

THE USE OF COMPUTATIONAL MODELING TECHNIQUES FOR  
CLEANROOM DESIGN

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ABSTRACT

A knowledge of the detailed flow environment within cleanrooms and supply ductwork can produce cost savings and improvements in air quality. This paper demonstrates how such knowledge may be obtained at the design stage.

INTRODUCTION

This paper presents the results of a computational and experimental study to assess the possible benefits of using mathematical modeling techniques for cleanroom design. Specific attention is paid to the separate problems of flow within HEPA filter plenums and the general flow environment within a class 100 cleanroom.

A two-dimensional modeling visualization has been used for each of the cases studied. This has the advantage that its relative cheapness allows more design variations to be analyzed than would be possible with a three-dimensional method. Full-scale measurements were also taken in the cleanroom which was the subject of the modeling exercise. The predictions of the computational model were found to be in good agreement with the measurements taken.

The results of this brief study suggest that significant cost saving may be achieved by incorporating methods of computational analysis in the cleanroom design procedure. The analysis technique used in this work can also provide a better understanding of the performance of existing cleanroom facilities.

#### TYPES OF PLENUM AND CLEANROOM

##### Plenum

According to Marsh and Quinn (1981) the HEPA filter is the key element in the laminar flow clean air system. It can be shown that the greatest inefficiency in the traditional laminar flow clean air module is in the method of air distribution from the fan to the HEPA filter. Figure 1 shows four of the many plenum designs which have been proposed to facilitate the necessary air distribution.

Such designs are all very well in theory, but many cleanrooms are constructed in existing buildings where space is at a premium. In such circumstances a much simpler plenum design may be attractive, such as that shown in Figure 2.

##### Cleanrooms

Figure 3 shows the two major classifications of cleanroom as defined in BS5295 (1976).

Figures 3a and 3b are laminar cleanrooms in which the entire 'body' of air within the room moves, ideally with uniform velocity, along parallel flow lines which may be either horizontal or vertical. It is worth noting in passing that while the flow of air in such clean rooms may be laminar when the room is completely empty, the introduction of equipment, work benches and personnel undoubtedly lead to turbulent air

flows being generated. Figure 3c is 'defined' as a 'conventional flow cleanroom', i.e. a cleanroom in which the flow is not unidirectional or of a uniform velocity.

The cleanroom design which was used for the modelling exercise is shown in half-section in Figure 4. This design was chosen because an existing cleanroom was available for use in obtaining full-scale measurements.

#### THE MATHEMATICAL MODEL

The computational prediction work was conducted using the program entitled CAFE (Computer Aided Flow Evaluation). This program is designed to solve flow problems which exhibit areas of recirculation. Although this was the first instance of using CAFE to predict air flow within cleanrooms, the program has been extensively used for related problems (see, for example, Broyd et. al. (1983)).

A detailed description of the program CAFE is not given in this paper. The following variables may be solved in either two or three dimensions (depending on the visualization used):

- momentum in each dimension
- continuity
- 2 turbulence equations (unless the flow is genuinely laminar)
- concentration
- temperature

It is possible to model flow domains of any desired geometry, and internal blockages may be used to simulate work benches, items of equipment, personnel, etc. The effect of heat-emitting (or absorbing) equipment or personnel may be modelled by introducing sources (or sinks) of heat

energy arbitrarily throughout the model domain, (although it should be pointed out that it is difficult to simulate accurately the effects of people moving around). Likewise the shedding of particles by plant or personnel may be modelled by making the analogy between small particles and concentration of gases. For example, Figure 5 indicates that there is little loss of accuracy by assuming that particles of  $< 10\mu\text{m}$  remain associated with individual "parcels" of air flowing through the cleanroom.

A full description of the solution technique used for CAFE may be found in Dean and Moulton (1978).

#### COMPUTATIONAL PREDICTIONS FOR SUPPLY PLENUMS

Two tests are presented, representing the following:-

Run 1. A baseline test which uses the physical geometry and fluid flow specification given in Figure 2 and Table 1 respectively. The filter is represented by an expression (equation 1) derived from the manufacturers; flow characteristic (Figure 6). The relationship calculates a value of equivalent filter porosity (on average = 0.0325) based on the filter local exit flow velocity ( $V_o$ ) and the pressure drop ( $\Delta P$ ) across the filter

$$\Delta P = 296.2 V_o^{1.1062} \quad (1)$$

Run 2. A test to represent a dirty filter at its maximum recommended pressure drop of  $450 \text{ N/m}^2$ . Equation 1 was modified to represent a dirty filter by applying a pressure axis shift to give equation 2.

$$\Delta P = 968.8 V_o^{1.1062} \quad (2)$$

The results obtained are illustrated as streamline plots on Figures 7 and 8. In addition the outlet vertical velocity profile is also given for each test case in Figure 8.

The streamlines plotted represent the streamlines at 10%, 20%, 30% etc. of the mass flow rate.

The results may be summarized as:-

- a) The presence of a 'low porosity' filter causes a high plenum pressure and strong recirculation within the supply ductwork. The use of a single plenum results in a non-uniform velocity distribution along the filtered area, with variations of around 15% from the mean velocity.
- b) Reduction of the filter porosity simulates an old, or dirty filter. The effect of this is to further increase the variation of outlet velocity along the filtered area.

## PREDICTIONS AND MEASUREMENTS IN CLEANROOM ENVIRONMENTS

### Computational predictions

Computations have been undertaken in the following configurations:

- Run 3. A baseline test case based on the specification given in Table 2 and the geometry illustrated in Figure 4.
- Run 4. The same specification as the baseline Run 3 above, except that flow is eliminated from the inlet filter, nearest the wall.
- Run 5. The same specification as the baseline Run 3 above, except that flow is eliminated from the two end inlet filters, nearest the wall.
- Run 6. The same specification as the baseline Run 3 above, except that the outlet duct is reduced in height from 450 mm to 250 mm.

The results of the four test cases are illustrated as streamline plots on Figures 10, 11, 12, 13 respectively. In addition, profiles of vertical and horizontal components of velocity at a working height of 1m above the floor are given in Figures 14 and 15.

The streamlines plotted represent the streamlines at 10%, 20%, 30% etc. of the mass flow rate, as before. Extra streamlines are plotted in regions of recirculating flow, for example Figure 11. In these diagrams a 'dividing' streamline is drawn, between the main flow and the recirculating region, and also four other streamlines are drawn which represent equal intervals between the dividing line and the stagnation point or line. Thus, it should be noted that equal spacing between the streamlines either side of the dividing line do not signify equal mass flows. In reality the recirculating air flows are a very small percentage of the total air flow within the room. While the presence of recirculation flows within cleanrooms is generally considered unwelcome, it is possible to consider each case on its own merits if the flow environment may be accurately predicted at the design stage.

The results may be summarized as:-

- a) Reduction of the filtered air supply from part of the ceiling area (e.g., Figure 11) causes significant localized effects, but has little effect on the bulk air flow through the room. Thus, the prime effect of reducing the filter area by 28%, the difference between Runs 3 and 5, is to produce a small area of weak recirculation.

- b) Reduction of the size of the air outlet duct has little effect on the bulk air flow through the room, but does of course produce larger outlet velocities.

### Measurement Techniques

Low velocity flow under atmospheric conditions presents a difficult measuring environment for most common flow measurement techniques; e.g. pitot tubes, hot wire anemometry, etc. Two different flow measurement techniques were used in this work, enabling comparisons of the results from different methodologies to be made.

Measurements were made with a single wire hot-wire probe yawed through  $90^\circ$  to locate a maximum reading when the wire was aligned perpendicular to the local flow direction. Both the magnitude and direction of the local velocity was obtained with this technique.

The second measurement technique involved tracking neutrally buoyant helium bubbles introduced into the flow. Knowledge of the camera shutter speed used to obtain pictures of tracks formed by individual bubbles enabled the magnitude of the velocity to be calculated. An example of pictures obtained with this method is shown in Figure 16.

Results from the helium bubble flow measurement technique were used to confirm the hot wire anemometer results. The hot wire results were then used to plot the velocity vectors for comparison with the computed results.

### Results and Discussion

The results of the flow measurements are shown on Figure 10, which shows velocity vectors of the experimental measured resultant flow velocity superimposed on the stream line plot, for the baseline test model.

Measurements were taken at 0.5m, 1.0m, 1.5m and 2.0m above the floor, and at four positions across the half-section of the room.

Comparisons of experimental and predicted results generally show a reasonable degree of correlation at all measuring heights. The correlation is best where velocities are largest. This is to be expected since measurements at these low velocities are at the lower limit at which a hot wire anemometer will operate accurately.

In general, the experimental results confirmed the flow predictions made with a relatively simple computer model and therefore show the possibilities afforded by this type of flow model in design studies for controlled environments such as cleanrooms.

Computer models similar to that used in this work can be developed to give greater degrees of correlation, by including other factors into the model, e.g. 3 dimensionality, temperature effects, etc. These would however, increase run time costs, but would further help to improve design procedures.

#### Differences between Predicted and Experimental Results

The differences experienced between predicted and experimental results are attributable to two different sources of inaccuracy

- a) Measurement technique errors
- b) Limitations in the computer model

The first source of inaccuracy includes errors normally associated with hot wire anemometry, e.g. temperature drift, contamination of the measuring sensor, etc. This source also covers human errors of judgment in alignment and location of the sensor and instrument error.



The second source of inaccuracy includes assumptions made in the flow model, for example the assumption of planar flow. The assumption of planar flow was shown by experiment to be well-founded for the clean-room studied herein, but cases of more complex geometry may need to be handled somewhat differently. Greater accuracy in flow modelling is possible with more sophisticated models. Also included here are the differences in the flow model domain shape as mentioned earlier and the difference in inlet flow velocity. These are not strictly accuracy problems however, as they could be eliminated by redefining the prediction model.

