PERFORMANCE OF PERSONAL VENTILATION SYSTEMS IN A MULTI-BED MATERNITY WARD.

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ABSTRACT

Personal ventilation (PV) is a method of supplying a small zone of an occupied space, with cool fresh supply air. Many studies have concentrated on, and shown positive benefits of, personal ventilation in office environments. However little has been done for hospitals. Computational fluid dynamics (CFD) was used to evaluate four different mechanical personal ventilation configurations in a maternity ward: canopy, pillow, headboard and footboard systems, with a fully naturally ventilated system as a base case. The results suggest a horizontal sinking flow will deliver supply air into the patient breathing zone (BZ). The head- and foot- board systems were able to accommodate changes in patient orientation, with negligible change in ventilation performance in terms of age of air, as well as providing comfortable uniform conditions. However, in order to achieve this, a compromise on air quality, albeit a small amount, is required. Overall evaluation suggests that the headboard-based PV system might offer the best all-round performance.

1 INTRODUCTION

Extensive research has been conducted on patient comfort and how this relates to the facilities and patients' experience during their stay in hospital. Investigations into the lighting and ward design are some of the issues highlighted in reports (Maben et al., 2012), with most of the issues being clearly perceivable by patients. However, the subject of ventilation and inhaled air quality is not. Ventilation can have a dramatic effect on thermal comfort and inhaled air quality, both of which could significantly influence patient well-being and recovery. Yet, the most effective, energy-efficient, way of delivering the best quality air to patients remains unclear. Developments in technology in recent years have meant increased interest in improving the quality of working and living environments (Lin, 2005), as people spend 90% of their lives indoors inhaling 20 kg of air daily (Zhang, 2005). Moreover, Zhou et al (2013) found a relationship between sleep quality and the ventilation system, both of which improve patient recovery in hospitals and efficiency of work in offices.

1.1 Personal ventilation – PV

A mechanical PV device can be used in combination with a room-scale natural ventilation (NV) system, to create a hybrid arrangement. The purpose of PV is to achieve the highest possible quality of inhaled air, by providing clean, young air, directly into the BZ (Melikov et al, 2012; van der Sanden, 2012), which could result in 100% of the air inhaled originating from the supply inlet (Drake, 2008). Results from laboratory settings, office mock-ups, experimental work using tracer-gas and numerical studies have all shown positive benefits of PV systems. Nevertheless, there has been little research regarding PV in a hospital environment, especially when in combination with NV. This paper addresses this knowledge gap.

2 METHOD

The general-purpose CFD software PHOENICS 2015 using the FLAIR interface was used to carry out steady-state modelling. This is an established tool for simulating and analysing fluid flow, air velocity and temperature, by quantitatively predicting the airflow paths, patterns and distribution (Walker, 2006). CFD has been applied in hospital-based studies (Li et al., 2015; Short et al., 2014; van der Sanden, 2012). A typical hospital maternity ward with four identical hospital bed arrangements (figure 1) (length × width × height = 8 × 8 × 3 m), with an openable window area of 3.83m^2 (to provide the natural proportion of the ventilation), was modelled in the CFD software. The opening sizes were calculated to provide NV rates for delivering medium to high indoor air quality

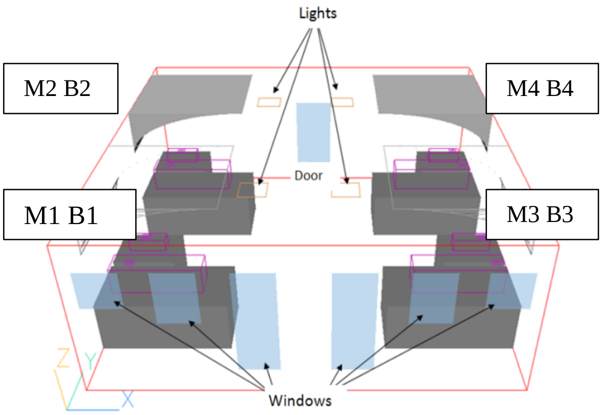

Figure 1 - Base case set-up. Mothers and babies represented by M and B, with respective bed arrangement number.

(IAQ) in accordance with European CEN Standard 13779 (2007) and designed in a manner that maintains patient privacy. Each arrangement consisted of a PV system, a mother and baby, and hospital equipment. Patients were positioned on beds at a height of 1.1m above the floor.

2.1 Boundary Conditions

A CFD simulation is defined by its boundary conditions. For patient breathing, the actual transient breathing process was simplified and modelled as a steady volumetric flow rate, these breathing rates being assigned to an inlet of 0.2×0.2m to account for the size of the patient's breathing zone (Snyder et al., 1975). Heat gains for lighting and equipment were assigned to objects within the domain (Table 1). The equipment heat gains were assigned to the beds, to create a concentrated heat source. The solely naturally ventilated ward served as the base case and contained none of the proposed PV systems (shown in figure 2) that were investigated. The pillow system delivers air around the patient's head from a typical pillow position. The head- and foot-board systems deliver air horizontally from either end of the patient's bed whereas an ascending supply of air is created by the canopy system (refer to figure 2). Figure 2 also shows the canopy, above the patients' bed, which is designed to aid acoustics.

