OPTIMUM VENTILATION AND AIR FLOW CONTROL IN BUILDINGS

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NATURAL VENTILATION DESIGN FOR A CONCERT HALL

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SYNOPSIS

This paper describes the ventilation analysis undertaken during the design of a new music centre for which it was desired to avoid the use of air conditioning and conventional ducted mechanical ventilation. The main objective was to predict the thermal comfort of occupants in the centre's main auditorium during summertime performances. The analysis was done using computational fluid dynamics (CFD) and a dynamic thermal model.

The CFD results were used to decide the size and location of openings for natural ventilation, which led to the final design having a much better distribution of incoming fresh air than the initial design. The peak fresh air ventilation rate was reduced, but this did not significantly increase the risk of summertime overheating.

The dynamic thermal analysis predicted that the time when the temperature would be over 25°C ranged from 0.3 performance hours/year with a dense concrete roof construction and an orchestra of 30 to 3.5 performance hours/year with a lightweight roof and an orchestra of 100. Given that the larger orchestra would not be formal and so could wear lighter clothing, it was concluded that natural ventilation should be a viable strategy for controlling the risk of summertime overheating. However, given uncertainties regarding the usage of the space and UK summertime temperatures in the future, it was recommended that provision was made in the design to enable mechanical cooling to be added at a later date.

1 INTRODUCTION

1.1 Background

HGa were appointed by the Wiltshire Music Centre Trust as M&E consultants in a design team led by Feilden Clegg Architects to design a music centre in Bradford Upon Avon, Wiltshire. The focus of the building was a concert hall holding an audience of up to 410 people and a 100 piece orchestra. The 1750 m² facility also incorporated 3 large rehearsal spaces, a number of smaller practice and tutorial spaces, a recording studio, offices and a catering facility.

1.2 Objectives

The aim was to achieve a low energy building by an integrated design which incorporated high insulation levels, daylighting and avoided the use of air conditioning and conventional ducted mechanical ventilation. The proposed ventilation strategy was to provide fresh air by means of controlled natural ventilation in summer, and with fan assistance in winter. The benefits of a high thermal mass roof structure and night-time ventilation in terms of lower summertime overheating risk needed to be assessed. The daylighting scheme had to take account of the acoustic criteria and the need for blackout on some occasions.

1.3 Methodology

HGa undertook a detailed analysis of the concert hall auditorium to assess the likely thermal comfort of occupants (orchestra and audience) during summertime performances. The analysis comprised two integrated elements:

- Estimation using the CFD package FLOVENT of the air change rate induced by natural ventilation under worst case (no wind) conditions.
- Prediction of internal temperatures throughout the year using the dynamic thermal model APACHE and assessment of thermal comfort using these temperatures, the air speed predicted by the CFD and the anticipated activities and clothing of the orchestra and audience.

This paper describes the main results from the analysis and shows how the design developed to achieve the brief's low energy objectives.

2 BUILDING DESCRIPTION

The floor plan of the proposed auditorium is shown in Figure 1. It comprised a stage area, a small space for removable seating and permanent raked seating. A dominant feature of the auditorium was the roof lantern positioned above the stage (see the building sections in Figure 2). The lantern was intended to provide both daylighting and a route for stale air to leave the space via controllable dampers protected by louvres.

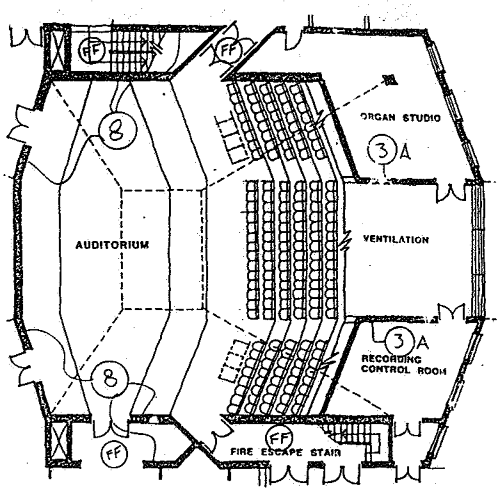

Figure 1 Floor plan of auditorium

In the proposed ventilation strategy, fresh air for the stage area was drawn from high level openings down two vertical builders work ducts at each end of the stage. From these the air would feed into a plenum running along the back of the stage and thence spill onto the stage through a series of low level grilles. Fresh air for the audience was designed to come primarily from a large louvred opening on the external facade which would supply a triangular cross section plenum running beneath the raked seating. The air would enter the auditorium through grilles in the step risers under each row of seats. Air extract from the auditorium was via louvred openings on each side of the roof lantern above the stage.