## THE EFFECTS OF GEOMETRY, HEAT AND PARTICLE SOURCES ON COMPUTATIONAL RESULTS

### The Cases Considered

The computer program CAFE has been applied to a number of further configurations, in order to assess the effects of changes in various input parameters. The geometry of the clean room, inlet and outlet conditions, etc. is the same as that in the baseline test case (Run 3) apart from the changes noted below:

#### Run 7. Increased Inlet Flow Velocity: Figure 17.

Increasing the inlet mass flow rate to give an increased inlet velocity from 0.3 m/s to 0.6 m/s makes no fundamental changes to the flow characteristics. It does not improve the vertical nature of the flow at any point in the room. The absolute velocities will however be higher in the 'stagnant' region in the centre of the room, which may improve the purging effect in this region.

Run 8. Introduction of a bench: Figures 18 and 19

Placing a bench in the 'stagnant' region of the cleanroom, as shown in Figure 18 causes only a slight disturbance to the baseline flow characteristics. Obstructions of this type at other points in the room would be expected to cause greater disturbances to the flow regime.

Run 9. Introduction of a heat source: Figures 20-22

In this design study the bench top was given a 15°C elevated temperature (a heat source of approximately 2.3 KW/m<sup>2</sup>). This created a large region of low velocity recirculating flow above and downstream of the bench. The main stream flow velocity is increased, but confined to the top and left hand side of the room as shown in Figure 20.

Run 10. Introduction of a source of particles: Figure 23

A source of particles introduced at a point above the bench results in the largest concentrations being experienced in the low velocity region downstream of the bench. The concentration values marked on Figure 23 are non-dimensionalized for a release concentration of 1.

### General Discussion

The results shown in Figures 17-23 have been presented in order to demonstrate the capabilities, and potential, of the computer program. Real cleanrooms will be three-dimensional, and many contain combinations of the effects studied, as well as transient effects which have not been

included here. In principle, such transient effects can be modelled, but it is felt that for many applications, steady state results can give a good indication of the type of flow pattern to be expected.

The heat source results are particularly noteworthy, and show how easily convection cells can be formed when the through-flow rate is so low. The fact that the clean air flow completely by-passes the work bench is obviously a poor design feature which could be spotted relatively easily if the model were to be used at the design stage.

The particle dispersion shown in Figure 23 assumes that the particle size is sufficiently small that fall-out is negligible. If larger particles were considered important, the program could be developed to calculate the trajectories of each particle size within the computed flow field. Combination of such computations with the inclusion of heat sources could provide very valuable information on the relative merits of different clean room designs.

## CONCLUSIONS

It has been shown that the air flow through a cleanroom may be well predicted by a mathematical model. The purpose of this paper has been to point out that such a capability exists, and the two components studied have not been refined to optimize their performance, as would happen in a full design study.

The benefits of using computational methods of flow analysis for cleanroom design may be summed up as follows:-

- prediction of flow patterns
- prediction of temperature effects
- prediction of particle flows
- bad design points picked up at design stage
- cost effective design

The disadvantages of using such an approach lie mainly in the factors of cost and time involved. However, such considerations will generally be far outweighed by the knowledge that a given design will perform up to its required standards of operation.

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2. BS5295 (1976). "Environmental Cleanliness in Enclosed Spaces, Part 1", British Standards Institution.
3. Moulton A & Dean R.B. CAFE - a computer program to calculate the flow environment. CAD80, 4th International Conference on Computers in Design Engineering, Brighton, 1980
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FLOW MODEL SPECIFICATION Table 1  
DUCTWORK MODEL

Geometry:

Length of duct (m)	12.20
Width of duct (m)	0.762
Height of duct (m)	0.940
Filter thickness (m)	0.078
Inlet duct (m)	0.7 x 0.762
Filter porosity (average)	0.0325

Fluid Properties:

Inlet mass flow rate ( $\text{m}^3/\text{s}$ )	4.25
Inlet pressure (bar)	1.00
Inlet temperature (K)	288
Inlet density ( $\text{kg}/\text{m}^3$ )	1.293
Inlet viscosity ( $\text{Ns}/\text{m}^2$ )	$1.85 \times 10^{-5}$
Inlet velocity (m/s)	7.96

FLOW MODEL SPECIFICATION Table 2  
CLEANROOM MODEL

Geometry:

Width of room (m)	9.011
Height of room (m)	2.825
Inlet Filter size (m)	1.247 x 0.623
Gasket separating inlet ducts (m)	0.003
Distance between centres for inlet ducts (m)	0.626
Size of dead space in roof (m)	0.122
Height of outlet duct (m)	0.450

Fluid Properties:

Inlet air velocity (m/s)	0.3
Density of inlet air ( $\text{kg}/\text{m}^3$ )	1.293
Inlet pressure (bar)	1.0
Viscosity of inlet air ( $\text{Ns}/\text{m}^2$ )	$1.83 \times 10^{-5}$
Inlet air temperature (K)	288

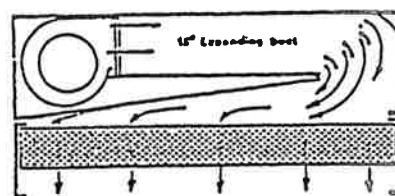
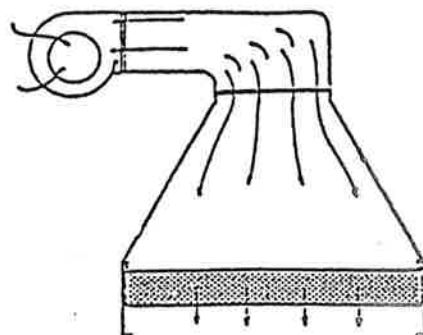
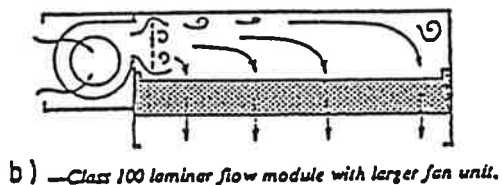
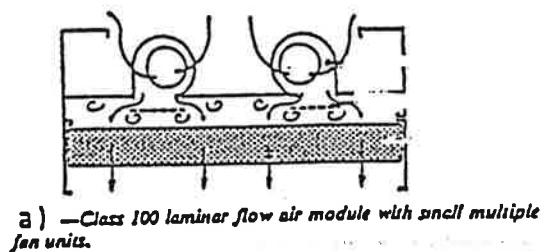


Figure. 1 Proposed filter plenums

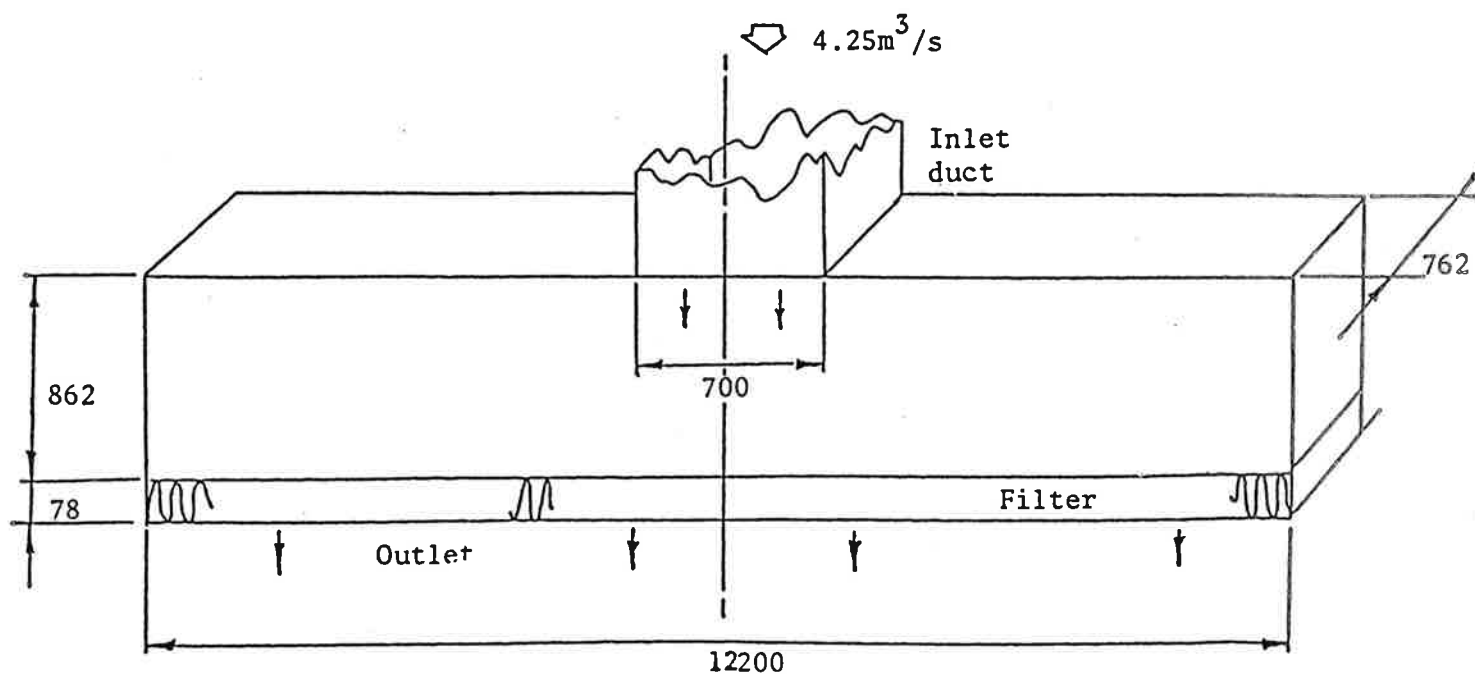
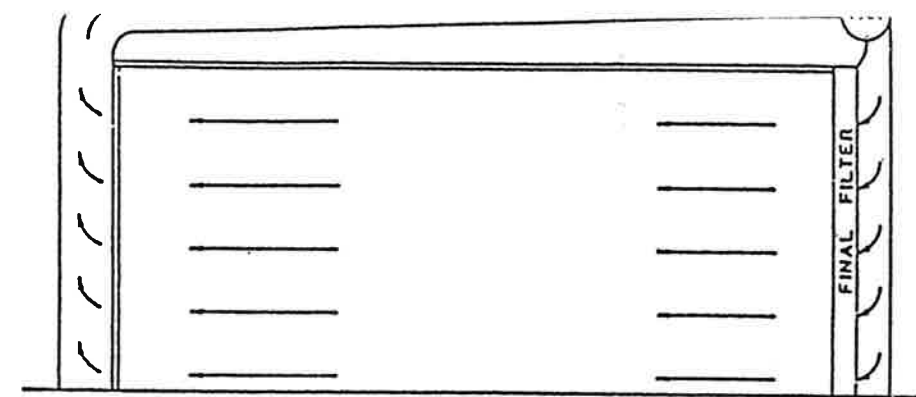
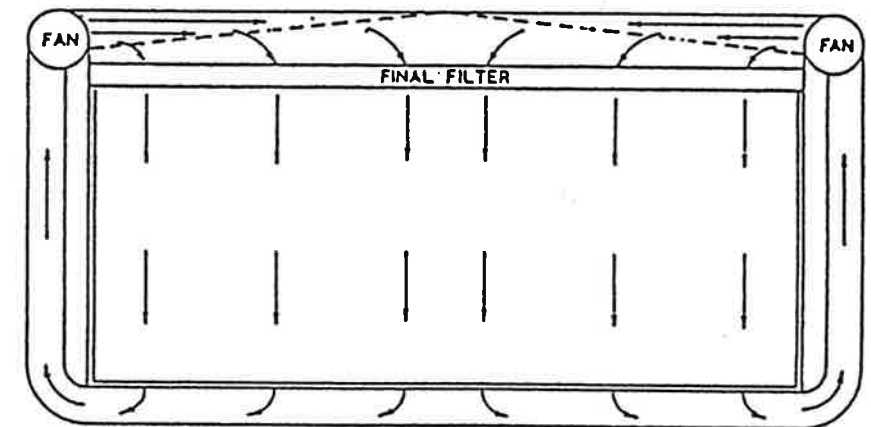


