

# Natural Ventilation in Auditorium Design: Strategies for Passive Environmental Control

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**ABSTRACT:** For centuries the theatre has posed a series of environmental problems to the passive designer due to intermittent heavy occupancy and high heat loads, the sedentary nature of the occupants and the requirement for high air change rates. Historically, developments in ventilation are closely linked to developments in lighting. Prior to the 19th century when buildings were lit with candles and oil lamps the chief method of ventilation was through opening windows. The introduction of gas lighting in the 19th century caused changes in building design that took into account this new method of illumination. The result was a variety of strategies for naturally ventilating assembly buildings, and towards the end of the century these methods became relatively sophisticated.

The advent of air-conditioning halted advances in passive ventilating techniques until recently. During the past ten years however a number of theatres utilizing passive ventilation have been built in Britain, but these tend to use similar solutions – low-level intake with high-level extract through stacks. This paper aims to discuss other methods for naturally ventilating theatres and assembly buildings, with reference to historical case studies such as Zurich Opera House on the continent, St George's Bristol and The Royal Hall, Harrogate in Britain. These buildings reveal traditional knowledge of ventilating principles that have not been used in auditoria since the advent of air conditioning. The methods exhibited here may be used to inform the design of modern naturally ventilated assembly buildings.

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## 1. INTRODUCTION

The environmental problems caused by large numbers of people crowded into confined space have been a problem since the theatre became a fully roofed enclosure. Added to this are the high heat loads from lighting, which has always been an important artistic tool for dramatic expression.

Contemporary design is becoming increasingly concerned with sustainability in buildings. Historic and vernacular buildings demonstrate passive responses to indoor and outdoor environments that hold many clues to the design of natural ventilation systems. Little has been written about ventilation in theatres but a study of surviving buildings, drawings and texts reveals interesting approaches to the problem of ventilating densely occupied spaces.

This paper aims to relate a brief history of the development of ventilation in theatre buildings so that the systems in three case studies can be considered in context. These 19<sup>th</sup> century examples utilise methods and details that are not in use in contemporary naturally ventilated theatres in the UK, but may be used as the basis for new designs in the future.

## 2. HISTORY OF NATURAL VENTILATION IN THEATRES

The history of theatre ventilation can be directly related to the three phases of lighting – the first being the use of candlelight and oil lamps, followed by the introduction of gas light at the start of the 19<sup>th</sup> century and finally in the late 19<sup>th</sup> century, the use of electric light.

### 2.1. The Era of Candlelight

The era of candlelight can be considered to extend from the birth of the theatre in Ancient Greece up until the start of the 19th century. In early times, before the theatre became a fully roofed enclosure and performances took place outside or within a partial enclosure, comfort and air quality would have been related to the external environment.

Theatre building ceased after the collapse of the Roman Empire but drama was revived by the church as part of Christian religious ritual. Between the 12<sup>th</sup> and 16<sup>th</sup> century drama moved out of the church onto pageant wagons that could be moved from place to place. Medieval manor houses became settings for private entertainment.

The rediscovery in 1427 in Renaissance Italy of a Roman manuscript which included comedies by Plautus and Terence prompted a realisation that medieval stages were not suitable either indoors or outdoors for the production of classical plays. Italian Renaissance theatres were based on the designs of Vitruvius c.16-13BC, but were on a much smaller scale than classical Roman theatres.

During the Renaissance natural light, the torch, the oil lamp and the candle were the principle sources of illumination. Designers experimented with light for special effects and most of the major conventions in dimming, positioning, colouring, floodlighting, translucencies and auditorium darkening had been established by the early 17<sup>th</sup> century [1]. Texts on theatre design by Serlio (1475-1554) and other Renaissance designers reveal a need to ventilate smoke from light sources [2], and that openings were required in scenery and in the building generally for ventilation. Windows directly into the auditorium were provided for ventilation e.g. Palladio's Teatro Olimpico, Vicenza (1584).

In England the design of Elizabethan theatres took the form of a raised platform stage with open space for spectators on three sides, and encircled by galleries. These unroofed theatres gave way to indoor theatres from the turn of the 16<sup>th</sup> century. The development of English theatre was greatly influenced by the Court masques produced between 1605-1613 by Inigo Jones (1573-1652). Jones had travelled widely in Italy and introduced Palladian ideas to England.

The emphasis in Italy and the rest of Europe was on the design of theatre for opera and music, while in England the emphasis was on the design of theatres for drama and tended to be a more commercial venture than elsewhere. During the 17<sup>th</sup> century opening windows were still used for ventilation, and natural light for day time performances – an example of this is Killigrew's Drury Lane (1663) [3]. The footlights appeared during the 17<sup>th</sup> century and were either oil 'float' lamps or candles during this period. The footlights persisted for centuries and were problematic due to the position they occupied between actor and audience.

