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THE PERFORMANCE OF NATURAL VENTILATION IN A DANCE STUDIO – LESSONS FROM TRACER GAS MEASUREMENTS AND CONTROL INTEGRATION

Fig 1: The Jarman Building, School of Arts, University of Kent, UK

Research summary

The naturally ventilated, three storey School of Arts Jarman Building provides two dance studios, an exhibition gallery, teaching rooms, video editing suites and offices. The main dance studio is double-height, has underfloor heating and accommodates sixty people. Fresh air enters from low level perimeter louvres and exits at high level through a stack that rises through the third storey to a stack terminal with motorized louvres. Tracer gas (CO_2) measurements were used to measure the ventilation rate in conjunction with hot-wire anemometry in the stack tower. The results showed that when all air inlet and exit louvres were set to closed, the residual air flow up the stack was 0.33m^3/s representing a potential heat loss of 9kW in winter at 0°C outside. When the louvres were all open, the air flow increased to between 0.49 and 0.62m^3/s, a level consistent with the studio's design occupancy. It was found that the studio's 4m high perimeter curtains represent a barrier to fresh air entering the main room space and cause the incoming air to migrate upwards towards the stack exit and effectively bypass the central part of the studio. Tracer gas decay rates showed that the main space experienced an air exchange rate 50% less than that for the overall studio. An investigation of the controls also revealed that the underfloor heating system operated independently of the control of the stack ventilation system, leading to simultaneous heating and venting. The research shows the vital importance of prescribing contractually that key controls are integrated, that fresh air dampers are well-sealed when closed, and the importance of designing a fresh air supply that matches the way a space is used.

Keywords: natural ventilation, stack ventilation, underfloor heating, controls, integration, tracer gas

1. Introduction

Naturally ventilated offices consume considerably less energy than air-conditioned offices. For example, in ECON19 (an Energy Consumption Guide for offices in UK) naturally ventilated open plan offices use 60% of the energy used in standard air-conditioned ones (BRECSU, 2000). The difference is mostly accounted for by the energy used for cooling, humidification and distribution.

There is thus much to be gained by using natural ventilation in a building's design and much has been learnt from the many good and bad exemplar offices that have been built and whose performance has been assessed. In the present case there is much less experience of designing a single building containing drama and dance studios, an art gallery, seminar rooms and cellular offices in a university setting.

Fig 2: The naturally ventilated Contact Theatre, UK

The community Contact Theatre in Manchester, UK, was built in 1999 and houses a 300 seat theatre, and an 80 seat studio used for dance and rehearsals, together with a café. Figure 2 shows the main entrance and the ventilation stacks with "H"-pots on top to reduce downdraught (reverse flow) in an urban turbulent environment (Short et al, 2005).

This theatre is designed to operate using passive stack ventilation enabled through nine tall stacks towering over the building, with high level slow moving fans available for peak times. Fresh air is admitted at low level through acoustic attenuators. When the building was assessed in 2001 as part of a European study of good exemplar buildings the occupants were reported as being very satisfied with the building (Kolokotroni et al, 2001).

In contrast, the School of Arts Jarman Building, at the University of Kent, UK, provides a mixture of both teaching and office space. It was completed in 2010 and provides 2,500m^2 of floor space over three storeys. See Figure 3.