Figure 2 Geometry of supply ductwork model

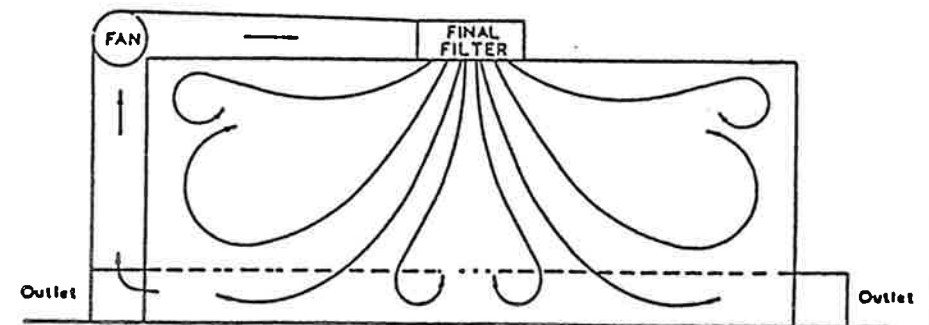
-not to scale  
-all dimensions are  
in mm.



(a) Unidirectional horizontal flow clean room



(b) Unidirectional vertical flow clean room



(c) Conventional flow clean room

Figure 3 Diagrams showing typical air flow

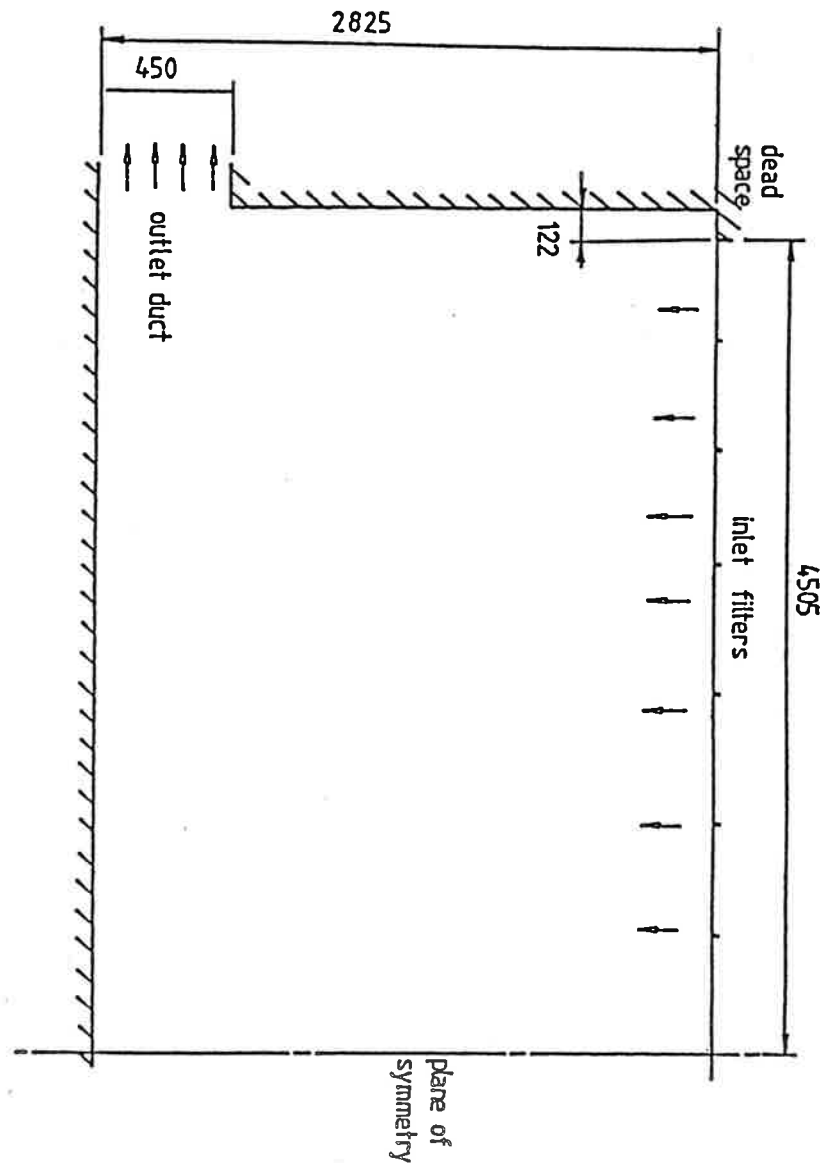


Figure 4 Geometry of cleanroom (baseline design).

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-all dimensions are in mm.

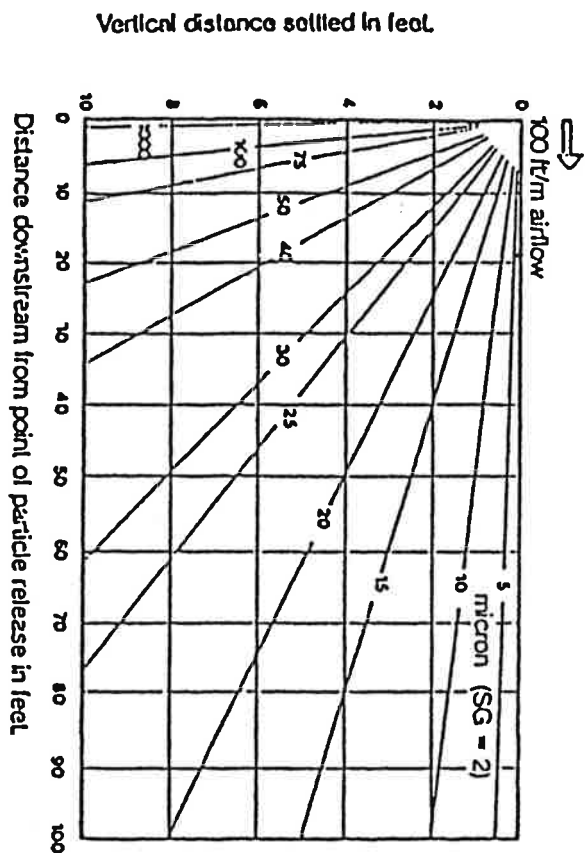


Figure 5 Particle fallout curves

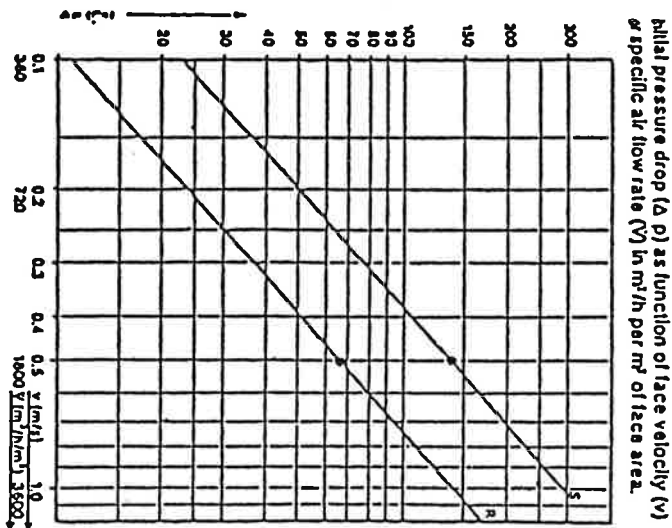


Figure 6 Filter manufacturers flow characteristics (s-type)