Table 1 – Boundary Conditions.

	Quantity	Total Heat Flux (W)	Breathing rates (m^3/s)
Mothers (1.7m tall)	4	90	1.5×10^{-4}
Babies (0.75m tall)	4	90	2.5×10^{-5}
Lights	4	110	-
Equipment	8	480	-

Buoyancy was modelled using the Boussinesq

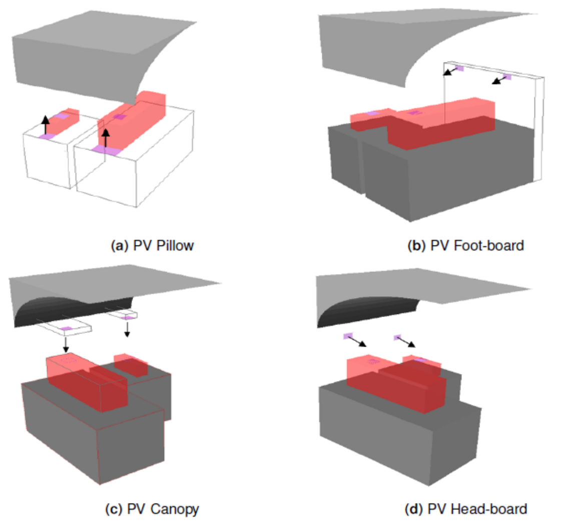

Figure 2 - PV Configurations. Arrows indicate the direction of the local mechanically supplied inlet air.

approximation in which density is assumed constant, except for the source term in the momentum equation. The RNG k-ε turbulence model was selected on recommendations from previous literature (Zhang, 2005, Chen, 2010). The supply jet flows were assigned 5% turbulence intensity at the inlet, compared to the 8% for patient breath (Lin et al, 2007). The walls and the floor of the domain were assumed to be adiabatic. The external ambient air temperature was fixed at 24°C. Wind and infiltration effects were not included, to enable only the buoyancy-driven flows to be examined.

To emulate a change in patient orientation in a steady-state CFD model, further simulations were performed with the patient's BZ positioned on either side of their head, to simulate a change in the direction, which patients were facing, and therefore inhaling (figure 8).

2.2 Mesh generation

A mesh sensitivity study was carried out to investigate the influence of different mesh densities on the predicted numerical results. Using the X-Y graph plotter of the post-processor, the air temperature across the x-axis at a height of 1.5m was plotted, to determine an optimal mesh (figure 3). Five mesh resolutions were examined (Table 2). The small reduction in change between the two final meshes (meshes 4 and 5) suggests that increasing the mesh density will have little effect on the results. Convergence was achieved after 3000 iterations, as the error in mass equation was less than 0.1% of the total mass entering the domain (kg/s) (CHAM, 2002, Walker, 2006). The residual values decreased by a factor of 100 from the initial sweeps, reaching a near constant value with minor oscillations, suggesting the CFD model will accurately predict the performance of the geometry (Cheung, 2011, CHAM, 2002, Walker, 2006). The final mesh adopted, mesh 4, consisted of 6.5×10^5 cells.

2.3 Simulation Experimental Method

Initially, the performance of the base case was explored, with an open, and then closed, door on the ward wall opposite to the windows. Secondly, the

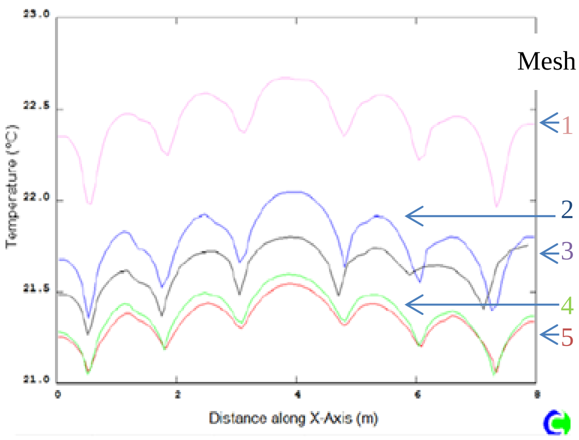

Figure 3 - Mesh Sensitivity Study. Average air temperature across the X-Axis at a height of 1.5m.

effect of the addition of a PV system was analysed using age of air, and the risk of local discomfort. Finally, patient movement was modelled by positioning the breathing zone (BZ) on the patient's side. Each of the PV systems was examined using ventilation rates of 0.3 L/s.p (for breathing), 5 L/s.p (for odour removal, and breathing), and 8 L/s.p (for breathing, odour removal and cooling).

