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Natural personalised ventilation: A novel approach

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ABSTRACT

The need to protect susceptible patients from cross-infection resulting from airborne pathogens is essential in hospitals, especially when patient immunity is either suppressed due to medical procedures or compromised by ailment. Personalised ventilation (PV) is a method of creating a local zone of high air quality around such patients. However, contemporary PV techniques are based on mechanical ventilation, which adds to the energy burden of healthcare buildings. In single-bed wards, a potential source of infection could be other occupants such as visitors and healthcare workers. Threats may also come from airborne pathogens migrating from adjacent zones, especially if the single-bed wards in question are not positively pressurised. While the World Health Organisation (WHO) has issued guidelines on using natural ventilation to control infectious bio-aerosols in hospital wards (with flow rates of up to 60 l/s/patient), how to achieve this rate without high energy and carbon costs, remains unanswered. The objective of the research reported here is to demonstrate a novel approach of using low-energy, buoyancy-driven natural airflow for personalised ventilation of single-bed hospital wards. The investigation has been carried out by undertaking dynamic thermal simulations (DTS) and computational fluid dynamics (CFD) simulations. Findings demonstrate that given appropriate design, it is possible to achieve personal protection for vulnerable patients using a natural mode of ventilation alone. Co-occupants could also benefit from the mixing characteristics offered by the proposed system, which does not occur in typical buoyancy-driven displacement ventilation.

Keywords: natural personalised ventilation, buoyancy, single-bed ward, dynamic thermal simulation, computational fluid dynamics.

1.0 BACKGROUND

The importance of clean air around patients has been aptly captured by Florence Nightingale, who promoted the first rule of nursing as being to “keep the air within as pure as the air without”. In her ‘*Notes on Nursing*’ she further emphasised the need to ensure that without chilling a patient, the air he breathed had to be as pure as the external air (Nightingale, 1859). The first modern attempts at hospital ventilation which focused on patients can be found Luciano (1977) including the Trexler Life Island Unit, made of plastic sheets, which did not get acceptance in the United Kingdom (UK) primarily because it was ‘*so very different from established methods*’ (White, 1981). Other types of patient-centred ventilation solutions did not use physical barriers. They were essentially ventilation ‘canopies’ over each patient in a multi-bed ward. Examples of this approach are the Robbins Aseptic Air Patient Isolation Canopy (Luciano, 1977) which was developed in the United States; as well as the Sterair Patient Isolator (White, 1981) whose canopy delivered HEPA-filtered air over a patient.

Gradually, the benefits of patient-centred ventilation saw the emergence of personalised ventilation (PV) as distinct airflow systems. PV has been defined by Melikov (2004) as a system which delivers cooler and cleaner air directly to or over an occupant in such a manner that allows them to customise the flow characteristics (temperature, flow rate, direction) according to their needs. PV systems have developed as a ventilation technique which works independently of any supplementary/additional room ventilation system, and in hospitals, it is common for them to be used for aseptic purposes.

Current developments in personalised ventilation systems are still in the research and experimental stage where many concepts have been developed. Notable studies from the last decade include Melikov et al (2002) and Melikov et al. (2003). Innovative approaches include the use of PV systems as parts of objects including: hospital beds (Nielsen, et al., 2007 and 2008); pillows (Nielsen, 2009)

and chairs (Niu, et al., 2007). These studies also assessed risk to occupants from contaminants generated in such spaces using pollutant exposure models. So far, all PV systems have been mechanical, adding to energy and carbon concerns as outlined by the UK Department of Health (DoH, 2006) where space conditioning accounted for over 40% of energy consumed in typical UK hospitals. There is hence a need to pursue more energy efficient options for PV, and crucially, no evidence currently exists in literature suggesting that natural ventilation has been exploited for PV purposes.

1.1 Objectives and justification of study

The aim of this study is to demonstrate the feasibility of using buoyancy as a driving force for natural personalised ventilation (NPV) in a novel way which delivers fresh air to patients in hospital wards. The case for using natural ventilation in ward ventilation within the UK comes from two main sources. Firstly, empirical evidence from weather studies indicate that for up to 8 months of the year, external thermal conditions in the UK favour the use of natural ventilation as shown in Figure 1 for the city of London.