Section A - A

Section B - B

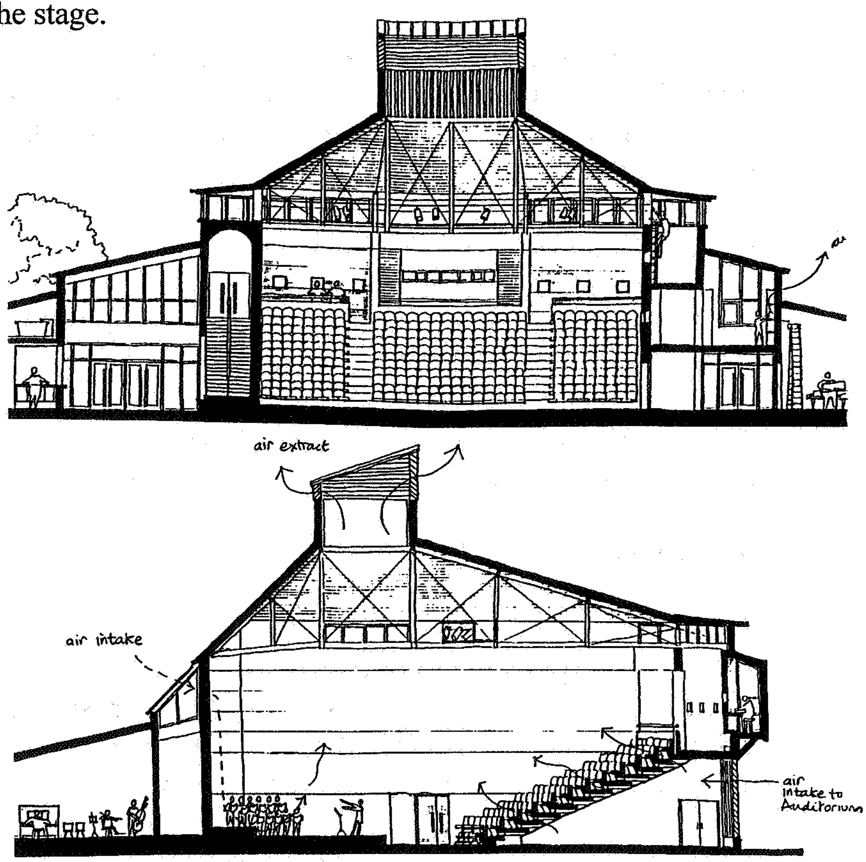

Figure 2 Building sections

3 AIR FLOW ANALYSIS

3.1 Initial Design Analysis

A full 3-D air flow computer model for the initial design of the auditorium was constructed using the FLOVENT CFD software. The objectives were to

- predict an overall bulk air flow rate for the space under worst case (no wind) conditions
- determine fresh air flow uniformity to the side banks of the audience
- assess the fresh air supply rate and uniformity to the orchestra
- predict air velocity around occupants (important for thermal comfort)
- identify any potential thermal hot spots

The model reproduced the geometry of the auditorium space and incorporated all the purpose built ventilation openings and pathways both to the outside and internally. Also included in the model were heat sources representing 100 musicians on the stage and 350 adults on the raked seating, with sensible heat emissions of 165 Watts and 80 Watts each respectively.

The results of this model predicted that the overall bulk air flow rate through the auditorium under worst case (no wind) conditions would be the equivalent of 8.3 ach (air changes per hour). With the given sizes of ventilation openings, some 90% of this total air flow went to the audience, giving each person on average 26 litres/second, and the remainder went to the stage giving each member of the orchestra an average of 9 litres/second.

