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Air Movement Studies in a Large Parish Church Building

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ABSTRACT

This paper presents a trial of applying a CFD package into an air movement study in an old English church. The possibility of adopting computational modelling in a complex shaped building has highlighted the problem encountered due to the large difference in scale between thermal elements and building enclosure. The results have demonstrated that there are still significant problems to be overcome in using CFD models in such situations.

1. INTRODUCTION

For several years there has existed thermal and ventilation problems in old English Parish Churches. Unsuitable heating systems and cold air currents experienced in these buildings are regarded as being the two main problem areas which result in uncomfortable internal thermal conditions being experienced by the occupants [(1)]

Solutions to these problems have not yet been fully established partly due to a lack of financial support and also to the difficulty of applying new technology to buildings of historical value. Mainly because of the second reason it is important to understand the air flows and temperature patterns prevailing in such buildings and to investigate a range of solutions using computing tools prior to installing new system systems or altering the building fabric.

This study into the air movement patterns found in an old English Parish Church, is an attempt to understand the problems faced by such buildings and to develop a CFD Model which is capable of dealing with them.

The CFD software chosen was FLOVENT as this particular model was specifically designed to deal with buildings.[(2)] FLOVENT is a commercially available programme and it is not intended in this paper to deal in detail with the theory behind the model. Issues regarding setting up the building will be explained in the following sections.

2 SPECIFYING THE PROBLEM

The building being modelled is the Parish Church in Dronfield Derbyshire which was founded in 1135 AD. This Church is unusual in that it has a large Chancel compared to the Nave. From the modelling standpoint, the interior of the church can be divided into two spaces connected by an arch 6 metres high. The Chancel has an area of 145m^2 with a pitched roof 14 m high. The other main space consists of the Nave, South Aisle and North Aisle. The highest point of the Nave roof is 11.5 metres. The aisles have shallow pitch lean-to roofs which are 6 metres high on average. There is no apparent thermal insulation anywhere on the roofs. The stone external walls have a thickness of 0.3 m . Except for six upper clerestory windows, all other windows are 1.2 m in width and 3.6m in height, the largest is in the east end of Chancel which is 5.5m wide and about 8.9m high. The heating system is a single pipe radiator system using cast iron pipes. A schematic layout of the church is shown in Fgure 1.

2.1 SETTING THE GRID

As it was intended to simulate the building operating under the influence of wind pressure, it was necessary to include in the grid structure the small cracks around the windows.(3) This meant that the grid structure had to be very fine at specific points, which resulted in the body of the church having a mixture of fine and course grids.

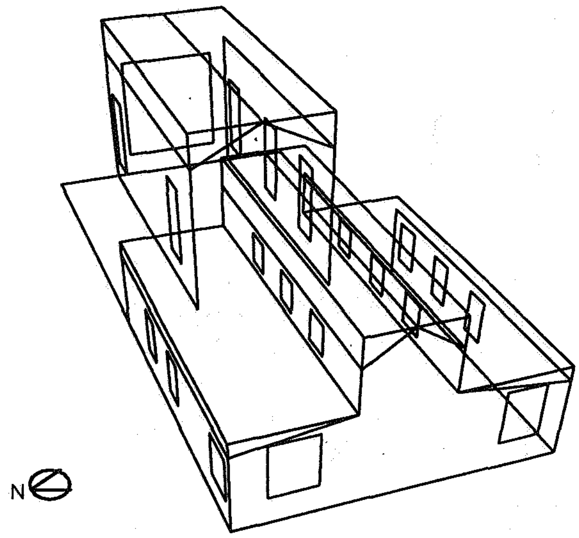


Figure. 1 The Final Model of the Church

The 3D grid structure used to simulate the performance of the Church had some 104,448 cells which took a significant amount of time to reach convergence. The finer the grid structure the greater the accuracy in establishing the temperature and flow fields. This is also true of the boundary conditions which require a fine mesh to give accurate solutions.