Figure 1: Annual external temperature fluctuations for London (TRY data)

This figure uses HTM 03-01 range of 18-28°C internal ward temperature (DoH, 2007). Secondly, the WHO has produced guidelines (Atkinson, et al., 2009) for utilising natural ventilation for infection control of healthcare buildings in which an absolute rate of 60 l/s/patient was ‘strongly recommended’ for general patient wards. As PV systems are designed to achieve such prioritisation of airflow directly over occupants, this study demonstrates how PV systems can work with natural ventilation to meet required airflow rates. Although room temperature will be considered, comfort is not part of current research objectives.

2.0 METHODS

Two methods are used in this investigation: dynamic thermal simulation (DTS) and computational fluid dynamics (CFD). The DTS investigations were used to assess annual bulk airflow patterns in the context of seasonal variations, and current guidelines on ward ventilation rates. The CFD studies predicted detailed room air distribution, effectiveness of heat removal, thermal stratification and contaminant dilution or removal efficiency. In both DTS and CFD studies, no control of the thermal environment was modelled as the goal was to evaluate the capacity of the proposed system to bring in fresh air. A single-bed ward sized according to the specifications of the Activity Database, ADB (DoH 2010) guideline was modelled using both DTS and CFD programs. The ward dimensions were 5m x 5m and a height of 3m. Three architecturally distinct concepts of delivering air over patients were conceived to exploit the buoyancy effects for supply air which, due to density differences, would fall into the space from a ceiling duct, before rising again upon being heated to escape via a stack. These concepts are illustrated in Figure 2. Figure 2a shows the entire supply from a wide duct (Case

1), while Figure 2b (Case 2) and Figure 2c (Case 3) show smaller supply ducts supported with variations of low-level inlets for supplementary ventilation.

The ducts in all cases serve to prevent entrainment of stale air with incoming fresh air which is released at the desired location. The openings were sized according to CIBSE's guidance for single-sided ventilation, using a temperature differential of 1K (CIBSE 2005). This gave an opening area of 0.66m² for 6 ACH based on ventilation provisions of HTM 03-01 (DoH, 2007). For simplicity the stack heights were 3m with cross-sectional area sized according to methods outlined in Lomas and Ji (2009). Based on floor area of the model wards, the computed cross-sectional area of stack was found to be to 0.25m².

Figure 2: Three conceptual design cases for proposed NPV

2.1 DTS Inputs and assumptions

The wall constructions for the wards comprised of 100mm outer-leaf brickwork, 58.5mm Styrofoam insulation, 100mm medium concrete blocks and 15mm gypsum plaster finish, giving a U-value of 0.35 W/m²K. The roofs were made of 150mm cast concrete, glass fibre quilt and bituminous felt with tiles, having a CIBSE U-value of 0.2487 W/m²K while floors were 130mm concrete with 3.0577 W/m²K. Low pressure ducts were assumed to be made of insulated sheet metal with CIBSE U-Value of 0.65 W/m²K. The occupancy schedule assumed one patient to be always present and two healthcare workers whose presence was scheduled intermittently. Occupants accounted for 380W of peak internal heat sources while lighting and equipment contributed 70W and 75W respectively.

2.2 CFD Boundary conditions

CFD simulations were carried out using a commercial package Phoenix, (Cham, 2009) using 52,920 cells to achieve converged results. Heat gains for occupants were purely convective and similar to assumptions made in the DTS models. The assumed breathing points of each occupant were represented using points of interest (POIs) shown graphically and with coordinates (in plan and 3D) in Figures 3a and 3b respectively. The convection-to-radiation split for the lighting was 20:80 (CIBSE, 2006). All other surfaces were assumed to be adiabatic. The RNG k- ϵ turbulence model (Yakhot and Orszag, 1986) was applied with the Boussinesq approximation for buoyancy. The external air temperature was assumed to be 20°C. A passive scalar contaminant source (C1) was emitted from an orifice of 0.0025m² located at the sitting visitor's mouth and based on Xie et al (2007), the speed of coughing was taken to be 10m/s with a mass flow rate of 0.03kg/s. The temperature of cough was taken as 32°C with density of particles similar to that of air, consistent with the observed behaviour of passive contaminants such as droplet nuclei (Morawska, 2006; Jiang et al., 2009). The limitations and validity of using passive scalars for bio-aerosol modelling of respiratory diseases using CFD can be found in Hathaway et al. (2011) and in Mao and Celik (2010). From these references, pathogenic particles less than 2 μ m in size are known to be fully airborne with negligible mass. Therefore, it was assumed in this work that passive scalars could be used for modelling bio-aerosols.