Table 2 – Mesh sensitivity study

Mesh	Number of cells
1	2.7×10^5
2	3.0×10^5
3	3.6×10^5
4	6.5×10^5
5	9.2×10^5

2.4 Criteria for assessment

Each scenario was assessed against the metrics of age and temperature of inhaled air, to indicate the quality of inhaled air. The risk of localised discomfort was determined through the temperature and air velocity gradient, as current thermal comfort standards proved inconclusive and may not be appropriate in a hospital environment due to patient posture and clothing index. For a fair comparison the nominal time constant (NTC), which is a ratio of the volume of the space (m^3) to the volume of supply air (m^3/s) for each room was used, as ideally the age of inhaled air should be below the NTC, which is also a representation of age of air in a well-mixed scenario. As the NTC does not vary in accordance with patient movement, it can be used for an evaluation of the system's performance to account for involuntary changes in patient orientation.

3 RESULTS AND DISCUSSION

3.1 Base Case Scenario

The scalar variable, age of air, was added to the CFD simulation. Figure 4 shows streamlines indicating the age of air (s). In PHOENICS this is calculated by setting age of air as zero for all supply locations. This was used for comparison with the PV systems shown in figure 2. The large variations in age of inhaled air between those patients near to the windows and those deeper into the ward, demonstrate how the supply air from these openings failed to reach the patients deep into the ward. These 'deeper' patients inhaled air of approximately 24°C, which was over double the age of that air inhaled by those closest to the openings. Upon opening the door, an even distribution of air was observed, as well as an increased ventilation rate from 0.7 to 1.2 air changes per hour (ACH). Despite this, some patients were exposed to similar or lower levels of air quality, as indicated by the age of inhaled air. Those patients closest to the openings experienced an increase in age of inhaled air up to 450s for mothers, and up to 1476s for babies. However, for the open door scenario, a reduction in age of inhaled air between 700-1000s was observed for patients deep in the ward, unlike the other patients who experienced an increase in age of inhaled air between 100-400s. Therefore opening the door affected all patients within the ward, both positively and negatively.

3.2 PV Configurations

The effect of the addition of a PV system became apparent when compared with the base case results. Figure 5 demonstrates these comparisons, with the patients closest to the windows still receiving fresher air than the patients deeper in the ward, especially for the PV pillow, which performed less well, which resulted in the highest age of air at point of inhalation. Similar results for the base case and pillow regarding M1, B1, M3 and B3, suggest the windows were still the dominant source of ventilation, with minimal change in conditions. However, all four systems performed similar to the base case scenario when using 0.3 L/s.p (Litres per second per person), and it was not until the ventilation rate was increased that the influence of the PV systems were observed. According to these results, the PV canopy system performed best regarding age of air however, the highest ventilation rate of 8 L/s.p was required, delivering air with an age 89% lower than the NTC, which was far greater than the 56% for the head- and foot- board systems.

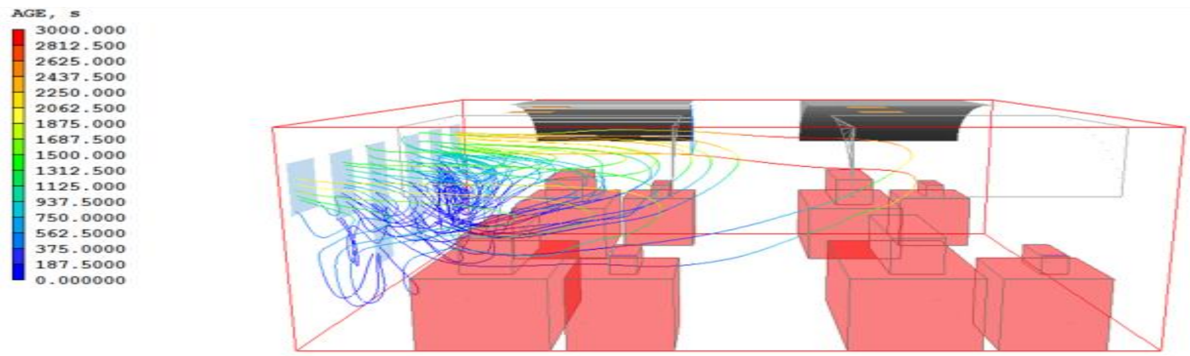

Figure 4 – Age of air streamlines realised from the windows in the base case scenario.

Figure 5 allowed a comparison between all the PV systems to be carried out and further demonstrated the variation in performance, as the pillow delivered air that was, on average, 25% younger than the NTC, showing the lack of effect this system had on reducing the age of air in the BZ. In view of this, from this point on, analysis of the PV pillow and the ventilation rate 0.3 L/s.p were discontinued, and the ward door was considered closed.

Interestingly the PV headboard system delivered younger air at the ventilation rate of 5 L/s.p, due to air bypassing the BZ when the higher ventilation rate was used. Figure 6 shows the increased patient exposure to younger supply air under the ventilation rate of 5 L/s.p, by the younger air being present in the BZ. This was the only one of the four PV systems whose best performance was not recorded at the highest ventilation rate of 8 L/s.p.