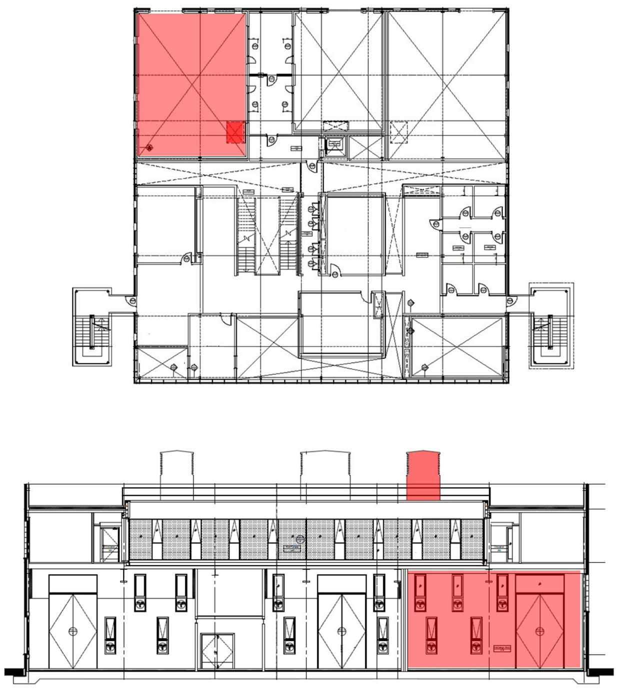

Fig 3: Plan and rear elevation of the Jarman building. The dance studio is highlighted in red.

The design sought to maximize the use of passive techniques with exposed thermal mass, control of summertime solar gain and the majority of the building is naturally ventilated. The mechanically ventilated and conditioned spaces are restricted to the internal seminar rooms and video editing suites. It was an innovative design decision to rely on natural forces to ventilate the bulk of the building including the drama studios and gallery.

Fig 3: The ventilation stacks of the Jarman building

2. Research objectives

The research was aimed at establishing how effective the natural ventilation strategy was in the main drama (or dance) studio. This 133m^2 room is 6m high with a volume of 798m^3, six openable windows, low level perimeter air inlet louvres and an exhaust stack with cross sectional area of 3.5m^2. One of the main parameters to be determined was the air exchange rate for the studio under different conditions. In particular, the impact of the position of the air inlet louvres and the black-out curtains in the room was tested. See Figure 4. Secondly, the leakiness of the studio was assessed when all openings (louvres, windows, and exhaust stack) were shut. Another goal was to identify the patterns of air movement in the space in three dimensions to help in assessing the provision of fresh air throughout the room which would be likely to have an impact on comfort.

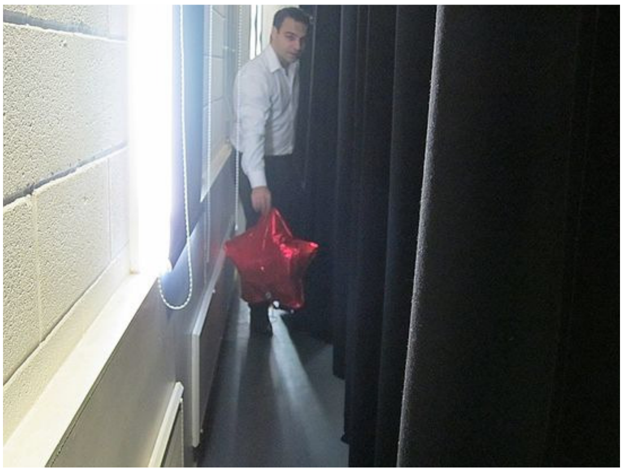

Fig 4: Testing behind the curtains, and showing the perimeter Passivent air inlet grilles

3. Method

3.1 Air movement testing

The first tests looked at how air was moving within the room, from the fresh air inlet louvres at the perimeter of the room, at low level, up to the entrance to the exhaust stack at ceiling level in one corner of the room. The method of flow visualization used was to employ neutrally buoyant balloons. These were prepared in advance of the tests and then rebalanced within the room after acclimatization, i.e. temperature equilibration.

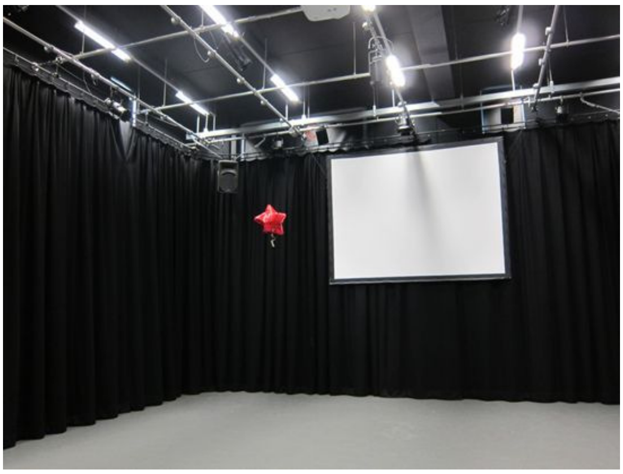

Fig 5: Air movement testing in the dance studio using neutrally buoyant balloons.