2.1.1 Grid Sizes

In order to investigate the effect of grid size on the accuracy of the solution three grid systems varying cell sizes were used in a 2D model of part of the Church. The section chosen included a radiator and a window. The cell sizes in the three grid systems used were $2.00*10^{-2}m^2$, $1.33*10^{-2}m^2$ and $1.00*10^{-2}m^2$

Figure 2 shows the results of the analysis for mesh size $1.33*10^{-2}m^2$ and $1.00*10^{-2}m^2$. It can be clearly seen that with the fine mesh size a more accurate solution can be found . The small grid size allows a more accurate solution of the convective heat transfer at the radiator surface to be achieved(4).

Figure 3, which shows the effect of grid size on the air velocity also indicates that a fine mesh size appears more accurate.

3. RESULTS OF THE FULL ANALYSIS

3.1 THE EFFECT OF WIND SPEED

The 2D model of the building was simulated for two different wind speeds, 2 and 4 m/s in order to establish the likely temperature and flow patterns. The wind direction used was the prevailing direction (south west). The cracks around the windows were simulated by openings with very small value of FAR (free area ratio) within FLOVENT. For a solution to be reached it was necessary to convert the wind speed into an equivalent pressure drop across the openings.

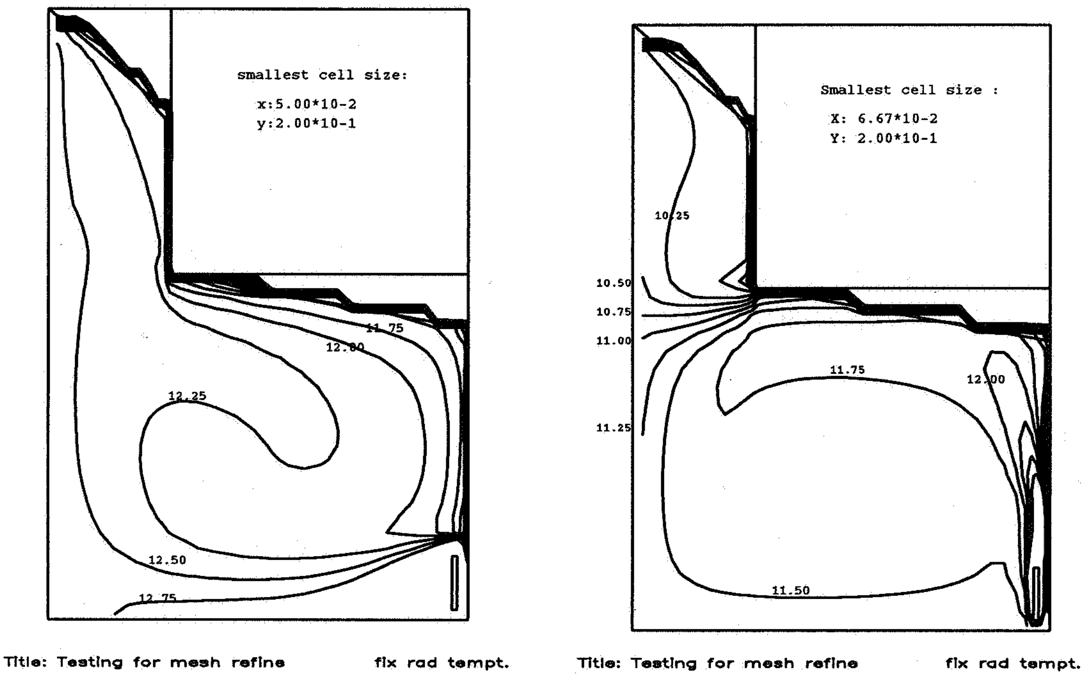


Figure. 2 Solutions of temperature field in 2D half-section from two different grid system
a) Temperature contour using medium size cells b) Temperature contour using fine grid.

Table 1 shows the results of this analysis. It can be clearly seen that as the wind speed increases the air flows across the window increased which was consistent with what would be expected.

