscosity, m_l; (4) the spray booth air velocity, U; (5) the height, H, and breadth, D of the worker; and (6) the total mass concentration in the breathing zone, C. Dimensional analysis, and some simplifying assumptions, produced four dimensionless parameters:

$$CUHD/m_o = F(m_a/m_l,\ p_n H/m_l U,\ orientation) \qquad (1)$$

Equation (1) states that the dimensionless concentration should be a function of the ratio of the air-to-liquid mass flows, the dimensionless source term, and the worker-plate-flow orientation. The dimensionless concentration was shown to be a function of orientation and the dimensionless source parameter by wind tunnel studies employing a mannequin and a spray nozzle similar to a compressed air spray gun. The ratio of air-to-liquid mass flows was found to be important in determining the overspray generation rate which is equal to the product of the gun transfer efficiency and paint flow rate. At values of the dimensionless source parameter representative of actual high pressure air atomized spray processes, the dimensionless concentration approached constant values of about 0.006 in the 180 degree orientation and 0.13 in the 90 degree orientation.

Computational Fluid Dynamics

Computational Fluid Dynamics, (CFD), is a tool which permits one to obtain approximate solutions to the equations governing the flow of fluids and contaminants suspended in them. There are different methods available and commercial packages can provide tools suitable for some simple investigations. The results presented here were generated using a commercially available package known as FIDAP. It employs a finite element approach to solving the equations.

Attempting to capture the full complexity of the multi-phase, compressible spray phenomenon coupled with three-dimensional turbulent air flow around a worker and object to predict particle and vapor concentrations is a challenging problem. At present research is underway to simulate this complex exposure problem, and as part of that effort a simple two-dimensional simulation was run to see if the spray patterns observed in the wind-tunnel studies described above could be reproduced, at least on a qualitative basis. As is the case with dimensional analysis a conceptual model is required. The two-dimensional Navier-Stokes equations with the standard k-e turbulence model were approximated for the two different spray orientations. The flat plate was modeled by using a very long thin ellipse, while the worker was modeled as a smaller thicker ellipse. The spray was treated very simply by considering a very small region on the surface of the ellipse representing the worker to be a an incompressible jet. The velocities for the jet and the crossdraft were selected at 700 and 50 cm/s respectively, and are not representative of actual spray operations. They were selected only to provide ease of simulation and a qualitative comparison. The simulations took approximately 15-30 minutes to run on a workstation machine and were considered to be the simplest model we could reasonably expect to capture the flow dynamics in 2-d. The graphical user interface of FIDAP made it very easy to generate the geometry and mesh.

Figures 2 and 3 present respectively the computed velocity fields for the 180 and 90 degree orientations. Figures 4 and 5 show tracer trajectories (i.e., massless particles) released into the velocity fields shown in Figures 2 and 3. The large recirculating eddy upstream of the worker in the 90 degree orientation is consistent with observations of the flow in our wind tunnel studies and has also been reported by field investigators[3] in actual spray painting operations. This flow pattern appears to be the cause of the increased exposure observed in this orientation in the experiments described above.

DISCUSSION

Although the two dimensional CFD simulations presented here do not provide a very realistic representation of an actual spray painting process; they do illustrate how a relatively crude abstraction of reality can help the industrial hygiene engineer gain insight into an exposure control problem. Speculating on the effect of orientation on exposure and using the numerical flow visualizations shown here it would be reasonable to predict the 90 degree orientation might result in the higher exposure, given the tendency for the spray flow to recirculate to the worker. Wind tunnel studies confirmed this result. However, important factors such as worker and spray nozzle motion may tend to reduce the differences observed here. CFD simulations have potential to predict exposure, however the complexity of the process and current limitations mean further research is needed.

The conceptual model using dimensional analysis has similar limitations but provides a more quantitative estimate of position effect. If we accept that the model represents the dynamics of a real spray situation reasonably well, then a question that might be asked is what is the relative benefit of orientation vs. booth air velocity. This can be examined by transforming the equations from dimensionless form into one with more direct interpretability. Again for the case of high pressure conventional spray guns we can write:

$$C_\theta = \alpha_\theta \left(\frac{m_o}{UHD} \right)$$

where the subscript indicates orientation and

$$\alpha_{90} = 0.13$$
$$and$$
$$\alpha_{180} = 0.006$$

For a given worker and paint application the ratio of concentration in the 90 degree orientation to that in the 180 degree position is predicted at about 22. Thus an increase in velocity of about 22 times would be required in the 90 degree position (relative to the 180 degree) to achieve the same reduction in exposure as the orientation change. It should be noted, as mentioned earlier, the lack of any motion in the gun and worker, and the idealized shape of the work piece will limit this model. Preliminary wind tunnel experiments suggest that motion of the arm and spray gun may reduce the differences somewhat although this is likely to be highly dependent upon worker technique.