The predicted air flow was very even between the centre and side banks of the same row, variations amounting to less than 10%. The air supply to the audience did however vary with the height of the row of seating, the lowest row receiving some 60% more fresh air than the top row ie about 34 litres/second per person compared with 21 litres/second per person respectively. The air flow pattern along the centre plane of the auditorium is shown in Figure 3. It confirms that there is no back-flow through the audience seating and that there is a strong plume removing the heat generated by the musicians.

The air flow model also predicted the air temperature distribution in the space. This was useful to see how much stratification there was and any potential 'hot spots', but because it is a steady state calculation (ie at a single point of time under fixed boundary conditions) the absolute values of temperature are not as meaningful as those predicted by a dynamic thermal model (see next section).

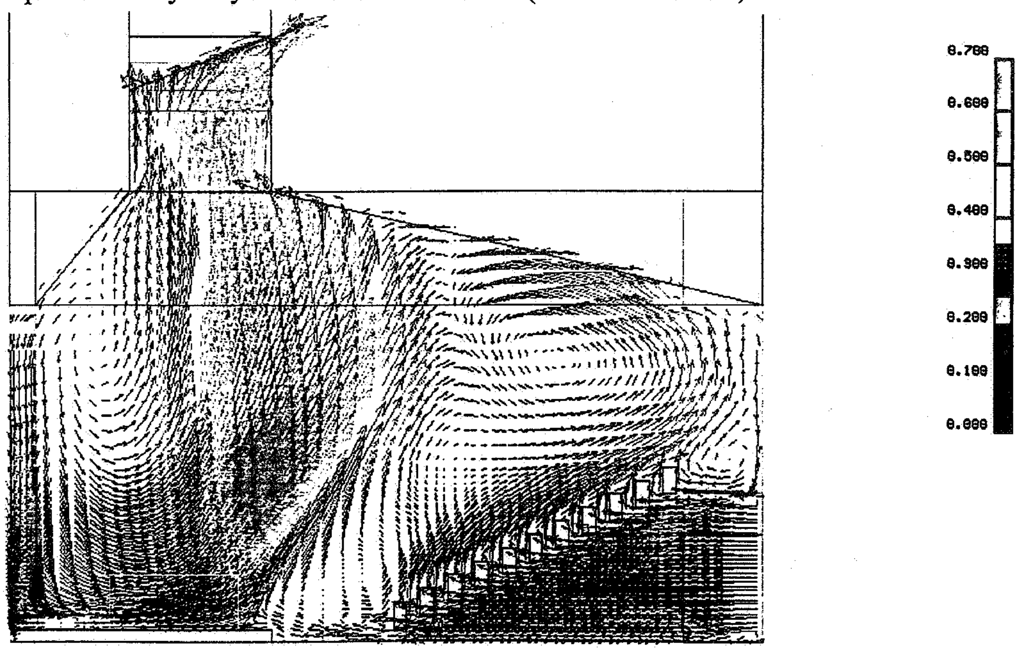

Figure 3 Air velocity vectors along vertical section through centre of auditorium.

3.2 Final Design Analysis

Subsequent to the analysis of air flow paths and rates in the initial design, the size of the ventilation openings for the auditorium, evolved due to two factors.

1. There was the desire to achieve a well daylit stage area for daytime rehearsals. With the initial design for the lantern, the skylight was completely occluded by noise attenuators suspended beneath the lantern to prevent noise breakout, and predicted daylight levels on the stage were very poor. This led to a proposal to divide the lantern into two halves, one to provide daylight and the other the pathway for air extract. To enable this proposal to achieve its aims successfully it was necessary to increase the size of the lantern throat from 6m by 4m to 6m by 6m (which also had structural advantages). The increased scale of the lantern throat enabled the daylight and air extract components of the lantern each to be 6m by 3m in plan. All the time it had to be borne in mind that the lantern design had to maintain a strict acoustic seal on the building and be able to achieve blackout without obstructing airflow.

2. There was a need to minimise the cost and therefore size of the acoustic attenuators on the auditorium air intakes and at the same time adjust opening areas to try to achieve a better balanced airflow between audience and orchestra.

