The Role of Ventilation
15th AIVC Conference, Buxton, Great Britain
27-30 September 1994

Tracking Air Movement in Rooms

D K Alexander, P J Jones, H Jenkins, N Harries

Welsh School of Architecture, UWCC Bute Building,
Cardiff, CF1 1AD United Kingdom

ABSTRACT

A measurement system is described to record the movement in a room of neutral density balloons or bubbles, and thus the movement of air in that room. It is based on photogrammetric analysis of coincident video recordings made from several view points. Under laboratory conditions, the system was found capable of measuring position to an accuracy of ±3 cm over a range of 8 m, and of measuring 3-D velocities to better than ±0.05 m/s. The system was usable under field conditions, and could be operated in an occupied building. The largest space tested was approximately 30x15x10m. In the course of this work, the applicability of the use of balloons and bubbles for recording air movement was also explored. Balloons were found suited to typical natural room movements, but were unsuited to use within jets; bubbles were more appropriate for those.

1 INTRODUCTION

The air movement within and between rooms of a building is of considerable interest to designers of low-energy and environmentally healthy buildings. Unfortunately air does not always behave as designers would wish, their design tools are limited in scope and prediction techniques are often too complex and difficult to use. Furthermore, there is no easy way of assessing performance during or after the commissioning of a building.

Room air movement can either be measured very accurately through the use of expensive anemometry equipment, or observed easily and inexpensively through the use of smoke, bubbles or balloons. The limitations with the former lie in its' cost and complexity. Due to the high cost, such measurements are generally restricted to a small number of discrete, fixed, points within the space. Due to the complexity and sensitivity of the equipment, they are more suitable to a laboratory based investigation, or to use in an unoccupied building. The limitations of the latter lie in the qualitative nature of the information provided.

This paper describes a relatively low cost measurement system developed to quantify the visualisation of room air movement. The system described uses video recording and computer analysis to convert the recorded motion of neutral density balloons or bubbles into 3-D positions and velocities. As part of the development of the system the characteristics and suitability of various types of balloons and bubbles were explored.

2 THE MEASUREMENT SYSTEM

A number of researchers have used neutral density tracers to visualise air movement in rooms and buildings (1-3). The authors have previously used helium balloons both for qualitative research explorations and for the demonstration of natural ventilation concepts to students.

The analysis of stereo photographs for extraction of 3-dimensional data is well established, for instance in the photogrammetric recording of building dimensions (4). In other fields, such as robotic vision, motion detection and assessment is currently undergoing considerable development (5). There have been a few attempts at 3-D measurement systems (6,7) relating to building problems.

2.1 Measurement System Overview

The mathematical basis of the system is a form of surveying by triangulation (8). If a scene is photographed through several spatially distinct positions, the position of objects within that scene may be calculated from simple geometrical and trigonometric relationships, figure 1.

If the images to be analysed have been made as a time sequence, in synchrony, then the motion of those objects can be estimated from the difference in position between time periods. The motion of a target can be resolved as a true 3-D velocity with u,v,w components.

To establish the position of a target object, at least two views are required. Each pair of views can provide an estimate of position; from a number of such pairs, both position and an estimate of error of that measurement can be calculated. Room clutter (furnishings, structure, people, etc.), and geometry mean that some positions will be obscured from any one view, so the more vantage points the better; the equipment developed allows for three or four views of each area of interest.

In this system, the motion of the tracer objects are captured by a number of domestic quality video recorders and wide-angle cameras placed at fixed vantage points. A desk-top PC computer, with a frame accurate playback deck and a video capture card, provides the means of capturing and analysing the sequences. The recording equipment is simple, portable and robust, and although it is time-consuming to set-up accurately, a site measurement can be carried out within one working day. The system can be used to cover a large zone (a whole room), or it can be focused down onto a small area (e.g. a desktop or outlet grill). The largest space tested during this work was approximately 30x15x10 m; larger dimensions could be perhaps be covered with more viewpoints. The velocities that can be measured could range from <0.05 m/s to >5 m/s.

