Temperature and Velocity Distributions in a Church with Floor Heating in Various Seasons

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# 6th International Conference
# on
# AIR DISTRIBUTION IN ROOMS

ROOM
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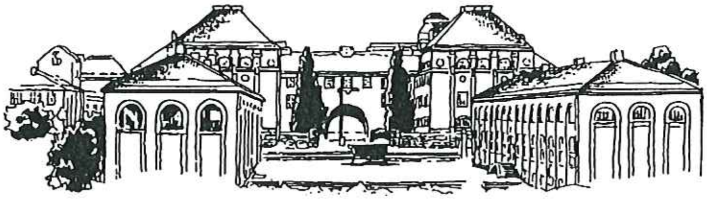
'98



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**June 14-17, 1998**

# ROOMVENT '98

## 6th International Conference on Air Distribution in Rooms
Stockholm - Sweden
June 14 - 17, 1998

## Proceedings: Volume 1

Editors:
Elisabeth Mundt
Tor-Göran Malmström

# ROOMVENT '98

Proceedings: Volume 1 of 2

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# PREFACE

It is a privilege to host the 6th ROOMVENT Conference, ROOMVENT '98, in Stockholm, Sweden. This is the principal international conference in this field.

The quantitative and qualitative control of indoor air flow is widely regarded as an important matter of public concern. It is one of the important means to control indoor climate and air quality, and it is important for energy conservation. Adequate air flow control is also essential in special fields such as clean rooms for use in high-tech industries.

New tools give new possibilities for the study of this important field. Computer simulation techniques are developing rapidly and progress is also being made in measuring techniques.

International symposia provide ideal venues for free exchange of information on state-of-the-art methodologies. ROOMVENT '98 brings together prominent researchers from universities and institutes, industrial engineers and government officials with the goal of surveying the latest techniques for analysing indoor air flow and evaluating ventilation effectiveness.

The ROOMVENT Conferences are initiated by SCANVAC, the Scandinavian Federation of Heating, Ventilating and Sanitary Engineering Associations in Denmark, Finland, Iceland, Norway and Sweden. The first conference, ROOMVENT '87, was held in Stockholm followed by Oslo, Aalborg, Kraków and most recently Yokohama in 1996.

As the ROOMVENT Conferences now enter their second decade, it is a special pleasure for those of us who arranged the first conference to again have this opportunity to welcome each of you.

We are pleased to acknowledge the valuable help received from the co-sponsoring organisations and the work of the international scientific committee, who reviewed the papers.

Tor-Göran Malmström  Elisabeth Mundt  Mats Sandberg

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## Calculations and Measurements, Heat Transfer in Rooms

# TEMPERATURE AND VELOCITY DISTRIBUTIONS IN A CHURCH WITH FLOOR HEATING IN VARIOUS SEASONS

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## ABSTRACT

In this paper the experiences carried out in a large church of Bologna equipped with a floor radiant panels heating plant are presented. High intensity air flows were measured not compatible with thermal comfort. Experimental data will form the basis for understanding and controlling thermal instabilities in very high halls.

## KEYWORDS

Natural convection, Thermal comfort, Full scale experiments, Public buildings

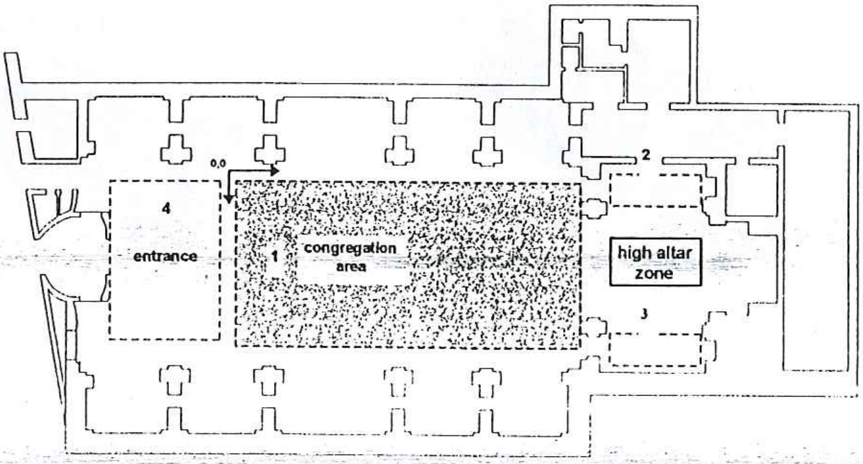

*Fig.1 - Planimetry of the Church; 1, 2, 3 and 4 are representative of heated zones*

## INTRODUCTION

Buildings used in industry are nearly always characterised by volumes and dimensions of considerable size, mainly in height, which favour the occurrence of thermal instability phenomena independently of the air-conditioning system or HVAC plants used. Indeed, the presence of temperature differences between the building curtain surfaces (floor, walls, ceilings, windows, etc.) and those relating to any internal thermal sources (lighting equipment and mechanical and electrical components) may create natural convection phenomena of great intensity.

This causes objective difficulties in controlling thermal comfort, indoor air quality and the dispersal of polluting substances.

An engineering solution commonly utilised is the installation of floor radiant panels heating systems.

Several are typical of that techniques advantages :

- a lower vertical air stratification compared with classic HVAC systems;
- reduced energy consumption on account of the low temperature of the heating fluid (35-45°C);
- absence of the obstacles due to the presence of HVAC terminal components.

This engineering typology is quite widespread in storage warehouses, in the food and electrical and electronic component industries.

However it has been noticed that those systems may cause natural convection phenomena of great intensity in tall enclosures.

It is however possible to get relevant quantitative data from non-industrial buildings characterised by comparable size where floor radiant panels are used. In fact similar effects are expected to appear in spite of different use of the buildings.

In the present circumstances a detailed measurement campaign has been carried out in a church in Bologna.