The opening areas in the initial design were therefore adjusted and the new design was analysed in a 2D model using FLOVENT. (A 2D model of the initial design had been shown to give bulk air flows in good agreement with those predicted by the full 3D model.) The predicted bulk air flow rate for the revised design was 5.1 ach compared with the 8.3 ach predicted for the initial design which had considerably larger opening areas. In the new design it was predicted that some 76% of the total air flow went to the audience, giving each person on average 14.3 litres/second, and the remainder went to the stage giving each member of the orchestra an average of 15.8 litres/second.

These results indicated that the new proposed opening areas produced a much better distribution of the incoming fresh air between orchestra and audience than the previous design even if the overall fresh air ventilation capacity had been reduced. It is shown in the next section that the reduced ventilation capacity did not significantly increase the risk of summertime overheating.

The air supply to the audience still varied with the height of the row of seating, and it was recommended that the air distribution be made more uniform by adjusting the size of the free area of the openings in the risers of each step; all these openings were assumed to be the same size in the computer model (height 200mm, free area 20%).

4 THERMAL COMFORT ANALYSIS

4.1 Introduction

The dynamic thermal performance of the auditorium was simulated using the APACHE modelling package. The objective was to quantify the risk of overheating during summertime performances with different design options eg roof constructions and different possible occupancy levels. The computer model calculated the heat flows in and out of the auditorium and its structure through a whole year as they were driven by hour-by-hour changes in weather, lighting, occupancy, air flow rates etc.

4.2 Tested Options and Results

A summary of the different permutations analysed and the key result for each run is given in Table 1. The base case conditions were assumed to be a lightweight roof construction, a peak ventilation capacity of 8.3 ach, an orchestra of 30 and an acoustic curtain retracted during a performance.

Run no.	Roof construction	Orchestra numbers	Other variants	Performance hours/year >=25°C with performance every day	Probable performance hours/year >=25°C with performance every 10 days
WMCT1 (base case)	lightweight	30		11	1.1
WMCT2	lightweight	100		35	3.5
WMCT3	lightweight	100	Acoustic curtain during performance	42	4.2
WMCT4	Siporex	30		8	0.8
WMCT5	dense concrete	30		3	0.3
WMCT6	lightweight	30	peak ventilation 5.3 ach	11	1.1
WMCT7	lightweight	30	no rehearsal	9	0.9
WMCT8	Siporex	30	no rehearsal	6	0.6
WMCT9	Siporex	100		23	2.3

Table 1 Risk of overheating under various conditions

The simulations assumed that a full day rehearsal and an evening performance with a capacity audience occurred every day of the year. Given that only about 10% of all days will in reality have a performance, the predicted probability of the temperature exceeding 25°C is about one tenth of the values calculated by the computer simulations eg a result showing 11 performance hours per year over 25°C with performances every day, indicates a probability of only 1.1 performance hour per year over 25°C if there is one performance every 10 days. (The night purge assumed in the model effectively decouples one day from the next, so that the methodology employed avoids the possible effects of a build up of heat over a number of days.)

4.3 Discussion of Results

The threshold for summertime overheating was set at a resultant temperature of 25°C in view of the activity level of the performers, who are perceived to be the critical group in this regard. The value of 25°C was arrived at using the concept of predicted mean vote (PMV).

The PMV is the predicted mean vote, on a seven-point thermal sensation scale (-3 to +3), of a large group of persons when they experience a particular combination of air temperature, mean radiant temperature, humidity and air velocity with their metabolic rate and clothing insulation at given levels. An individual is deemed to find conditions acceptable if his vote is one of the three middle points of the scale (-1 to +1). Variance between individuals, and interestingly between the same individual on different occasions, means that even when the PMV is at the centre of the scale, statistically 5% of the group will have voted outside the central three points and are therefore considered to be dissatisfied. The International thermal comfort Standard ISO 7730, based on PMV, adopts the criterion that 10% uncomfortable is acceptable as a working maximum which statistically translates to the PMV lying in the range -0.5 to +0.5.

If members of the orchestra were wearing summer clothing ie the equivalent of long trousers and open-neck short sleeve shirts, and assuming an air speed of 0.4 metres/second which was predicted by the CFD analysis, their PMV at a resultant temperature of 25°C would be +1.15 given the assumed 'medium work' activity level. Wearing a jacket and tie under the same conditions would mean the PMV would rise to +1.7. Thus with summer clothing at this activity level, 25°C is on the border of the satisfactory range for an average person, albeit, on a statistical basis it translates to 33% of a large group being dissatisfied. With a jacket and tie at this activity level, 25°C is approaching the PMV level of +2 which is deemed "warm" in the ISO standard and translates to 60% of a large group being dissatisfied.