This system is intended to fill the gap between subjective observation and objective measurements using hot-wire or LDA techniques. Whilst it may not be capable of the high precision of those latter systems, it is simple and robust, is suitable for use in occupied buildings, and is capable of covering large spaces.

2.2 Tracer Objects

Balloons made from metalised polypropylene, filled with helium, were the main balloon type used. No other materials were found to be suitable, as they allowed too fast an escape of helium, and some were prone to static electric forces. The smallest balloon found to be feasible was 22 cm, made from 15μ polypropylene.

Bubbles from a number of sources were also tested, ranging from small seeds (1-2mm diameter) meant for wind tunnel visualisation, through to 5 cm diameter. Bubbles in this size range could be made visible to the cameras, at a distance of 1-2 m, provided that illumination could be controlled.

3 Error Characteristics of System

The overall error characteristics of the system can be identified as having four major components; errors in converting the camera image to direction angles, errors in triangulation positions from those angles, errors in timing or synchrony of the images, and errors introduced by the non-ideal nature of the tracers used.

3.1 Camera Image Errors

A requirement of the analysis is the conversion of the camera view to a digital bitmap image. Each pixel location must be identifiable as relating to a vector (altitude and azimuth) leading from the optical centre of the camera to the object imaged at that pixel. Each camera system (camera case, CCD, lens, tape recorder, and capture card) was calibrated, using a "gridded" surface (a wall marked off in 5°± 1' steps). After this calibration angular positions could be determined from the images to ±6' (within a 90° horizontal view angle).

3.2 Positional Errors

Practical uncertainties in the position of the viewpoints, the orientations of the cameras, and in the determination of the centre of the targets under varying lighting conditions affect the ability of the system to precisely determine a position. Tests made in controlled conditions within a room sized laboratory (8m maximum range) indicated that high contrast targets could be located to ±3 cm around the room. Tests on a smaller scale (a desk-top set-up of ~1m dimensions) showed a positional accuracy of ±0.5 cm was achieved.

In measuring speed, some error in absolute position may be tolerated if differences between positions can be resolved with higher accurately. This was tested by measuring the distance between two targets, placed at a number of points around the test room. The targets were separated by a fixed amount; 42 cm. The system was able to measure this difference to ±1 cm.

3.3 Errors in Velocity

Velocity determination requires the measurement of the difference in position of a target between two moments in time. The time aspect requires that both the time interval between positions be known accurately and that all images from different viewpoints be synchronous. The time accuracy of the recording and playback equipment was checked and found to be better than 1/25 sec. The individual recorder's frame rates were similar enough such that several minutes of recording could be made before error of that magnitude was found between them. Synchrony in longer recordings was enabled by the use of a periodic electronic flash; each flash lasted less that 1 frame and so provided a unique time point every few minutes.

As a final lab based test of the system, a target was towed along a known path (a wire strung diagonally across the room) at a known speed. The system was able to measure the target velocities to within 5% over the range 0.1 - 0.7 m/s (figure 2).

3.4 Errors in Non-ideal Tracers

The measurement accuracy of the system would be immaterial if the tracer objects could not satisfactorily follow the movement of air. The requirements of an ideal tracer are that it be neutral (i.e. the same density as the surrounding air), be physically small, and have no inertial mass. All physical tracers will vary from this ideal, and each excursion will have a bearing on their accuracy in following air movement. The measurement errors associated with real tracers can be summarised in three subjects; size and visibility, ease of trim and longevity of neutral density, and air resistance or terminal velocity.

3.4.1 Size and Visibility

The larger the target object, the more easily it will be identified and tracked. However the larger the target, the less ideal it becomes as a tracer. The ability of a neutral weight tracer to follow the path of air will depend on its inertial mass; an object with high mass will accelerate slowly and may miss rapid changes of direction. It will also depend on its physical size; a good tracer should also be smaller than a characteristic dimension of the flow i.e. the width of a jet.

