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MIXING VENTILATION CAN REDUCE ENERGY COSTS

By Shaun Fitzgerald and Andrew Woods

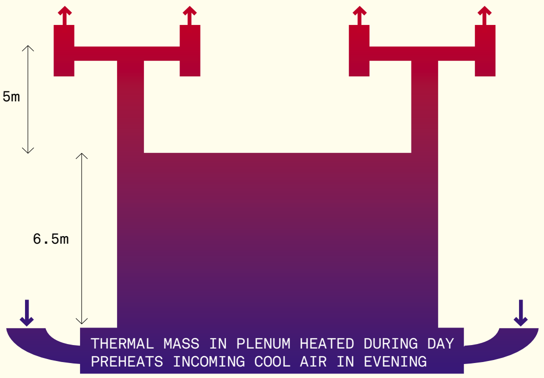
Increasing energy costs coupled with concern about carbon emissions has intensified interest in natural ventilation. Ventilation experts Shaun Fitzgerald and Andrew Woods study 'mixing' ventilation, which recent research from Cambridge University's BP Institute suggests can achieve better energy savings in buildings such as theatres and schools than conventional 'displacement' ventilation.

A number of UK theatres have recently been completed using displacement ventilation. Given the large ventilation requirements associated with the high density of occupants, displacement ventilation can provide an effective means of regulating temperature and air quality. Air is brought in at low level and is heated through a combination of heat loads, primarily from the audience and stage lighting, before rising through vents in the roof.

But displacement ventilation has inherent inefficiencies because it requires some heating and cooling capacity due to seasonal fluctuations in source air temperature. During cooler months the incoming air requires preheating to satisfy thermal comfort criteria. This increases the heat load and ventilation rate required to flush the heat from the theatre. In the summer, upward displacement ventilation can only operate if the theatre interior is warmer than the external temperature. This may lead to uncomfortably hot interior temperatures, necessitating a cooling system. The theatre interior then becomes cooler than the external temperature, resulting in downward natural ventilation through the stacks. Downflow may be undesirable if the cooling is provided by thermal mass at low level, since it can only function effectively with upflow ventilation. This can be achieved by low-wattage fans in the outflow stacks.

These principles of displacement ventilation have been used at Manchester's Contact Theatre and the Garrick Theatre in Lichfield. Both theatres include an underfloor plenum to buffer the temperature of inflowing air. To assess the actual operation of the ventilation in each theatre, we documented temperature fluctuations by locating thermocouples in the auditorium, the plenum, the ducts and the stacks, and recording temperatures at five-minute intervals over an extended period. At the Contact Theatre the internal temperature remained comfortable, but there was an inflow through one of the stacks during the cold evening and morning periods, while the other stacks continued to operate in an outflow mode. Our data was less conclusive at the Garrick, but it also appears to operate in a hybrid mixing-displacement ventilation mode – some high-level stacks provide inflowing air to complement air supplied at low level from the plenum.

Our research indicates that neither theatre is operating according to the displacement-ventilation principle upon which they were designed. Hybrid mixing ventilation has an important impact on both the ventilation rate and the thermal comfort of the theatres. With an inflow of cold air through a high-level vent, a descending plume of it develops within the space, becoming progressively more dilute as it approaches the occupied zone above the floor. A key issue is whether it is sufficiently dilute that



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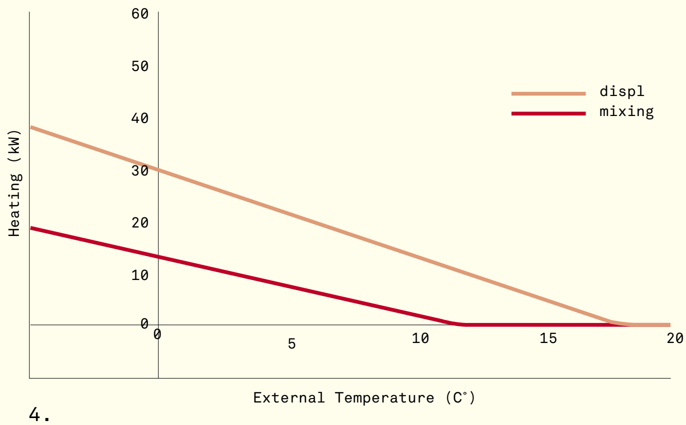