The continued need to calibrate model prediction with reality is an essential part of bringing both CFD and dimensional analysis into the arsenal of weapons to combat worker exposure with ventilation. The need is to evaluate whether the conceptual model is accurate enough and the conclusions are warranted, or whether more complicated and detailed simulations are required. The model resulting from the dimensional analysis described above was evaluated in field studies conducted in US Air Force Spray booths. Fifty - Five separate spraying tasks on 8 different individuals were sampled. 71% of the measured exposures were within a factor of 3 of model predictions and 40% within the measurement uncertainty. Discrepancies between predictions and measurement were related closely to limitations of the model and the situation actually sampled. Details of the field evaluation can be found in Carlton and Flynn[4].

CONCLUSIONS

Exposure models employing dimensional analysis and computational fluid mechanics offer additional techniques to help examine contaminant control problems using ventilation. Although still at a relatively crude level, further research and application will continue to bring these techniques more into the mainstream as design and analysis tools. Studies are needed to calibrate model predictions with real-world data and evaluate the adequacy of the conceptual model used. The sensitivity of model predictions to variations in boundary conditions is also an important area for study.

REFERENCES

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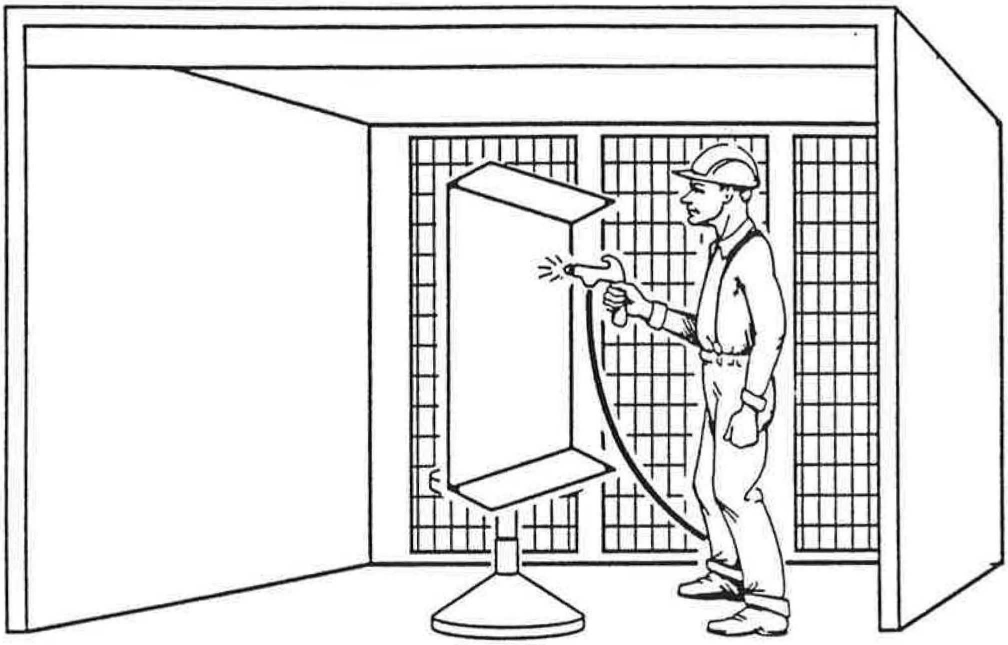
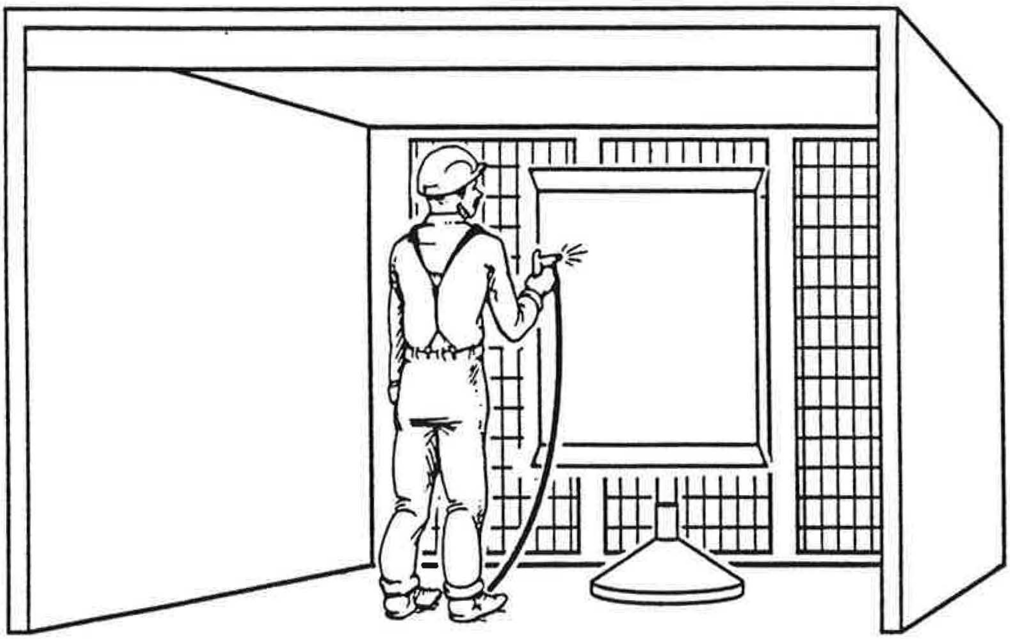
APPENDIX
Figure 1 – Worker Orientation for Spray Painting a Flat Plate