One of the first devices to appear specifically for ventilation in a place of assembly is the pyramidal vent. Sir Christopher Wren (1632-1723) used four such vents at high level in the House of Commons. A reconstruction of a theatre from a sketch in the Wren collection shows a large possible vent louvre at high level above the pit [3]. Wren's pyramidal vents were reportedly unsuccessful as they were a source of cold draughts and in 1723 Dr Desagulier (1683-1744) was asked to solve the problem. He did this by connecting the pyramids to the fire grate so that ventilation could be assisted by convection. Desagulier also invented the first centrifugal fan installation in the 18<sup>th</sup> century, which was mounted in the House of Commons in 1736 and hand-operated by a man called a 'ventilator'.

Towards the end of the 18<sup>th</sup> century there is evidence that openings in the theatre ceiling were used to flush the atmosphere during intervals [4]. These panels were closed when the performance resumed.

Up until the end of the 18<sup>th</sup> century the theatre had very little service equipment. During the 18<sup>th</sup> century there were few significant changes to theatre lighting. By the end of the 18<sup>th</sup> century however designers recognised that a specific arrangement was required to deal with increases in the size of crowds and theatre buildings in general. This fact, along with

developments in lighting and heating technology which occurred around the turn of the 19<sup>th</sup> century identifies the start of a consciously integrated approach to heating, lighting and ventilation that was to have a marked impact on the form of the buildings of the 19<sup>th</sup> century.

## 2.2 The Era of Gaslight

The use of gas lighting became widespread in the theatre towards the end of the second decade of the 19<sup>th</sup> century and continued until the 1870's and beyond. The by-products generated by gas were of an order previously unparalleled by candles and oil lamps. The increased heat load accompanied by water vapour, carbon oxides and pure carbon inevitably led to innovations in the ventilation of buildings.

By 1817 the development of gas production, storage and metering was virtually complete. By the opening of the 1817-1818 season the Lyceum, Drury Lane and Covent Garden were all gaslit. The introduction of gaslighting at Covent Garden also incorporated a bespoke system of ventilation designed by the Marquis of Chabannes. Although gas lighting provided a much brighter source of illumination it had a marked effect on the quality of the environment.

There was a trend over the years for increasingly large chandeliers. The 'sunburner' invented in approximately 1825 was a very large multiple gas burner built into the theatre ceiling above the pit. This feature required a ventilation exhaust directly to the building's exterior. The large central duct is a prominent feature of nearly all of the sections through contemporary theatres drawn by Sachs at the end of the 19<sup>th</sup> century [5]. A network of ducts venting hot air or gas by-products from other parts of the house would connect to the central duct or connect directly to the exterior at the roof apex. During the early part of the 19<sup>th</sup> century progress was slow in overcoming the environmental problems caused by gas.

Dr David Boswell Reid (1805-1863) draws attention to the intolerable oppression caused by excessive gas lighting arising not only from the escape of unconsumed gas but also from the return of the products of combustion to the zone of respiration [6]. His design and description of a scheme for theatre ventilation shows an appreciation of the driving forces of ventilation, the necessity of avoiding draughts and the need for control in the distribution and exhaustion of air. Reid describes the fans available at the time, but considers the use of fans a last resort preferring instead natural ventilation driven by buoyancy and negative wind pressure.

That there was debate about upward (displacement) versus downward (mixing) ventilation during the mid 19<sup>th</sup> century is evident from discussion published in Chalmers Information (1842) [7] but designers tended to favour displacement ventilation.

The use of heat to aid ventilation meant that the whole structure of a building would be adapted to the needs of convected air circulation. In large scale institutional buildings this was in the form of giant brick ducts often with their own source of heat to stimulate air movement. Auditoria and council

chambers were often provided with large thermal siphon extract ducts, powered by braziers or heating coils at their bottoms e.g. St George's Hall, Liverpool (1851-4). Ventilation did not however significantly improve until the development of effective fans.

The period after 1860 saw the flourishing of fan design. The application of fans was held back until the last years of the 19<sup>th</sup> century by a lack of aerodynamic knowledge and the lack of small power adaptable to fans of domestic or personal scale. Ventilation until this time used heat as a source for convecting power, but this was problematic for summer cooling. Stacking ice in the intake ducts was one method of overcoming the problem (or towards the end of the 19<sup>th</sup> century the use of cooled coils supplied by refrigerating plant) but comfort was not necessarily improved since the process could increase the relative humidity [8].