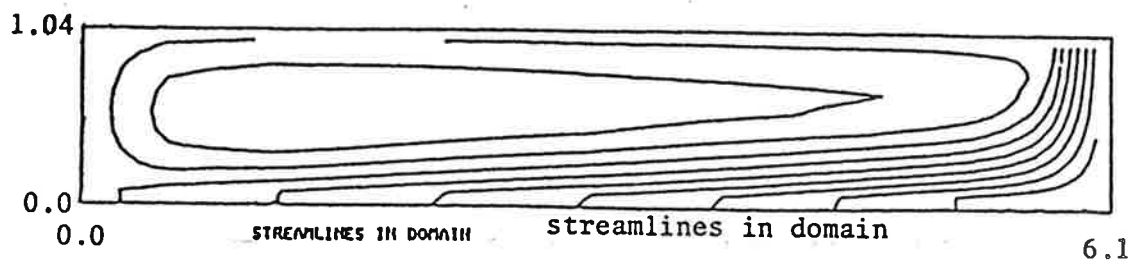


Figure 7 Baseline test (run 1)

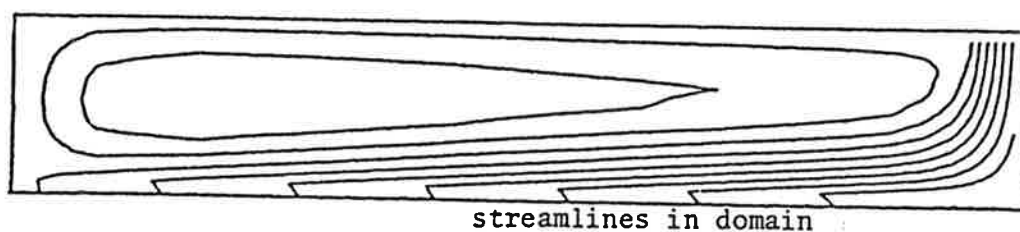


Figure 8 Test case 2 (run 2)