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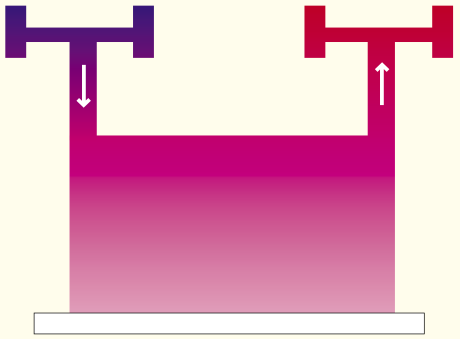

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1. Ventilation stack at the Contact Theatre, Manchester
2. Contact Theatre design concept: upward displacement ventilation
3. Contact Theatre actual ventilation: mixing ventilation
4. Graph showing potential savings in required heating when mixing ventilation is used instead of displacement ventilation

occupants do not experience localised zones of cold air. Our data indicates that in tall spaces such as theatres, with interior heights of more than 5m, the ventilation plume will dilute sufficiently.

It is difficult to determine which flow pattern will develop at a given time, especially with multiple equally sized stacks. Fortunately, effective control of the stacks does not rely in detail on modelling the flow pattern, but often involves comparing the prevailing flow regime with the desired flow regime, and then establishing a procedure to evolve the flow to the desired regime. To determine the prevailing flow regime, it is possible to measure temperature and CO_2 levels in the stacks and infer the flow pattern by comparing the data with the exterior and interior values. By installing small low-wattage fans in each stack, and using these in combination with the dampers, the flow can be adjusted. Once flow has equilibrated, the stack-driven flow becomes stable and fans may be turned off.

The potential financial savings of a mixing ventilation strategy can be estimated by examining the preheat requirements throughout the year. A graph (*above*) comparing the energy needed to preheat incoming air to 18°C using displacement ventilation with the heating required to simply maintain the interior conditions at 22°C using mixing ventilation in the winter shows that, once the external temperature falls to below 18°C, the heating system is required for a displacement ventilation strategy, whereas the heating system is not required with a mixing ventilation strategy until the exterior temperature falls to around 12°C.

Hybrid ventilation systems can also be used in buildings with conventional ceiling heights, such as schools, but when the vertical distance between the entry point to the stack and the occupied zone is less than 5m there is a risk of cold draughts in winter because the incoming fresh air is not able to mix sufficiently with the air in the room before reaching the occupants. This can be controlled by a new patent-pending e-stack natural ventilation system which uses a series of dampers, plus temperature and CO_2 sensors within the stack, to ensure that the appropriate ventilation rate is provided. The system has been installed in a number of schools. Data comparing the performance of a classroom using the e-stack natural ventilation system to the same classroom operating without the e-stack suggests that the CO_2 levels in the classroom are substantially lower when using the e-stack system.

Naturally ventilated theatres do not always operate in the simple upwards-displacement ventilation mode, even if they are designed to do so. Mixing ventilation, with counterflow in the stacks, can occur. The e-stack natural ventilation system has been developed to enable the energy-saving benefits of mixing ventilation to be applied in smaller buildings as well as in theatres.

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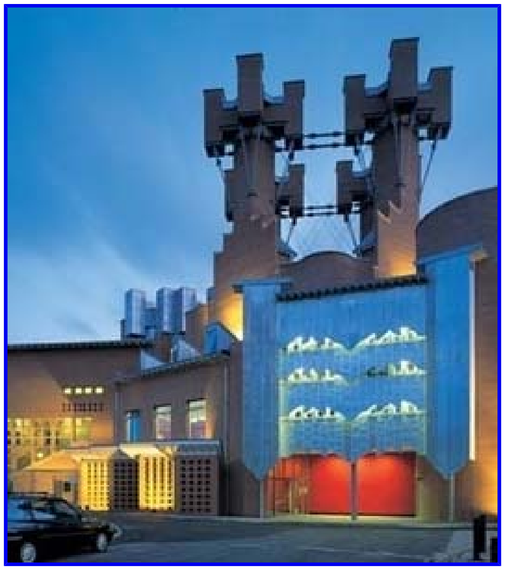
E-stack offers RIBA-approved CPD seminars and workshops on natural ventilation, low-energy building design and complying with Parts L and F. Visit: www.e-stack.co.uk



Dramatic ventilation

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Displacement natural ventilation has been used in several new theatres, but it does not always behave as designers expected, explain Shaun Fitzgerald and Andrew Woods

Increasing energy costs, coupled with growing concerns about carbon emissions, has intensified interest in natural ventilation. In response to this drive, a number of theatres in the UK have been designed and built using some of the established ideas of displacement natural ventilation.