The footlights had also become a much greater problem since the introduction of gas lighting. Comparatively innocuous in the era of candlelight, the footlights were now open rows of gas jets, sometimes shielded but sitting at full height on the forestage [1]. A waving stream of hot air distorted the audience's view of the stage, and caused noxious surges of air that tended to roll over the audience in the pit. Reid suggested these be enclosed with ducting to carry away the products of combustion directly in 1844, this was finally realised during the 1860's when patents for the improvement of footlights emerged. Other patents included designs for opening ceilings and sliding roofs [9].

Vienna Court Theatre (1874) designed by Gottfried Semper (1803-1879) is considered to possess one of the most elaborate systems for heating and ventilating. Fresh air was provided at various temperatures by means of a combination of collecting, heating and mixing chambers, with the chief mixing chamber placed under the auditorium with openings below the seats. Air extract was through ducting above the central chandelier.

### 2.3 Ventilation in the Era of Electric Light and the Advent of Air-Conditioning

By the late 1870's electric light was starting to exert its influence at the theatre.

The advent of electric lighting eased the problems of ventilation caused by gas. During the era when gas was prevalent, it was recognised that openings in the ceiling were required for ordinary ventilation but it was a necessity that a large opening above the customary gas chandelier be provided. According to Sachs [5] however, those theatres in which there was any attempt at ventilation beyond the duct above the central chandelier were exceptional. The chandelier remained a characteristic feature of the auditorium until the end of the 19<sup>th</sup> century. Many of the 19<sup>th</sup> century and earlier European theatres have been fully or partially destroyed by fire or World War II bombing. Electric chandeliers or a modernist equivalent persist today in some of the theatres that have been rebuilt or partially refurbished. The Vienna Opera House and Court Opera House, Dresden are two such examples.

The introduction of electric lighting meant that the large duct above the central chandelier was no longer required. Sachs, writing at the end of the 19<sup>th</sup> century, suggested that with the introduction of electric light general ventilation openings could equally well be placed elsewhere [5]. Destruction or refurbishment of 19<sup>th</sup> century theatres has meant that there are few remaining vestiges of the old natural ventilation systems to be found. At the Paris Opéra the enormous duct above the chandelier has been truncated and the roof void above converted into ballet practice rooms.

By the end of the 19<sup>th</sup> century effective fans and fan power were in existence. The use of ice or cooling coils to control air temperature on summer days was effective in lowering temperature but could raise relative humidity. Willis Carrier's (1876-1950) patent for dew-point control in 1906, accompanied by further patents for fans and refrigerants distinguishes him as the 'father of air-conditioning' [10]. Initially confined to air-conditioning factories and industrial buildings, Carrier's opening into the comfort market came when he air-conditioned the Metropolitan Theatre in Los Angeles in 1922. Cool dehumidified air was delivered at high level and extracted under the auditorium seats – reversing the direction of air flow that had been the norm in earlier displacement systems. By 1930 the Carrier Engineering Corporation had air-conditioned 300 theatres and this became the preferred mode of ventilation for theatres during the 20<sup>th</sup> century.

### 3. DESIGN OF NATURAL VENTILATION SYSTEMS IN MODERN BUILDINGS

The oil crisis of 1973 prompted a resurgence of interest in low-energy naturally ventilated buildings. Since the 1990's several small naturally ventilated auditoria have been built in Britain. The approach to the modern naturally ventilated auditorium is aided by the availability of contemporary computer and physical scale modelling tools for the prediction of internal temperatures. The drivers behind the new designs are different to those of the 19<sup>th</sup> century. Electric lights are in use ubiquitously, but modern audiences expect a sanitised environment. The internal environment of the theatre is therefore expected to provide air quality on a par with air-conditioning.

Strategically the designs for the intake and extraction of air are similar to those used in the 19<sup>th</sup> century. Modern theatres do not however have a large sunburner in the centre of the ceiling above the pit, requiring bespoke ventilation. Modern lighting systems tend to be dispersed within the theatre at high level, gallery level, and at the sides of the stage (depending on the theatre format). Air intake is through labyrinthine intake ducts of thermally heavyweight material, partially lined with acoustic insulation for the prevention of noise ingress. This duct provides pre-cooling in summer, and keeps the air warmer than the ambient in winter. Heating in winter is via heating coils in the ducts. Air is introduced into the auditorium through openings

under the seats or grilles dispersed throughout the room. Hot air is generally exhausted directly through shafts that connect the auditorium to the external air.