Crack location	ΔP=0.48	ΔP=1.92	ΔP=4(lower), 8(upper)*
Upper right	- 2.3*10^{-3} / 8.3	4.8*10^{-3} / 5.0	1.2*10^{-2} / 5.0
Lower right	4.7*10^{-3} / 5.0	9.2*10^{-3} / 5.0	1.5*10^{-2} / 5.0
Upper left	-4.9*10^{-3} / 8.4	-7.1*10^{-3} / 8.2	1.3*10^{-2} / 8.0
Lower left	-4.2*10^{-3} / 10.8	9.0*10^{-3} / 10.5	1.4*10^{-2} / 10.3 **

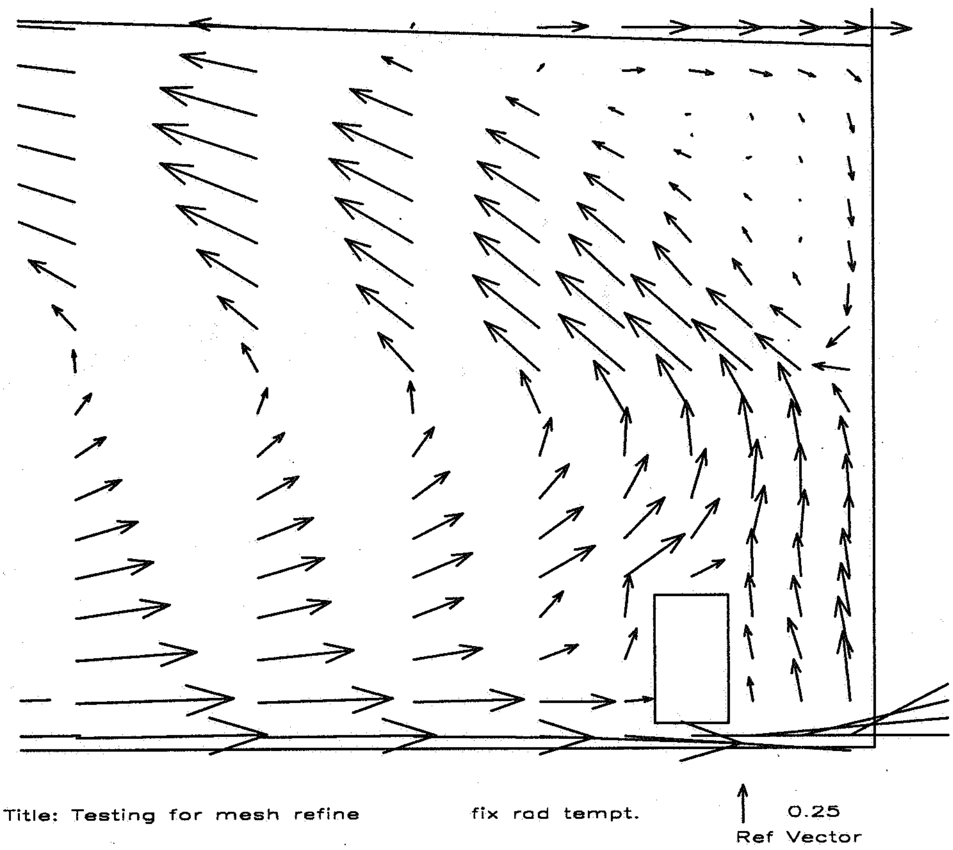
* Unit of Pas and WPC are set to different values, hence higher pressure difference value for crack on upper windows.
F.A.R (free area ratio)= 0.002
** Air flow rate(kg /m^2 s) / air temperature (°C)

Table 1 Air Flow Rates and temperature of the air through the cracks when pressure difference varies due to wind speed.

