

# Accessing the Thermal Mass above Suspended Ceilings via a Perimeter Gap: a CFD Study of Naturally Ventilated Spaces

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There is a growing desire to reduce peak temperatures within non-domestic buildings by accessing the thermal mass of separating floors. These floors are typically formed of concrete and can store reasonable amounts of heat. Unfortunately, they are usually thermally isolated from the room below by a suspended ceiling. Therefore, some architects try to access the concrete by leaving a perimeter gap in the suspended ceiling in each room to allow airflow across the underside of the separating floor. For visual and acoustic reasons, there is the desire to make this gap as small as possible. Using computational fluid dynamics we examine the relationship between gap size and airflow above the suspended ceiling for naturally ventilated spaces.

We show that although the precise details of the airflow depends on the size of the room, levels of incidental gains, ventilation rates and the location of heat sources, in all cases increasing the perimeter width within realistic bounds results in a linear increase in the mean tangential speed of airflow across the underside of the ceiling. This is common for both single sided and cross ventilated rooms and for both single and double raft designs; however, the double raft design performs significantly better.

**Keywords:** CFD, thermal mass, ventilation, suspended ceiling, airflow.

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## 1. Introduction

There is considerable interest in the potential use of the fabric of buildings to store heat, thereby leading to reduced temperature extremes and potentially reduced heating and cooling loads. Natural ventilation is considered by many as a sustainable approach that can be used to both maintain acceptable air quality for occupants and provide cooling (Heiselberg 2004). However, the full passive cooling potential of many buildings remain unharnessed (Beggs et al 1995). Concrete ceilings, walls and floors have a large capacity to store and release heat, which can be utilised as a heat buffer. Absorbing and storing heat during occupied hours, and returning it to the space during unoccupied hours, delays and reduces peak temperatures, regulating the internal environment. During the summer, outdoor night temperatures are usually lower than indoor temperatures, and thus this process can be helped by the application of night ventilation (Heiselberg 2004 and Balaras 1996). The regulation of internal temperatures can lead to reduced cooling loads in the summer months and the storage of heat in the winter (Hacker et al 2008) can lead to reduced heating loads. Here we focus on the thermal mass present in the separating floors of offices and other non-domestic buildings. Typically these are constructed of concrete, which is ideal for the storage of heat due to its high density and relatively high heat capacity.

The concrete's ability to provide heat storage depends on two factors:

- Its physical and thermal characteristics (e.g. area, thickness, admittance, heat capacity etc).
- The environmental conditions (e.g. temperatures, air speed, incident radiation etc).

Unfortunately, concrete separating floors are usually thermally isolated from the room below by the inclusion of a suspended ceiling. This prevents the thermal mass of the concrete from being exploited, increasing the need for additional ventilation to maintain desirable conditions. Therefore, some architects have made an effort to access the concrete by leaving a gap around the perimeter in the suspended ceiling of each room to allow airflow along the underside of the separating floor. However, there is no published guidance on the relationship between perimeter gap width and efficiency. Suspended ceilings are the primary mechanism for the control of reverberation in many spaces and furthermore they allow easy integration of light fittings, masking of pipes and ductwork plus other services, therefore, there is normally the desire to make this perimeter gap as small as possible. There is also the need to ensure any raft design does not conflict with the fire regulations or the requirements of insurers. Removing the suspended ceiling requires new solutions and designs to provide the same service and visual appeal, possibly at additional cost. Experiments have shown

that the use of permeable tiles across the entire ceiling can provide a degree of convective thermal exchange between the internal air and the concrete above. It is suggested that the maximum open area of a permeable grid that can be used, if the concrete is to remain hidden, is 20%. (Kendrick 1999). Depending on material, a small number of measurements undertaken by Kendrick suggest that an open area of 20% will allow approximately 40% of the convective heat transfer that would occur with a fully exposed concrete ceiling. Numerous possible solutions have been proposed (Brister 1995, 1996) but a simple compromise using a conventional suspended ceiling design with gaps may offer a cost effective generic solution. This would allow improved thermal performance, whilst maintaining good acoustics and service integration, yet added installation and design costs would be kept to a minimum. In this paper, we

examine the relationship between the size of the perimeter gap and the flow of air above the suspended ceiling.

## 2. Room Design

Two rooms were studied in this investigation; the first could be considered typical of a classroom and the second representative of a larger, open-plan office. Airflow was either single sided ventilation or cross ventilation at 80 l/s and 160 l/s. Two suspended ceiling designs were investigated, namely a single raft and a double raft. Also, three heat source geometries were investigated: a number of discrete heat sources, a uniform heat source and a large single heat source (see table 1). In total nine combinations of raft geometry and dimension, ventilation philosophy and rate, ceiling design, room size and heat source were investigated.

Room Type	Ventilation Philosophy	Ventilation Rate	Raft Design	Heat Source	Case No.
Classroom	Single Sided	80 l/s	Single Raft	Discretised (0.5m x 0.5m)	Case 1
Classroom	Cross Ventilated	80 l/s	Single Raft	Discretised (0.5m x 0.5m)	Case 2
Classroom	Cross Ventilated	80 l/s	Single Raft	Uniform (6m x 9m)	Case 3
Classroom	Cross Ventilated	80 l/s	Single Raft	Large Single (6m x 0.8m)	Case 4
Office	Cross Ventilated	80 l/s	Single Raft	Discretised (0.5m x 0.5m)	Case 5
Classroom	Cross Ventilated	160 l/s	Single Raft	Discretised (0.5m x 0.5m)	Case 6
Office	Cross Ventilated	160 l/s	Single Raft	Discretised (0.5m x 0.5m)	Case 7
Classroom	Single Sided	80 l/s	Double Raft	Discretised (0.5m x 0.5m)	Case 8
Classroom	Cross Ventilated	80 l/s	Double Raft	Discretised (0.5m x 0.5m)	Case 9

Table 1 The range of simulations undertaken in this investigation, with the corresponding case number for ease of reference.