In this case high velocity current and temperature fluctuation occur during winter heating and produced very uncomfortable conditions within the church. Similar effects encountered have been noted in other churches, such as Tübingen Cathedral in Germany and the Church of S.Maria della Ghiara in Reggio Emilia.

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| S3 | 14,9 | 21,5 | 19,7 | 30,2 | 25,2 | 18,5 | 17,2 | 21,0 | 26,3 |
| S4 | 27,3 | 25,0 | 20,5 | 24,0 | 31,4 | 18,5 | 15,6 | 22,3 | 19,5 |
| S5 | 28,1 | 30,5 | 18,2 | 25,0 | 32,5 | 16,1 | 22,5 | 24,5 | 18,0 |
| S6 | 31,5 | 24,6 | 22,9 | 30,5 | 28,6 | 30,4 | 17,5 | 18,0 | 14,2 |
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| S8 | 30,0 | 28,5 | 26,0 | 25,1 | 31,1 | 18,6 | 26,4 | 29,0 | 21,2 |
| S9 | 28,6 | 27,0 | 20,0 | 28,6 | 28,7 | 26,2 | 21,5 | 27,6 | 24,2 |
| S10 | 29,1 | 21,8 | 26,1 | 27,3 | 29,1 | 27,7 | 23,5 | 33,3 | 25,4 |
| S11 | 26,9 | 23,4 | 29,1 | 24,3 | 28,0 | 28,0 | 27,3 | 29,9 | 20,5 |
| S12 | 29,1 | 32,1 | 17,6 | 26,3 | 28,8 | 31,2 | 23,1 | 27,7 | 25,5 |
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altar

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| S5 | 17,1 | 17,8 | 18,7 | 17,8 | 17,2 | 17,2 | 17,5 | 17,0 | 16,7 |
| S6 | 17,1 | 18,0 | 18,8 | 17,7 | 17,3 | 16,7 | 17,6 | 17,5 | 16,7 |
| S7 | 17,3 | 17,7 | 18,3 | 17,7 | 17,4 | 16,4 | 17,1 | 16,6 | 16,3 |
| S8 | 17,4 | 17,5 | 18,5 | 17,7 | 17,2 | 16,9 | 17,2 | 16,5 | 16,3 |
| S9 | 17,2 | 17,7 | 18,4 | 17,7 | 17,2 | 16,7 | 17,2 | 16,5 | 16,2 |
| S10 | 17,1 | 17,6 | 18,1 | 17,7 | 17,2 | 16,4 | 17,1 | 16,3 | 16,3 |
| S11 | 17,2 | 17,8 | 18,1 | 17,9 | 17,4 | 16,5 | 16,9 | 16,6 | 16,5 |
| S12 | 17,1 | 17,6 | 18,2 | 17,9 | 17,2 | 16,4 | 16,9 | 16,1 | 16,4 |
| S13 | 17,2 | 17,9 | 17,7 | 17,8 | 17,5 | 16,3 | 16,5 | 16,2 | 16,5 |
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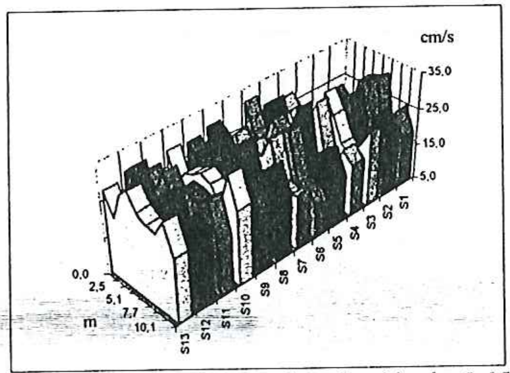

*Fig. 2 - Mean velocity values (cm/s) - h=0.15 m - feb. 96*

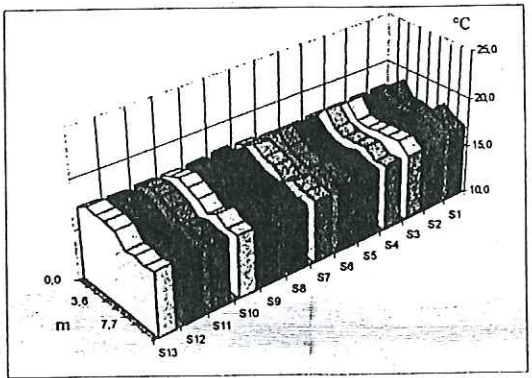

*Fig. 3 - Mean temperature values (°C) - h=0.15 m - feb. 96*

The problem has received little attention in the literature in spite of its practical importance. Such a lack of information is presumably due to the enormous amount of data which is necessary to get a sufficient view of the temperature and velocity fields. Also, it practically impossible to carry out a complete experiment in industrial environments. On the other hand Computational Fluid Dynamics modelling is also extremely complex and time demanding for huge ambients.

## THE MEASUREMENT CAMPAIGN

The Church of S. Maria della Pietà was built in the early part of the 1600s and is 40 metres long, about 20 metres wide and 22 metres high. The room is divided by a central nave or aisle, ten lateral aisles and the altar area. The floor radiant panels were installed only in the central nave and, in small portions, at the sides of the altar area (Fig. 1). The following parameters have been controlled in the course of the experiment campaign:

- temperature of the surfaces of structural casing;
- air velocity and temperature at three different heights (.15, 1.25, 3.0 *m*) from the floor.

and temperature only at the points considered most significant.

The surface temperature were measured by Avio-Hughes (Probeye™ TVS 2000) thermograph. Air velocity and temperature measurements were carried out by a hot-wire anemometer, (DISA 54N50). The local velocity direction was approximately determined using incense sticks.

