Theory and Practice of Natural Ventilation in a Theatre

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ABSTRACT: We report on a detailed monitoring exercise and an analogue experimental study of a naturally ventilated theatre in operation in the UK which can take audiences up to 300 people. The theatre has a raked seating area, and two outflow stacks, with a ring of air inflow vents on the floor which supply air naturally from an underfloor plenum. Detailed temperature measurements over a period during the winter 2003/2004 broadly indicate that the air within the theatre is stratified in temperature, with a relatively cool zone near the lower inflow vents and a progressive increase in temperature up to the roof space, where the temperature decreases again. A series of analogue laboratory experiments designed to simulate the natural convective flow, to help understand this thermal profile and the air flow pattern, identifies a series of fascinating flow regimes which depend on the inflow opening area at the base of the theatre. In general, the raked seating leads to a large scale circulation upwards and backwards across the audience which then spreads across the roof space and partially vents. The remaining flow rising from the seating zone recirculates in the upper part of the air space creating a weakly stratified upper layer. Lower in the theatre, the inflow of relatively cold air through the floor develops small inflow jets which mix with some of the warm air in the theatre and then spread laterally to form a cooler lower layer of air. This is mixed by the convective plume rising over the raked seating area and heated up as it is then carried into the upper part of the theatre. The experiments point to some design rules in order to achieve satisfactory ventilation within the space, without leading to excessive or insufficient cooling.

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1. INTRODUCTION

In the past ten years several naturally ventilated auditoria have been built. The first of these were the lecture theatres at De Montfort University, Leicester, completed in 1993 by Alan Short Associates. This building was followed by others such as the Olivier Theatre at Bedales School, Hampshire (1996), Feilden Clegg Bradley, the Auden Theatre at Gresham’s School (1998) Arts Team at RHWL, the Contact Theatre, Manchester (1999) and the Lichfield Garrick Theatre, Lichfield (2003) both by Alan Short Associates.

The high heat loads and intermittent heavy occupancy in auditoria pose a challenge to designers in ensuring the satisfactory removal of heat, odours and carbon dioxide [1]. Assembly halls and auditoria are generally characterised by large but variable occupancy levels, relatively high floor to ceiling heights, sedentary occupation, and stringent acoustic requirements [2]. These buildings do not usually have windows and require strict blackout conditions.

Auditoria can be classified as ‘large enclosures’ according to the definitions given by Heiselberg et al [3]. Large enclosures tend to have a number of different zones with particular heat gains, air and surface temperatures and ventilation conditions [4].

The de Montfort auditoria have been extensively monitored and empirical formulae derived from the data was used for development of simple thermal and ventilation models [5] but little has been written about the design of naturally ventilated theatres on a strategic level.

We report on a detailed monitoring exercise in the Auden Theatre at Gresham’s School, Holt, Norfolk during the winter 2003/2004. The Auden Theatre can be considered representative of small shoebox theatre typology – another example is the Tricycle Theatre, Kilburn, London. A series of parametric analogue laboratory experiments designed to simulate the natural convective flow were undertaken in order to understand the thermal profile and airflow pattern in the theatre. The location and opening area of inlet and outlet vents and geometry of seating is shown to have a profound effect on both thermal
profile and airflow pattern. An overview of these results suggests simple guidelines for consideration during the design phase of a naturally ventilated auditorium.

2. CASE STUDY BUILDING

The Auden Theatre at Gresham’s School is sited, amongst other detached school buildings, in acres of woodland on the edge of the village of Holt in Norfolk. The theatre is an entirely new, stand-alone building comprising a foyer, service accommodation, toilets, offices and the main auditorium. Externally the building has a barn-like appearance with a pitched roof and heavy eaves.

The building is designed to seat 300 people, and includes foyer and support accommodation. The rectangular auditorium occupies the majority of space within the building and is accessed at ground level from corridors on either side, through doors located approximately half way down the length of the auditorium – see Figure 1. At first floor level the audience enters through doors at the rear of the auditorium.