3.0 VENTILATION PERFORMANCE METRICS

3.1 Contaminant removal efficiency

The first metric applied to this study is contaminant removal efficiency, CRE (Zang (2005)). A passive scalar airborne contaminant, (C1) representing a generic bio-aerosol was assumed to be emitted from a sitting visitor's mouth (POI = E). The initial non-dimensional concentration of 1.0 was assigned to C1. CRE was estimated using the model described in Eq. (1).

$$CRE = \frac{C_e}{C_p} \quad (1)$$

where C_e is contaminant concentration at outlet and C_p is contaminant concentration at specific POI. An ideal CRE would be equivalent to 1.0. Three other metrics were used to evaluate the performance of each ventilation technique. These are local air change index, (LACI), mean air exchange efficiency (MACE) and effectiveness of heat removal (EHR), all derived by Awbi, (2003).

Figure 3: The points of interest (POIs)

These metrics have also been demonstrated and applied in Karimipناه et al., (2007 and 2008). LACI is calculated from the ratio of mean age of air in the room to the mean age of air at the POIs. The nominal time or air turnover time τ_n is essential in calculating LACI accurately and it is calculated from Eq. (2).

$$LACI = \frac{\tau_n}{2\bar{\tau}_p} \quad (2)$$

where $\bar{\tau}_p$ is age at particular point (in this case at PoI). MACE is derived according to Karimipناه, et al. (2007) as shown in Eq. (3):

$$MACE = \frac{\tau_n}{2\bar{\tau}_i} \times 100 [\%] \quad (3)$$

where $\bar{\tau}_i$ = local age of air at a point in space (e.g. POI). EHR is derived as follows in Eq. (4).

$$EHR = \frac{T_e}{T_m} \quad (4)$$

In this case, T_e is temperature at exhaust; and T_m is mean room temperature. Air turnover time (ATT) is a time constant of a ventilation system's capacity to remove a contaminant from a well-mixed space (Zhang, 2005). The model is given by Eq. (5) and is also referred to as the nominal time. The ATT of

a ventilation system is measured in seconds and should not be construed as CRE, which deals specifically with efficiency (of contaminant removal) and is non-dimensional.

$$ATT = \frac{V}{Q} \quad (5)$$

where V is volume (m^3) and Q is flow rate (m^3/s). Specifically, the inverse of ATT is air turnover rate (Q/V) which is not employed as a metric in this study.

4.0 RESULTS AND DISCUSSION

4.1 Bulk airflow characteristics

Ventilation rates of 60 l/s/patient and 6 ACH were used as basis for assessing all cases. Table 1 summarises the number of days for which specific ranges of air change rates were achieved for each case. The predicted variation in bulk airflow pattern over four different weeks in each ward is shown in Figure 4a for Case 2 when areas of openings are $0.66m^2$. This shows volumetric flow in a typical week in the middle of the four seasons (April 14-20 for spring; June 14-20 for summer; October 13-19 for autumn and January 13-19 for winter). Figures 5a and 5b are for the scenario when stack cross-sectional area is $0.25m^2$ giving insight into the capacity for NPV to meet the required air flow rates.

Table 1: Number of days of occurrence of 6 to 10 air changes at two openings

		< 6 ACH	6 to 7ACH	7 to 8 ACH	8 to 9 ACH	9 to 10 ACH	> 10 ACH
$0.66m^2$	Case-1	60 days	59 days	80 days	50 days	17 days	99 days
	Case-2	46 days	49 days	74 days	66 days	26 days	104 days
	Case-3	50 days	53 days	78 days	61 days	22 days	101 days
$0.25m^2$	Case-1	345 days	18 days	3 days	0 days	0 days	0 days
	Case-2	342 days	20 days	3 days	0 days	0 days	0 days
	Case-3	346 days	18 days	2 days	0 days	0 days	0 days

Other Cases (1 and 3) were also computed for similar weeks but are not reported, as the pattern is largely similar. Notably, (from Table 1 and Figure 4a) the three NPV concepts are all robust enough to meet the 6 ACH requirement.