Because of the vastness of the room, it was necessary to select areas critical beforehand. To that aim preliminary experiments were conducted and allowed to distinguish three

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| S2 | 18.5 | 22.4 | 14.6 | 23.1 | 22.5 | 22.9 | 15.1 | 17.7 | 31.3 |
| S3 | 18.5 | 22.0 | 17.7 | 23.0 | 23.2 | 26.9 | 22.2 | 20.4 | 21.7 |
| S4 | 24.3 | 20.5 | 17.3 | 26.0 | 24.8 | 20.2 | 22.0 | 20.0 | 28.6 |
| S5 | 17.9 | 23.9 | 17.3 | 26.9 | 26.3 | 19.0 | 27.0 | 23.7 | 29.0 |
| S6 | 25.3 | 26.9 | 18.2 | 33.0 | 23.6 | 21.9 | 18.5 | 24.2 | 28.4 |
| S7 | 29.0 | 24.3 | 17.6 | 27.5 | 30.3 | 24.1 | 22.9 | 28.7 | 25.1 |
| S8 | 25.7 | 21.8 | 21.5 | 31.9 | 31.9 | 26.1 | 23.1 | 27.0 | 29.1 |
| S9 | 24.4 | 21.4 | 19.6 | 23.0 | 28.3 | 21.0 | 20.2 | 33.1 | 29.3 |
| S10 | 26.8 | 23.1 | 18.6 | 26.5 | 29.6 | 27.3 | 20.5 | 27.0 | 29.4 |
| S11 | 24.8 | 27.0 | 19.0 | 26.3 | 28.1 | 27.0 | 20.5 | 30.7 | 29.7 |
| S12 | 22.3 | 21.6 | 18.2 | 23.2 | 27.2 | 29.8 | 20.5 | 27.9 | 30.6 |
| S13 | 29.5 | 24.2 | 27.8 | 22.8 | 26.5 | 30.2 | 29.2 | 27.9 | 25.0 |
| | 24.1 | | 28.2 | | 30.2 | | 21.1 | | 28.2 |
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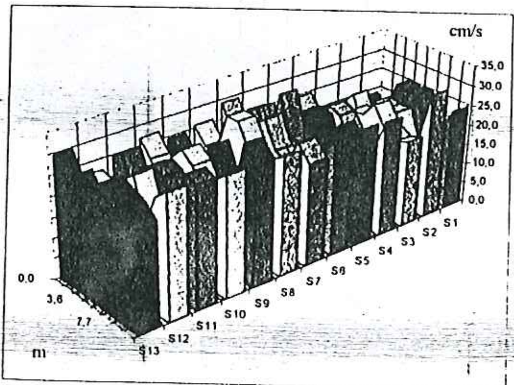

*Fig. 4 - Mean velocity values (cm/s) - h=1.25 m - feb 96*

altar

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| | 17,5 | | 17,2 | | 17,3 | | 16,9 | | 17,2 |
| | | | 17,4 | | 17,2 | | 16,8 | | |
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| S2 | 17,4 | 17,4 | 17,5 | 17,2 | 17,5 | 16,8 | 16,9 | 17,1 | 16,9 |
| S3 | 17,3 | 17,7 | 17,5 | 17,2 | 17,4 | 16,6 | 16,9 | 16,9 | 16,6 |
| S4 | 17,2 | 17,6 | 17,5 | 17,5 | 17,2 | 16,6 | 16,2 | 16,5 | 16,6 |
| S5 | 17,0 | 17,3 | 17,7 | 17,5 | 17,2 | 16,6 | 16,2 | 16,4 | 16,1 |
| S6 | 16,9 | 17,5 | 17,6 | 17,3 | 17,3 | 16,4 | 16,7 | 16,5 | 16,1 |
| S7 | 16,9 | 17,4 | 17,8 | 17,5 | 17,1 | 16,2 | 16,2 | 16,3 | 16,0 |
| S8 | 16,9 | 17,2 | 17,7 | 17,3 | 17,1 | 16,3 | 16,3 | 16,3 | 16,1 |
| S9 | 16,9 | 17,7 | 17,5 | 17,7 | 17,1 | 16,3 | 16,4 | 16,0 | 16,1 |
| S10 | 17,0 | 17,6 | 17,5 | 17,6 | 17,1 | 16,2 | 16,3 | 16,0 | 16,1 |
| S11 | 17,0 | 17,2 | 17,5 | 17,4 | 17,0 | 16,0 | 16,3 | 16,0 | 16,0 |
| S12 | 17,0 | 17,6 | 17,5 | 17,7 | 16,9 | 15,9 | 16,2 | 15,9 | 16,0 |
| S13 | 17,0 | 17,3 | 17,5 | 17,5 | 16,9 | 15,9 | 15,9 | 15,9 | 16,1 |
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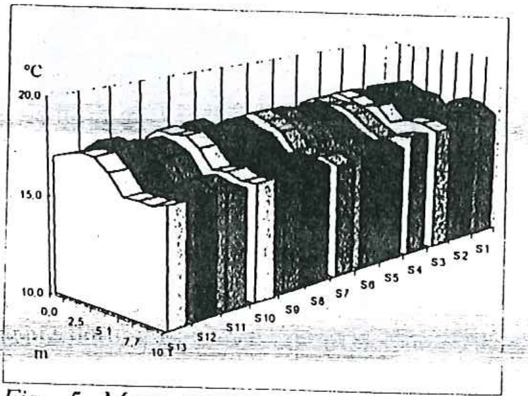

*Fig. 5 Mean temperature values (°C) - h=1.25 m - feb 96*

With a view to the objectives expounded above, it was thought to acquire experimental values for the surface temperature of all the internal curtain structures of the building (walls, floor and ceilings) and for air velocity clearly dis-homogeneous area: the altar area, the congregation area and the entrance area, as shown in Fig. 1.