Performances are likely to entail either an orchestra of up to 30 who might normally wear the equivalent of jacket and tie or an orchestra of up to 100 who would find 'summer clothing' perfectly acceptable. It was concluded that with an orchestra of 30, a temperature of 25°C should represent a strict upper limit, whilst with an orchestra of 100 a small number of performance hours over 25°C would be an acceptable risk.

Under the base case conditions, the analysis predicted that there was a probability that only 1 performance hour in a typical year would incur a temperature over 25°C. This was considered to be an acceptable risk. With the size of the orchestra increased to 100, the risk of overheating increased to 3.5 performance hours per year, again an acceptably small risk given the associated lighter clothing level.

If the thermal capacity of the roof construction were increased by incorporating Siporex lightweight concrete, exposed on its underside, enabling it to absorb heat and moderate temperature rises, the risk of overheating would be reduced to 0.8

performance hours per year with an orchestra of 30 and to 2 hours per year with an orchestra of 100. With a dense concrete roof the risk of overheating with an orchestra of 30 would be reduced to 0.3 performance hours per year. The probable number of hours at or above 23°C during performances for the base case lightweight roof construction and with the same conditions except a dense concrete roof (runs WMCT1 and WMCT5) are presented in Figure 4. The results confirm that the dense concrete roof produces a general downward shift in warm temperatures of about 1°C.

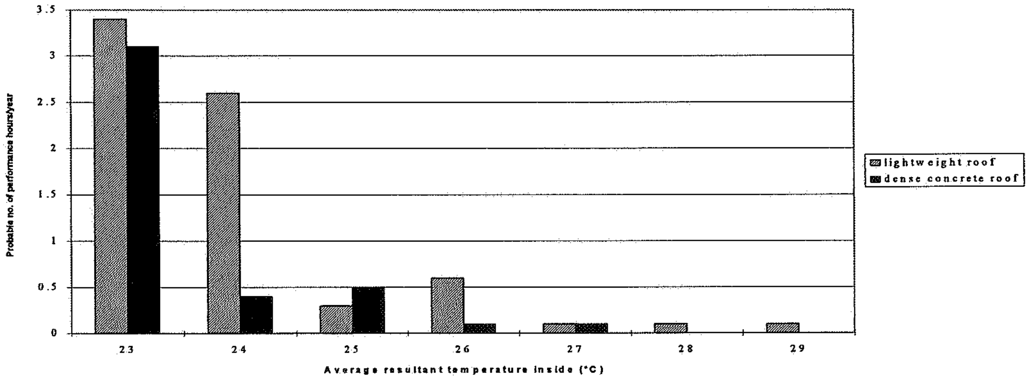

Figure 4 Frequency of internal temperatures at or above 23°C during performances

The run where the ventilation capacity was reduced from 8.3 to 5.3 ach showed no increase in overheating, which suggested that the lower overall fresh air ventilation capacity predicted for the new design with the reduced opening areas would not lead to a significant increase in overheating risk. The explanation for this result is that on those days when the internal temperature exceeds 25°C, the outside temperature is even warmer than the inside temperature, which means that the ventilation rate would be held back at its background level (to avoid introducing warmer air). Under these circumstances, a higher potential ventilation capacity is redundant.

5 CONCLUSION

CFD was successfully used to refine the design of a natural ventilation scheme for a concert hall. The size and location of openings were adjusted to obtain a uniform distribution of fresh air. Integrated analysis by a dynamic thermal model indicated that natural ventilation should be a viable strategy for controlling the risk of summertime overheating in the auditorium. However, the risk of overheating was not zero and there are a number of uncertainties regarding the usage of the space in the future. These factors, combined with the possibility that UK summers might continue to be hotter than the long term historical average, meant that it was recommended that provision should be made in the design to enable mechanical cooling to be added at a later date in case it proves to be necessary.

ACKNOWLEDGEMENTS

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