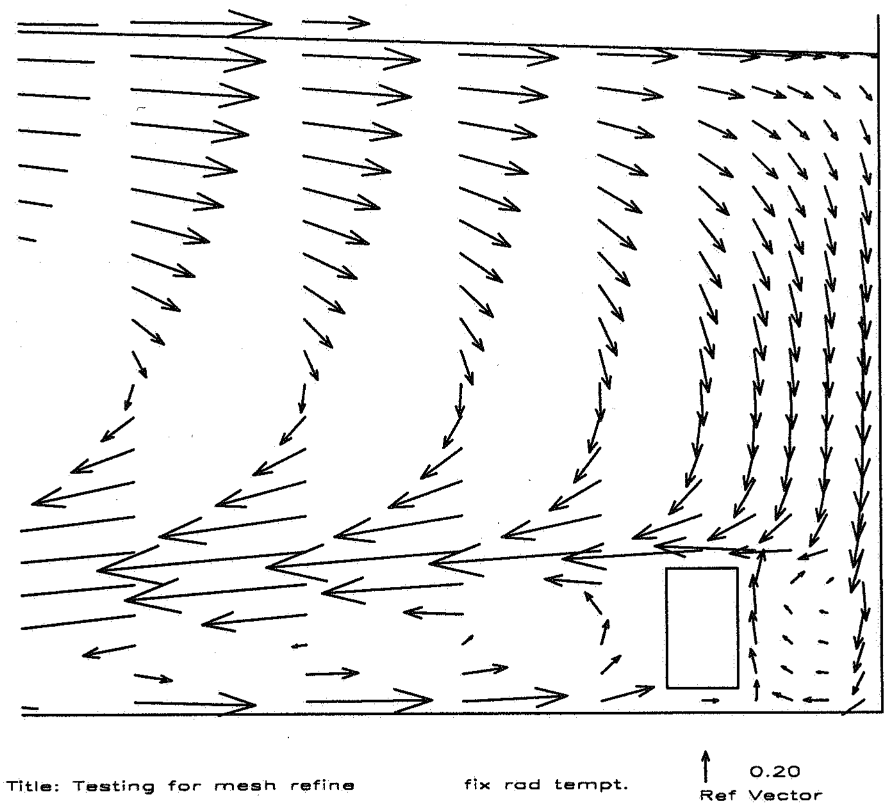
3.2 THE EFFECT OF WIND ON 3D MODEL

3.2.1 Input Parameters

A complete 3D model of the church was set up including all existing windows and radiators. As the flow field is subject to indoor temperature distribution and outdoor infiltration. Two typical cases were simulated to study the field dominated by either infiltration influence due to a high wind speed or buoyancy forces due mainly to free natural convection. For the former condition, the pressure difference across the six upper clerestory windows was set to 8.0 Pa