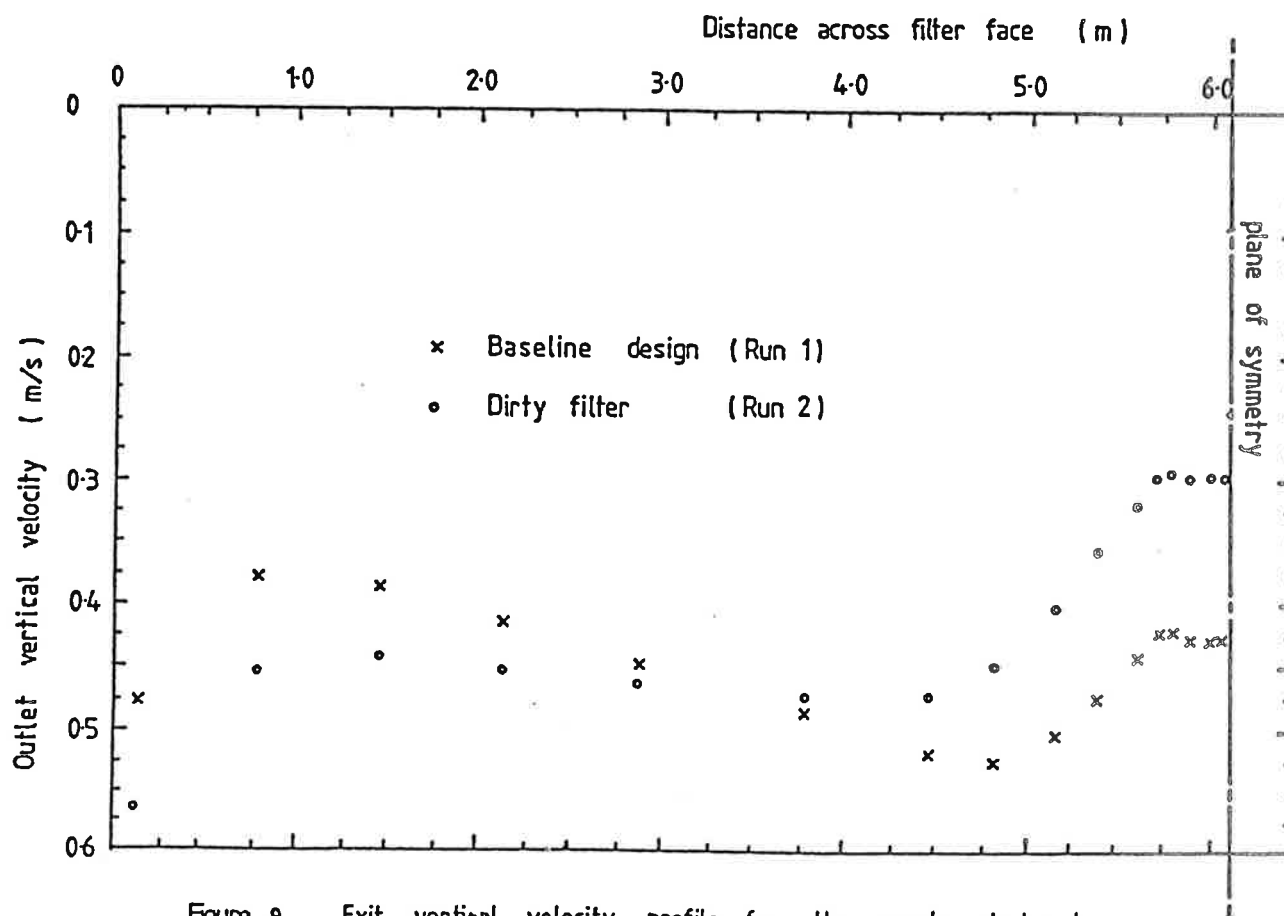


Figure 9 Exit vertical velocity profile for the supply ductwork

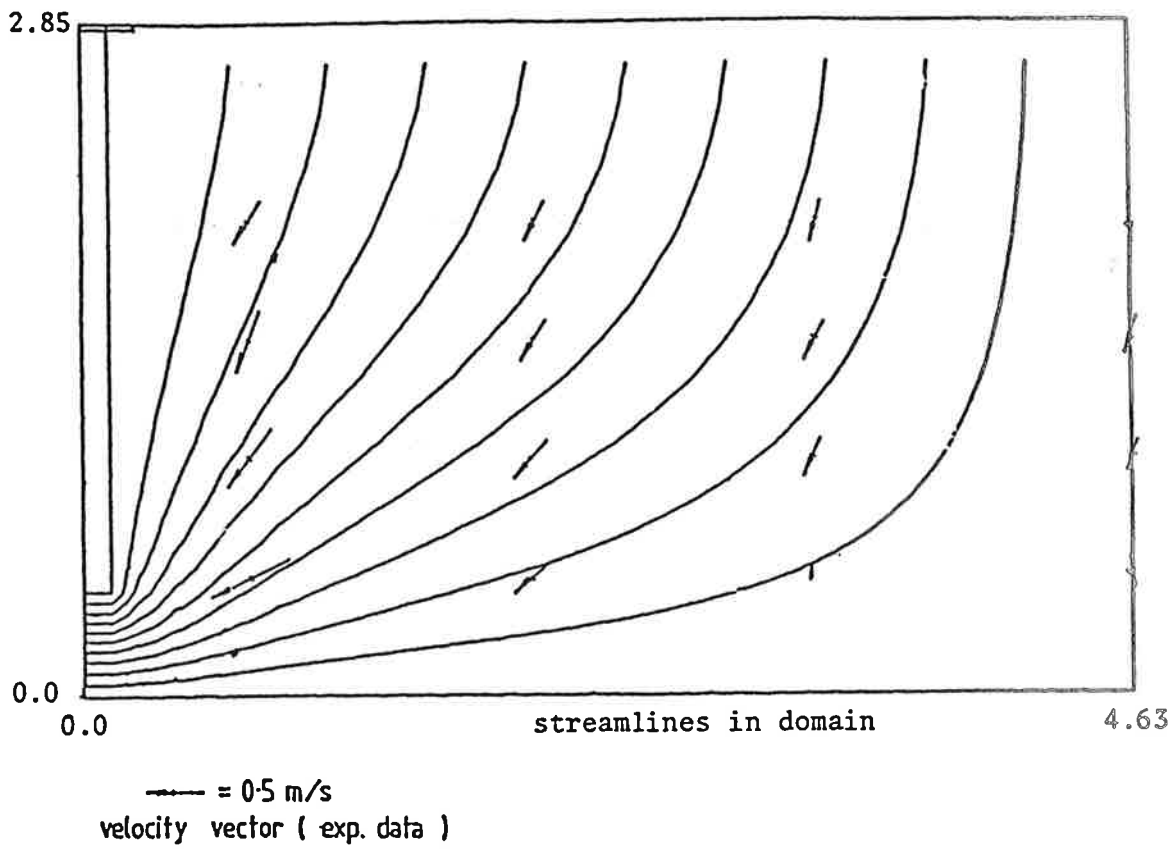


Figure 10 Baseline test case with experimental results

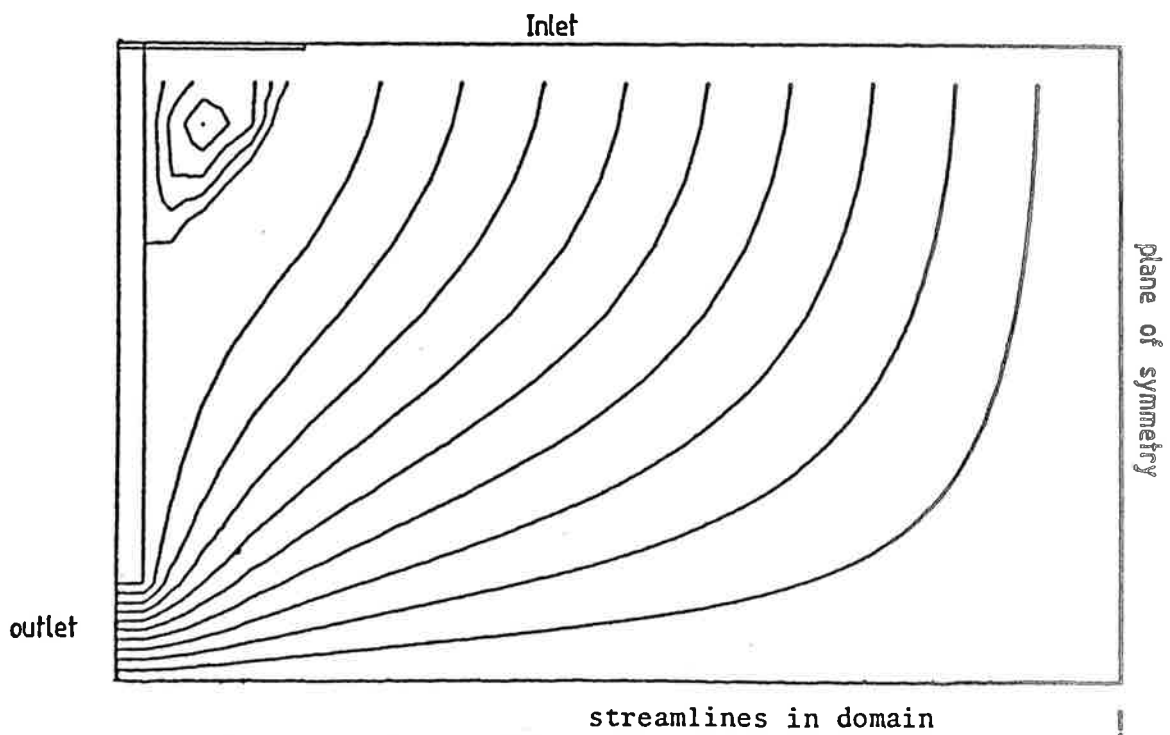
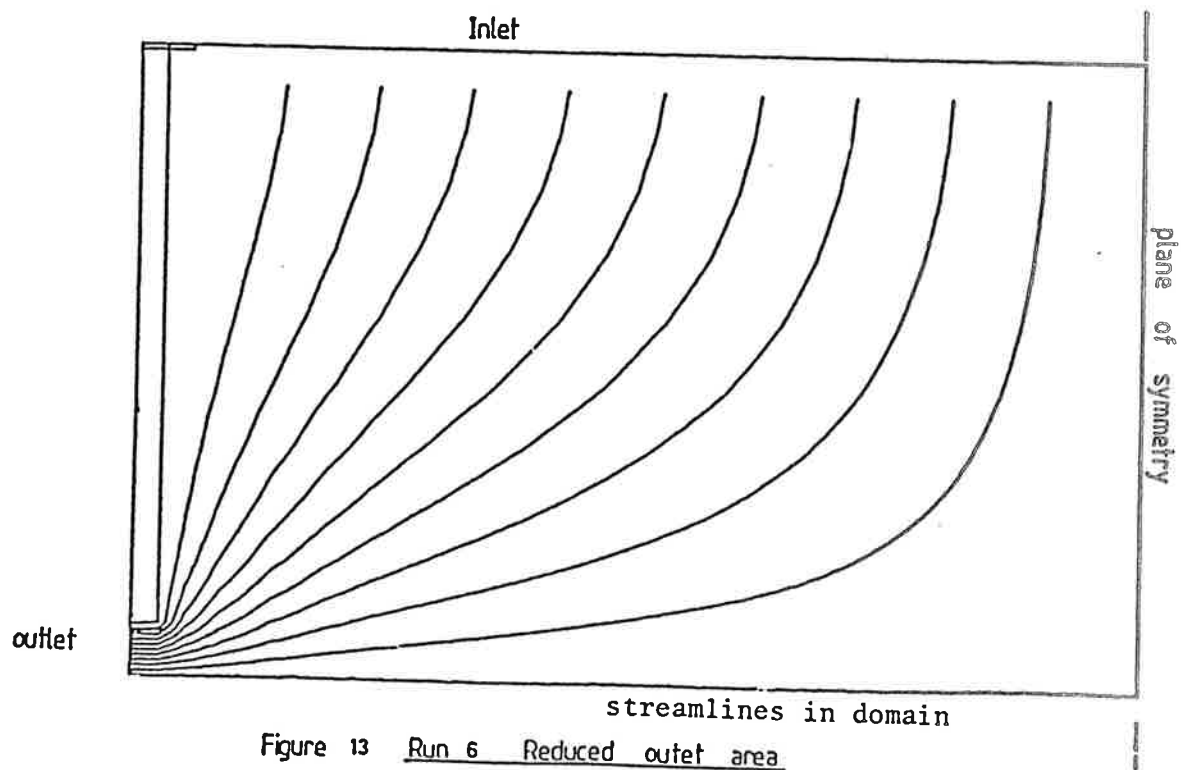
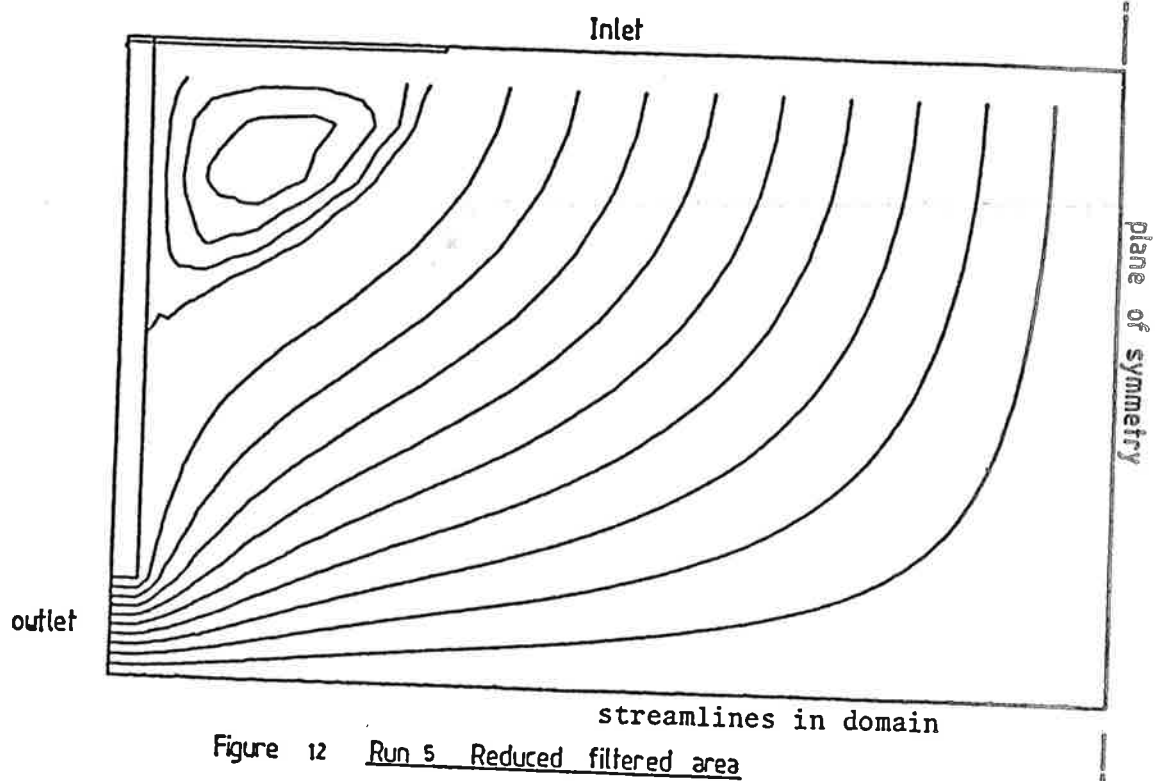