The Garrick Theatre in Lichfield and the studio at the Contact Theatre in Manchester were both designed in this way. In such designs, it is usual for air to be brought into the theatre at low level, where it is heated through the combination of heat loads, primarily from the audience and the stage lighting, before rising through vents in the roof of the theatre back to the outside.

But studies have cast doubt on this simple concept of upward displacement ventilation. Instead, research has found that, in some situations, air flows into the building through some of the out-flow vents, and flows out through other vents which leads to the theatre’s ventilation operating in an unpredictable hybrid mixing-displacement ventilation mode.

Before going into detail on the hybrid mode, it is useful to consider the concept of displacement ventilation in theatres. Displacement ventilation can provide an effective means of regulating the temperature and air quality of a theatre, even with their large internal heat loads and the large ventilation requirement of the high density of occupants per unit area.

However, it does require some heating and cooling capacity, particularly associated with the seasonal fluctuations in the exterior temperature. For example, when it falls below the range 15-17ºC, the incoming low level air requires some pre-heating to ensure a comfortable temperature. This, in turn, increases the heat load in the space, and hence the ventilation rate required to flush the heat load from the theatre.

In the summer in very hot conditions and in the absence of wind forcing, upward displacement ventilation can only operate if the interior is warmer than the exterior. This may lead to unsatisfactorily hot interior temperatures, and thus a cooling system is needed.

With such a cooling system, for example associated with thermal mass or chilled panels, the interior space would then become cooler than the exterior and the natural ventilation would become a downward displacement flow.

If the cooling is to be provided by thermal mass at low level or in an undercroft, this can only chill the air passing through the theatre if there is up-flow ventilation. Here, during very hot conditions, a forced up-flow would be needed to maintain the ventilation and benefit from the cooling. This may be achieved through low wattage fans in the outflow stacks.

These principles have been developed and applied in practice in a number of theatres. For example, both the Contact Theatre in Manchester and the Garrick Theatre in Lichfield include an underfloor plenum to provide thermal mass which, in principle, can buffer the temperature of the inflowing air.

Studio, Contact Theatre, Manchester

The Studio at the Contact Theatre is a very simple space, 12 x 12 m, with floor level inflow vents around the perimeter of the theatre, and four outflow vents above the four sides of the space (Figure 1). The inflow vents draw air from the outside through a thermally massive concrete plenum and into the theatre space.

The outflow vents lead to four large stack structures with an H-pot termination design, whose purpose is to buffer the effect of wind and prevent ingress of rain. Each stack also includes a fan, although these are not designed for use in the default natural ventilation mode.

A study was carried out of the temperature fluctuations in the theatre, the plenum and the stacks at the studio theatre, in order to assess the actual operation of the ventilation. We placed a series of temperature recorders in the building and sampled the local temperature every five minutes over the course of two months during the summer 2004.

Figure 2 illustrates a typical time series of the temperature measurements which we collected in the four stacks, at high level in the theatre and, for reference, the external temperature.

The data show a regular diurnal fluctuation of the exterior temperature (black line). However, each evening, as the external temperature falls, it can be seen that the temperatures in the stacks begin to diverge, with one of the stacks (stack 3 yellow line) showing a fall in temperature which follows the decrease in the external temperature, while the other stacks remain much warmer. Stack 2 (purple line) also occasionally decreases in temperature for short periods.

It can also be seen from the data (dark purple line) that the temperature in the theatre itself remains comfortable at all times, ranging from about 18ºC in the middle of the night to 22-23ºC during the day. This may indicate that, at least during the cold evening and morning periods, there is an in-flow of air through stack 3, while the other stacks, which still register warmer temperatures continue in an outflow mode. This interpretation is supported by more detailed data collected in the stacks.

This distribution of the temperatures within the stacks varied on a day-to-day basis, and we found that, in some cases, the temperature data implied inflow through stacks 1 and 4 and outflow through stacks 2 and 3.

For example, data collected one week after that shown in Figure 2 illustrates a reversal in the stack temperatures, with stacks 1 and 4 being colder than either stacks 2 or 3.

These observations of the stack temperatures cast some doubt on the simple picture of upward displacement ventilation on which the concept of ventilation for this theatre was designed.

Instead, the theatre appears to operate in a hybrid mixing-displacement ventilation mode, whereby some of the high level stacks provide inflowing air to complement that being supplied at low level from the plenum. The other high level stacks provide outflow paths for the ventilation.

Such a picture of mixed ventilation has been demonstrated in a simplified analogue laboratory experiment using two stacks and a single low-level inflow vent (Chenvidyakarn & Woods 2005), but the field data provide strong evidence that the phenomenon actually arises in practice.