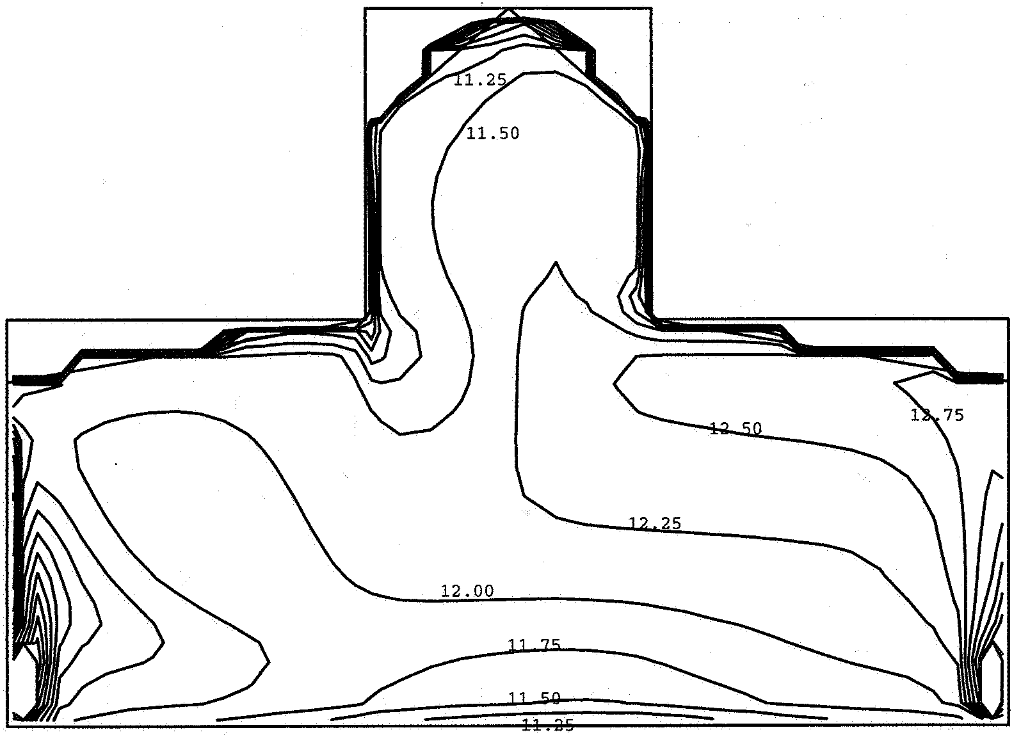


a) Air-movement around radiator, grid system with medium size cell



b) details around radiator when finer grid applied

Fig. 3 Solutions of vector field in 2D half-section from two different grid sustem



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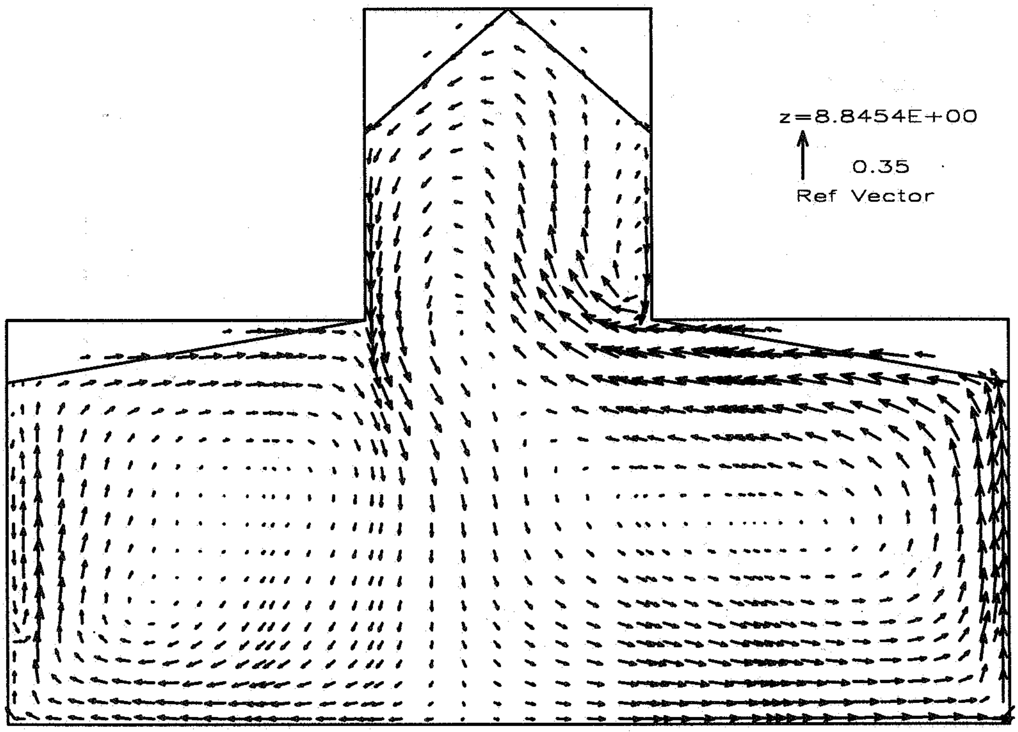
a) Temperature contour



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b) Air movement, vector field

Fig. 4 Solutions on plane XY, z=8.5m. A cross section of aisles and nave . Side radiators, windows and upper clerestory windows are included.

and other windows to 4.0 Pa. The wind at speed chosen had a velocity of 2.0m/s. from the south-west:

3.2.2 Results

The calculated temperature is higher in the case when there was less infiltration than when the wind was strong. The average difference in temperature at the monitor points was 0.3°C. Table 2, shows air flow rates through cracks and their temperature under the two condition. Although the buoyancy effects always exist, infiltration due to wind pressure will become a more important factor which affects both temperature and velocity.