The classroom was 6 m wide, 9 m deep and 3 m high, with the suspended ceiling at 2.7 m leaving a 0.3 m cavity (figure 1). The office was 12 m wide and 18 m deep, with height and cavity depth the same as the classroom. The suspended ceiling was 0.024 m thick and made of compressed glasswool; further details are given below. The inter-floor ceiling is comprised of 0.15 m of cast concrete. The floor, roof and walls were compliant to English 2002 building regulations. Both model rooms are south facing and have similar thermally linked rooms built adjacent to their rear, left and right walls. Of the three south facing external windows, the middle window was modelled to have a central pivot, leaving a maximum open area of 0.375 m<sup>2</sup> for the classroom and doubling to 0.7 m<sup>2</sup> for the office, at both the top and the bottom, with the other two windows permanently closed. Both the rear external and internal window had an area of 0.325 m<sup>2</sup> for the classroom, and doubling to 0.65 m<sup>2</sup> for the office, available for airflow. However, for this investigation, the external windows were opened at 75% to limit the incoming flow rate. Similarly, the internal window was opened to 25% or 75% to achieve either 80 l/s or a 160 l/s flow rate respectively. Barnard et al. (2001) suggests analysis of

a system's thermal mass performance should incorporate day-to-day variations in temperature rather than weather data from a single repeated day. In addition, the weather data chosen should be appropriate for the parameters involved, i.e. if natural ventilation is used wind speed and direction data would be required in addition to other variables. In this study, we have used observed weather data from the London (Heathrow) test reference year, spanning 3 weeks in June. The test reference year is a composite year made up of the most average months chosen from the period 1983-2005. Airflow data was taken from 4pm June 10<sup>th</sup> from the London test reference year, giving a south-westerly wind at 4.6 m/s and an air temperature of 21 °C.

As previously mentioned, three heat source geometries were considered. The first consisted of 20 discrete heat sources representing occupants, each providing 100 W of sensible heat (figure 2a). To reduce computation time significantly, occupants have been modelled as (0.5 × 0.5 × 1) m<sup>3</sup> boxes to represent seated individuals rather than a more realistic form, as the computing time cost for detailed modelling of the

occupants shape was too great for the comparatively small increase in airflow accuracy.

For the case of cross ventilation, two alternative 2 kW heat source geometries were also simulated; the uniform heat source (figure 2b) spanning the whole floor area and the large single heat source (figure 2c). Additionally, the open-plan office model was simulated using 80 discrete occupants providing a total of 8 kW of sensible heat (figure 2d).

The suspended ceiling was modelled as being impermeable to air. Although previously mentioned research shows small amounts of heat transfer through permeable ceilings, these effects have not been included in this investigation as they depend on the choice of suspended ceiling material and this is a general study. The two ceiling designs investigated in this paper are a single and a double raft design, as shown in figure 3. The initial aim of this research was to study the effect of perimeter width around the single raft. However, from early inspection it was clear that the majority of vertical airflow would come from the centre of the room due to heat radiated from the occupants. It was therefore decided to compare the single raft with a composite design that allows a proportion of the warm rising air to flow directly from the occupants to the concrete. In this double raft design, the central void and the two short edges have the same exposed area the single raft design.

The perimeter gap width around the single raft ceiling ranged from 0.1 m to 1.5 m for the classroom model, and 0.1 m to 3 m for the office model. The 0.1 m to 1.5 m range is deemed reasonable for use in a real classroom with reasonable acoustic and aesthetic targets. This range corresponds to exposed areas of 2.8% to 66.7% of the total ceiling area, which was conserved for the double raft ceiling design to provide equal exposure. Results for both rooms with no suspended ceiling were also calculated for reference and for normalisation of the results.

### 3. CFD Modelling

There are typically three approaches used to study natural ventilation: experimental measurements, simple equations representing bulk exchanges and computational fluid dynamics (CFD) (Jiang et al 2004). Bulk exchange equations normally only consider flows between rooms, or between rooms and the external environment, not the flow pattern within rooms and as such give no indication of where air flows within a room, so dead zones can be missed. Experimental measurements have proved to be expensive and time consuming, additionally, experimental data may not be detailed enough for understanding the underlying physical mechanism. Conversely, CFD is becoming a popular tool due to its relatively low cost and the information it produces

(Jiang et al. 2004). Frequent research has demonstrated the usefulness of CFD as a design tool for ventilation systems (Cheong et al. 2003, Jiang et al. 2004 and Allocca et al. 2003). It enables the velocity and temperature fields to be investigated in significantly greater detail than is possible with either simple analytical or experimental models (Cheong 2001). Combined with dynamic thermal models, CFD allows the true thermal dynamics of the building to be taken into account, albeit by a series of instantaneous 'snapshots' of airflows. They can illustrate the quality of air and temperature distribution and verify whether the ventilation design can provide a satisfactory environment for all occupants (Chow 1995). Generally, it has been shown that CFD calculated airflows are in good agreement with measurements (Nishizawa 2003).

CFD models incorporate equations describing conservation of mass, energy and momentum. There are numerous CFD software packages available to produce these models, and this investigation uses IES Virtual Environment CFD software (microflo). Combined with approximations for viscous stress and turbulence, the time-averaged Navier-Stokes equations are solved for three-dimensional, compressible, non-isothermal flows using a finite volume technique. A turbulence model is needed to determine the unknown Reynolds stresses in the underlying equations. Although there is a range of models, this investigation uses the standard *k-e* turbulence model as described in Launder and Spalding (1974). Chen (1995) compared five different *k-e* models for indoor airflow computations; the standard *k-e* model proved to be very stable and required the least computing time.

The boundary conditions were calculated using a whole building dynamic thermal model (IES Virtual Environment) incorporating a bulk airflow simulation model that uses a fast multi-zone thermo-fluid solver to simulate the interactions between airflows, pressures and thermal conditions, including surface temperatures used in the subsequent CFD analysis and there is no dynamic link between these boundaries and the airflow pattern within the room. This simulation showed that the maximum drop in room temperature obtained by removing the suspended ceiling and exposing the concrete was 1.65 °C and 1.46 °C for single-sided and cross-ventilation respectively. For the case of single-sided ventilation, a ceiling surface temperature of 19.96 °C was found without a suspended ceiling and 22.68 °C with a suspended ceiling. For the cross-ventilated classroom, ceiling surface temperatures of 20.1 °C and 23.19 °C were found respectively.