In this work two sizes of balloon were found to be usable, both were made of polypropylene. A standard commercial balloon, with a diameter of approximately 35 cm had a mass of ~10.5 gm. A hand-made balloon, made from thinner material (15μ) could be made neutral down to a diameter of ~22 cm; its' mass then was 4.5 gm. When in a jet or fast rising plume, the smaller balloon showed a markedly faster acceleration. In normal room air currents, of 0.5 m/s or less, their was felt to be little difference between them. When surrounded by smoke, the balloons and smoke were seen to travel coincidentally (although the smoke eventually dissipated through small scale turbulence). Both sizes were visible and identifiable at up to 30m on the captured images.

The generation of suitable bubbles was found to be more problematic than that of balloons. Bubbles in the range 0.2 to 5 cm diameter could be generated by a number of sources, but the quality was always variable; some long-lived, some short-lived and some positively, some negatively buoyant. All sizes were found to be visible in the analysis images when they could be side lit with spot-lights. Image performance was best against a dark plain background. This confirms that bubbles are more suitable for laboratory or controlled environment testing, than for use in occupied buildings.

3.4.2 Longevity of Neutrality

Vitally important to the use of an object as an air following tracer is the ease of achieving, and the longevity of maintaining, neutral buoyancy. Helium is generally the medium through which buoyancy is achieved; it is preferentially lost through the envelope, and so the objects loose buoyancy over time. The buoyancy of bubbles is also be affected by evaporation.

Tests were made of the rate of buoyancy loss for several balloon types and materials. Positively buoyant balloons were tethered, in a draught free cabinet, to an recording electronic scale. The commercial polypropylene balloons performed best, loosing only 3 mg/hour. The handmade polypropylene balloons, when carefully made, lost approximately 6 mg/hour. These rates were sufficiently low so as to allow time to trim to neutral buoyancy and to allow several tens of minutes of recording time between trims. Rubber balloons (of helium grade) on the other hand lost buoyancy at a rate of 230 mg/hour, so fast it was not possible to reliably trim them to neutrality.

The buoyancy loss of bubbles was could not be measured with the equipment available, but in the light of the tests on balloons, the longevity of helium filled bubbles will be small; suitable for only a few seconds, perhaps a few minutes, of use.

3.4.3 Terminal Velocity

The intent in achieving neutral buoyancy is to keep the balloon stationary relative to the surrounding air. However, due to drag it is considered that a certain degree of non-neutrality is acceptable; a tracer will quickly reach a terminal velocity and this may be considered to be the error in the tracer motion. As long as this speed is small compared to the velocity of air movement observed, the resulting error will be small.

Tests were made of the terminal velocity of balloons under various degrees of positive buoyancy, by timing their flights in a draught free cabinet. It was found for the larger balloons that terminal velocities of <0.05 m/s could be achieved if the balloons weight was within ±10mg of neutrality. The smaller balloons, due to their smaller size, showed less drag; their usable range to 0.05 m/s was considered to be ±5mg. This is shown in figure 3.

Standard bubble solutions produced relatively wet, heavy bubbles. Their terminal velocities were estimated to be approximately 0.3 m/s. The use of exotic surfactants allowed significantly lighter bubbles, with corresponding lower terminal velocities; 0.03 m/s was achieved using Hyamine 2389. This is more appropriate for use in typical room flows, but unfortunately this liquid is toxic. The standard bubbles are felt to be useful for the higher velocities found near and within jets.

The information for the buoyancy loss rates and the terminal velocities combine to indicate that the larger balloons, when correctly trimmed, can be considered accurate to 0.05 m/s for up to 3 hours. The smaller balloons can be considered accurate to 0.05 m/s for just under an hour.

All together, the laboratory based tests suggest an estimate for the overall accuracy measurement of velocity of better than 0.05 m/s is achievable when using balloons in typical room air movement (i.e. <1 m/s). The use of balloons within jets is less reliable due to their size and mass, but here bubbles may be more appropriately used.