The experimental grid was therefore sized in different way according the expected fluid-dynamic behaviour. So in the altar area a

2.5x2 *m* (width by length) grid, with 15 measurements points was assumed sufficient. In the congregation area 117 points a 1.3x1.5 *m* was used; in the entrance area the grid was 2.4x3.3 and 20 points. The air velocity and temperature measurements were carried out at three different heights, equal to 15 *cm*, 125 *cm* and 300 *cm*. In total 456 measurements were taken in three different periods: February, March and April 1996.

measurements by contact have actually confirmed the reliability of those assumptions.

## EXPERIMENTAL DATA

The first survey was made in February. External temperature conditions were 0°÷2 °C and the measurements were taken at 15 *cm* and 125 *cm* from the floor.

A strong current was revealed from the entrance towards the altar. The average air velocity and temperature data are presented in Figs. 2,3, 4 and 5. The tables represent a planimetric view of the church. To the point (0,0) of Fig.1 corresponds the box located at the row S13 in the first column of every table. The zone between the rows S1-S13 corresponds to the congregation area, while the zone upper row S1 represents the high

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| S2 | 19,1 | 21,1 | 19,7 | 20,9 | 24,9 | 21,0 | 18,9 | 20,7 | 16,2 | 8,2 |
| S3 | 18,0 | 23,0 | 17,5 | 17,0 | 21,0 | 21,7 | 20,9 | 20,9 | 19,4 | |
| S4 | 19,7 | 22,0 | 23,4 | 18,5 | 19,9 | 21,1 | 21,5 | 22,3 | 20,5 | |
| S5 | 15,7 | 20,6 | 23,6 | 19,7 | 22,5 | 17,5 | 16,9 | 19,5 | 20,4 | 7,4 |
| S6 | 12,5 | 19,5 | 19,5 | 18,2 | 21,1 | 20,3 | 17,5 | 19,6 | 22,6 | |
| S7 | 12,4 | 17,5 | 24,0 | 20,0 | 23,6 | 19,4 | 18,0 | 23,6 | 17,3 | 7,0 |
| S8 | 12,5 | 16,0 | 16,5 | 19,5 | 24,4 | 17,0 | 14,9 | 17,8 | 16,0 | |
| S9 | 10,0 | 13,7 | 19,1 | 18,6 | 23,1 | 16,8 | 14,6 | 18,0 | 18,6 | |
| S10 | 12,6 | 15,1 | 16,8 | 19,2 | 19,3 | 16,0 | 13,7 | 19,4 | 18,2 | 7,3 |
| S11 | 14,1 | 17,9 | 11,5 | 16,5 | 23,0 | 19,1 | 16,3 | 13,9 | 19,5 | |
| S12 | 18,3 | 20,8 | 16,0 | 16,3 | 16,7 | 19,3 | 15,6 | 14,8 | 15,3 | 7,1 |
| S13 | 17,0 | 16,7 | 18,7 | 18,5 | 27,9 | 14,3 | 15,9 | 9,1 | 22,5 | |
| | 12,5 | | 16,9 | | 22,1 | | 19,8 | | 9,5 | |
| | | | | | | | | | | 5,2 |
| | 11,6 | | 15,1 | | 14,0 | | 10,3 | | 14,6 | |
| | | | | | | | | | | 15,5 |
| | 15,7 | | 15,6 | | 13,9 | | 14,5 | | 15,6 | |
| | | | | | | | | | | |
| | 11,7 | | 16,7 | | 13,1 | | 13,2 | | 14,8 | 6,7 |

altar

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | |
| | 19,6 | | | | 19,8 | | | | 19,6 |
| | 20,1 | | | | 19,7 | | | | 19,6 |
| | 19,9 | | | | 19,8 | | | | 19,9 |
| | 20,0 | | | | | | | | 19,8 |
| | | | | | | | | | |
| | | | | | | | | | |
| | 19,7 | | 19,8 | | 19,6 | | 19,7 | | 19,8 |
| | | | | | | | | | |
| | | | | | | | | | |
| | | | | | | | | | |
| S 1 | 19,7 | 19,8 | 19,7 | 19,7 | 19,7 | 19,2 | 19,3 | 19,4 | 19,3 |
| S 2 | 19,7 | 19,8 | 19,8 | 19,7 | 19,8 | 19,1 | 19,5 | 19,4 | 19,3 |
| S 3 | 19,7 | 19,7 | 19,9 | 20,0 | 19,8 | 19,3 | 19,2 | 19,3 | 19,3 |
| S 4 | 19,8 | 19,8 | 19,0 | 19,8 | 19,8 | 19,3 | 19,3 | 19,4 | 19,2 |
| S 5 | 19,8 | 19,7 | 19,7 | 19,9 | 19,8 | 19,5 | 19,6 | 19,3 | 19,3 |
| S 6 | 19,9 | 19,9 | 19,8 | 19,9 | 19,8 | 19,4 | 19,6 | 19,5 | 19,3 |
| S 7 | 19,9 | 19,9 | 19,8 | 20,0 | 19,9 | 19,6 | 19,8 | 19,6 | 19,3 |
| S 8 | 19,9 | 19,9 | 19,9 | 20,2 | 19,9 | 19,9 | 19,8 | 19,4 | 19,3 |
| S 9 | 20,1 | 19,9 | 19,9 | 20,6 | 20,0 | 19,8 | 19,9 | 19,6 | 19,3 |
| S 10 | 20,1 | 19,9 | 20,0 | 20,4 | 20,1 | 19,9 | 19,7 | 19,5 | 19,3 |
| S 11 | 20,1 | 20,2 | 20,4 | 20,6 | 20,2 | 19,8 | 19,6 | 19,6 | 19,3 |
| S 12 | 19,5 | 19,7 | 19,9 | 20,2 | 20,2 | 19,8 | 19,7 | 19,6 | 19,3 |
| S 13 | 19,5 | 19,8 | 19,6 | 19,9 | 19,7 | 19,9 | 19,7 | 19,8 | 19,6 |
| | 19,8 | | 19,9 | | 20,1 | | 20,5 | | 20,4 |
| | | | | | | | | | |
| | 20,1 | | 19,9 | | 20,1 | | 20,0 | | 19,8 |
| | | | | | | | | | |
| | 20,2 | | 20,2 | | 19,8 | | 20,0 | | 19,8 |
| | | | | | | | | | |
| | 19,9 | | 19,9 | | 19,8 | | 19,9 | | 19,7 |