Ideally it would be possible to link the CFD and building model and run a simulation on an hourly, or

smaller, time step over a complete year. Unfortunately, this is beyond common desktop computing power. The corollary is that we must find a proxy metric to represent the difference in thermal capacity provided by differing airflow patterns. The most obvious metric is the mean tangential velocity of the air flowing along the underside of the ceiling as it is this air that is transferring heat to and from the ceiling.

The exact heat exchange will depend on the environmental conditions and changes to this velocity will depend on many additional factors, such as occupancy patterns, weather and heat gains from other rooms. For this research we have chosen to focus on the access to the thermal mass of the bulk of the air in the room as a metric of the effectiveness of differing suspended ceiling raft layouts, and in particular, how this velocity is reduced as the size of raft increases. The convective heat transfer coefficient,  $h_c$ , at the velocities in question can be given by (Duffie 1974):

$$\text{eqn. 1 } h_c = 5.7 + 3.8v,$$

where  $v$  is the velocity of the air. Therefore  $h_c$  is linearly related to  $v$  and hence in the following we use changes in  $v$  as a proxy for changes in the heat transfer coefficient and hence to changes in the accessibility of the thermal mass. Changes in the thermal conditions within a space as this accessibility changes will be more complex, dependent on the temperatures involved and are also time varying, hence cannot easily be assembled into a single metric of performance.

The CFD mesh used for this investigation typically consisted of cells  $0.2\text{ m} \times 0.2\text{ m} \times 0.2\text{ m}$  decreasing to  $0.2\text{ m} \times 0.2\text{ m} \times 0.04\text{ m}$  for the uppermost  $0.4\text{ m}$  of the room. This was to ensure sufficient detail above the suspended ceiling whilst significantly reducing the computing time. All reported velocities were taken at a height of  $2.96\text{ m}$  (i.e. from the cell in contact with the underside of the exposed concrete) to characterise the tangential velocities across the surface of the concrete ceiling. For the classroom models, the reported velocities were taken from a subset of 40 cells on a  $1\text{ m}$  grid, and similarly the office model from a subset of 77 cells on a  $1.5\text{ m}$  grid. The speed reported for each cell is formed from the  $x$  and  $y$  velocities parallel to the ceiling plane:

$$\text{eqn. 2 } v = (v_x^2 + v_y^2)^{1/2},$$

where  $v_x$  and  $v_y$  are the velocities in the  $x$  and  $y$  plane respectively. These are then averaged to give the mean tangential speed  $V$ :

$$\text{eqn. 3 } V = \sum_{i=1}^N \frac{v}{i},$$

where  $N$  is the number of cells considered (40 for the classroom and 77 for the office). In the case of no suspended ceiling, the mean tangential velocity is labelled  $V_{ex}$ .

## 4. Results and Discussion

In the following, the relative mean tangential speed parallel to the ceiling is plotted against the perimeter gap width. The speeds have been expressed as a percentage of the value predicted for a totally exposed ceiling (i.e. the relative mean tangential speed  $V/V_{ex}$ ). A table of results for  $0.3\text{ m}$ ,  $0.6\text{ m}$  and  $1.2\text{ m}$  are given in table 2.

### 4.1 Single Sided Ventilation

Figure 4 shows the variation in relative mean tangential speed with changing perimeter widths and exposed area (case 1).

It can be inferred from the trend shown in figure 4 that the average speed across the slab is greatest for a room with no suspended ceiling and that, in general, increasing the perimeter width/exposed area increases the relative mean tangential speeds linearly, and so the access to the thermal mass is proportional to the perimeter width. (For very small gaps, this is unlikely to be true as  $V/V_{ex}$  must equal zero for a gap size of zero.) In this case, increasing the perimeter gap from  $0.1\text{ m}$  to  $1.5\text{ m}$  increases the access to the thermal mass from 30% to 55%, at a gradient of  $0.2\text{ m}^{-1}$ . As shown in figure 5, air entering the room at low level flows towards the occupants, where their body heat raises the air temperature. This in turn forces the air to rise towards the ceiling, where it disperses outwards across the underside of the suspended ceiling. For a room with no suspended ceiling, this warm air disperses across the concrete ceiling, cools, and then sinks back into the room where it later passes back out of the window. For rooms with a partial suspended ceiling, this warm air must flow across the suspended ceiling before it can access the concrete above. However, some air will sink into the room before it can reach the perimeter gap, and some will be drawn into the channel of air flowing out of the room. This results in a lower average air speed directly below the concrete. In essence the air above and below the suspended ceiling are not fully mixed (see the appendix for a table of absolute velocities and air temperatures). As seen in figure 4, it appears that a linear relationship describes the results reasonably

well for gap sizes of less than 1.5 m (66% exposed area).

## 4.2 Cross Ventilation

### Classroom Model with Discretised Heat Sources (Case 2)

The cross ventilated room was analysed using the same increments in gap size (figure 6), and with the same flow rates as those used for the single sided case.

The results for the cross ventilation are similar to those for single sided ventilation. The results show that for cross ventilated rooms, although the speeds are higher, increasing the perimeter width up to 1.5 m has a smaller effect on the relative mean tangential speed than it does for a room with single sided ventilation. The higher air speeds of the cross-ventilated case verifies the use of the proxy metric shown in eqn. 1, the higher ceiling temperatures indicate that more heat has been transferred to the concrete. For both single raft models, a perimeter gap of approximately 1.2 m (the width of two typical ceiling tiles) provides speeds half that of a totally exposed ceiling. For the cross-ventilated case, however, 40% of the speed from a totally exposed ceiling can be achieved with only a 0.2 m gap.