Equipped with fully retractable seating, the theatre can be used in a variety of formats by filling in the orchestra moat or removing the apron. During the monitoring period presented here the seating is in a raked configuration that extends from ground to first floor.

2.1 Ventilation System

The building is ventilated using assisted natural ventilation. Air is drawn into two concrete inlet ducts beneath the auditorium from an air inlet vent located at the rear of the building adjacent to the terrace. The 3.29m² vent comprises openable louvers, a vermin screen and a control damper to limit the amount of air entering into the building (Figure 2). The inlet ducts run either side of the auditorium underneath the slab and enter the auditorium through floor-mounted grilles. Heaters in the duct below the grilles preheat the air to minimise cold draughts in the occupied zone. Radiators are mounted against the side walls to provide space heating within the auditorium.

3. MONITORED DATA

Temperature was logged and measured at 70 locations in the theatre using Tinytag Ultra TGU-1500 data loggers during the winter of 2003. Data was recorded at 5 minute intervals.

Typical results presented here show the development of the thermal profile during a performance of Les Misérables on Thursday 18 March 2004 from 20:00-23:00h. Heat loads in the building included an audience of 298 with 66 cast members (estimated as 35-40kW), a maximum heat load of 55.1kW from stage lights, and heating from the heating system switched on at 21:00h.

The thermal profile at 20:00h shows the coolest temperatures are recorded at the bottom of the raked seating with a gradual increase in temperature up the
rake. The zone above the raked seating is warmer and well mixed up to ceiling height (Figure 4a). At 20:50h, before the heating is turned on but after the air has been warmed by the audience and lights for nearly an hour (Figure 4b), the anchor point (i.e., temperatures at ground level) are consistent with those at 20:00h at approximately 17-19°C, whereas the temperature above the raked seating has increased by 1°C.

Figure 4c shows temperatures at the end of the show when the pre-heating system in the plenum has been operational since 21:00h. The temperature of the anchor point (at the bottom of the rake) has also increased, owing to the preheating of the air in the plenum. The structure of the thermal profile is consistent, although the spread in temperatures at higher levels indicates that the upper stratified layer of air is less well-mixed than at the start of the performance.

4. ANALOGUE MODELLING

A series of analogue laboratory experiments designed to simulate the natural convective flow in the building were used to understand the thermal profile and airflow pattern in the theatre. This technique has been used to research fundamental principles of natural ventilation [6,7].

4.1 Methodology

The water-modelling technique used for this research utilises water as the working fluid, a sealed Perspex 1:75 scale model of the building and a plate with a hot wire strung across it in rows to simulate the audience heat source. The scale model is immersed in a larger tank of ambient fluid to simulate external conditions.

The hot wire is connected to an external heat source, the strength of which can be controlled. 15 K-type thermocouples are used to take temperature measurements at 1cm vertical intervals in the model. Ambient tank temperature is also recorded.

Figure 5: Plans and elevation of 1:75 scale model used for analogue experiments.

The experimental tank has 12 circular holes each 9.5mm diameter in the base (Figure 5 – floor plan), and 2 circular holes of 15mm diameter at the apex of the roof (Figure 5 – roof plan). The experiments presented here explore the significance of changing
basal opening area. Profiles were recorded once the flow had reached steady state.

4.2 Results

Results show that when the tank operates in displacement ventilation mode there is a large scale circulation cell upwards and backwards across the audience which then spreads across the roof and partially vents. The remaining flow from the seating zone recirculates in the upper part of the space creating a weakly stratified upper layer. Lower in the theatre, the inflow of relatively cold water through the floor develops small inflow jets which mix with some of the warm fluid in the theatre and then spread laterally to form a cooler lower layer of air. This is mixed by the convective plume rising over the raked seating area and heated up as it is then carried into the upper part of the theatre (Figure 6).