entr

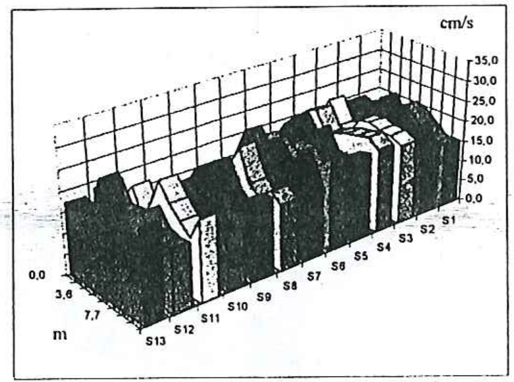

*Fig. 6 - Mean velocity values (cm/s) - h=1.25 m - mar 96*

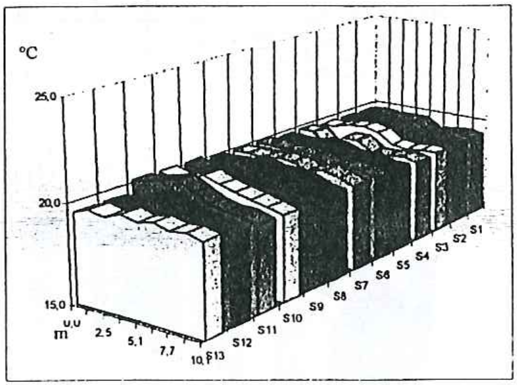

*Fig. 7 - Mean temperature values (°C) - h=1.25 m - mar 96*

Average air velocity were obtained setting equal to 1 minute the integration time of the anemometer. The root mean square deviation and mean temperature were also measured over the same integration time. The emissivity of the walls and the floor were set equal to .92 and .93 respectively using tabular data for plaster and for Venetian floor. Temperature altar area and the zone under row S13 the entrance of the church.

The data show that in the congregation zone air velocity is in general high up to 33.3 *cm/s*. Similar values are found in the entrance zone. Velocity is lower in the altar zone, values ranging from 6 to 22,3 *cm/s*. In the congregation zone the air velocity decreases from the entrance to the altar with presence of two minima in the crosswise direction. All values are characterised by a high turbulent intensity, up to 30%.

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | |
| | 9,6 | | | | 7,3 | | | | 14,3 |
| | 10,9 | | | | 7,9 | | | | 11,0 |
| | 8,0 | | | | 13,5 | | | | 11,5 |
| | 12,0 | | | | | | | | 14,3 |
| | | | | | | | | | |
| | | | | | | | | | |
| | 17,8 | | | | 16,8 | | | | 17,4 |
| | | | | | | | | | |
| | | | | | | | | | |
| | | | | | | | | | |
| S1 | 14,4 | n.r. | n.r. | 14,2 | 14,5 | 16,0 | n.r. | n.r. | 12,5 |
| S3 | 17,5 | n.r. | n.r. | 18,0 | 17,7 | 18,5 | n.r. | n.r. | 17,6 |
| S5 | 18,0 | n.r. | n.r. | 22,2 | 24,3 | 23,5 | n.r. | n.r. | 20,8 |
| S7 | 16,8 | n.r. | n.r. | 22,1 | 24,3 | 21,5 | n.r. | n.r. | 12,5 |
| S9 | 16,0 | n.r. | n.r. | 18,4 | 24,7 | 24,2 | n.r. | n.r. | 17,5 |
| S11 | 10,0 | n.r. | n.r. | 24,8 | 25,3 | 30,9 | n.r. | n.r. | 18,1 |
| S13 | 17,3 | n.r. | n.r. | 22,3 | 24,5 | 22,5 | n.r. | n.r. | 34,5 |
| | | | | | | | | | |
| | | | | | | | | | |
| | 18,5 | | | | 19,4 | | | | 11,0 |
| | | | | | | | | | |
| | 15,8 | | | | 13,0 | | | | 14,8 |
| | | | | | | | | | |

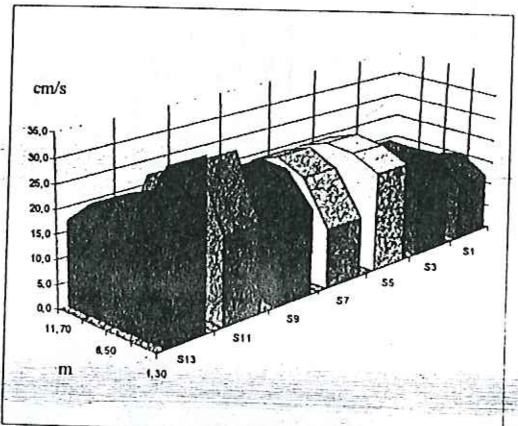

*Fig. 8- Mean velocity values (cm/s) - h=3 m on the floor - march 96*

In the same area the temperature values are everywhere higher than 16 *°C* and therefore sufficient for thermal comfort. However thermal conditions are highly non uniform.

Air temperature increases from the entrance zone to the abside and the crosswise maximum temperature values are found in correspondence with velocity minima.

Results at 1.25 *m*, shown in Figs. 4 and 5, indicate the velocity and temperature fields remain similar to the previous data but generally the velocity are higher and temperature lower. The second survey was made in March. Outdoor temperature was about 16 *°C*. Data were taken at heights 1.25 and 3.0 *m*. It is interesting to observe that in this case the general air flow was directed from the altar towards the entrance.