Figure 11 Run 4 : Reduced filtered area



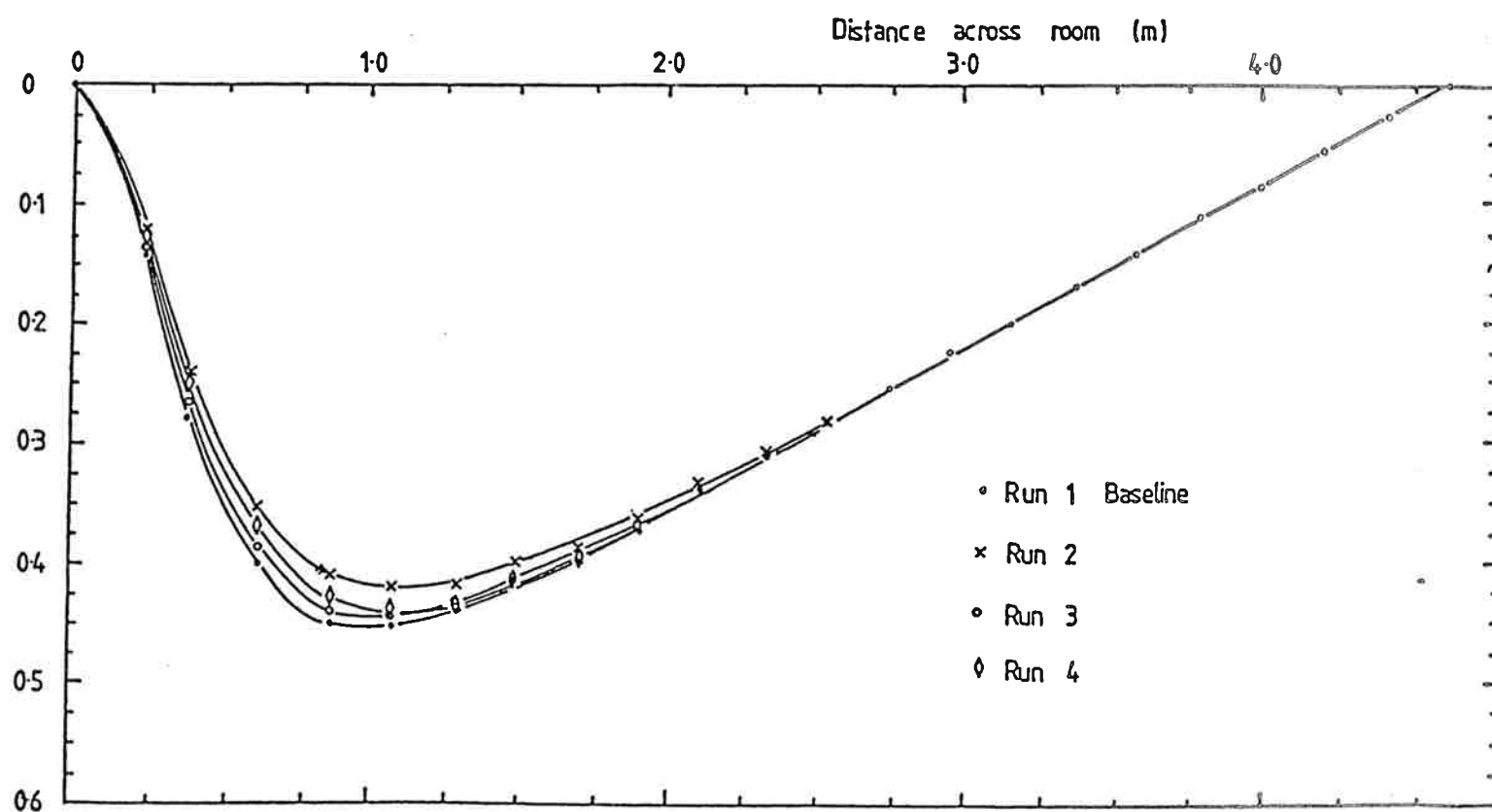
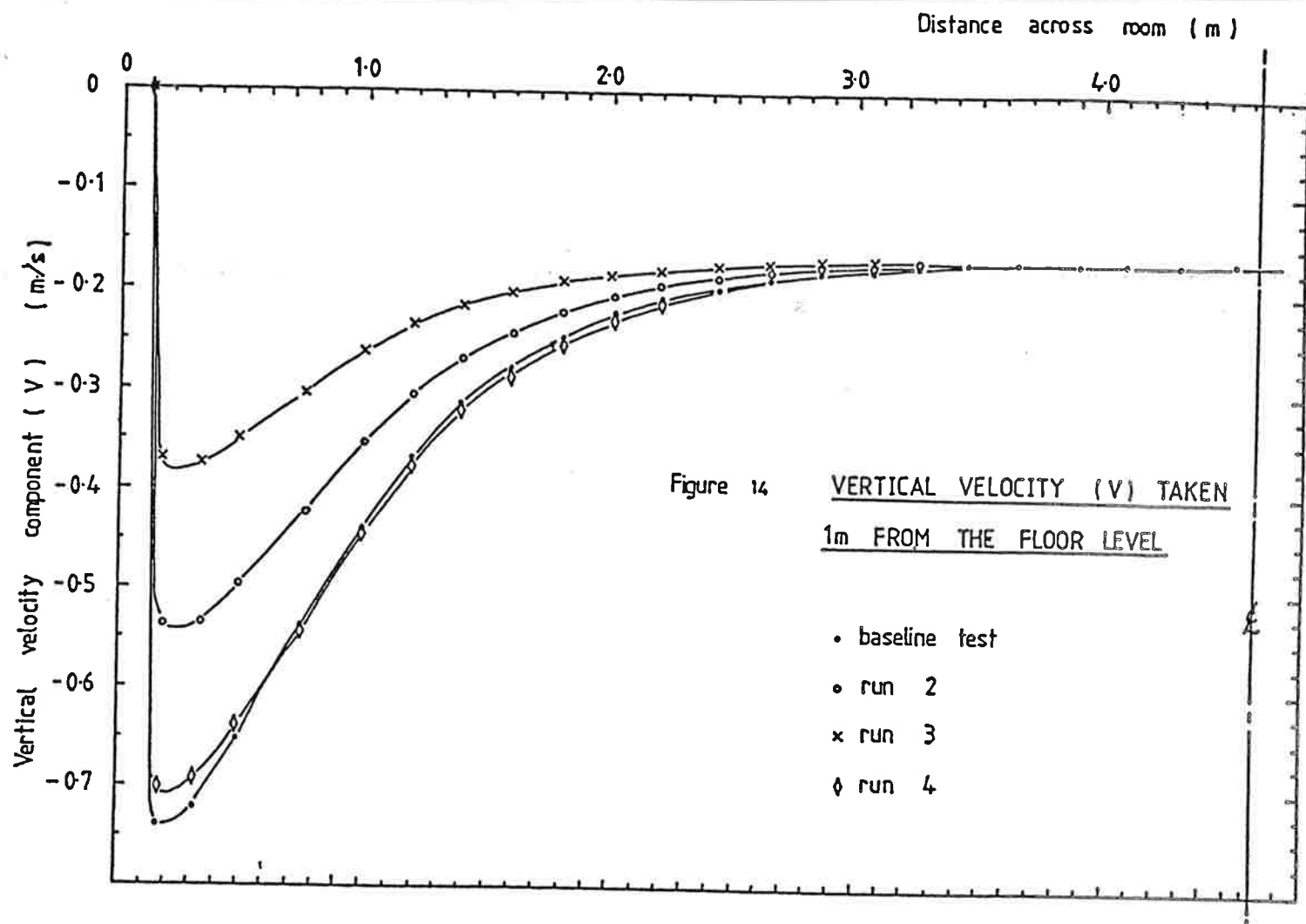
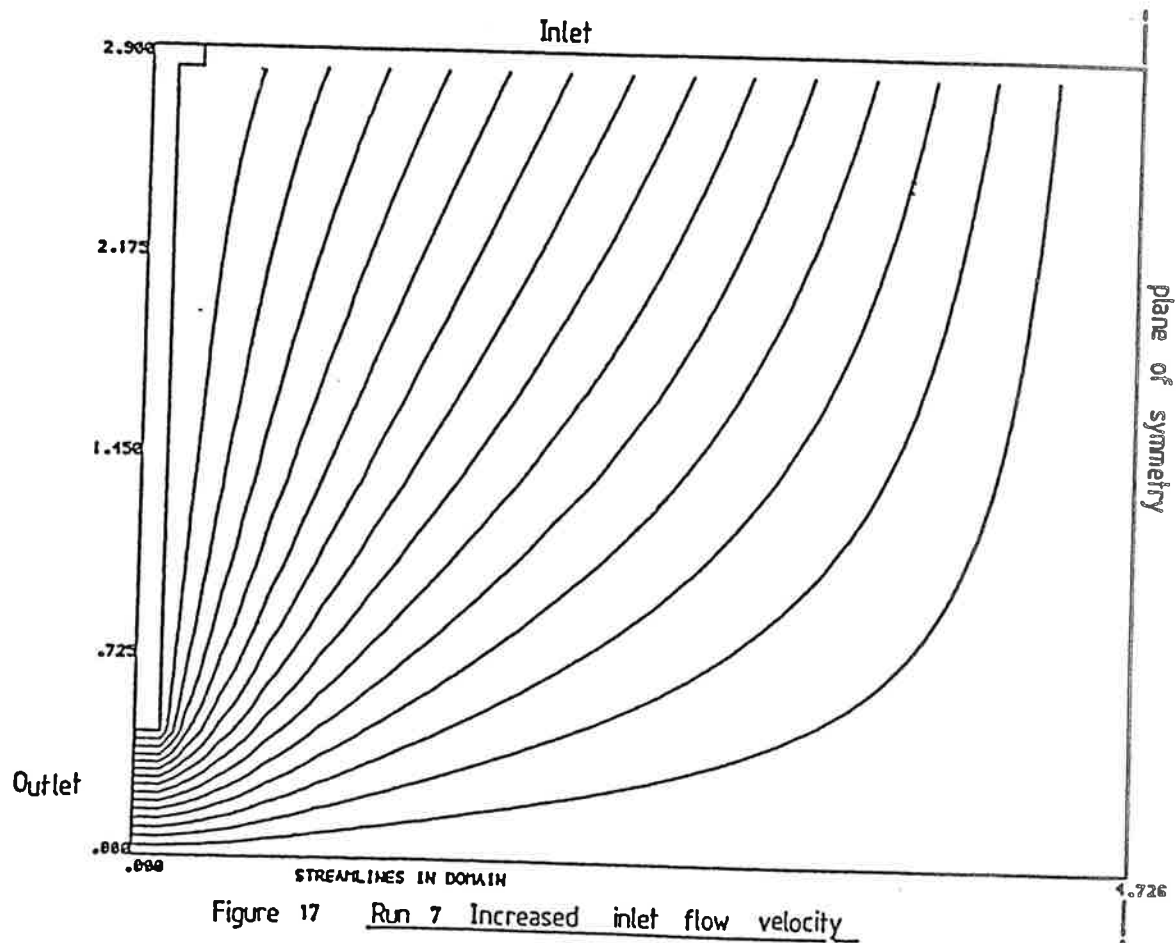