Figure 4: Weekly flows for $0.66m^2$ opening into (a) ward and (b) duct

With respect to the WHO recommended flow of 60 l/s/patient (which the NPV strives to meet) actual flow through the duct of Case 2 are shown in Figure 4b. Although the flows generally fall short of 60 l/s/patient and fluctuations due to seasonal variations do occur, this result demonstrates the potential for the NPV to deliver the minimum design flow rate. Similarly, total flows into the ward when cross-sectional stack area is $0.25m^2$ are shown in Figure 5a while actual flows through the NPV duct for same stack size are given in Figure 5b.

Figure 5: Weekly flows for 0.25m² opening into (a) ward and (b) duct

Whereas the direct flow through the NPV duct is significantly lower when stacks are 0.25 m² compared to when they were 0.66m²; with proper design and manipulation it is possible to enhance the performance of the NPV system to meet the optimum flow rate. For instance, when effects of wind or fan-assisted modes of natural ventilation (both not considered in this study) are incorporated, the potential of NPV becomes more apparent. Indeed, if 60 l/s/patient must be maintained in summer, fan assistance may be necessary in situations when temperature differentials are small, and buoyancy-induced flows are sluggish. Even then, the potential for overheating has to be considered too. A comparison of the flow through the NPV ducts for cases 1, 2 and 3 are shown in Figure 6 for a mid-July week. Clearly, the large duct of the NPV in Case 1 outperforms the smaller ducts in Cases 2 and 3. The optimum duct size that would deliver sufficient flow rates for the patient as well as background ventilation for the ward, lies somewhere between Case 1 and Case 3 and this presents an interesting theme for further research.

Figure 6: Weekly flow of air into ducts of Cases 1, 2 and 3

4.2 CFD output: The ventilation metrics

The CFD investigation sought to capture the fresh air distribution in the NPV cases and to evaluate the performances of the cases using metrics mentioned earlier (LACI, MACE, EHR and ATT). The values of these metrics for Cases 1, 2 and 3 are given in Figure 7. The ATT for Case 1 is 170.45s while that of Cases 2 and 3 are 352.66s and 170.44s respectively. It is noticed that while there is a correlation between the Age, LACI, MACE, EHR and ATT (where Case 2 records the best set of values as shown in Figures 7a, 7b and 7d respectively), the same is not true for contaminant removal. With respect to efficiency of contaminant removal, there is no generalised way of providing a performance evaluation. This indicates that contaminant removal requirements in a ward would depend on who is most at risk, as each Case is largely unique for the POIs. Notably though, the CRE values at point D (source location) are similar for each case.

When interpreting Figure 7, it should be noted that for some of these metrics, a lower value is ideal e.g. for Age and ATT which deal with time; whereas for LACI, CRE, MACE and EHR, higher values are desirable. Figure 7c suggests that flow through the NPV duct of Case 1 performs well as identified by CRE at PoIs B and C; the NPV duct in Case 3 performs well in CRE at PoIs A, B and E, and to some extent at point C. Compared with previous results, it is obvious that the performance of an NPV system in delivering the air flow rates is not directly proportional to its effectiveness in dilution or removal of contaminants from a space. Careful studies of the clinical needs of each ward space should determine which strategy is best. Figure 7d reveals the MACE, EHR and ATT performances of each strategy. It can be observed that while there is marginal difference in EHR values (percentages); the differences in MACE are significant. The MACE for case 2 is 50.4% which is about twice the MACE of Cases 1 and 2 which are 19.5% and 23.3% respectively.

4.3 CFD output: Room air distribution

In Case 1, the large downward flow of air caused by the large size of opening and temperature difference creates substantial mixing around the bed area (see Figure 8). It should be noted that the top of the inlet duct was located at 0.5m below the ceiling which separates the incoming air from stale buoyant air accumulating at the ceiling level.

Figure 7: Airflow metrics with (a) Age (b) LACI (c) CRE and (d) MACE, EHR and ATT for all Cases

The presence of low level inlets and a raised higher NPV inlet in Cases 2 and 3 do not appear to provide as much mixing as Case 1 around the patient's bed area. This is indicated by the typical weekly air flow patterns for each season as indicated in Figure 6. The significant difference can be attributed to the smaller mass of air descending from the NPV inlet in both Cases 2 and 3. However, this behaviour contrasts with the age of air at POIs shown in Figure 7 where Case 1 has relatively higher age of air values than Cases 2 and 3. The behaviour of air through the different NPV ducts is depicted by streamline vectors which indicate the pattern and direction of air from inlets to outlets as shown in Figures 8a, 8b and 8c.