At 1.25 *m* the data are shown in Figs. 6 and 7. In comparison with the data of February velocities are more uniform with a variability range of 10 *cm/s*, but the distribution is much less regular. The temperature distribution is now much more uniform then in first survey ranging between 19.2 and 20.3 *°C*.

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | |
| | 21,0 | | | | 20,9 | | | | 20,5 |
| | 21,0 | | | | 20,9 | | | | 21,0 |
| | 21,1 | | | | 20,5 | | | | 20,9 |
| | 20,7 | | | | | | | | 20,6 |
| | | | | | | | | | |
| | | | | | | | | | |
| | 20,4 | | | | 20,7 | | | | 20,7 |
| | | | | | | | | | |
| | | | | | | | | | |
| | | | | | | | | | |
| S1 | 20,6 | n.r | n.r | 20,7 | 20,7 | 20,7 | n.r | n.r | 20,8 |
| S3 | 20,5 | n.r | n.r. | 20,8 | 20,4 | 20,6 | n.r. | n.r. | 20,5 |
| S5 | 20,4 | n.r. | n.r. | 20,6 | 20,8 | 20,4 | n.r. | n.r | 20,4 |
| S7 | 20,5 | n.r. | n.r | 20,6 | 20,7 | 20,9 | n.r | n.r | 20,6 |
| S9 | 20,6 | n.r. | n.r | 21,0 | 20,6 | 20,5 | n.r | n.r | 20,7 |
| S11 | 21,0 | n.r. | n.r | 21,1 | 20,6 | 20,7 | n.r | n.r. | 20,7 |
| S13 | 20,7 | n.r. | n.r | 21,3 | 21,3 | 21,4 | n.r. | n.r | 22,1 |
| | | | | | | | | | |
| | | | | | | | | | |
| | 20,7 | | | | 21,3 | | | | 21,6 |
| | | | | | | | | | |
| | 20,8 | | | | 21,3 | | | | 20,7 |
| | | | | | | | | | |
| | 21,1 | | | | 21,2 | | | | 21,1 |
| | | | | | | | | | |

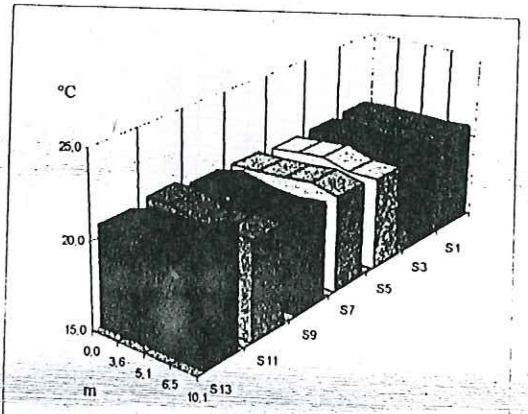

*Fig. 9 - Mean temperature values (°C) - h=3 m on the floor - march 96*

|  |  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|
|  |  |  |  |  |  |  |  |  |  |
|  | 12,5 |  |  |  | 4,7 |  |  |  | 12,3 |
|  | 16,7 |  |  |  | 8,0 |  |  |  | 16,4 |
|  | 11,7 |  |  |  | 17,3 |  |  |  | 14,4 |
|  | 13,1 |  |  |  |  |  |  |  | 14,2 |
|  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |
|  | 17,7 |  |  |  | 11,9 |  |  |  | 15,5 |
|  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |
| 1 | 11,9 | n.r. | 19,5 | n.r. | 22,6 | n.r. | 25,2 | n.r. | 11,0 |
| 4 | 15,8 | n.r. | 12,5 | n.r. | 19,2 | n.r. | 18,9 | n.r. | 15,7 |
| 7 | 16,7 | n.r. | 18,8 | n.r. | 24,9 | n.r. | 20,5 | n.r. | 14,5 |
| 10 | 10,0 | n.r. | 14,4 | n.r. | 24,7 | n.r. | 16,5 | n.r. | 12,1 |
| 13 | 13,0 | n.r. | 17,5 | n.r. | 18,6 | n.r. | 13,9 | n.r. | 12,7 |
|  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |
|  | 11,9 |  | 13,7 |  | 22,5 |  | 17,1 |  | 14,5 |
|  |  |  |  |  |  |  |  |  |  |
|  | 12,4 |  | 13,9 |  | 18,6 |  | 17,8 |  | 17,5 |
|  |  |  |  |  |  |  |  |  |  |
|  | 14,0 |  | 15,0 |  | 17,1 |  | 19,8 |  | 12,5 |