Despite the PV canopy delivering inhaled air with an age less than half of the other systems, it performed worse in terms of draught risk and posed a large amount of uneven cooling. The PV canopy system created a direct flow path into the BZ, ideal for air quality, but resulted in the system only conditioning this small zone. Figures 6 and 7 show the reduction in temperature recorded around the BZ and the large contrast it creates in comparison to other regions of the body, unlike the horizontal air delivery systems, such as the head- and foot-board. The bypass characteristic is shown by the increase in temperature towards the head when 8 L/s.p is used for the headboard system, whereas there is a gradual decrease either side of the BZ when using 5 L/s.p. The resultant smooth sinking airflow path of the supply jet delivered lower quality air into the BZ, with an age of 300s greater than the canopy system, but it did create uniform conditions regarding air temperature and velocity.

3.3 Localised Discomfort

The variations in age of air, air velocity and body temperature of patients, are shown in figures 6 and 7, with a patient's body superimposed over the contours and under the graphs to demonstrate relative location. Figures 6 and 7 show varying conditions across the patient's body for the four PV systems in figure 2. An important factor would be clothing index, as it is assumed that the head and ankle regions of the patient's body would be uncovered, therefore increasing the risk of localised discomfort around these regions. The canopy system would deliver high velocity cool supply air directly onto uncovered regions of the body, which is in stark contrast to the warmer unconditioned covered areas of the body, such as the midriff. This localised cooling of the head region created a temperature gradient of 1.5K across the patient, unlike the gradual change of 0.7K when using the headboard system; which would arguably be perceived as more comfortable by patients. This is shown by the contours on the far right of figure 7, with the light blue area illustrating the coolest temperatures, which are situated around the patient's head. Further discomfort could be caused through draught risk, as a result of the high velocities shown by the yellow section of the contour (figure 7, bottom right). Cooler air was observed in the same area as the youngest air. The youngest and coolest air shows where a large percentage of the supply jet meets the patient's body. Considering all the contours in figure 7, it can be deduced that the canopy system delivers the largest proportion of young air directly into the

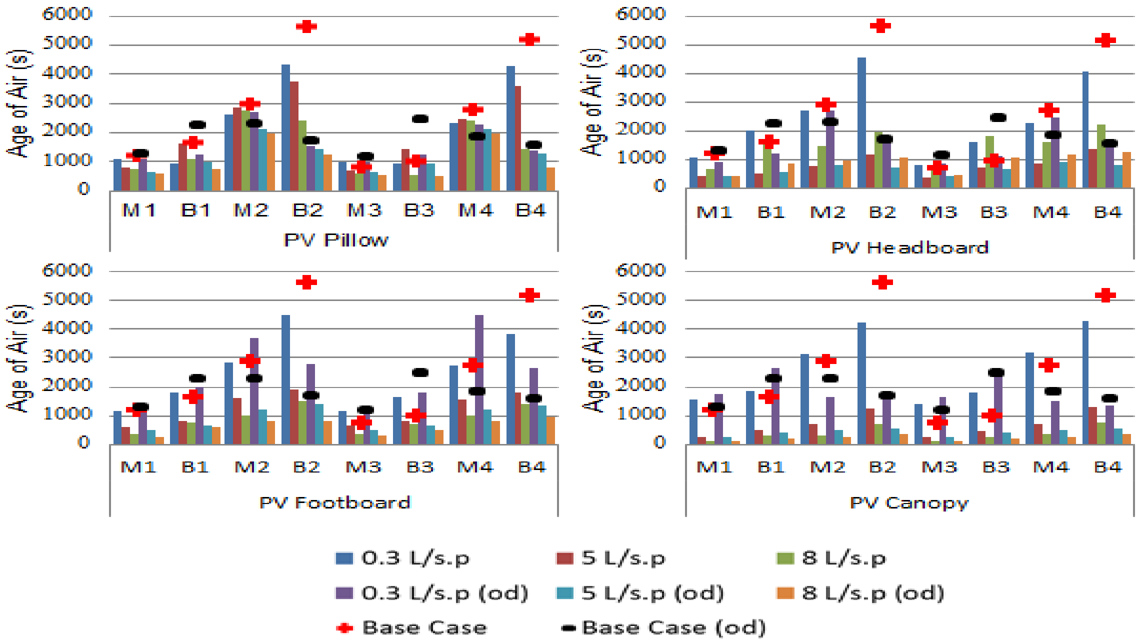

Figure 5 - Effect of PV system in comparison to the base case with and without the open door, as demonstrated by age of air (s).