The balloons were inflated with a mixture of helium and air. They were released at various points and tracked visually and on camera noting the path taken and their velocity. The advantage of using balloons is that they can be seen and tracked easily in a very large space when alternative methods, e.g. using smoke, are problematic. See Figure 5.

3.2 Air change rate testing

Exhaust air from the room travels up an insulated stack which passes through the third floor of the building and continues up to four metres above the roof level where there is a louvred stack terminal. A hot wire anemometer and a carbon dioxide probe were placed inside the stack just below the control louvres. See Figure 6. Air temperature here was 23°C.

Fig 6: The top of the stack where air velocity, temperature and carbon dioxide were measured.

Carbon dioxide concentration was simultaneously measured in the centre of the drama studio at a height of 1.2m. In a series of tests, the room's CO_2 concentration was increased by releasing CO_2 from two cylinders until a relatively high value (compared to the background level) was obtained, from between 3000 and 4000ppm. See Figure 7. It was then allowed to decay.

Fig 7: Releasing CO_2 as a tracer gas in the studio.

The studio was tested in three states:

a. All windows and vents closed and curtains drawn closed.

b. All automatic window and vents open and curtains drawn closed.

c. As "b" but with the curtains opened.

In all the tests, the doors into the studio were shut and the window from the control suite shut. CO_2 was discharged near the centre of the room but directed away from the central measurement location. The gas was initially discharged through an electric fan heater to compensate for the temperature drop from the gas expansion. However, this was stopped later as the room temperature climbed when all the windows and vents were closed. After initial use of one cylinder a second gas cylinder was used in different parts of the room to hasten the room charging, and help with mixing. The room was repeatedly manually mixed using two 4m high central room dividing curtains.

The underfloor heating was on during all the tests, with a surface temperature, measured with a surface contact probe, of about 25°C. The outside temperature was 9°C and CO_2 concentration 450ppm, with a light breeze.

The stack velocity data were for the velocity upwards at the centre of the stack at high level in the inspection chamber beneath the stack outlet. These data were converted to a mean flow rate to obtain the volumetric flow rate by multiplying the central velocity by 0.60, a factor that was determined by calculation from velocity traverses across the stack diameter.

4. Results

4.1 Air change rates from stack anemometry

a. The main purpose of the first test was to measure the air flow rate up the stack when the whole system was closed, whilst charging the room up to a target of 3-4000ppm. The mean flow rate during the initial charging period was 0.33 m^3/s. This is equivalent to an air change rate of 1.5 ac/hour.

b. The second test measured the stack flow rate with the Passivent system open. This mean flow rate was 0.62 m^3/s. This is equivalent to an air change rate of 2.8 ac/hour.

c. The third test also measured the stack flow rate with the Passivent system open. This mean flow rate was 0.49 m^3/s. This is equivalent to an air change rate of 2.2 ac/hour.

The difference in air change rates between tests **b** and **c** (2.8 and 2.2 ac/h) is probably caused by a change in mean wind speed during the tests. In test **a**, it was surprising that the air flow rate up the stack was so high when the system was nominally closed (dampers at high level closed, all Passivent air inlets and windows in the room closed). However, there are external doors to the studio, two sets of internal doors, and all the inlet air inlet grilles at low level; these present a potentially large total crack length. It is also assumed that there is some high level leakage path, e.g. ill-fitting stack dampers.