		Buoyancy Dom.		Wind Pres. Dom.	
	Crack location	Air flow $*10^{-3}$ kg/s	Temp. °C	Air flow $*10^{-3}$ kg/s	Temp °C
1	S. lower	4.60	11.2	-11.37	5.0
2	S. upper	4.20	11.5	-7.36	5.0
3	N. upper	5.35	11.8	9.74	11.6
4	N. lower	8.46	12.6	14.20	12.4
5	west window	13.17	12.3	-30.83	5.0
6	East wd	68.33	10.0	122.11	9.83
7	S. of Chancel	11.84	9.6	-21.89	5.0
8	N. of Chancel	18.82	9.7	29.99	9.5

1,2,3 & 4 on Plane XY, Z= 8.5m. 7,8 on plane XY, Z= 22m

Table 2 **Mass flow across cracks driven by the force dominated by natural convection and by natural convection and infiltration caused by wind pressure together. Air flow in(+) and out(-) of cracks and its temperature.**

Figures 4 and 5 shows both the temperature and velocity field in two cross sections including side and clerestory windows and radiators. It can be easily seen that the air near to the window on the left side was cooled by infiltration. The radiator underneath the window creates an up-draught which improves the temperature at ground level. Unfortunately in the real church not all windows have radiators installed underneath, thus unpleasant cold draughts are inevitable in winter. There is also flows from the Chancel to Nave at low level (which has been noted in the church)

4 CONCLUSION AND FURTHER WORK

The trial mentioned above has shown that installing radiators right under the windows is more likely to solve the problem of cold down-draught in winter, consequently improving the indoor thermal environment. The promising result indicates that further research and development in the area of thermal remedial measures for old buildings by computer simulation is worthwhile.

The most interesting point to be gained from the work is to improve the software's grid generating function. Although it is possible to establish a uneven mesh in calculation domain with FLOVENT, all grid lines dividing the domain into cells are required to extend across the whole solution domain (Figure. 6a-b). This grid system is quite capable in dealing with most common problems such as rooms in offices, hotels and houses where there is simple enclosure and not significant difference in scale due to heat emitters and other elements.

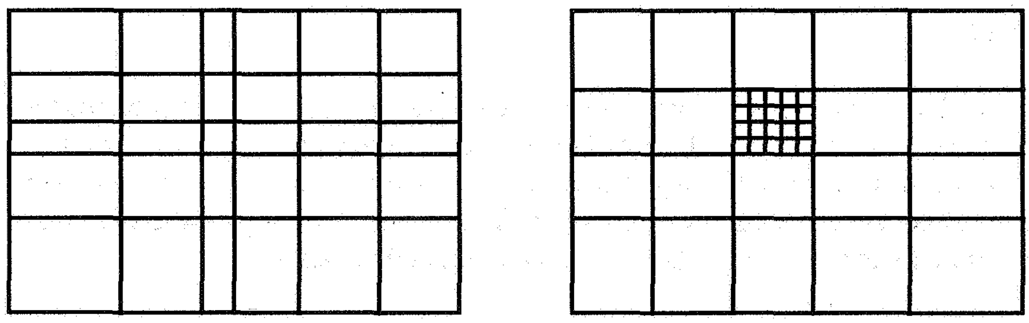

Figure .6 a) Grid in Domain of FLOVENT b) Grid in Local Grid-refinement System

However, for large enclosures such as described above a finer mesh is necessary for accurate flow and natural convection calculations. To avoid generating too many cells to solve within a tolerant time period, two alternatives for conventional single-grid system have been studied in, Grid Patching and the Local Grid Refinement Method. The main idea behind the methods is that the whole domain can be divided into several sub domains where grids with different sizes can be adapted according to the either object's size or Rayleigh number in the area. Finer grids can result in more accurate solution and reveal more flow details in the sub domain while coarse grids given to other area save calculating time(5). These method benefit such problems when an irregular shape is involved and spaces are required to represent outdoor ambient environment. If one of the above methods were to be applied to FLOVENT, then the program way be more versatile and powerful.