3.5 Field Trials

The system was tested under field conditions in three circumstances; recording the flow near a small desk fan using bubbles, recording the flow patterns caused by a de-stratification fan in a factory using balloons, and recording the air movement in the glazed atrium of an art gallery, again using balloons. The system performed satisfactorily, though it was noted that due to the effort required to site and accurately survey the positions and orientations of the viewpoints, it was not responsive to changing conditions, i.e. if another area of interest was identified, the equipment could not be quickly or easily moved and re-sited. This means that careful planning is required for its use.

The use in the gallery in particular showed that the system is tolerant to a high degree of "clutter", is capable of handling difficult and changing lighting conditions, and can be operated in an occupied building. Of particular concern to the staff of the gallery, the use of balloons as tracers meant that no damage was possible to the exhibits; the staff would not have permitted the use of smoke or bubbles.

Figures 4 and 5 show the recorded paths of the flow above the desk fan (a soldering station fume extractor; a small axial fan blowing upwards). It displays the swirling flow expected from this type of fan.

Figures 6 and 7 show some of the flow patterns recorded in the art gallery atria. The space is supplied by inlet grills at high level along the top and left hand walls. The air system was in cooling mode at the time of the measurements; the inlet air was approximately 1°C lower than the bulk air of the space. Inlet speeds were approximately 2 m/s; air speeds through the space were generally found to be ~0.5 m/s. The projected section illustrates common patterns of recirculation found on either side of the inlet jets. Monochrome printing restricts the amount of information that can be shown in these diagrams.

4 CONCLUSIONS

The system described is a suitable method for recording and measuring room air flow patterns. It is capable of measuring 3-D positions and velocities to a reasonable degree of accuracy (±3 cm, ±.05m/s) within large spaces. It can provide a quantified measure of bulk air flow patterns, and is particularly suited to the low velocities found in naturally ventilation buildings. The system is readily transportable and usable in occupied buildings.

The use of balloons in tracking the flow of air is justifiable within air velocities typically found in rooms, that is velocities less than ~1 m/s. When suitably prepared, they can adequately follow the bulk movement of air for a considerable period of time, indicating velocities, areas of recirculation and highlighting problems such as "short circuiting". Balloons are less able to follow the movement of air within small jets, due to their relatively large size and mass. Bubbles, apart from problems associated with their production and with their residue, are better suited for use near or within jets.

REFERENCES

1. Trollope, M., Seager, A., Palmer, J., Watkins, R., Shaw,P., "IEA XI Advanced Case Study: Gateway 2", IEA XI Advanced Case Studies Seminar, April 1991. ETSU Harwell, 1991. 213-236
2. N D Vaughan, P Jones, D K Alexander, H Jenkins, M Fedeski, S Lannon, P Taylor, P E O'Sullivan, "Technical Report: Victoria House: Hampshire Training and Support Headquarters", ETSU 1163/28, ETSU Harwell, 1992
3. Pickering, P.L. , Cucchiara A.L., Gonzales, M. and McAtee, J.L, "Test Ventilation with Smoke, Bubbles and Balloons", ASHRAE Trans. 93, Part 2, 1987, 898-907
4. Ghosh, S.K., "Analytical Photogrammetry", Pergamon Press, New York, 1988. ISBN 0-08-036103-X
5. Shirai, Y. "Three-Dimensional Computer Vision", Springer-Verlag, Berlin, 1986. ISBN 3-540-15119-2
6. Gottschalk, G., Revesz, Z., Suter, P. and Tanner, P., "Experimental Method to Measure 3D Air Velocity", 10th AIVC Conference, Finland, 1989, 251-263
7. Kaga, A., Inoue,Y., Yoshikawa, A., "Velocity Distribution Measurement Through Digital Image Processing of Visualised Flow Images", Proceedings RoomVent '90, Oslo, 1990, B1-14
8. Allan, A.L. "Practical Field Surveying and Computations", Heinemann, London, 1968.