Figure 15 Horizontal velocity taken 1m from floor level



Figure 16 Photograph of helium bubbles



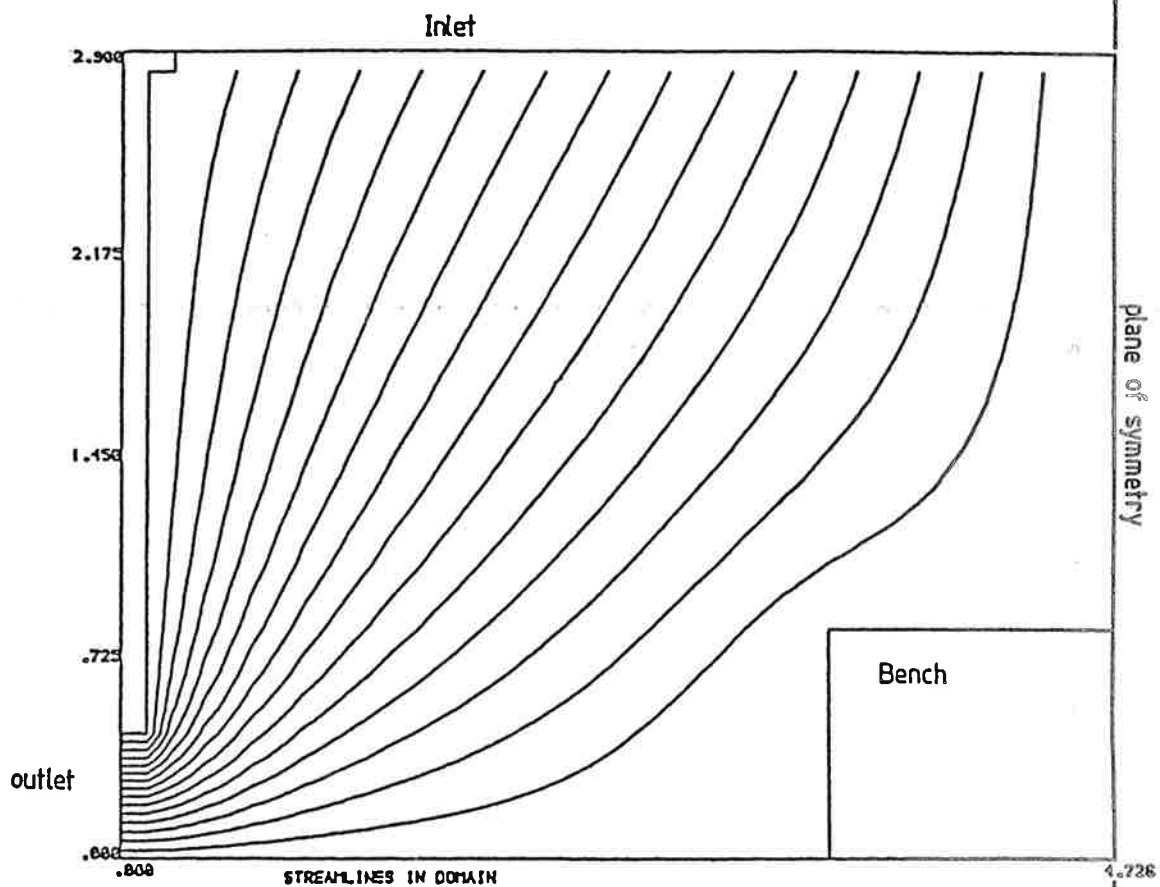


Figure 18 Run 8 : Introduction of a bench

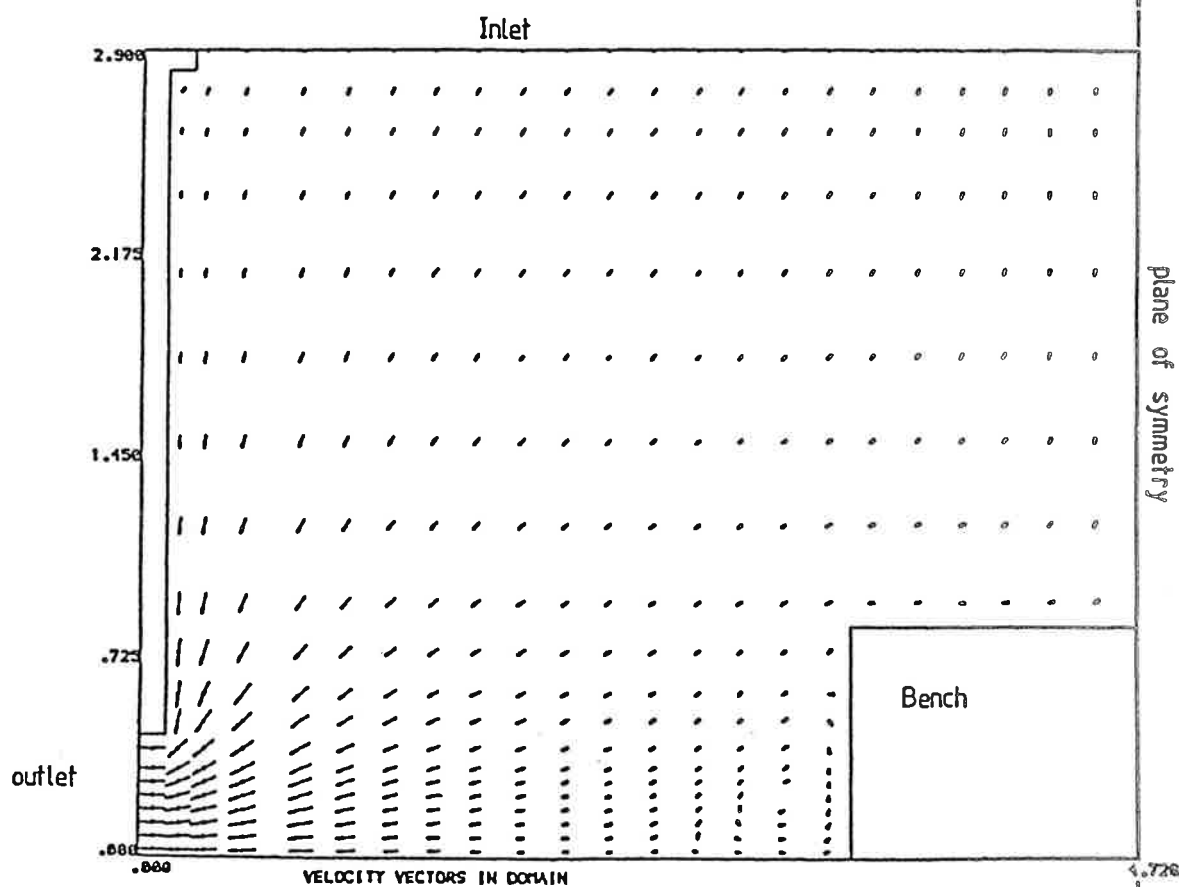


Figure 19 Run 8 : Introduction of a bench

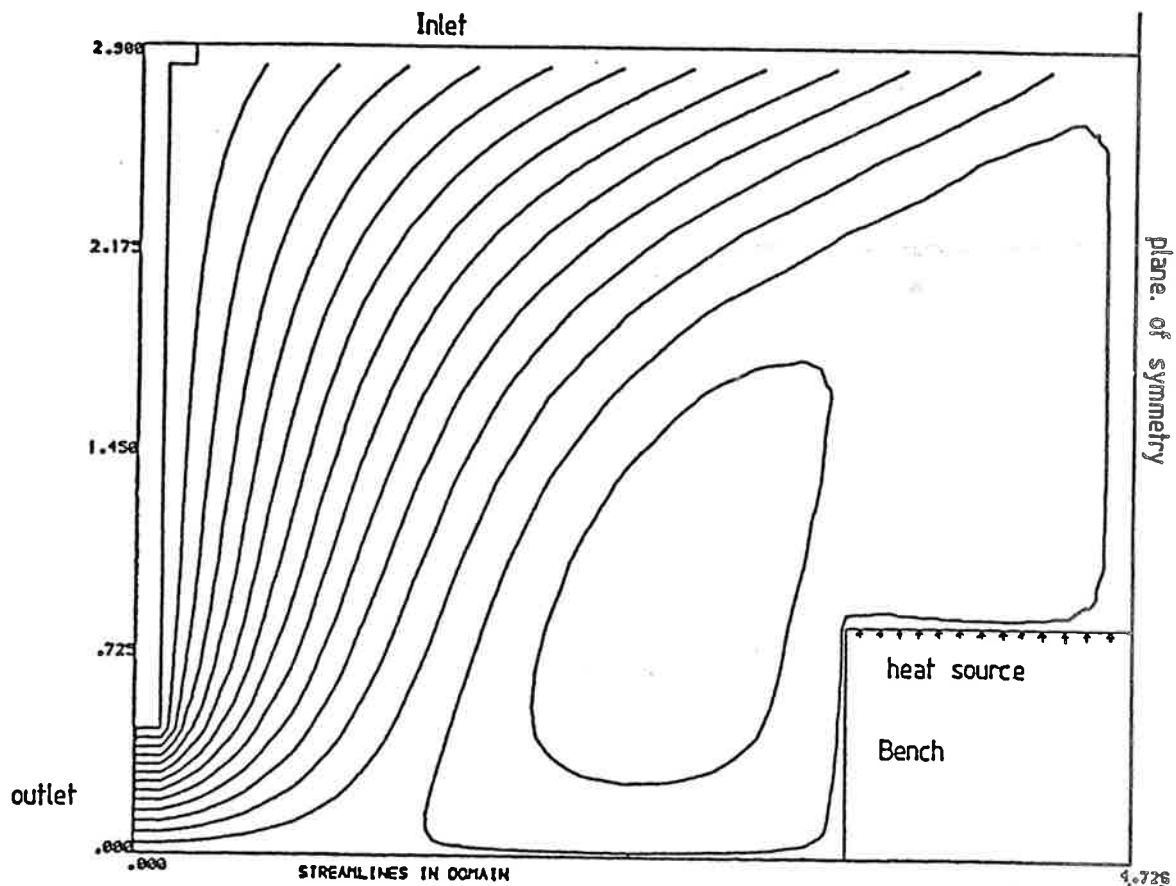