BZ. However, the contours of the other parameters suggest that the canopy system creates the largest temperature and air velocity gradients across the patient's body. This can be observed from the quickly changing conditions (figure 7) and the steep gradients (figure 6). Furthermore, this column of high velocity, cool air could pose a risk in terms of localised discomfort, thermally or in the form of draught risk, especially as this would be located around the patient's uncovered head, face and neck region. For example, the observed velocities within the BZ for the canopy system are between 40 and 50% higher than the other systems examined (figures 6 and 7). The base case scenario does have similar air velocities to the PV footboard (5 L/s.p) and headboard (8 L/s.p). These air velocities could be considered comfortable due to their similarity to the natural conditions of the base case. Nonetheless, these results are interesting as the headboard inlet is positioned far closer to the head but produces surprisingly low air velocities within the BZ, in comparison to the other systems. However, these velocities do increase significantly towards the patient's chest area, creating an air velocity difference of 0.175 m/s between the patient's waist and neck. Considering a smooth gradual temperature and velocity gradient, both the foot- and head- board systems perform best according to these results, which complements previous research, which is in favour of a sinking airflow supply. Comparing the two systems foot- and head- board, the effect of having a supply close to the BZ is apparent. The lower ventilation rate (5 L/s.p) performs better, for all parameters, when used with the headboard system, as the lower ventilation rate aided the sinking process. The contours associated with this scenario demonstrate how the air sunk and entered the BZ, before travelling across the entire body in a uniform manner. Whereas, the higher ventilation rate meant the supply air travelled over the BZ, and falls on the patient's feet. This is shown in figure 7 by the youngest and coolest air being observed around the patient's ankle region, and is demonstrated by the light blue section of the air temperature contour for this scenario.

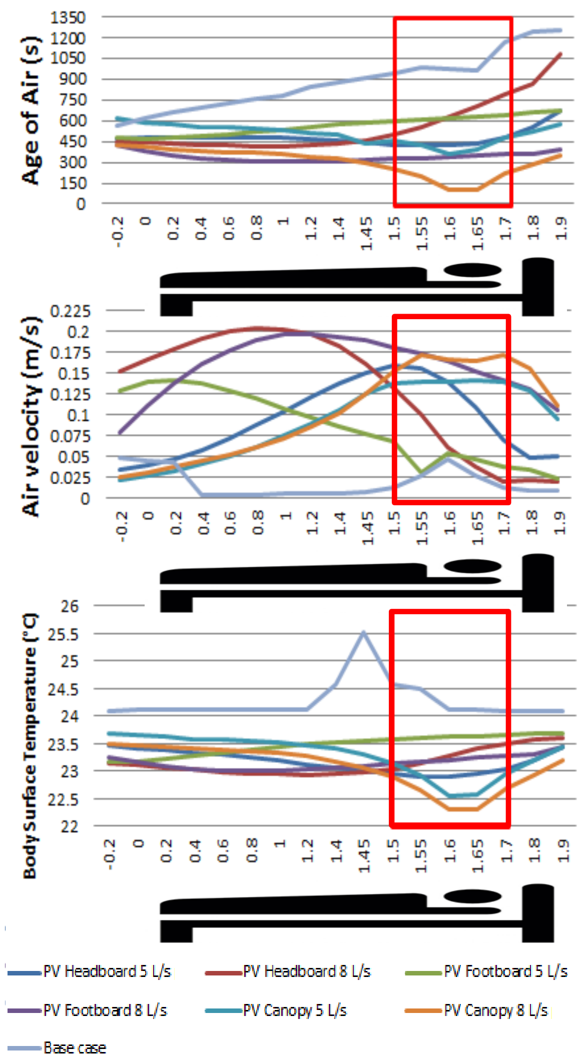

Figure 6 – Criteria assessment metrics at different distances from the patient's foot (metres) shown on x-axis. Red box indicates the BZ. Data are for M1.

These results demonstrate some correlation between the age of air and body surface temperature i.e. the younger the air, the cooler the patient. This is likely to be a result of the concentrated flow of air directly into the BZ, along with the naturally occurring phenomenon of the cooler denser supply air sinking, thus increasing the velocity further. It is observed in figure 6 that certain ventilation rates may perform better, minimising localised discomfort from draught risk. In addition, at higher ventilation rates, the patient may feel as if air was being forced into their mouth and nose. For example, the footboard system at 8 L/s.p supplies the BZ with the youngest air with a uniform temperature throughout the BZ, in contrast to all other PV configurations. However, the air velocity difference of this scenario, from the patient's neck to the top of their head, is approximately 0.1 m/s, which is similar to the PV system when using 5 L/s.p. Furthermore, research has suggested that a sleeping person is more sensitive to air velocity than air temperature (Zhou et al., 2013). According to these results, the distribution of the parameters follows a similar pattern throughout all scenarios. Figure 7 demonstrates the potential compromise between high inhaled air quality and localised discomfort, as well as the variations in temperature and air velocity gradient. As shown in this study, younger inhaled air is often accompanied by high air velocities and lower temperatures. Although the energy associated with each ventilation rate is not examined here, it would be expected that providing 5 L/s.p would consume less energy than the 8 L/s.p. This could be an influential factor when considering the design of the PV system, as it can be seen that some systems, most noticeably the headboard system, performs better when using 5 L/s.p. The evaluation process is complicated by the many metrics that could be used.