90° Orientation



180° Orientation

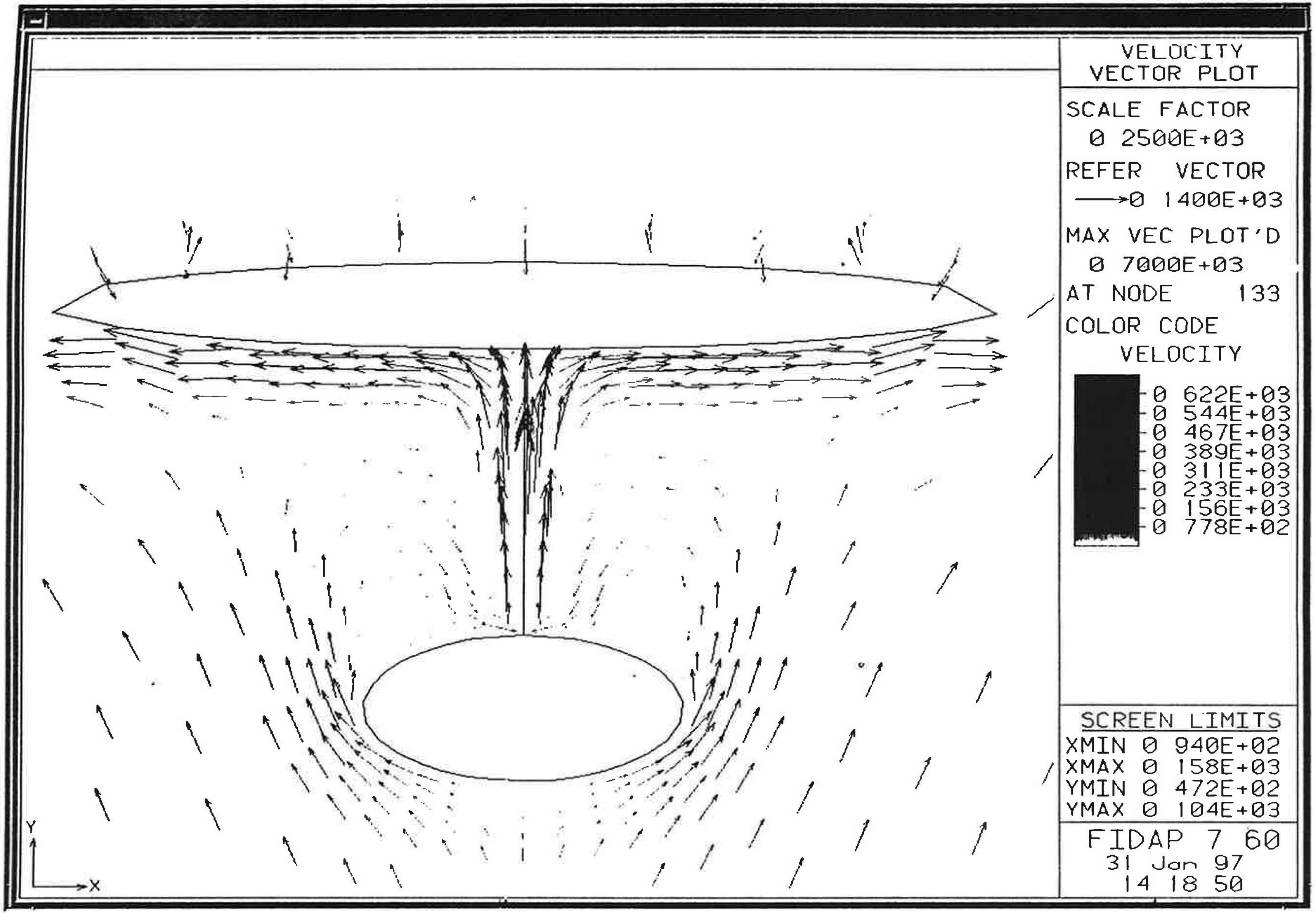


Figure 2 : Two Dimensional Computational Simulation of Air Velocity Field for 180 degree Orientation