The Garrick Theatre, Lichfield

The new Garrick theatre in Lichfield opened in the summer of 2003, and this was also designed to operate in an up-flow displacement ventilation mode. Low level vents were incorporated to allow ingress of air at low level, while there were eight stacks at high level to provide the outflow for the air (Figure 3).

The underfloor air supply system allows air to enter the space through a series of low level vents on the side of the building, as well as the large down-flow stack that gives access to outside air from high level. Air was expected to rise and flow out of the eight large stacks in the ceiling of the theatre.

In order to test the performance of this theatre, we collected a series of temperature data in the different stacks during summer of 2003, and we also recorded the flow speeds through a subset of the stacks and inflow ducts using readings from the airflow sensors which were installed in this subset of the openings and stacks.

Unfortunately, not all the stacks were instrumented and so, to interpret the data, we multiplied the measured flow rates (flow speed multiplied by cross-sectional area) by the number of inflow and outflow stacks, assuming for simplicity that the inflow stacks were all inflow, and the outflow stacks were all outflow. The result of this simple interpretation of the data is shown in Figure 4, which illustrates the air flow.

The graph shows that the cumulative air inflow rate through the inflow ducts is five to six times smaller than the outflow through the stacks. This suggests simple multiplication of the measured flows is too naive, and raises the possibility that some of the stacks were, in fact, in a state of inflow to balance the overall air flux to and from the space.

The temperature data in several of the stacks and the inflow ducts provide further support for this hypothesis because there are considerable temperature differences between the stacks, with one of the stacks being colder than one of the low level inflow ducts.

Although the evidence is perhaps not as conclusive as it is for the Contact theatre, the data indicate that it is likely that there is both inflow and outflow through the ceiling stacks, leading to a regime of mixing ventilation.

Implications of mixing ventilation for comfort

What are the implications of such mixing on the ventilation rate and the thermal comfort in the space? With inflow of cold air through a high level vent, a descending cold plume develops within the space.

This plume mixes with interior air, becoming progressively more dilute as it approaches the occupied zone above the floor (Figure 5). A key issue is whether the plume is sufficiently dilute that it has warmed up to within 3-4ºC of the temperature of the space so the occupants do not experience localised zones of anomalously cold air.

Figure 6 illustrates the temperature decrease with depth for plumes of various volume flux at the inflow vent. It is seen that in a depth of 10 m, plumes become very dilute and the temperature decreases to within 2-3ºC of the ambient even if the inflowing plume fluid has an initial temperature 20ºC colder than the interior.

Experimental models of mixing ventilation

To determine some of the flow regimes and the possible complex coupling of flows in different stacks in a building with multiple stacks, we explored the ventilation patterns in a model building using a small-scale water bath to replicate the airflow in a building.

The model had six stacks positioned uniformly in a 2 x 3 grid on the roof of the building. In our experimental system, we used a tank of dimensions 20 cm x 30 cm x 20 cm with stacks of length 4 cm and diameter 1 cm. The stacks protruded 1 cm below the ceiling of the experimental tank into the tank.

A high resistance wire was placed in a coil on the base of the tank to provide a distributed heat source and heat loads of 400-500 W were passed through the wire.

The tank was immersed in a large external reservoir.

To commence the experiment, the stacks were opened. The fluid in the tank heats up and a counterflow develops between the different stacks. In our experiments we recorded very stable regimes with (i) 2 inflow : 4 outflow; (ii) 3 inflow : 3 outflow and (iii) 2 inflow : 4 outflow. It is possible to model the detailed flow and to estimate the temperature in the space, given the flow pattern, and we now present a simple model for this.

Flow rate for a given heat load and flow

In a model building with, for example, n roof stacks, each of vertical extent h, the natural ventilation flow in which m stacks are inflow and n-m stacks are outflow has a volume flow rate in the inflow stacks given by

$$Q = mcA[\Delta p]^{1/2}$$

where c is the loss coefficient in each opening of cross-sectional area A, and Dp is the pressure difference between the interior and exterior at points below the stacks. The corresponding outflow stacks have an equal volume flow, which may also be expressed in terms of the buoyancy of the up-flowing fluid

$$Q = (n-m)cA[gh\Delta T/T - \Delta p]^{1/2}$$

where DT is the temperature excess in the room and g the acceleration of gravity, as before.