4.2 Carbon dioxide decay rates

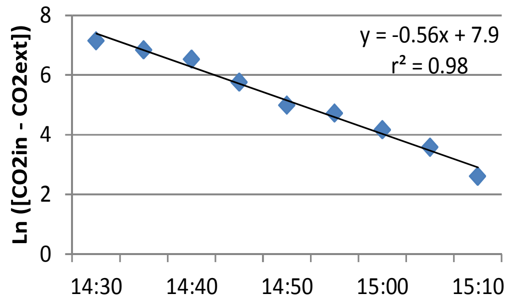

Fig 8: Decay of CO_2 in stack – Curtains CLOSED

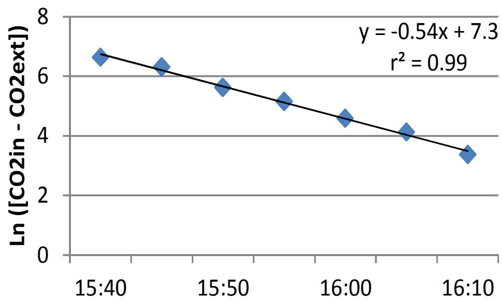

Fig 9: Decay of CO_2 in stack – Curtains OPEN

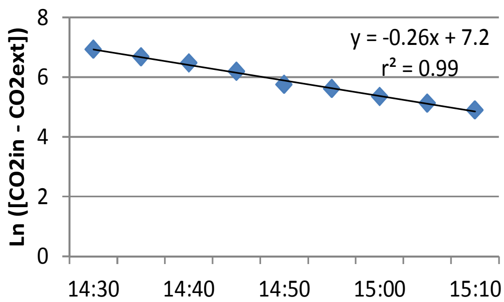

Fig 10: Decay of CO_2 in studio -Curtains CLOSED

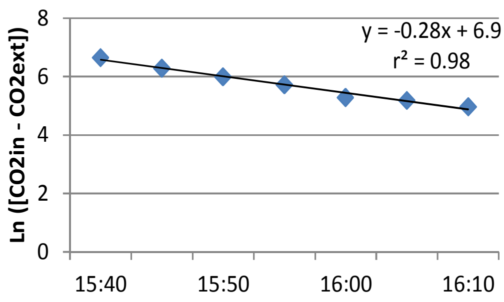

Fig 11: Decay of CO_2 in studio – Curtains OPEN

It is clear from the graphs that the logarithmic decay curves are close to being linear whick implies adequate mixing of the air. From the CO_2 concentration data, the local air change rate, the average age of the air and the air exchange effectiveness were determined.

The local air change rate was calculated as follows:

$$Air\ change\ rate = \frac{\ln Ct2 - \ln Ct1}{\Delta t}$$

where:
Ct2 = [CO_2] at the start of the test
Ct1 = [CO_2] at the end of the test
t = duration of test

The average age of the air each sampling location was calculated as follows:

$$Age\ of\ air = \frac{Average\ [CO_2]\ during\ test}{[CO_2]\ at\ beginning\ of\ test}$$

The air exchange effectiveness was calculated as follows:

$$Air\ exchange\ effectiveness, E = \frac{Average\ age\ of\ air\ (stack)}{Average\ age\ of\ air\ (studio)}$$

E < 1.0 indicates less than perfect mixing, E = 1 indicates perfect mixing.

Table 1: Air exchange effectiveness at the centre of the studio with curtains open/closed

	Curtains	Local ac rate	Age of air, h	Effectiveness
Stack	open	6.5	0.24	-
	closed	6.8	0.21	-
Studio	open	3.4	0.29	0.84
	closed	3.1	0.31	0.67

There is a marked difference in the local air change rate in the working area of the studio (taken as the centre of the studio floor) and in the exhaust stack. The ground floor air exchange rate is approximately half the rate at the exhaust. When the curtains were drawn back (opened), there was a small increase in the air change rate with the centre of the studio, and a small parallel decrease in the local air change rate at the stack, as would be expected. In terms of ventilation effectiveness relative to the stack, this increased from 0.67 with the curtains closed, to 0.84 when they were opened.