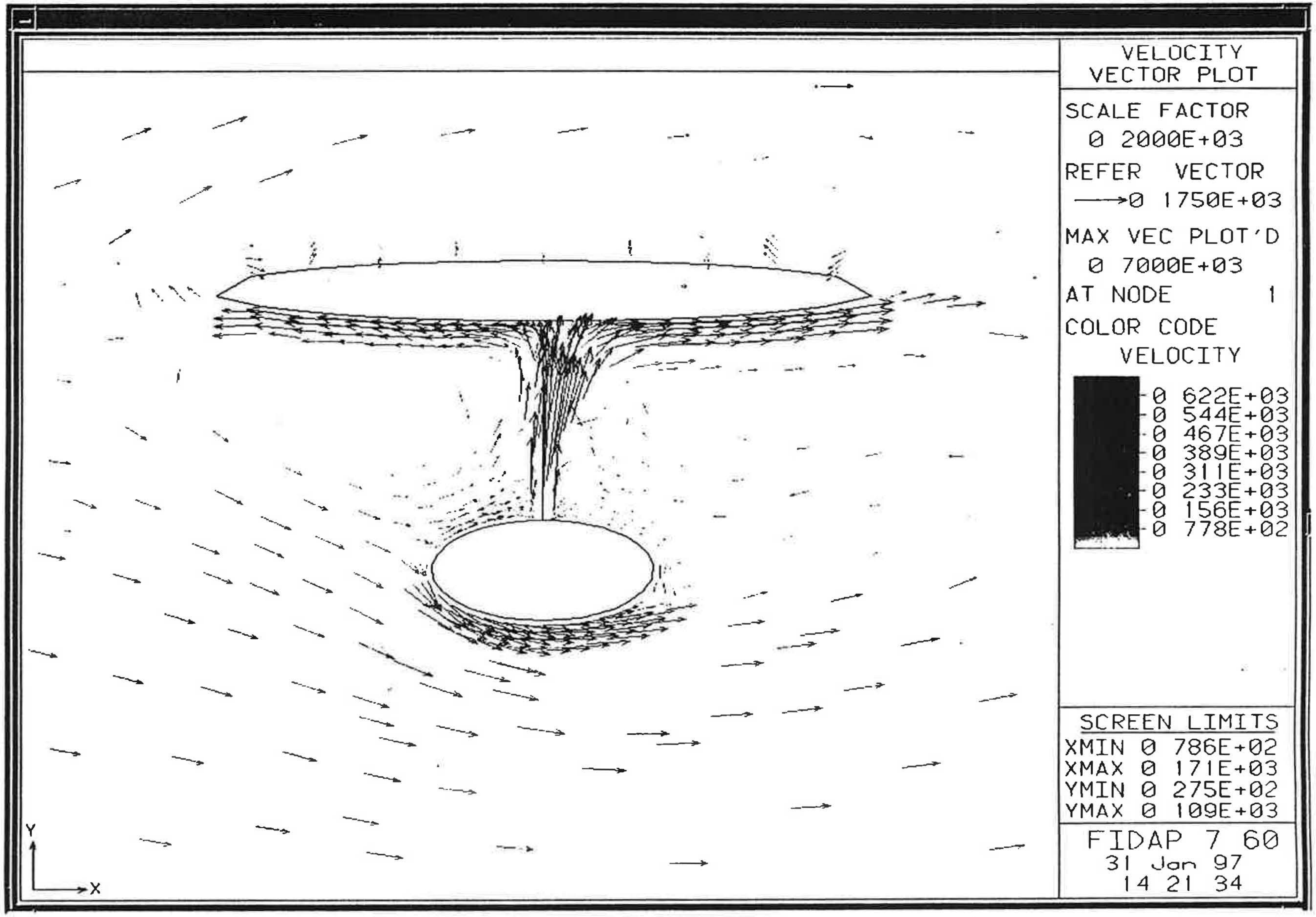


Figure 3: Two Dimensional Computational Simulation of Air Velocity Field for 90 degree Orientation