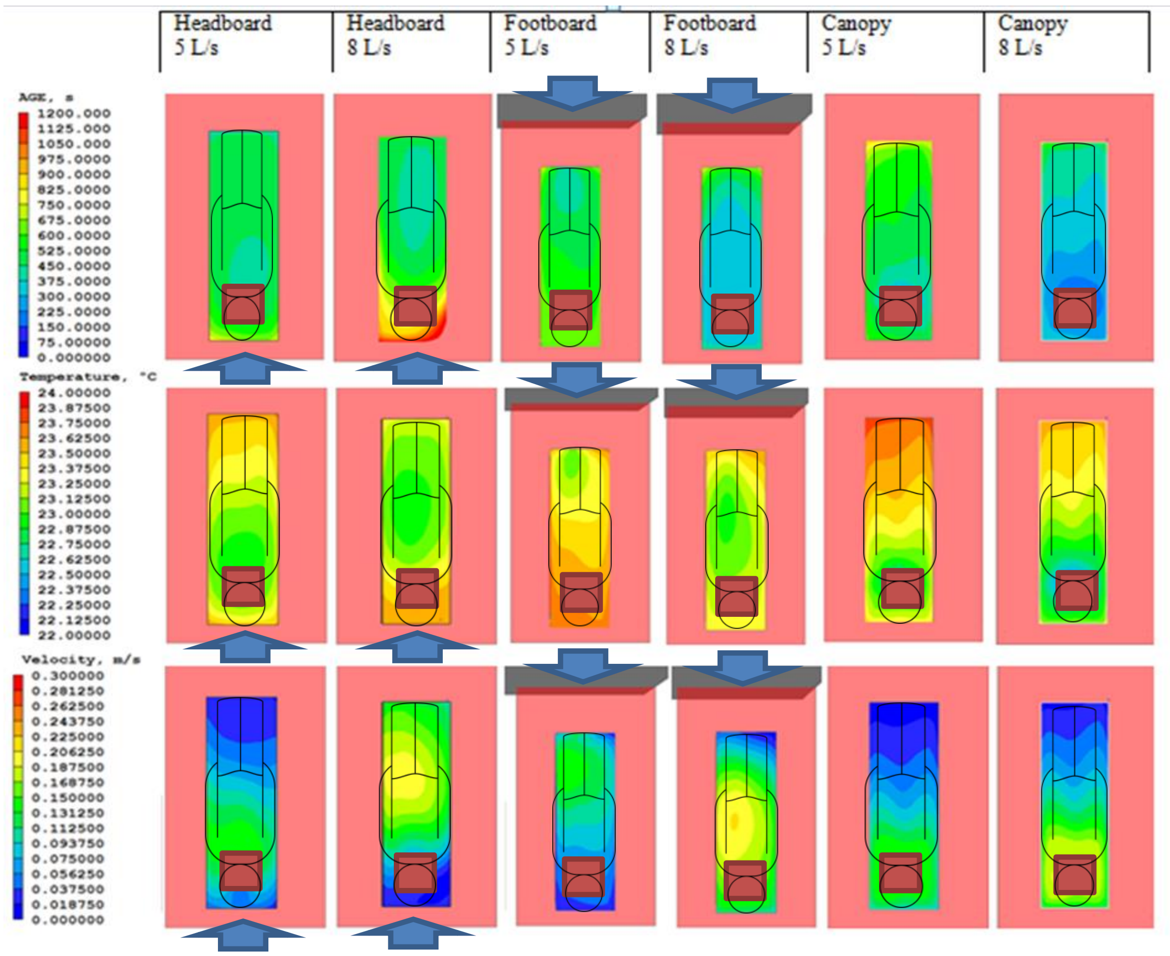

Figure 7 – A comparison of age of air, air velocity and temperature contours for different ventilation scenarios. Contours shown are from M1. Red box indicates breathing zone. Blue arrows represent supply airflow direction. Windows are positioned to the right of patients in the figure. Canopy system delivers air from above the BZ.

It is therefore important to determine what the expected or desired outcome of the system is. The variations in performance metrics are either a result of system or the ventilation rate. However, this performance will vary depending upon the desired outcome of the system and what is considered optimal performance.

3.4 Effect of patient orientation

The effect of patient body orientation in bed was modelled by changing the direction of inhalation (figure 8). By comparing the age of inhaled air with the NTC, the effect of patient position could be determined. The smooth sinking process, of the foot- and head- board system was also able to accommodate a change in patient orientation. The supply air sinking slowly over the entire patient meant the supply air could enter the BZ, whilst still maintaining uniform conditions. For the headboard system at 5 L/s.p, the difference between age of inhaled air and NTC decreased by 12%, which was similar to the PV canopy system at this ventilation rate, demonstrating a reduction in performance. Nevertheless, at 8 L/s.p, the reduction in performance increased for both systems, with the PV canopy experiencing a 75% reduction in performance, regarding the age of inhaled air prior to a change in patient orientation. This effect is illustrated in figure 9, which shows the difference in ranges and average of inhaled age of air, for both orientations. These metrics considered all patients, therefore nullifying

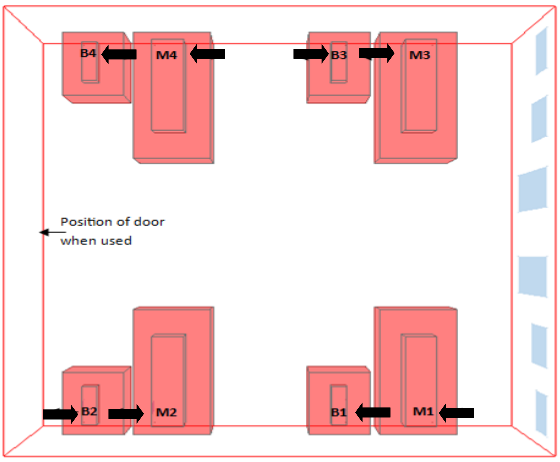

Figure 8 - Change in patient orientation simulated by a change of inhalation direction as shown by the arrows. Windows (openings) on the right hand side. Door on the left as indicated.