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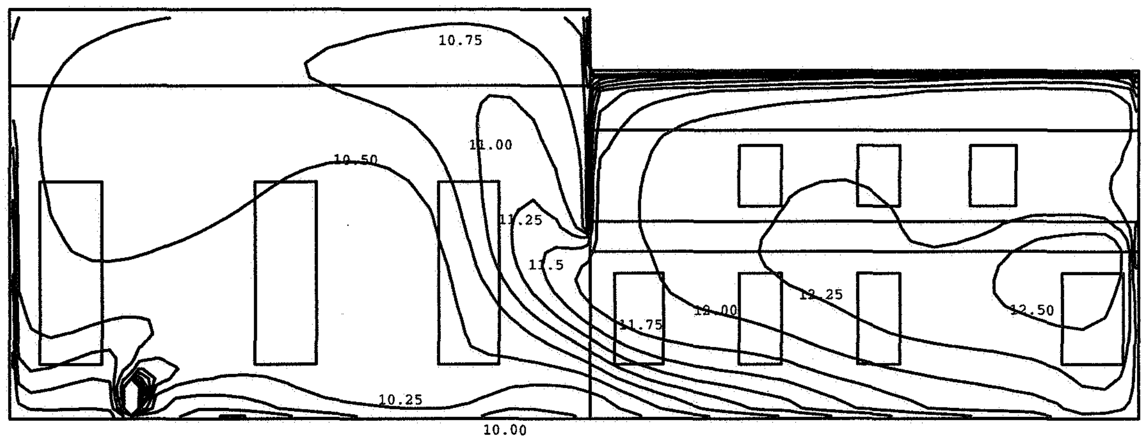

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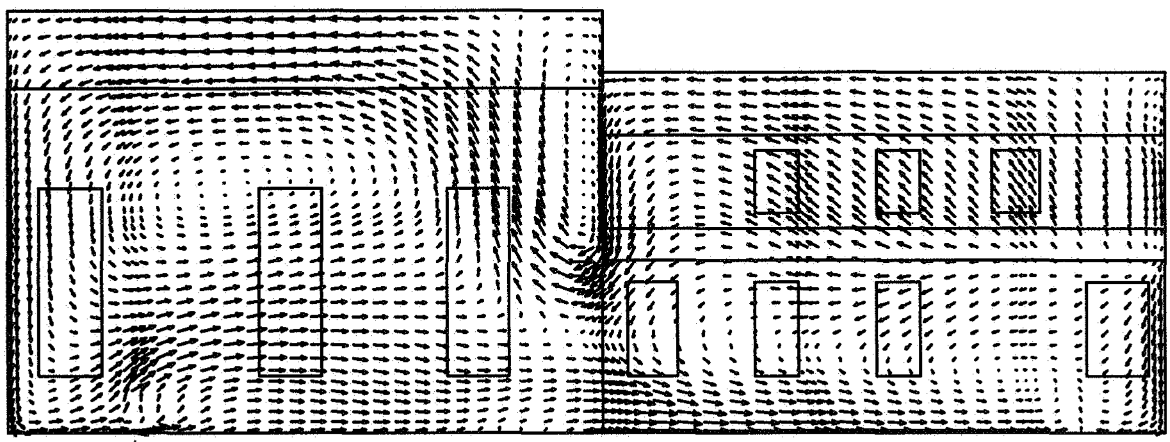
a) Temperature contour



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0.35
Ref Vector

b) Air movement.

Fig. 5, Solutions on the plane YX, X=8.0m, the central sector paralle to the symmetric axial.