### Alternative Heat Source Geometries (Cases 3 & 4)

To examine whether these results were of general form, two alternative models were investigated with different heat source distributions. The uniform heat source, producing  $37 \text{ W/m}^2$ , as expected resulted in a substantially smaller maximum vertical velocity of rising air than shown in the other models. The predictions for the relative mean tangential speed are interesting: a 0.6 m perimeter gap would yield the same relative mean tangential speed as a fully exposed ceiling (figure 7), and therefore exposing any more would only be detrimental to the aesthetics and acoustics of the room. From this result it can be argued that for naturally ventilated rooms with low or no occupancy (i.e. at night), or very even (modest) heat distribution, a suspended ceiling need only use a maximum characteristic gap of 0.6 m (the width of a typical suspended ceiling tile).

The large single heat source redistributed the heat as a  $6 \text{ m} \times 0.8 \text{ m} \times 0.5 \text{ m}$  box spanning the width of the room, keeping a surface area similar to the 20 discrete heat sources. Due to the shape of the heat source, by increasing the perimeter widths of the ceiling the concrete was being continually exposed to a constant amount of rising air, resulting in a linear relationship (figure 8). This supports the conclusion that in general the trend in velocity with perimeter gap is linear.

### Open-Plan Office

A large open plan office similar in design to the classroom was also modelled but with  $x$ - $y$  dimensions doubled. The predicted velocities are plotted against perimeter gap and alongside the results of the classroom model in figure 9. Both the 80 l/s and 160 l/s airflow simulations are plotted for comparison. It is clear that for perimeter widths up to 1 m there is a straight-line trend in average velocity, which is consistent in the 80 l/s and 160 l/s airflows for both the classroom and the office. It can also be seen that for the 80 l/s airflow, the gradient of the trend is approximately equal for both models, supporting the idea that the results are general. However, by changing the airflow from 80 l/s (cases 2 & 5) through to 160 l/s (cases 6 & 7) the gradient has approximately doubled for the office, yet changed little for the classroom. The airflow into the classroom equates to  $1.77 \text{ ach}^{-1}$  or 4 l/s per person increasing to  $3.55 \text{ ach}^{-1}$  or 8 l/s per person both of which could be deemed as adequate airflows. However, for the office this equates to  $0.44 \text{ ach}^{-1}$  or 1 l/s per person increasing to  $0.88 \text{ ach}^{-1}$  or 2 l/s per person, these levels of ventilation are far lower than for the classroom. This suggests that there may be an increase in the gradient of the linear response of the relative velocity to increasing gap size to an upper limit. In this case the gradient is dependent on the air changes per hour until a set value is reached at which point the gradient ceases to increase further. However, to verify this would require more simulations to be carried out, such an upper limit could depend upon many factors such as the size and shape of the room as well as the number and orientation of any heat sources in the room.

## 4.3 Single Sided and Cross Ventilation with Double Rafts

For a direct comparison of the effectiveness of a perimeter gap, systems with two suspended ceiling rafts were also considered. Although many architects will want to avoid exposing significant areas of the concrete ceiling in the centre of a room for aesthetic reasons, it does produce many advantages whilst maintaining comparative acoustic performance. The relative mean tangential speed is plotted against area of exposed ceiling in figures 10 and 11 for the classroom model with single-sided and cross ventilation (cases 8 & 9), where they are compared to the results from a single raft design of corresponding area.

Mean tangential speeds across the concrete ceiling were substantially higher than the speeds of a single raft design with an equivalent perimeter gap in the ceiling. Furthermore, the rate at which the velocities increase is much higher than the single ceiling designs, at  $0.62 \text{ m}^{-1}$  compared to  $0.13 \text{ m}^{-1}$  and  $0.20 \text{ m}^{-1}$ . This means that multiple raft designs may have considerable benefits over single raft designs. Significantly, half of the mean tangential speed given

by a totally exposed ceiling can be achieved with only a 0.25-0.3 m gap, considerably smaller than the exposure needed with a single ceiling design. Furthermore, it is predicted that a 1 m gap may provide approximately 100% of the possible thermal access; significantly more beneficial than the single ceiling design.

The reason for such a substantial improvement is due to a proportion of the warm air rising directly to the concrete ceiling before falling each side of the suspended ceiling. This circulation encourages more air to flow above the suspended ceiling, from the centre outwards (figures 12 and 13). Air that rises

outside of this partition can still disperse outwards and around the suspended raft similar to a single ceiling but this air is prevented from reaching the concrete by the faster air flowing out of the cavity.

## 5. Conclusions and Future Work

This investigation has produced insight into the airflow above a suspended ceiling with perimeter gap. The predicted results offer a guide to accessing the thermal mass above a suspended ceiling, through both a perimeter gap and in combination with the use of a central void, but they also highlight the importance of careful modelling. Table 2 summarises the findings.

Perimeter Gap	Case No.								
	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7	Case 8	Case 9
0.3 m	32%	42%	73%	51%	59%	42%	60%	50%	54%
0.6 m	38%	46%	99%	59%	63%	45%	68%	69%	73%
1.2 m	50%	54%	99%	74%	-	-	75%	98%	100%

Table 2. Relative mean tangential speeds for 0.3 m, 0.6 m and 1.2 m for the nine cases investigated.

The conclusions that can be drawn from the single suspended ceiling results are:

- In all cases, increasing the perimeter gap produces a linear increase in mean tangential speed of air across the concrete ceiling for realistic gap sizes.
- For both single sided and cross ventilated rooms, a perimeter gap of 0.1 m is sufficient to allow some air to flow over the suspended ceiling, with 1.2 m (two typical ceiling tiles) providing half the mean tangential speed experienced without a ceiling.

In the case of a double raft:

- For perimeter widths less than 1 m, the rate of increase in relative mean tangential speed is far greater than for a single raft.
- Mean tangential speeds are continually higher than the corresponding single ceiling speeds, and therefore a double raft design is the preferred design.
- Half the relative mean tangential speed experienced without a ceiling is achieved with only a 0.3 m characteristic gap, and 100% access can be achieved with 1.2 m, substantially better access than the single raft ceiling design.