When the curtains are drawn across (closed) they present something of a barrier to fresh air entering the main part of the studio and this could explain the much higher local air change at the stack than in the centre of the studio. However, it was a little surprising that the air change rate at the centre of the studio remained lower when the curtains were opened. It may be that the high surface temperature of the floor is inducing a circulation pattern where fresh air continues to partially bypass the central area. Nevertheless, the effectiveness of the air exchange did increase in the studio central area from 0.67 to 0.84, i.e. significantly closer to unity, when the curtains were opened.

5. Control integration

During the wider assessment of the Jarman building it became apparent that the control system for the dance studio was less than ideal. The Passivent control system operated the opening of windows and/or low level motorized louvres to allow the entry of fresh air in to the studio and opened the dampers at high level in the stack. This was triggered by the carbon dioxide level or internal air temperature. The underfloor heating however, was controlled by its own temperature sensor, and operated independently from the Passivent control algorithms. This inevitably led to the heating system calling for heat when the Passivent system was trying to ventilate heat away/enhance the fresh air intake.

6. Conclusions

The air movement tests using neutrally buoyant balloons showed that air speeds in the studio are very low (around 0.1 m/s). It was also seen that convection cells exist across the floor, presumably as a result of the high surface temperature of the floor (25°C) from the underfloor heating system. These cells extended upwards but only to 2-2.5m above floor level, when air descended. The cells will encourage mixing of the air.

The observations of balloons placed behind the curtains also showed vertical movement but only to two to three metres. What appeared to be happening is that cold air enters at about 300mm above floor level through the Passivent grilles and "accumulates", is effectively dammed behind the curtains and at the same time starts to be warmed by the floor's warm surface. The air then migrates through the gaps in the vertical joins in the sections of curtain, and possibly through the fabric itself, and enters the studio's central area.

In the experiment, it had been expected that balloons would move upwards and toward the inlet to the ceiling stack. However, this was not seen, except when a balloon was manually raised to 4m above floor level, when it did move upwards the remaining two metres towards the stack's grille where it became trapped in the upward air stream.

The curtains, when closed, appear to be effective in dispersing the incoming cold air in the channel or annulus between the walls and the material. They effectively give time for the air to warm up and slowly "diffuse" through the curtains to the main area.

In the tests on air exchange rates, it appears that the incoming air preferentially bypasses the main central area in favour of ventilation paths towards the stack exit. Decay rates in the stack were twice those in the centre of the studio. When the curtains were opened, more fresh air moved towards the centre of the studio giving a higher exchange rate, and there was a commensurate reduction in the stack exchange rate. In the testing, the draughts from the incoming air from the Passivent grilles were very noticeable five metres away, when the curtains were open.

It is notable that the air change rate when the Passivent system was completely closed remained at about 0.33 m^3/s up the stack, equivalent to 1.5 air changes and hour, or potentially sufficient fresh air for over thirty people. Given that the underfloor heating schedule in the heating season is continuous (24 hours a day, seven days a week), this represents a significant waste of heating energy, at a rate of about 9 kW at 0°C outside. The heating system is turned off manually for the summer.

When the Passivent system was completely open, the air change rate in two tests was found to be 0.49 m^3/s and 0.62 m^3/s (a mean of 0.55 m^3/s). Variations in wind speed could account for the difference. The mean flow rate of 550 litres/s potentially provides sufficient fresh air for 55 people, at 10 l/s/person. This compares well with the design limit for the studio. The legal limit (for health and safety reasons) that the studio must comply with is to accommodate a maximum of 60 people. On this basis the natural ventilation system appears adequate. However, it is known that when the curtains are opened back that the fresh air entering the room from the Passivent low level grilles causes discomfort from cold draughts in the winter as the air is not pre-conditioned before entering the space. This would appear to be an unfortunate omission in the design.

The wider monitoring showed the importance of control integration, something that is important for both mechanical and natural ventilation systems. The failure here seems to have resulted from a contractual oversight where the requirements did not specifically prescribe a sufficient level of system integration in the heating, cooling and ventilation design.

7. Acknowledgments

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