ACKNOWLEDGEMENTS

The work presented here was funded through the EPSRC.
The authors would also like to acknowledge the interest, information and support provided by:

Jane Porter of The Burrell Collection,
Mr C Boon, Silsoe Research Institute,
ICI,
and the Welsh Development Agency.

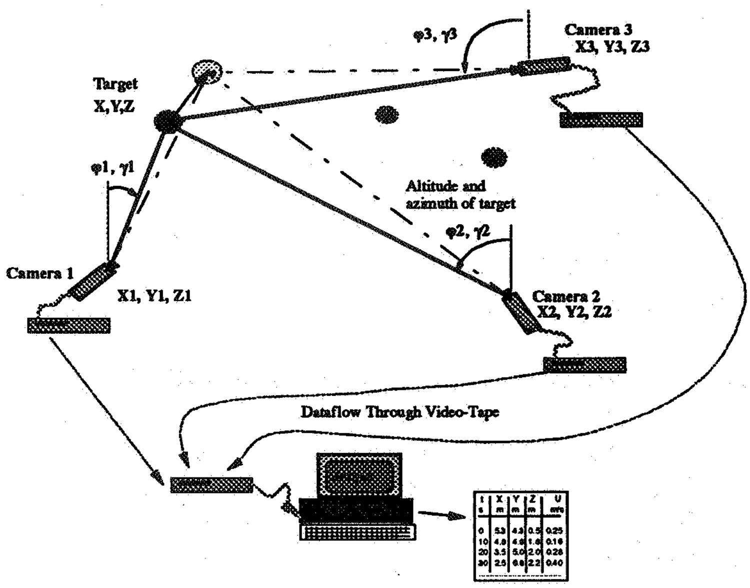