#### 4. CASE STUDIES

Although many 19<sup>th</sup> century theatres are still in existence, the building elements for ventilation have frequently been altered such that the existing system is destroyed. Descriptions and details of three buildings that have wholly or partially survived are given in the following sections.

##### 4.1 The Royal Hall (Formerly the 'Kursaal'), Harrogate, Uk (1903)

Architects: Frank Matcham and Robert Beale

The Royal Hall was designed as a multi-purpose space, intended for daytime use as well as evening performances. The seats in the pit were removable so that it could double as a ballroom. During the day it would be used for a diverse range of events from tea parties to orchestras. The building was designed for natural ventilation – much of the system had survived in tact when the author visited the building in 2000. Because of its multi-purpose function the theatre is not a 'black box' and has windows on the lower and upper levels; some of which are opening.

Fresh air inlets for the pit, stage, staircases, vestibule, and 'bio' box are situated on the roof. The inlets are chiefly square ducts, with louvres on all sides at roof level. Fresh air for the theatre is entrained at externally at roof level through four ducts and delivered at ground level at the rear of the auditorium.

This air is heated in the auditorium and rises into the roof void through a latticed ceiling. It is exhausted via six outlets in three orientations on the roof surrounding the lantern. Two inlets either side of the stage deliver fresh air to the actors.

Air intake to the basement was controlled by dampers in the shafts – remnants of this machinery can be seen on site. At basement level air is entrained into a substantial air shaft, where, warmed by heating coils, it rose up through two hot air ducts at

the back of the stage and was exhausted over the stage into the roof void above the lattice ceiling. This air path with convective heating would probably have been used to 'kick-start' or help drive the displacement ventilation system.

Modern fire regulations require complete compartmentation between the stage and the pit and a separating wall has since been built into the roof void blocking this air duct.

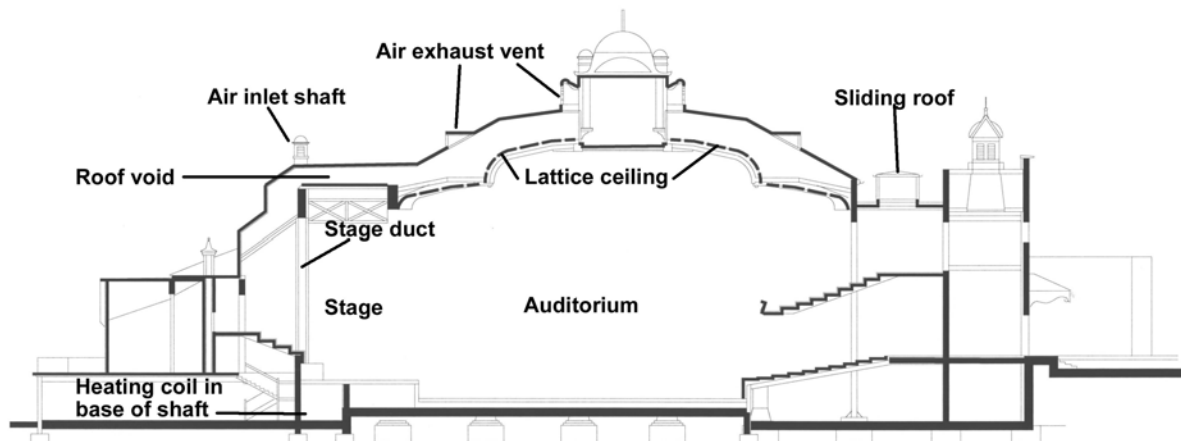
The large concentration of inlets on the staircases (four in all), may have been in order to make provision for crowds in the lobby during interval. The presence of smokers would have required a higher air change rate.



**Figure 2:** Latticed ceiling in the Royal Hall, Harrogate seen from below (top) and above (bottom).

At the uppermost level in the auditorium a separate ventilation circuit is created. There is an air intake shaft over the access point to the upper circles and extract through a sliding roof over the upper circle seating. This arrangement creates a direct exhaust air path to the external environment.

The design of the displacement ventilation system at the Royal Hall is sophisticated. The concept for



**Figure 1.** Diagrammatic long section through the Royal Hall, Harrogate (1903).

'top-down' ventilation ducts is well-known but these are seldom seen in operation. The opening areas of the ducts are relatively small by today's standards, but large in comparison to those in the following two case study buildings. The fact that much of the ceiling area is latticed means that the opening area into the roof void is very large and the effective height of the auditorium is increased. The roof outlets are however relatively small.