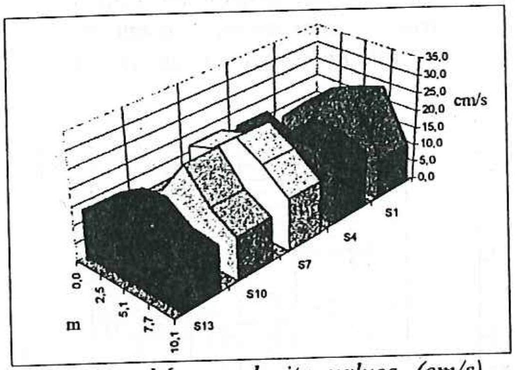

*Fig. 10 - Mean velocity values (cm/s) - h=0.15 m - april 96*

|  |  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|
|  | 22,5 |  |  |  | 23,0 |  |  |  | 22,5 |
|  | 22,2 |  |  |  | 22,3 |  |  |  | 22,2 |
|  | 22,4 |  |  |  | 22,0 |  |  |  | 22,8 |
|  | 22,7 |  |  |  |  |  |  |  | 22,5 |
|  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |
|  | 22,5 |  |  |  | 22,2 |  |  |  | 22,5 |
|  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |
| S1 | 21,8 | n.r. | 22,2 | n.r. | 21,4 | n.r. | 21,3 | n.r. | 22,6 |
| S4 | 22,1 | n.r. | 22,8 | n.r. | 21,6 | n.r. | 22,5 | n.r. | 22,2 |
| S7 | 21,7 | n.r. | 22,3 | n.r. | 22,0 | n.r. | 22,6 | n.r. | 21,6 |
| S10 | 22,5 | n.r. | 22,5 | n.r. | 21,9 | n.r. | 22,8 | n.r. | 21,9 |
| S13 | 21,5 | n.r. | 22,2 | n.r. | 22,2 | n.r. | 22,1 | n.r | 21,6 |
|  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |
|  | 22,2 |  | 22,1 |  | 21,6 |  | 21,6 |  | 21,0 |
|  |  |  |  |  |  |  |  |  |  |
|  | 22,5 |  | 22,3 |  | 22,2 |  | 22,1 |  | 22,0 |
|  |  |  |  |  |  |  |  |  |  |
|  | 22,5 |  | 22,5 |  | 22,1 |  | 21,6 |  | 21,2 |

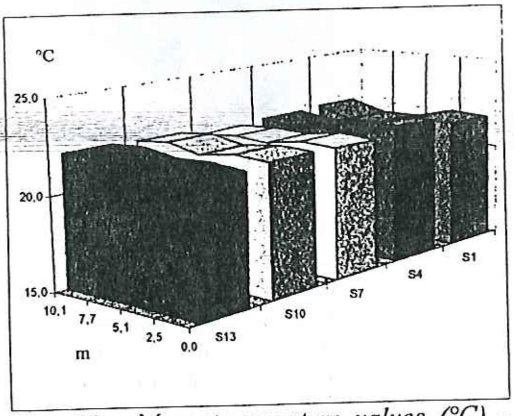

*Fig. 11 - Mean temperature values (°C) - h=0.15 m - april 96*

|  |  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|
|  | 14,1 |  |  |  | 4,5 |  |  |  | 10,6 |
|  | 9,5 |  |  |  | 6,2 |  |  |  | 9,5 |
|  | 11,6 |  |  |  | 15,5 |  |  |  | 10,6 |
|  | 11,3 |  |  |  |  |  |  |  | 10,5 |
|  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |
|  | 15,2 |  |  |  | 20,8 |  |  |  | 14,5 |
|  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |
| S1 | 16,1 | n.r. | 17,5 | n.r. | 13,9 | n.r. | 17,7 | n.r. | 13,3 |
| S4 | 6,8 | n.r. | 20,3 | n.r. | 18,0 | n.r. | 19,2 | n.r. | 16,1 |
| S7 | 10,4 | n.r. | 16,4 | n.r. | 19,0 | n.r. | 17,0 | n.r. | 18,1 |
| S10 | 10,2 | n.r. | 15,6 | n.r. | 22,7 | n.r. | 13,5 | n.r. | 12,0 |
| S13 | 8,1 | n.r. | 11,8 | n.r. | 18,3 | n.r. | 13,9 | n.r. | 10,0 |
|  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |
|  | 13,3 |  | 13,8 |  | 10,0 |  | 8,2 |  | 8,0 |
|  |  |  |  |  |  |  |  |  |  |
|  | 16,0 |  | 11,6 |  | 14,7 |  | 10,2 |  | 11,6 |
|  |  |  |  |  |  |  |  |  |  |
|  | 13,9 |  | 13,5 |  | 9,5 |  | 12,0 |  | 11,1 |

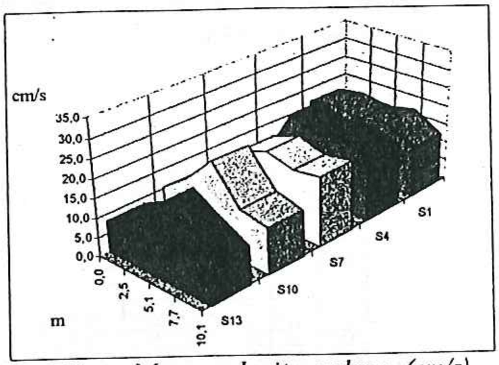

*Fig. 12 - Mean velocity values (cm/s) - h=1,25 m - april 96*

|  |  |  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|---|---|
|  | 22,6 |  |  |  | 23,2 |  |  |  | 22,8 |
|  | 22,7 |  |  |  | 22,8 |  |  |  | 22,4 |
|  | 22,7 |  |  |  | 22,2 |  |  |  | 22,5 |
|  | 22,6 |  |  |  |  |  |  |  | 22,5 |
|  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |
|  | 22,5 |  |  |  | 22,4 |  |  |  | 22,6 |
|  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |
| S1 | 21,8 | n.r. | 21,9 | n.r | 21,4 | n.r. | 21,4 | n.r. | 22,0 |
| S4 | 22,2 | n.r. | 21,7 | n.r. | 21,8 | n.r. | 21,6 | n.r. | 21,9 |
| S7 | 21,9 | n.r. | 22,0 | n.r. | 21,7 | n.r. | 21,8 | n.r | 21,7 |
| S10 | 22,0 | n.r. | 22,1 | n.r. | 21,8 | n.r. | 22,2 | n.r | 22,0 |
| S13 | 21,8 | n.r. | 22,0 | n.r. | 21,9 | n.r. | 22,2 | n.r. | 22,1 |
|  |  |  |  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |  |  |  |
|  | 22,3 |  | 22,2 |  | 22,0 |  | 22,1 |  | 22,1 |
|  |  |  |  |  |  |  |  |  |  |
|  | 22,5 |  | 22,1 |  | 21,9 |  | 22,0 |  | 22,1 |
|  |  |  |  |  |  |  |  |  |  |
|  | 22,0 |  | 22,2 |  | 22,1 |  | 21,9 |  | 22,1 |