The constant of proportionality in eqn. 1 suggests that the actual heat transfer will grow more rapidly than the mean tangential speed (which will also depend on the surface temperature of the ceiling). In addition, because the mean air temperature directly below the ceiling also increases as the mean tangential speed increases, the true heat transfer is likely to again increase somewhat faster than eqn. 1 suggests. This is

due to the heat transfer also being dependent on the difference in temperature between the air and the ceiling. Since during the day the ceiling is at a lower temperature than the air below it the heat transfer increases for increases in air temperature.

This investigation would benefit from full-scale experiments, which currently do not accompany these results due to time and financial constraints, to confirm these findings. Furthermore, as previously mentioned, research has been undertaken on the effectiveness of permeable suspended ceilings on thermal mass access. Combining permeable suspended ceilings with exposed perimeters may lead to improved access to the thermal mass above. Coupling this with a double raft design, it would be of interest to research and investigate an optimum suspended ceiling design for buildings such as schools and offices. This can be taken further by exploring multiple raft designs and those with a separating slot in the alternative direction (i.e. across the width of the room rather than down its length). This may offer improved integration of services across the ceiling whilst maintaining the thermal benefits predicted for the double raft ceiling. It would also be valuable to investigate the airflow due to very small perimeter gaps, the impact of grille-like structures and the impact of heat emitted by the light fittings.

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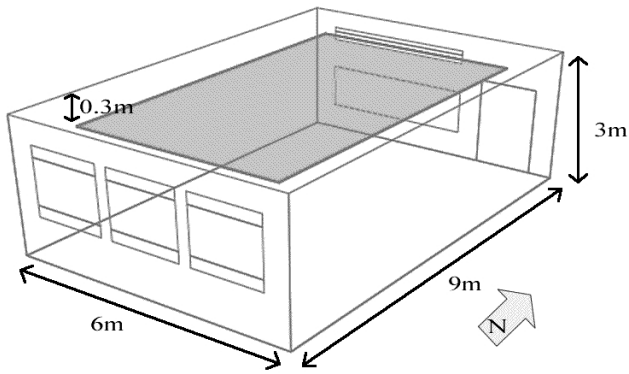


Figure 1 Dimensions of the model classroom with a single raft suspended ceiling positioned to provide a 0.3 m high cavity. Opening areas of the external window are 1.5 m × 0.25 m and the internal window is 3.25 m × 0.1 m in size. The design of the external openings is intended to represent a central pivoted window.

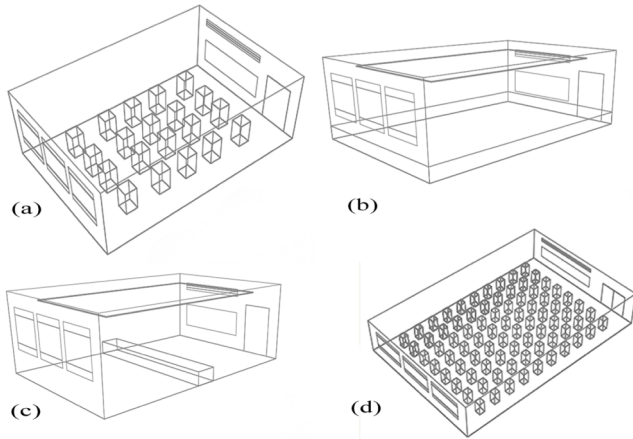


Figure 2. (a) Twenty discrete heat sources positioned to represent a classroom during operational hours, (b) The model with the uniform 6 × 9 m heat source, (c) the 6 × 0.8 m heat source across the room width and (d) the open-plan office with 80 occupants.

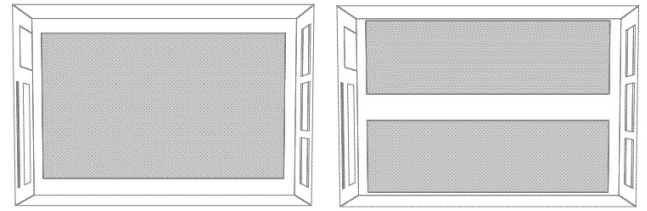


Figure 3 Single and double raft suspended ceiling designs with equivalent area. The double raft exposes the ceiling directly above occupants to increased vertical airflow.

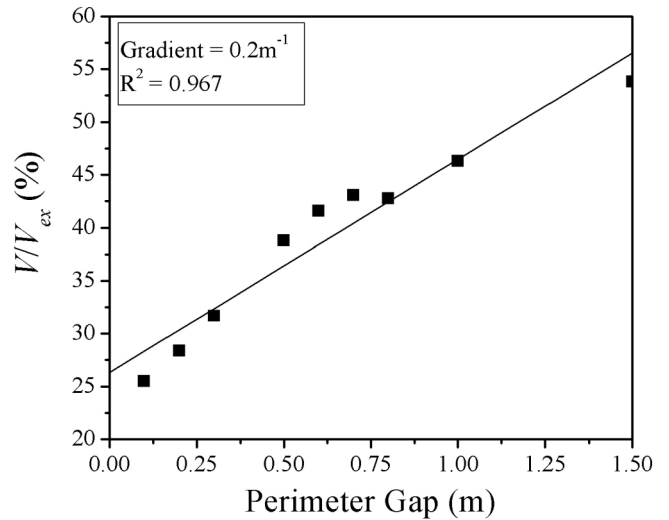


Figure 4 Case 1 (single sided ventilation with single raft ceiling). Relative mean tangential speeds are plotted against perimeter width up to 1.5 m.