The two fluxes are equal, and so the flow rate is

$$Q = \frac{m(n-m)cA}{(m^2+(n-m)^2)^{1/2}}\left[gh\frac{\Delta T}{T}\right]^{1/2}$$

The heat flux QH in the building necessary to maintain this flow is

$$QH = \rho C_p \Delta T Q$$

and so, for a given heat load, the temperature of the room depends on the number of inflow and outflow vents according to the relation.

$$\Delta T = \left[\frac{(m^2 + (n-m)^2)^{1/2}}{m(n-m)}\right]^{2/3}\left[\frac{Q_H T^{1/2}}{Ac(gh)^{1/2}}\right]^{1/3}$$

The model shows that the flow rate is maximal and the room temperature a minimum when there is an equal number of inflow and outflow stacks. As the flow become more asymmetric, the flow decreases and the room warms up.

Control of the flow

Determination of which flow pattern will develop at a given time is challenging, especially with multiple, equi-sized stacks, in which case each of the stacks may involve inflow or outflow.

Fortunately, effective control of the stacks to provide satisfactory ventilation does not rely in detail on modelling the flow pattern. Instead, it often involves comparing the prevailing flow regime with the desired flow regime, and then establishing a procedure to evolve the flow to the desired regime.

In order to determine the prevailing flow regime, it is possible to measure temperature and CO2 levels in the stacks, and then infer the flow pattern by comparing this data with the exterior and interior values, as shown in the data reported earlier in this paper.

By installing small low-wattage fans in each stack, and using these in combination with the dampers, the flow can be adjusted until the desired flow regime is achieved. Then, once this has equilibrated, the stack driven flow becomes very stable, and the fans may be turned off. Selection of the desired flow regime depends on the occupancy pattern, but it may be that, during performances, it is desirable that the flow direction is periodically reversed in order to assist the large scale mixing.

One of the key lessons from such experiments is the richness and complexity of the competing steady state flow regimes, and therefore the difficulty in predicting the flow pattern.

Energy savings

The potential heating bill savings that can be achieved by adopting a mixing ventilation strategy when the outside temperature is below that at which exterior air can be brought in at low level can be estimated by examining the pre-heat requirements throughout the year.

Let us consider a relatively small theatre which, for illustrative purposes, has an internal heat generation of 10 kW. This heating load is equivalent to 100 people with no other load or, more realistically, 50 people with a modest lighting load of 5 kW. If we neglect fabric losses to the exterior, since the energy requirements for the occupied space are dominated by any losses associated with the ventilation with well-insulated buildings, then we need to assess the ventilation requirements for the auditorium.

The minimum ventilation requirement in order to comply with Part F of the building regulations would suggest a ventilation rate of 50 people x 10 l/s/person, or 0.5 m3/s. However, in terms of thermal comfort, it may be desirable to stipulate a minimum and maximum temperature of, say, 18 and 24ºC in the space. If this is the case, then the minimum ventilation flow required to remove 10 kW using only a 6ºC temperature difference between the incoming fresh air and outgoing heated air in upwards displacement mode ventilation is 1.7 m3/s.

The minimum ventilation requirement is therefore governed by thermal comfort rather than quality of fresh air if a displacement ventilation scheme is used in the colder months. The heating energy required to pre-heat incoming air to 18ºC with a displacement ventilation compared with the heating required to simply maintain the interior conditions at, say, 22ºC in the winter for the occupied theatre is illustrated in Figure 7.

It can be seen from Figure 7 that once the external temperature falls below 18ºC, the heating system is required for a displacement ventilation strategy, whereas the heating system is not required with a mixing ventilation strategy until the exterior temperature falls to around 12ºC.

Furthermore, since the ventilation requirements to ensure thermal comfort are higher in the case of a displacement ventilation strategy, the additional heating required for every 1ºC drop in external temperature is commensurately higher.

The calculations in Figure 7 can be combined with hourly weather data in order to assess the value of adopting the mixing ventilation strategy in the colder months for different parts of the UK. Weather data were analysed for six locations in the UK and the theatre was considered occupied between 2pm and 11pm. Figure 8 shows the heating requirements for a fully occupied theatre during these hours.

It is evident from Figure 8 that the difference in heating requirements is significant, and adopting of a mixing ventilation strategy when the exterior temperature is less than, say, 18ºC can lead to significant savings. The calculations of annual heat loads presented above do not account for the fact that the theatre is not used every day through the winter, but serve to demonstrate that the potential savings are significant.

Note also that the difference in strategies relies on the efficacy of the mixing ventilation scheme to ensure that the incoming air is sufficiently diluted with the air in the space so as to avoid cold draughts; theatres are well suited to this scheme owing to the vertical extent of the space, whereas other types of building such as classrooms may require assistance. For more details, see www.e-stack.co.uk

Postscript :

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