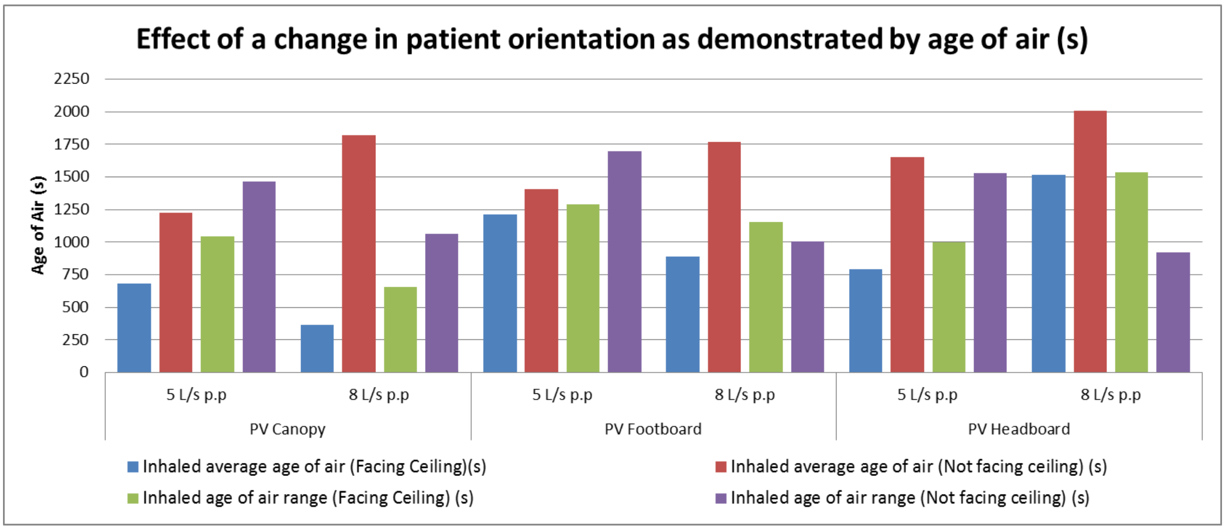

Figure 9 - Effect of a change in patient orientation on system performance, using age of air at the point of inhalation to indicate inhaled air quality.

the positional bias of patient being closest to the windows. A comparison of these metrics allowed examination of the system's ability to cope with involuntary patient movement. These results show that the targeted flow, which had previously been very beneficial, was now negatively affected by involuntary patient movement. The PV canopy continued to perform worst when considering air velocity and temperature uniformity. The majority of the systems had a reduced performance in terms of accommodating patient movement, albeit to varying degrees. Considering all metrics, the PV headboard at 5 L/s.p performed best, and would be expected to be widely accepted by patients due to the uniform air temperature and velocities. Despite a small reduction in air quality, patients were exposed to uniform thermal conditions and lower draught risk potential because of an even covering of supply air from the naturally occurring sinking process. In a ward where airborne infection transmission risk was assumed to be low, the perceivable metrics of air velocity and temperature could be deemed more influential when determining patient comfort and influencing the quality of their stay in hospital. Using the key and scoring system in figure 10, the authors qualitatively evaluated each system in turn with regard to the performance criteria in an attempt to identify the best system. The results are shown in Table 3. In the authors' opinion, the headboard system when using 5L/s.p was deemed the best overall system. The canopy system at 8L/s.p performed worst. For a more customisable evaluation, each parameter could be weighted in a simple traffic light scoring system, as used here (Table 3).

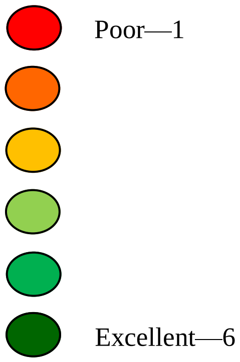

Figure 10 - Overall performance key.

4 CONCLUSIONS

Four personal ventilation (PV) systems were investigated using CFD analysis, in comparison to a base case of ward natural ventilation. A number of metrics were used to determine the performance of each PV configuration. It was apparent that a compromise would be required on air quality in order to create a system that was capable of accommodating a change in patient orientation. In

Table 3 - Overall performance of each PV configuration; assuming an equal weighting for each criterion.