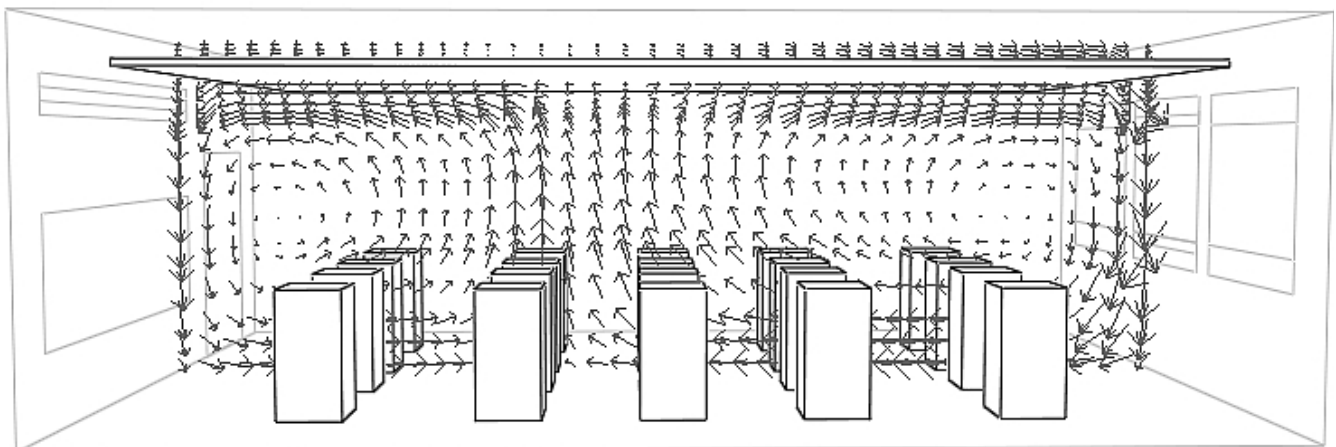


Figure 5 Airflow velocity diagram showing a slice in the  $y$ - $z$  plane for single sided ventilation with single raft suspended ceiling, with air flowing in and out of the room from the right side. Warm air rises from occupants and spreads across the underside of the suspended ceiling, causing circulation currents at either end of the room. The size of the arrows shows the relative velocity of the air in each cell.



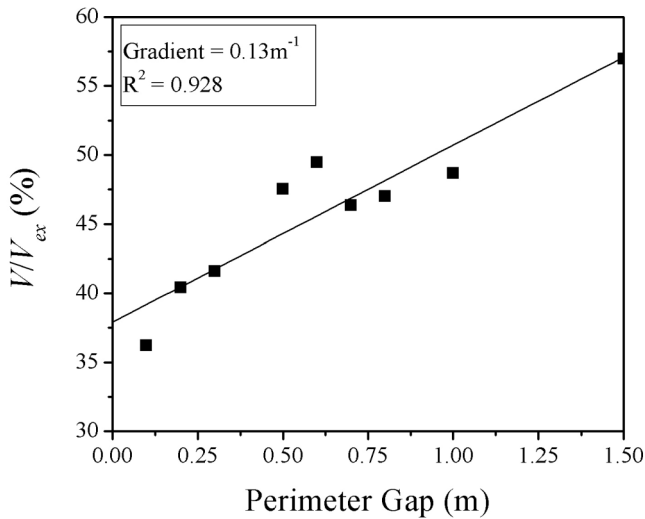


Figure 6 Case 2 (cross ventilation with single raft ceiling). Average velocities are plotted against perimeter width with straight trend lines.

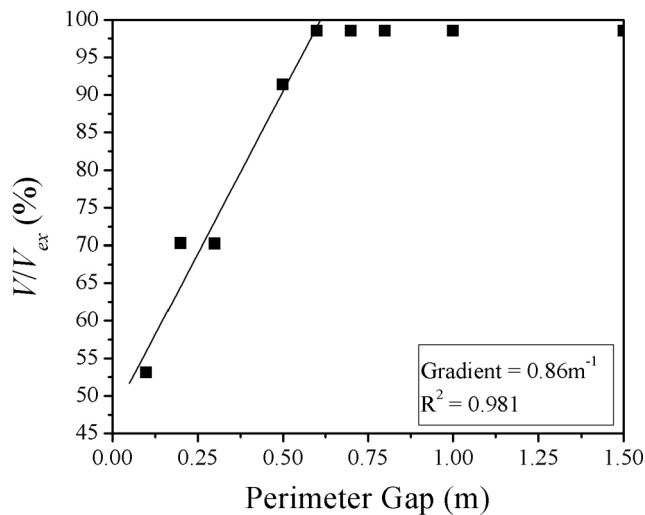


Figure 7 Case 3 (cross ventilation with single raft ceiling and uniform heat source). Relative mean tangential speed is plotted against perimeter gap - with perimeter gaps larger than 0.6 m the speed is constant.

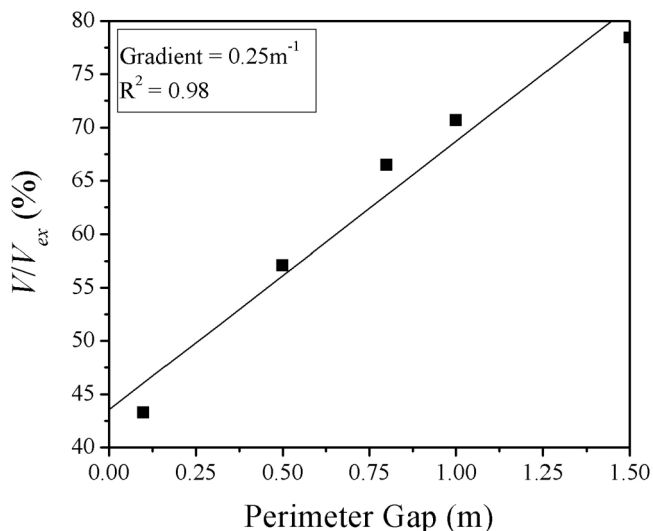


Figure 8 Case 4 (cross ventilation with single raft ceiling and large single heat source). Relative mean tangential speed is plotted against perimeter gap with a linear trend line.