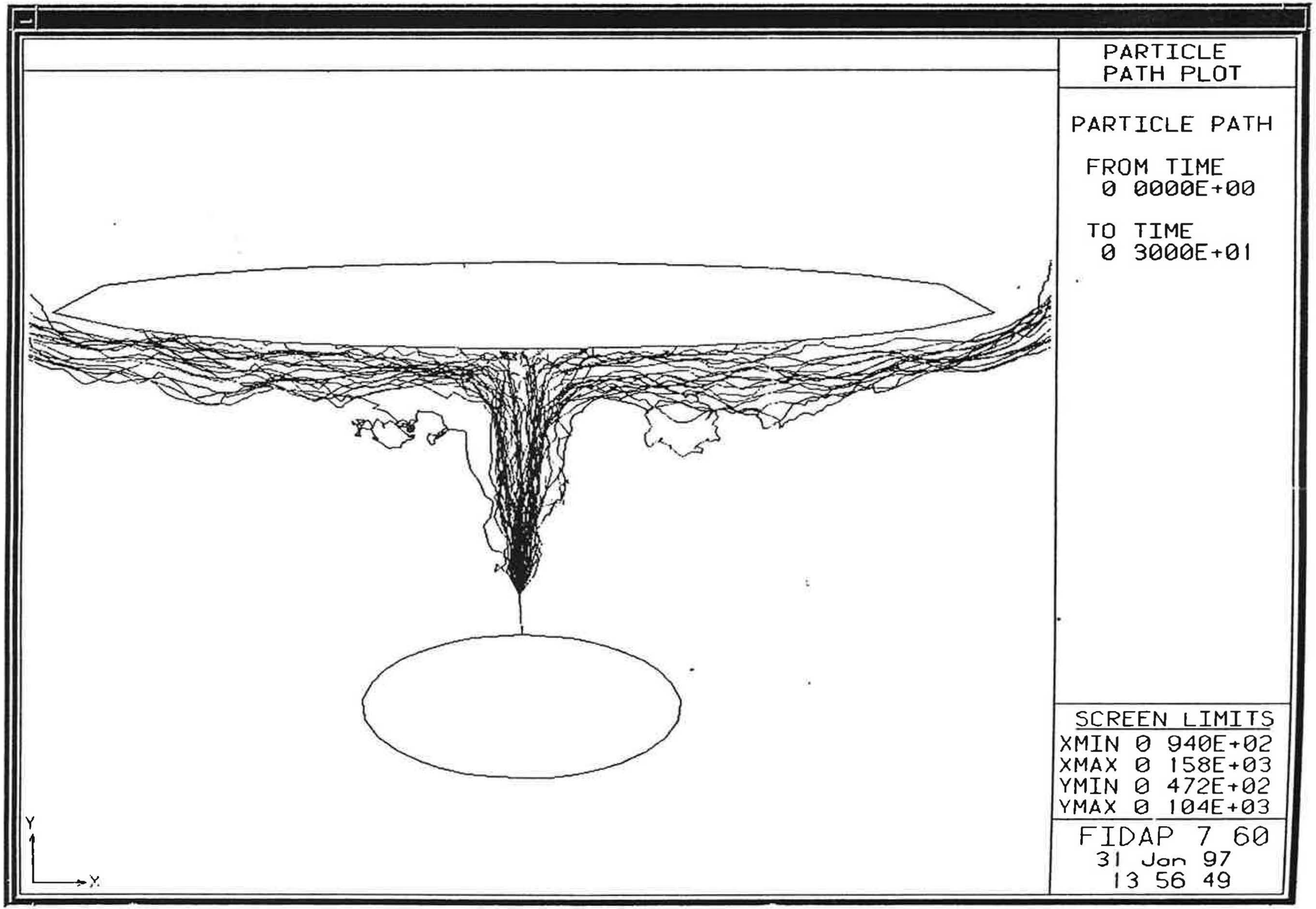


Figure 4: Tracer Particle Trajectories for the simulation shown in Figure 2 (180 degree)