PV System	Ventilation Rate	Inhaled air quality	Draught Risk potential	Localised thermal discomfort	Ability to cope with patient orientation	Total Score:
Headboard	5 L/s.p					21
	8 L/s.p					18
Footboard	5 L/s.p					10
	8 L/s.p					15
Canopy	5 L/s.p					12
	8 L/s.p					9

addition to this, a direct delivery of supply air into the BZ could pose a draught risk to the patient due to their increased exposure to uncovered areas of the body, and large air velocity and temperature gradients. These results imply that the highest ventilation rate may not always be the best option, as design of the system, patient orientation, and desired outcome, will influence what the best ventilation rate will be. If air quality was the sole metric then the canopy system would be the best option, ignoring the fact that it is likely to create localised discomfort and doesn't perform as well when accommodating for patient movement, according to these results. Furthermore, many ventilation standards do not recognise spatial variation in distribution of supply air, nor is there acknowledgement of metric gradients. The results from the base case show how increases in air changes per hour do not necessarily translate into improvements in inhaled air quality. Air change rate demonstrates an average improvement in air quality throughout the space, but as there is no spatial acknowledgement of these, it is difficult to determine the location of the best quality air within a space. The detail from the CFD model was able to expose this, highlighting variations in conditions throughout the space. Many regulations require a minimum and maximum acceptable parameter value, with no measurements of parameter gradient throughout the space or, more locally, across the patient, even though this difference has been known to be more perceivable than extreme values. As a result, a measurement-based field study would be beneficial in determining patient comfort when exposed to a variation of parameter gradients. The importance of this would increase because of a patient's lack of adaptability and stationary position in a hospital environment. This study and evaluation procedure demonstrates the variation in system performance across the different assessment criteria and the potential comparison required in order to achieve certain conditions. Moreover, a simple evaluation system could potentially demonstrate and clearly communicate a ventilation system's performance, however performance may be judged. Based on a subjective evaluation of the PV systems, where equal weighting was placed on the performance metrics of: inhaled air quality; draught risk potential; localised thermal discomfort; and ability to accommodate patient orientation, a headboard-based system appeared best overall. However, wider considerations and practical evaluations would be needed before such a system could be recommended for patient use.

REFERENCES

CHAM, 2002, Phoenics-VR 3.5 Reference Guide, CHAM Ltd., London, UK.

Q. Chen, K. Lee, S. Mazumdar, S. Poussou, L. Wang, M. Wang, and Z. Zhang. 2010. Ventilation performance prediction for buildings: Model assessment. Building and Environment, 45 (2):295–303.

J. Cheung. 2011. CFD Modelling of Natural Ventilation in Multi-cellular Spaces : Case Study SSEES Building. In People and Buildings, number September 2011, London, 2011.

S. Drake, (2008). The use of personal ventilation in open plan offices: a study of the TASK AIR system.

European CEN Standard 13779. 2007, Ventilation for non-residential buildings – Performance requirements for ventilation and room-conditioning systems

C.-L. Lin, M. H. Tawhai, G. McLennan, and E. A. Hoffman. 2007. Characteristics of the turbulent laryngeal jet and its effect on airflow in the human intra-thoracic airways. Respir Physiol Neurobiol, 157((2-3)):319–339.

Y. Li, J. Tang, C. Noakes, and M. J. Hodgson. (2015) Engineering control of respiratory infection and low energy design of healthcare facilities. Science and Technology for the Built Environment, 21(1):25–34.

Z. Lin, (2005). Effect of Air Supply Temperature on the Performance of Displacement Ventilation (Part I) - Thermal Comfort. Indoor and Built Environment, 14(2):103–115, Apr. 2005.

J. Maben, C. Penfold, G. Robert, and P. Griffiths, (2012) Evaluating a major innovation in hospital design. Technical Report June, National Nursing Research Unit, Department of Health Policy and Management.

A. Melikov, T. Ivanova, and G. Stefanova, (2012). Seat headrest-incorporated personalized ventilation: Thermal comfort and inhaled air quality. Building and Environment, 47: 100–108, Jan. 2012.

N.P.M van der Sanden, (2012) Personal ventilation to control airborne infectious diseases in hospital patient rooms. MSc Dissertation. Eindhoven Faculty or architecture, building and planning. University of Technology.

C. A. Short, C. J. Noakes, C. A. Gilkeson, and A. Fair. (2014) Functional recovery of a resilient hospital type. Building Research & Information, 42(6):657– 684.

W. Snyder, M. Cook, E. Nasset, L. Karhausen, G. Howells, and I. Tipton. Report on the task group on Reference Man: Anatomical, physiological and metabolic characteristics. Technical report, Elsevier, New York, 1975.

C. Walker. Methodology for the Evaluation of Natural Ventilation in Buildings Using a Reduced-Scale Air Model. PhD thesis, Massachusetts, 2006.

Y. Zhang, (2005). Indoor Air Quality Engineering. CRC Press LLC, Boca Raton.

X. Zhou, Z. Lian, and L. Lan, (2013). Experimental study on a bedside personalized ventilation system for improving sleep comfort and quality. Indoor and Built Environment, 23 (2):313–323, Oct. 2013.