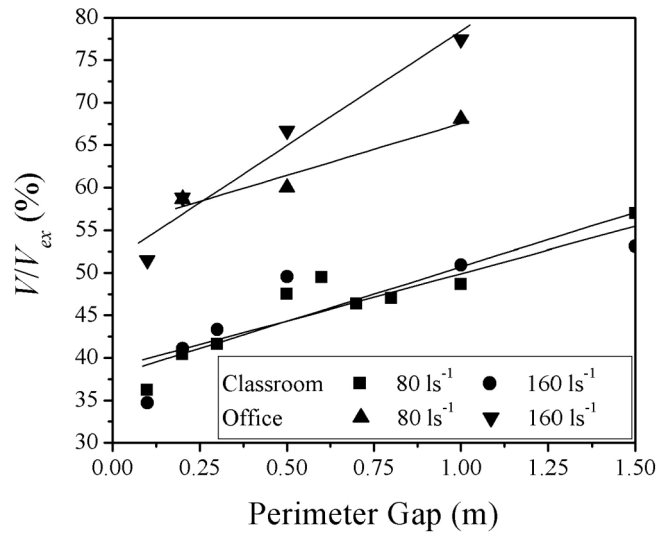


Figure 9 Relative mean tangential speed is plotted against perimeter width for 80 l/s airflow (cases 2 and 5) and for 160 l/s airflow (cases 6 and 7). Gradients (and  $R^2$ ) are  $0.128 \text{ m}^{-1}$  (0.928),  $0.122 \text{ m}^{-1}$  (0.969),  $0.111 \text{ m}^{-1}$  (0.863) and  $0.269 \text{ m}^{-1}$  (0.979) for cases 2, 5, 6 and 7 respectively.

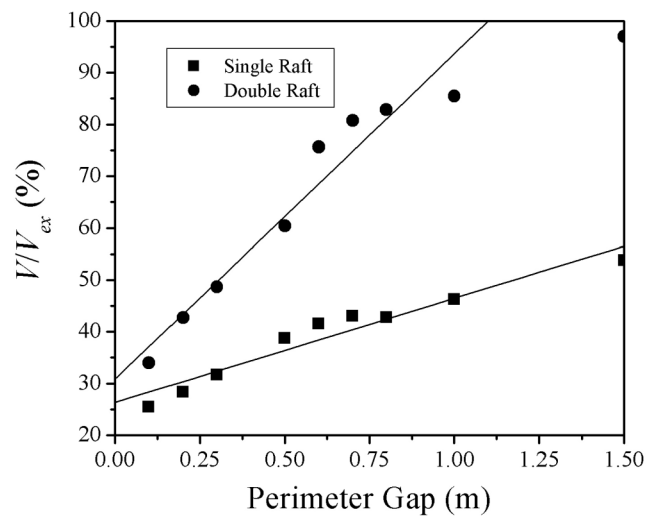


Figure 10 Case 8 (Classroom single sided ventilation with double raft ceiling). Double raft results for relative mean tangential speed against perimeter gap for single sided ventilation. Results from a single raft ceiling are plotted for comparison. Gradients are  $0.20 \text{ m}^{-1}$  and  $0.62 \text{ m}^{-1}$  with  $R^2 = 0.967$  and  $0.976$  for the single and double rafts respectively.

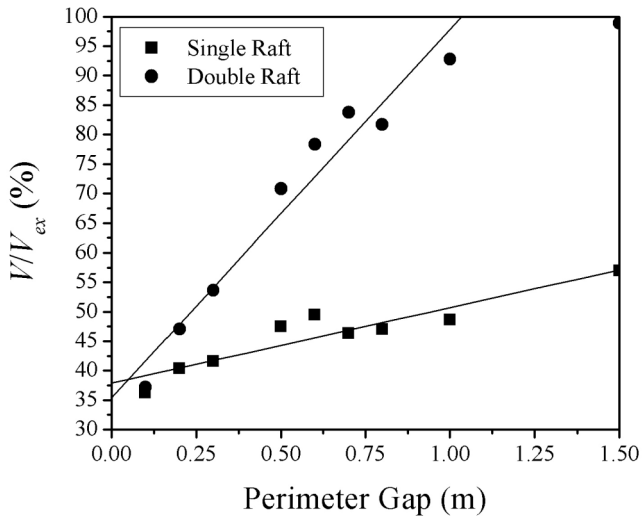


Figure 11 Case 9 (Classroom cross ventilation with double raft ceiling). Double raft results for relative mean tangential speed against perimeter gap for cross ventilation. Results from a single raft ceiling are plotted for comparison. Gradients are  $0.13 \text{ m}^{-1}$  and  $0.63 \text{ m}^{-1}$  with  $R^2 = 0.928$  and  $0.969$  for the single and double rafts respectively.