Figure 1 Functional Block Diagram of Measurement and Analysis System

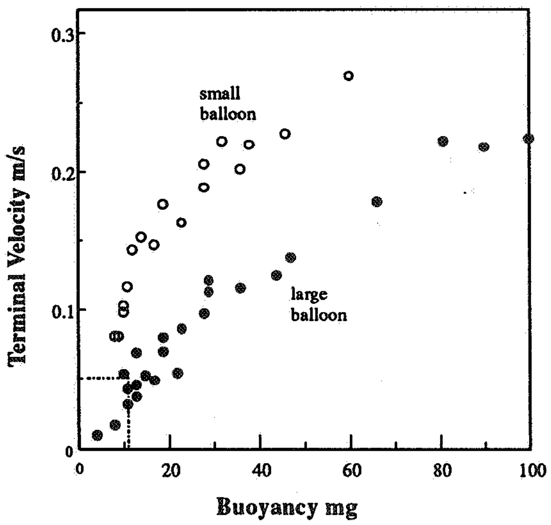

Figure 2 Terminal Velocity of Balloons for Differing Amounts of Buoyancy

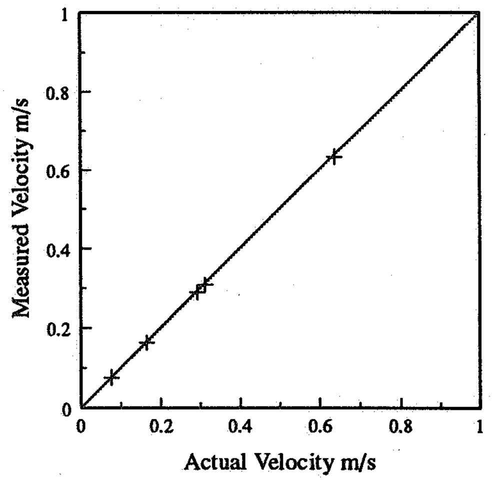

Figure 3 Comparison of Measured and Actual Velocities of Test Targets

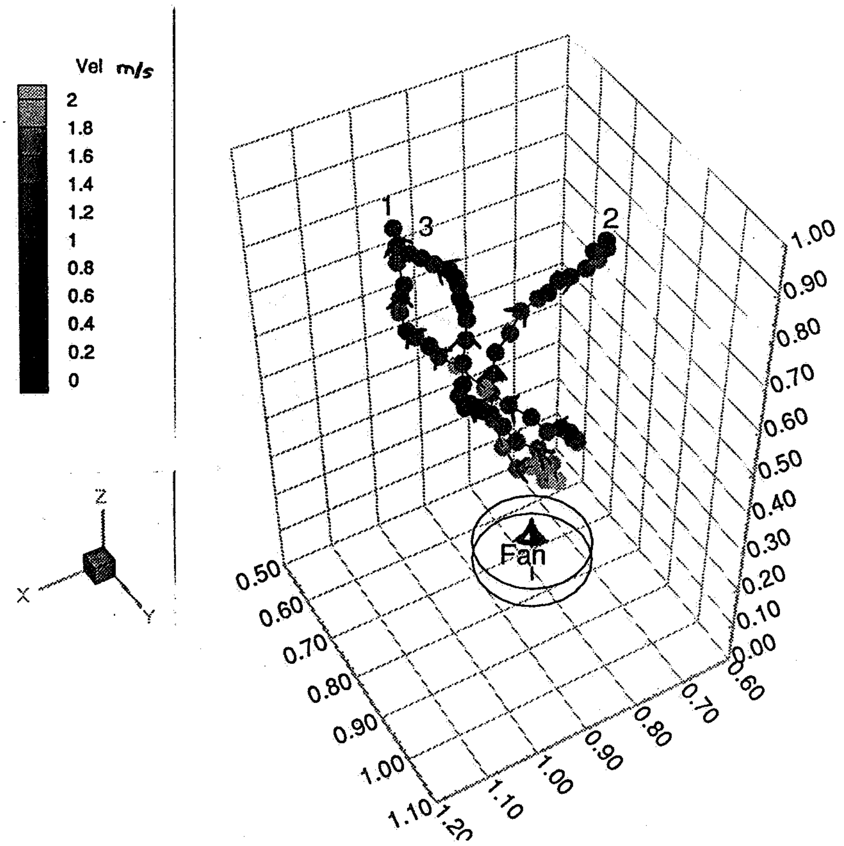