The age of air observed above the duct in Case 1 supports this mixing behaviour (Figure 9a). In all Cases, but most prominently in Cases 2 and 3, the fresh air does not just descend into the space, but a horizontal 'throw' from incoming jet of air is observed for about 0.3m in Cases 1 and 3 and up to a distance of about 0.5m in Case 2 (Figures 9a, 9b and 9c). This throw distance of cooler incoming jet of air has been described by Koestel (1955) and in Awbi (2003).

Figure 8: 3D vector streamlines in (a) Cases 1, (b) Case 2 and (c) Case 3

The throw distance can be used to determine the exact location of fresh air delivery (e.g. the upper portion or midsection of a lying patient) although an adjustable system could be more practical. In Case 1, the significance of the large duct area is evident, where the mean age of air at bed level is about 305s compared to Case 2 where it is up to 353s. A large pocket of relatively stale air (469s)

collects at the ceiling level in Case 2. The age of air at POI-E (patient's head) is found to be lowest in all cases (Figure 7a).

Figure 9: Age of air and 2D Vectors in (a) Cases 1, (b) Case 2 and (c) Case 3

The thermal distribution obtained from the three Cases (Figure 10) also exhibits different behaviour for each strategy. At the bed level, there is a more even temperature distribution over the patient in

Case 1 (~23.7 °C), compared with Cases 2 and 3. In the latter cases, the momentum of the incoming air generates a cool zone in the centre of the bed (about 22.8 °C for Case 2 and about 22.6 °C for Case 3) relative to the head and foot of the bed where the temperature is about 24°C.

Figure 10: Temperature contours in (a) Cases 1, (b) Case 2 and (c) Case 3

In Cases 2 and 3 however, cooler air rising from low inlets encroach the foot of the bed, and with respective mean room temperatures being 23.2 °C and 23.5 °C compared to Case 1 where mean is 24.2 °C; this signifies the importance of having the low level inlets, which is absent in Case 1. It can be deduced that low level inlets contribute to cooling and heat removal (EHR values for Case 2 and 3 are higher than Case 1).

CONCLUSIONS

Three conceptual cases were investigated to demonstrate a novel approach for delivering fresh air directly to patients in hospital wards. DTS and CFD modelling indicated that all three concepts are feasible and could be useable without extra heating for up to 8 months in a year (early March to end of October) in an urban setting such as London. This is using the 18 - 28°C thermal range (of HTM 03-01) as shown earlier in Figure 1. However, detailed comfort studies will be required under several climatic conditions as well as the use of heating setpoints. All concepts are able to create more mixing than obtainable in basic (bottom-to-top) displacement strategy. Mixing has already been shown to be a desirable feature of ward ventilation for bio-aerosol control (Beggs et al., 2008) and in this case, mixing occurs due to the falling of cooler air and its subsequent rise upon being heated by internal sources. Case 1 in which the supply inlet is large and directly over the patient has significant potential for prioritising patient ventilation over that of co-occupants. This could be especially beneficial for immune-compromised or immune-suppressed patients. Cases 2 and 3 demonstrate the benefits of having supplementary airflow from floor level inlets. Overall, the study shows that direct delivery of cooler air into the breathing zone of the patient with warmer air in the surrounding area (usually desirable in PV systems) can be achieved using natural ventilation powered by buoyancy forces. These concepts present a novel approach to meeting fresh air and contaminant dilution requirement of hospital wards. Using an NPV strategy in wards can help 'keep the air within as pure as the air without' (Nightingale, 1859) as well as lowering the energy requirements of hospital ward ventilation. There are however opportunities for further refinement of the NPV technique.

Future work will include experimental validation of the NPV technique using brine in water. There is also need for further studies in terms of: thermal comfort performance for each strategy; patient interaction in adjusting flow rates to their needs; potential for hybrid modes/heat recovery and fan assisted flows as well as the impact of wind. As with all natural ventilation systems in the UK, overheating in summer where outdoor temperatures could approach 30°C, as well as determining appropriate trickle ventilation rates for winter are also opportunities for further research. The possibility to utilise the NPV system for retrofitting multi-bed wards is also being considered as personalised airflow for each bed area could improve individual comfort and alleviate airborne cross-infection amongst co-patients. Finally, integrating NPV systems with advanced natural ventilation (ANV) methods (Lomas, 2007) is likely to be a realistic way forward and worth developing.

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