The basic thermal profile shown in Figure 7 did not change regardless of the amount of basal opening area between 2-12 holes, or the magnitude of the heat source. Reducing the amount of basal opening area increases the temperature of $T$ (Figure 8). As the opening area at the base of the model tends to zero (less than 2 holes open) there is a change in ventilation regime such that the model no longer ventilates in displacement mode. Instead, an oscillating flow is observed with alternate periods of counterflow and exchange flow through the two high level vents (Figures 9a and 9b), separated by a period of transient flow where short bursts of fluid (c.1s) would enter and exit at each vent.

![Figure 6: Annotated image of analogue experiment exhibiting displacement ventilation regime. All inlets and outlets are open; arrows indicate direction of fluid flow up rake of large scale circulation cell.](image)

![Figure 7: Structure of thermal profile in displacement ventilation mode. $T$ is the average temperature of the upper hot layer above the top of the rake.](image)

![Figure 8: Graph showing change in $T$ with basal opening area](image)

The oscillations in flow regime were accompanied by small changes in the temperature of the fluid in the model. In Figure 10 (overleaf) we show one cycle of the oscillation and denote the periods where one regime was stable for up to 10s and the transitional periods.
It may be seen that the exchange flow mode is associated with increasing temperature whereas the counterflow mode is associated with a period of decreasing temperature. These observations imply that the ventilation rate is higher in counterflow mode and lower in exchange flow mode. This seems reasonable as the interaction of ascending and descending flows in each vent in exchange mode is likely to exhibit a greater overall resistance than uni-directional flow through each vent.

Figure 9a Model ventilates using counterflow

Figure 9b Model ventilates using exchange flow

Figure 10: Oscillations in the temperature of the fluid as the flow regime flips between exchange flow, denoted by ‘E’, and counterflow ‘C’. The intervening transitional period is denoted by ‘T’.

Figure 11: Structure of thermal profile with height in mixing mode with oscillating flow through roof vents. This image shows the profile during exchange flow through both roof vents (see Figure 9b for illustration).

The structure of the thermal profile of the fluid in the tank is not stratified and is reasonably well-mixed. Figure 11 shows temperature data collected during exchange flow through the roof vents. The thermal structure with counterflow is essentially the same.

4.3 Results with flat rake

The structure of the thermal profile in displacement mode depends on the geometry of the heat source. When the rake is laid flat (i.e. floor level ‘seating’) the environment above is well mixed (Figure 12) and no gradual increase in temperature up to a height of 4cm, as in Figure 7, is observed.

The spread in temperatures at 2cm in Figure 12 is due to the location of some of the thermocouples in the boundary layer of the heating source.

Figure 12: Structure of thermal profile in displacement ventilation mode with a flat rake.

5. DISCUSSION

The results above indicate how strategic decisions regarding choice of seating geometry and inlet and outlet design and location can change the structure of the thermal profile in an auditorium space. Both the monitored results in the real theatre and modelling with the analogue model in displacement mode show that the hottest temperatures occur at the top of the raked seating. The temperature of the hot
upper layer can be reduced with greater opening area for ventilation, as illustrated by Figure 8. The use of a flat rake also creates a well-mixed environment with slightly lower temperatures (Figure 12) overall than the comparative experiment with the rake in place (Figure 7).

The use of mixing-mode ventilation through roof vents may be worth considering as an alternative to displacement mode ventilation. Although overall temperatures in the space were much hotter than in displacement mode (c.19°C warmer), the total opening area in the model was reduced to less than half. This method of ventilation has the advantage that raked seating could be used without the associated temperature gradient. The ventilation mode and temperature oscillations are a fascinating phenomenon and further experimentation is required to fully understand the triggers.

6. CONCLUSIONS

The geometry of a naturally-ventilated auditorium at a strategic level has been shown to have an effect on thermal profile, temperature and ventilation regime.

In a situation where flexible seating is used, the associated changes to vertical temperature structure should be considered when designing a ventilation system. The use of mixing-mode ventilation through roof vents is an alternative ventilation strategy that avoids the temperature gradient associated with raked seating.

REFERENCES


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