Figure 4 Example Bubble Tracks Produced By An Axial Fan

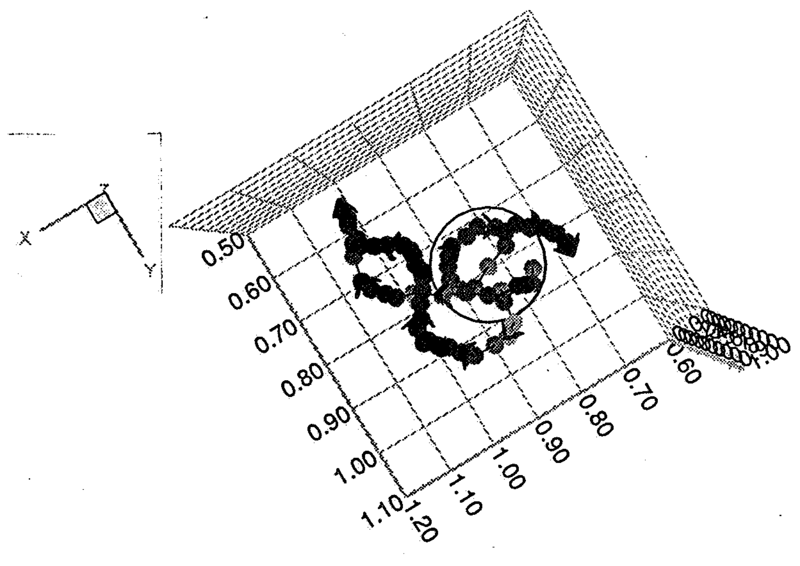

Figure 5 Plan View of Above

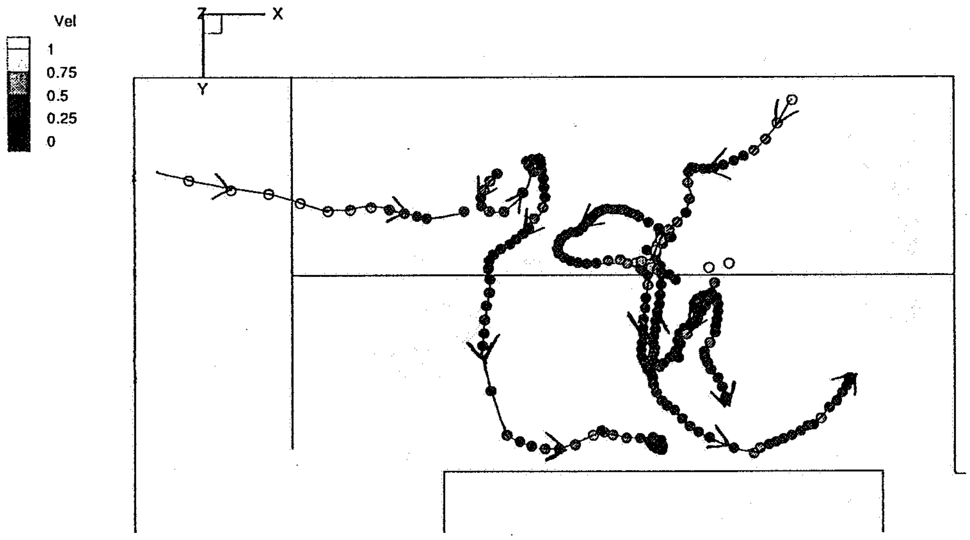

Figure 6 Plan View of Flow Patterns In Large Gallery

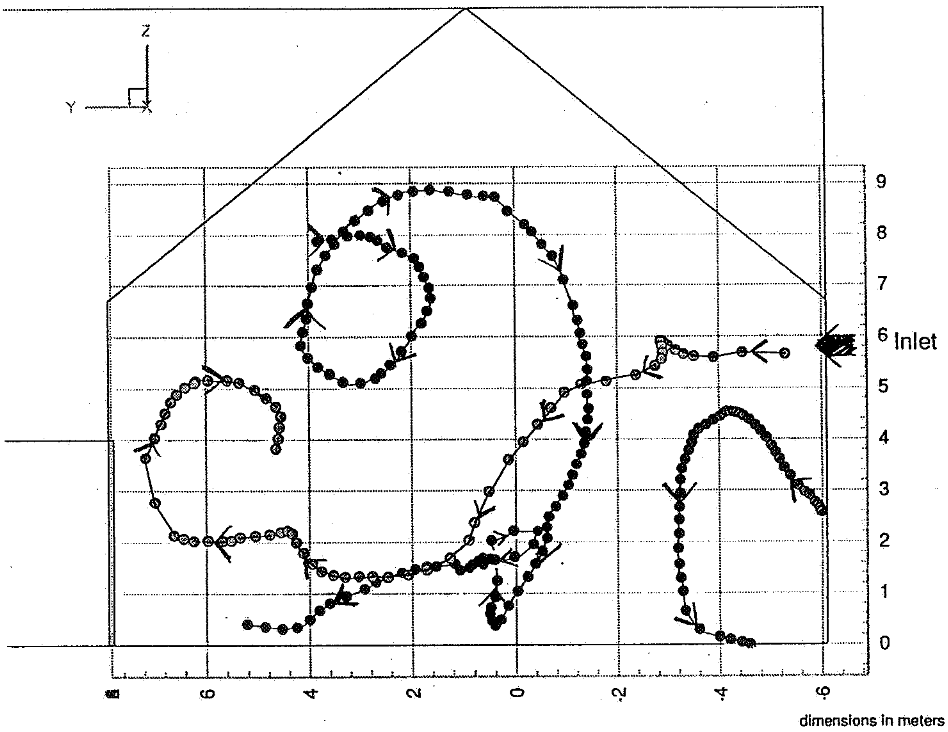

Figure 7 Projected Sectional View of Flow Patterns in Gallery