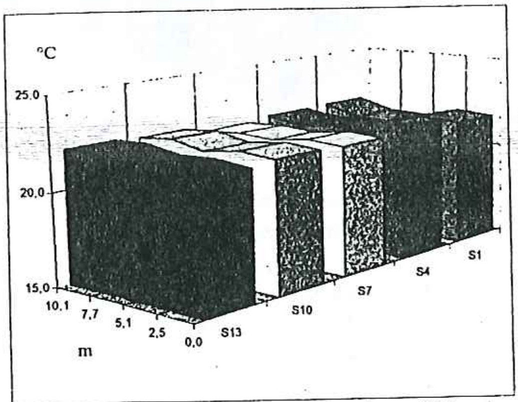

*Fig. 13 - Mean temperature values (°C) - h= 1,25 m - april 96*

The data, at 3 *m* from the floor, just confirm the above trend and are shown in Figs. 8 and 9. The third survey was carried out in April with external temperature of about 20 *°C*. Two heights, 0.15 and 1.25 *m*, were considered and less measurement points was utilised (Figs. 10, 11, 12 and 13). The overall air movement, in this case also, was from the altar towards the entrance, with a pronounced left component

As expected the velocity are lower and the temperatures higher than in the second survey This can be observed in Figs. 12 and 13 at 1.25 *m* from the floor.

A summary of walls, ceiling, floor temperatures, as obtained by infrared thermography, is given in Table 1: are reported average values of the air temperatures at 1.25 *m* from the floor and the inlet of the working fluid. the heating plants is efficient in terms of air temperature provided.

The complete structure of the air movement within could not be detected due to the size of the height of the hall (22 m at the top of the vault). However, it is possible to infer from the data the formation of a large convective cell filling the whole ambient, characterized by horizontal current at the living quotes which should be balanced by a reversed current at the vault level.

The literature indicates that the leading parameters for natural convective circulation in enclosures is the Grashof number *Gr*. This is based on the leading temperature difference and third power of the vertical dimensions, as follows:

$$Gr = \frac{gL^3 \beta \, \Delta T}{\nu^2}$$

*Tab. 1 - Mean temperature (°C) of the different internal structures of the Church, of internal, external air and heating fluid*

| | FEBRUARY | MARCH | APRIL |
|---|---|---|---|
| *Nave floor* | 20 ÷ 21 | 23,5 ÷ 24 | 25 |
| *Altar zone floor* | 14 ÷14,8 | 16,4 ÷ 17 | 18 ÷18,5 |
| *Altar corridors* | 20 ÷ 21 | 25 | 26 |
| *Ceiling* | 12,5 ÷13,5 | 17 ÷ 18 | 18,5 ÷ 19 |
| *Raised structures* | 15,5 ÷12,5 | 18,5 ÷17,5 | 19 |
| *Closure walls* | 20 | 23 | 25 |
| *Air ambient* | 17 | 20 | 22 |
| *External air* | 0 ÷ 2 | 16 | 20 |
| *Heating fluid* | 38 | 38 | 38 |

It can be note that the latter temperatures remain constant throughout the whole heating period, due an incorrect setting of the temperature controller.

The maximum difference between the ceiling and the floor was 8 *°C* in February. In March and April this dropped to 6 *°C* even if the ceiling temperature was as high as 18-19 *°C*.

## DISCUSSION

The whole experience demonstrates that the introduction of a new radiant panel heating system originates the uncomfortable conditions within the church. These derive from the very high velocity and turbulence level at the living quotes. On the other hand Using the temperature difference between the floor and the ceiling as *ΔT* and the average height of the vault as *L*, it is found that the Grashof number is as high as $10^{13}$. Such a very high value is no only sufficient to promote and sustain a convective cell but also corresponds to high turbulence levels [1]. That it is coeherent with the experimental data. This basic model is, however, influenced by a number of secondary elements, whose relevance is impossible to predict for the time being. These are:

- the temperature of the vertical surfaces which vary during day and along the season. The lateral temperatures actually influence the direction of the circulation;

- the presence of large windows in the upper part of the enclosure which locally affects the vertical wall temperatures;
- the presence of non heated areas of the floor;
- the complex geometry of the ambient with columns and secondary chapels in the lateral naves.

It is therefore evident that the above scheme is not sufficient to explain all the characteristics of the problem. In fact the Grashof number does not change too much during the heating period, while qualitative and quantitative differences are stressed by the experimental data.

## CONCLUSIONS

The results of the experimental campaign carried out in the church of S. Maria della Pietà in Bologna can be synthesized as follows:

- horizontal air currents are present at the living quotes with prevailing direction from the entrance towards the altar zone in February. The current reverses in March and April;
- velocities are particularly high in February with a maximum of 33.3 cm/s. The turbulence intensity is also very high, up to 30%, in this period. Lower velocity and turbulence levels are detected in subsequent surveys;
- pronounced velocity and temperature non-uniformities are detected in February.
- longitudinal lines with maximum temperature and minimum velocity are observed in correspondence to central columns at the end of the congregation area (in evidence in fig. 1);
- the internal surface temperatures are quite different all along the heating period with a maximum difference temperatures of 8 °C between the heated floor and the main vault.

The above effects are linked to the presence of a large convective cell filling the church enclosure. This is promoted by the temperature difference between floor and ceiling, but is definitely affected by a number of secondary elements which probably contribute qualitative and quantitative modifications to the flow structure.

The complexity of the problem imposes the necessity of the use of CFD modelling .

## REFERENCES

[1] T.Inagaki, K.Komori *"Heat transfer and fluid flow of natural convection along a vertical flat plate in the transition region: experimental analysis of the wall temperature field"*. Int.J.Heat Mass Transfer. Vol.38, No.18, pp.3485-3495, 1995