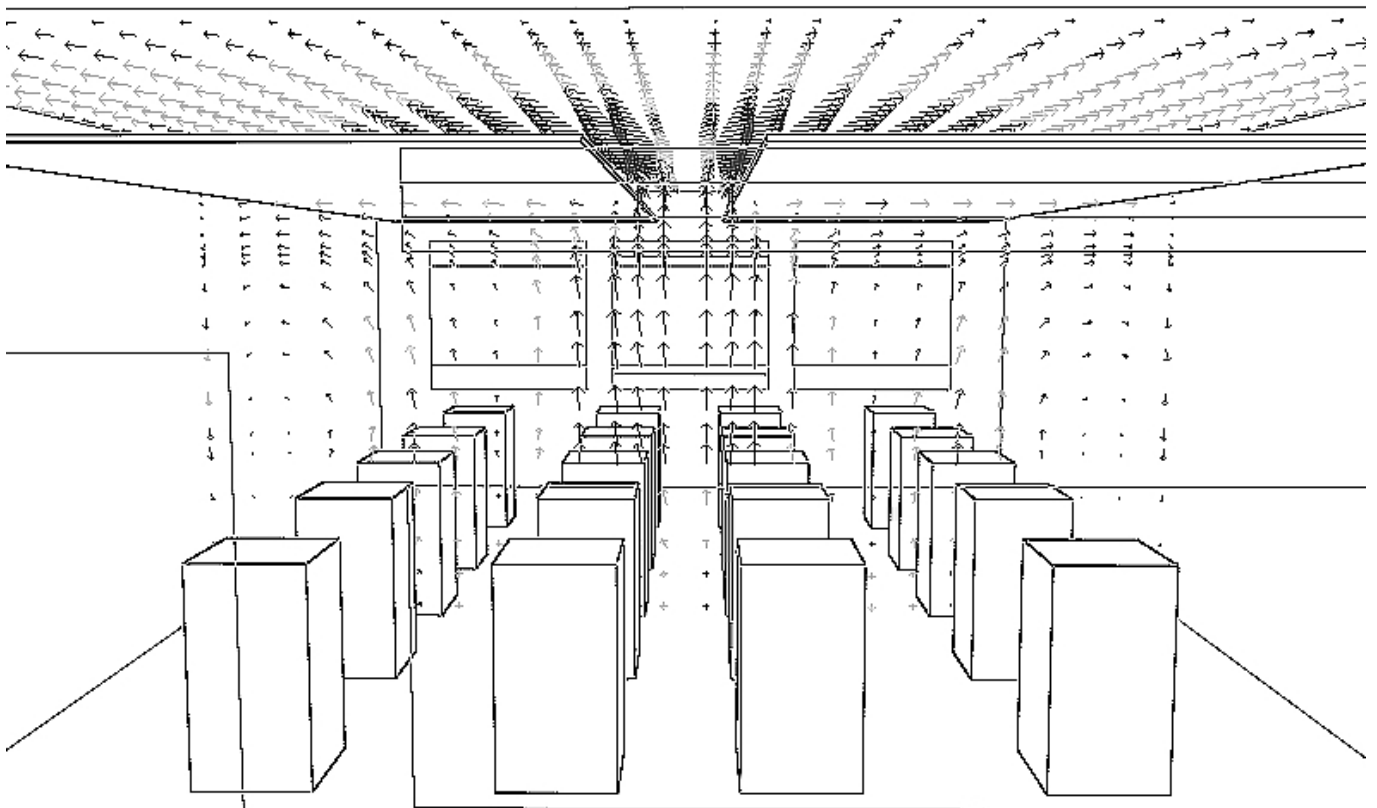


Figure 12 The velocity of air across the concrete ceiling, with incoming airflow from out of the page. One can clearly see that the gap in the suspended ceiling allows for considerable air movement across the ceiling. The size of the arrows indicates relative speed of airflow.

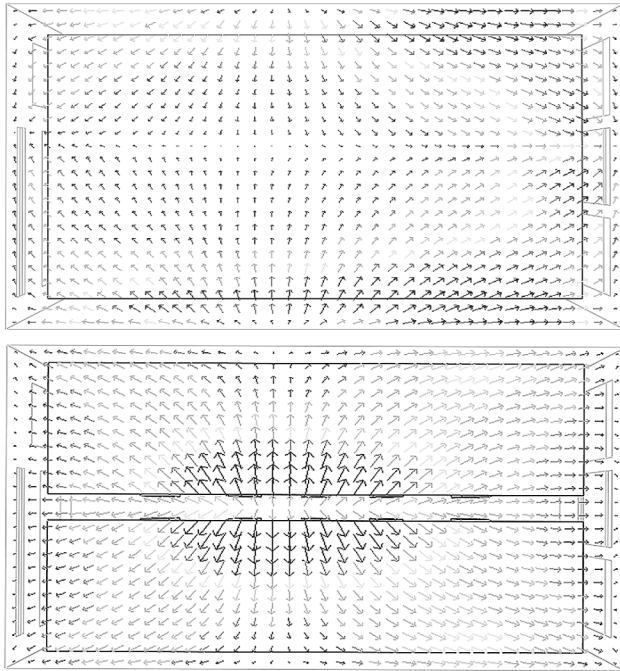


Figure 13 Air velocity diagrams for a single sided ventilated classroom with a single raft and double raft suspended ceiling with a 0.5 m perimeter gap. The size of arrow indicates relative speed of airflow.

### Appendix 1: Absolute Speeds and Air Temperatures

Table A1 lists the absolute mean tangential speed and mean air temperature of the cells in contact with the concrete ceiling for cases 1, 2, 8 and 9 with gap size up to 1.5 m.

Classroom Design	Mean Tangential Speed and Air Temp - Perimeter Gap m								
	0.1	0.2	0.3	0.5	0.6	0.7	0.8	1	1.5
Single Ventilation Single Raft	0.042ms <sup>-1</sup> 21.8°C	0.047ms <sup>-1</sup> 22.1°C	0.052ms <sup>-1</sup> 22.1°C	0.064ms <sup>-1</sup> 22.4°C	0.068ms <sup>-1</sup> 22.5°C	0.071ms <sup>-1</sup> 22.5°C	0.07ms <sup>-1</sup> 22.6°C	0.076ms <sup>-1</sup> 22.8°C	0.089ms <sup>-1</sup> 22.8°C
Cross Ventilation Single Raft	0.056ms <sup>-1</sup> 22.4°C	0.07ms <sup>-1</sup> 22.8°C	0.08ms <sup>-1</sup> 22.8°C	0.099ms <sup>-1</sup> 23.0°C	0.125ms <sup>-1</sup> 23.0°C	0.133ms <sup>-1</sup> 22.9°C	0.136ms <sup>-1</sup> 22.9°C	0.14 ms <sup>-1</sup> 22.9°C	0.16ms <sup>-1</sup> 22.9°C
Single Ventilation Double Raft	0.056ms <sup>-1</sup> 22.0°C	0.07ms <sup>-1</sup> 22.2°C	0.08ms <sup>-1</sup> 22.1°C	0.099ms <sup>-1</sup> 22.3°C	0.125ms <sup>-1</sup> 22.3°C	0.133ms <sup>-1</sup> 22.3°C	0.136ms <sup>-1</sup> 22.5°C	0.141ms <sup>-1</sup> 22.6°C	0.16ms <sup>-1</sup> 22.7°C
Cross Ventilation Double Raft	0.059ms <sup>-1</sup> 22.3°C	0.074ms <sup>-1</sup> 22.7°C	0.084ms <sup>-1</sup> 22.7°C	0.111ms <sup>-1</sup> 22.8°C	0.123ms <sup>-1</sup> 22.9°C	0.132ms <sup>-1</sup> 22.8°C	0.129ms <sup>-1</sup> 22.9°C	0.146ms <sup>-1</sup> 22.8°C	0.156ms <sup>-1</sup> 22.8°C