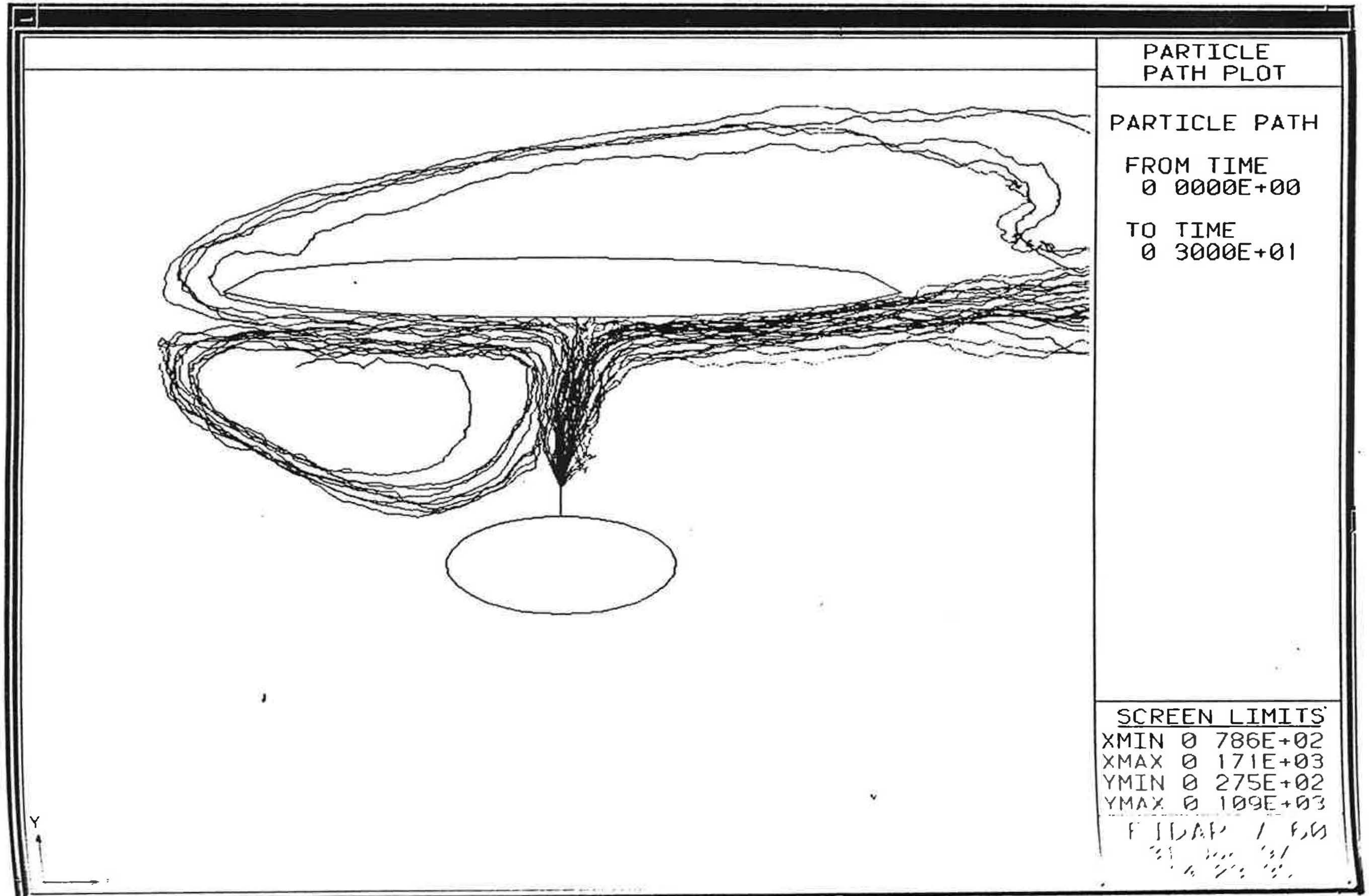


Figure 5: Trace Particle Trajectories for the simulation shown in Figure 3 (90 degrees)