Figure 20 Run 9: Introduction of a heat source

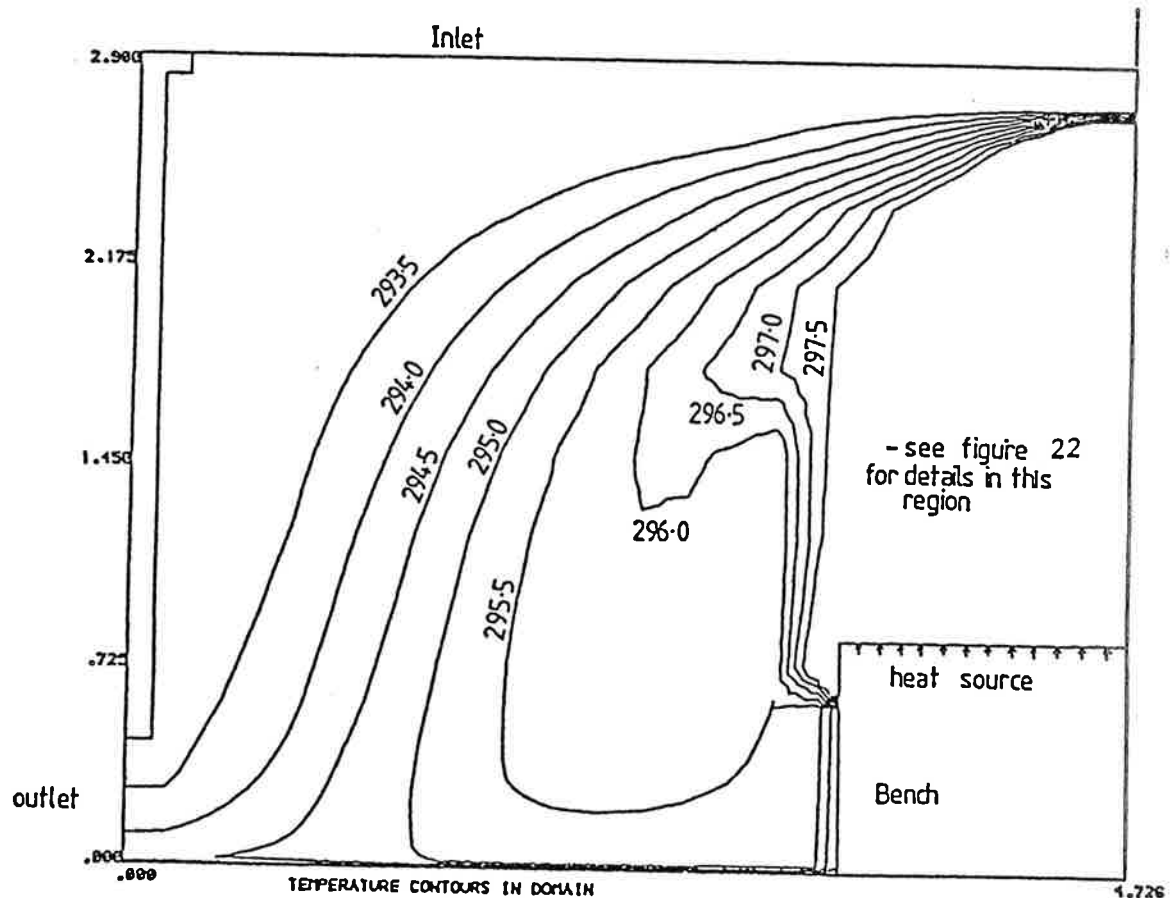


Figure 21 Run 9: Introduction of heat source

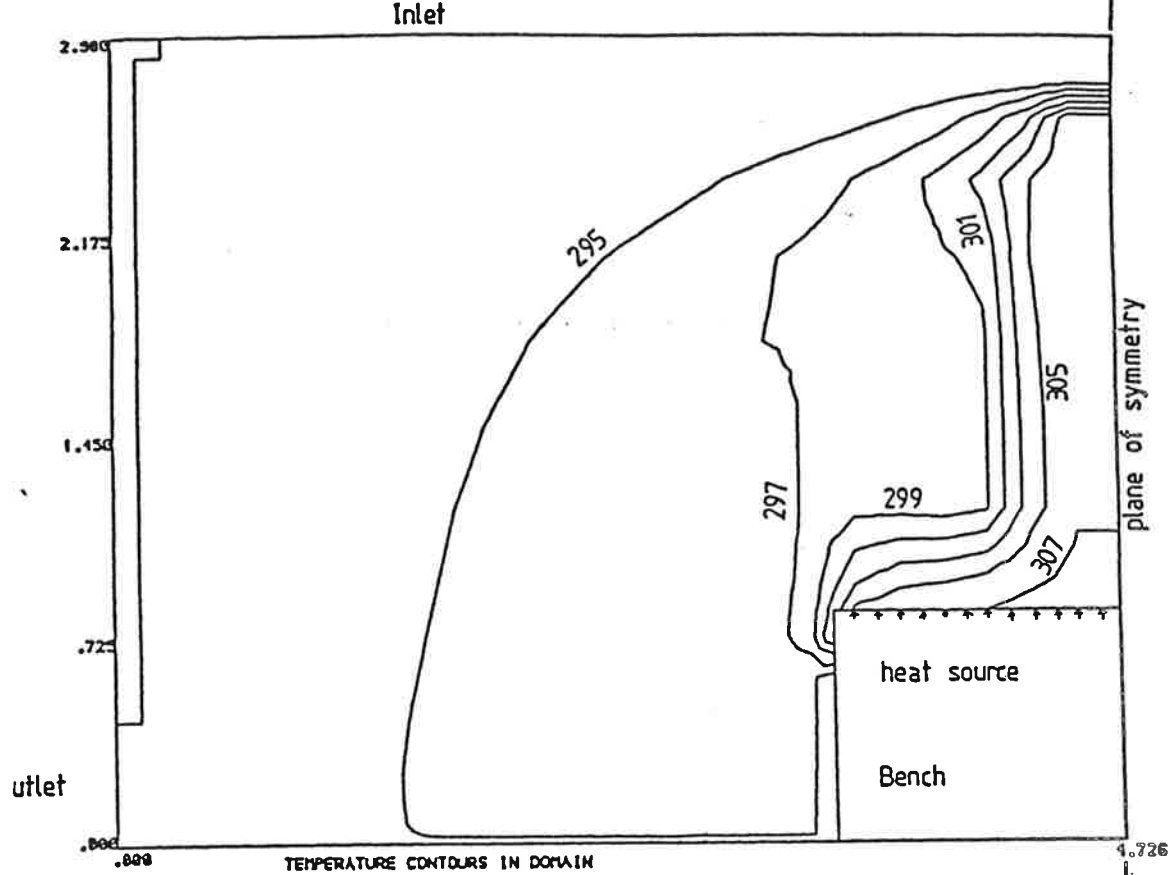


Figure 22 Run 9 : Introduction of a heat source

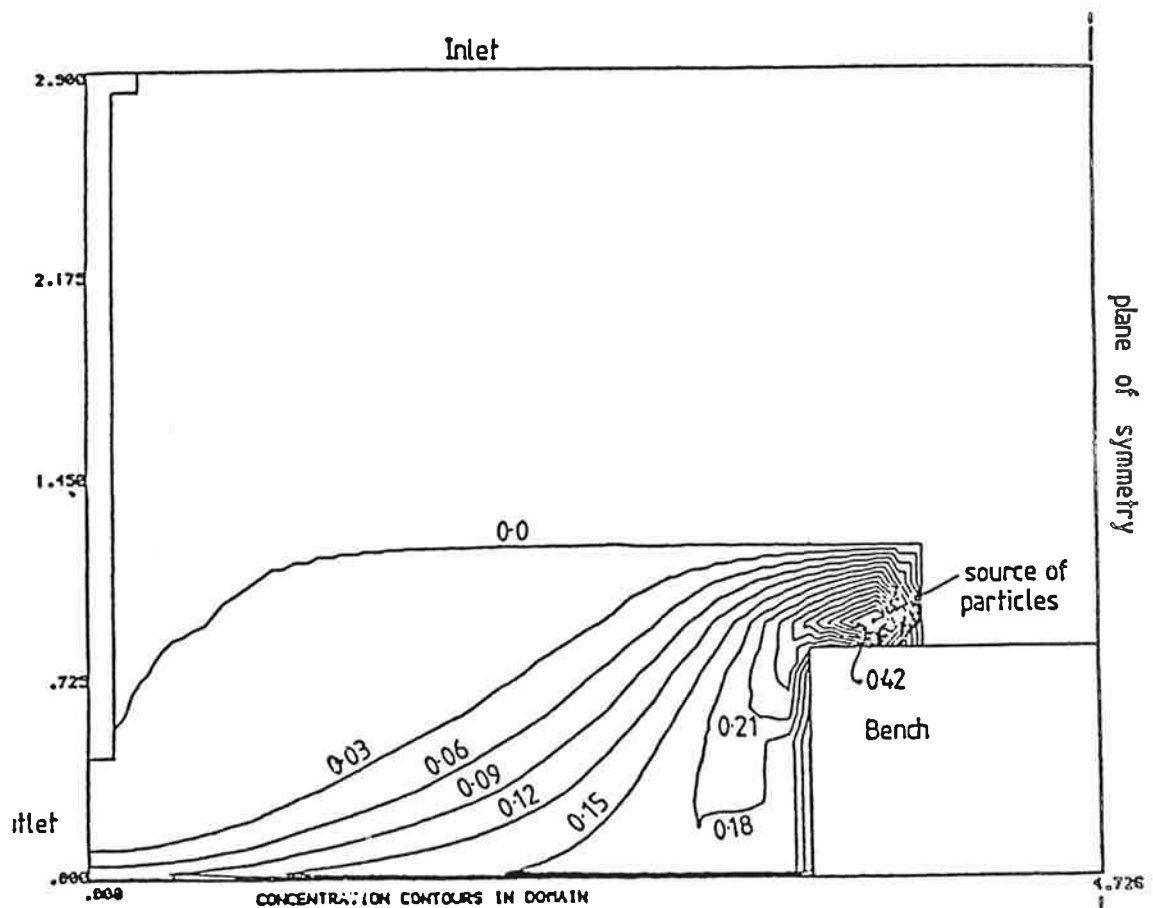


Figure 23 Run 10 : Introduction of particulates