#### 4.2 Zurich Opera House, Zurich, Switzerland (1891)

Architects: Ferdinand Fellner and Hermann Helmer

The Zurich Opera House opened in 1891, and then underwent refurbishment in 1984. The air-conditioning system in the building has been in place since the refurbishment, but remnants of the old natural ventilation system can still be seen in the ceiling and roof void.



**Figure 3:** Mesh above central chandelier vents hot air into roof void, Zurich Opera House.

It is not clear how air is introduced into the auditorium but it appears to have been at basement level through vents running along the sides of the building. Sectional drawings suggest a large plenum under the seating [5]. The auditorium is equipped with the classic large chandelier. A large circular section of the ceiling directly above it is composed of mesh which allows the heat to escape into the roof void (Figure 3). It is lightweight, porous and visually decorative so that from below the void above is not apparent.

Above the highest tier of seating there are orifices for ventilation that can be opened or closed (Figure 4). The shape of these vents appear to be a decorative feature of the ceiling when viewed from below. They are spaced at regular intervals in semi-circles around the room, with one opening above each box.

External vents are visible around the roof on all sides, and there is large central vent at the roof apex with slatted sides.



**Figure 4:** Openable ceiling vent, Zurich Opera House seen from within the roof void.

#### 4.3 St Georges Bristol, Bristol, Uk (1823)

Architect: Robert Smirke

Originally a church, St George's Bristol became a venue solely for music in 1976. In 1999 the building underwent major refurbishment during which time the existing natural ventilation system was replaced with a mechanical system. Remnants of the original system remain as part of the auditorium ceiling and in the roof void.

A series of 16 perforations in the auditorium ceiling for the venting of hot air into the roof void are articulated with ceiling roses. Four central roses are larger and more porous than those on the sides of the ceiling (Figure 5). The roof void is connected directly to the cupola through a large opening. The cupola itself has small louvred openings in all directions to the external air for ventilation.



**Figure 5:** Ceiling rose vents hot air into roof void, St George's Bristol.

Hot air above the chandeliers was extracted directly through three large timber ducts that terminated at the apex of the pitched roof. Smaller branch sections fed into the main extract duct (Figure 6). These have been truncated as part of the recent refurbishment, but nevertheless remain a fascinating example of historical ducting.





**Figure 6:** Truncated 19<sup>th</sup> century timber ducts in roof void, St Georges Bristol. The existing ventilation system was replaced during the 1999 refurbishment.

## 5. DISCUSSION

The naturally-ventilated case study buildings described above provide some insight into the detailing of historic ventilation systems which is not apparent from architectural drawings. Internally ventilation openings are treated as part of the interior design of the auditorium, unlike subsequent modern services design in which visible elements of the ventilation system have a machine aesthetic.

Common to the three case studies is the use of a roof void from which air is extracted. The ventilation system is a decorative element of ceiling design, with varying degrees of opening area. Utilising elements of the ventilation system as architectural expression can be seen in modern examples, most notably in Alan Short's theatres where exhaust stacks or ventilation towers are highly articulated. The historic examples however give elegant expression to the ventilation system internally.

The Royal Hall, Harrogate is particularly interesting because of the incorporation of 'top-down' chimneys. Although the movement of cool air could be felt at the base of these ducts, there are not sufficient numbers of them to ventilate the auditorium to modern standards. Although the potential use of top-down chimneys has been modelled using small scale water models [11] the principle has yet to be used in a contemporary theatre.

The large latticed ceiling at the Royal Hall provides a much larger free opening area for the hot air in the auditorium to move into the roof void in comparison to the vents in Zurich Opera House and St George's Bristol. This is perhaps the result of the culmination of a century of intense experimentation with ventilation design.

## 6. CONCLUSIONS

Evidence of the sizes of 19<sup>th</sup> century openings in the ceilings for ventilation, shafts for extract and delivery of air and the sizes of vents in the roofs of theatres is that the free opening area of components

of the ventilation system are much smaller than in contemporary naturally ventilated theatres. The exception to this is the giant duct above the main chandelier in 19<sup>th</sup> century examples. The new naturally ventilated theatres in the UK have simpler designs – shorter, more direct air paths typically, but neither the sizes nor capacities of the contemporary theatres compare to the 19<sup>th</sup> century examples. Vertical shafts for the delivery and extract of air running the full height of the building and into the building's structure are no longer used. The use of the roof void above the auditorium as a plenum is evident in all three of the case study buildings, and this is accompanied by the use of decorative perforated ceilings over the auditorium. Neither of these two ideas is in use in contemporary examples.

With the use of modern simulation and modelling methods these historical devices may yet reappear in modern naturally ventilated buildings as sustainable design gains further expression in contemporary architecture.

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