Evaluation of the energy impact of PCM tiles in an Airport Terminal Departure hall

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Abstract

In most past studies, passive PCM (phase change materials) systems have been tested for relatively small office spaces where the airflow is of minimal consequence in the overall energy consumption of the space. This paper on the other hand, reports on the application of PCM tiles on the floor of an Airport terminal space, similar to London Heathrow Terminal 5 departure hall, where in such large open spaces, the influence of airflow is crucial for the evaluation of the energy performance of AC units.

In this paper, the evaluation of the energy performance of PCM tiles is obtained through a coupled simulation of TRNSYS and CFD. TRNSYS simulates the AC unit and PID control systems, while CFD is used to simulate the airflow and radiation inside the terminal space. The phase change process is simulated in CFD using an in-house developed model which considers hysteresis effects and the non-linear enthalpy-temperature relationship of PCMs.

Although, a displacement ventilation (DV) system is actually employed at Heathrow Terminal 5, this study also compares the performance of the PCM tiles for a mixed ventilation (MV) system. Due to large computing times associated with CFD, discrete time-dependent scenarios under different UK weather conditions are used. The yearly energy demand is then determined through the heating/cooling degree day concept using base temperatures of 18 and 23 °C for HDD and CDD, respectively, similar to the comfort temperature range in the Terminal.

The results show that the use of PCM tiles on the floor of the Terminal departure hall can lead to annual energy savings of around 3% for the DV system and 6% for the MV system, corresponding to 174 MWh/year and 379 MWh/year for the Terminal building.

Keywords Phase change materials, HVAC systems, CFD-TRNSYS coupling

1.0 Introduction

In the context of buildings, phase change materials (PCM) refer to materials with enhanced heat storage capabilities. This extra energy storage potential or thermal mass is obtained through the latent heat capacity of the material as it changes phase in a specific temperature range. Contrary to conventional building materials which provide thermal mass through sensible processes, PCMs allow large energy storage over a relatively small temperature range. Kuznik et al. [i] showed that a 5 mm thick 60% micro-encapsulated paraffin PCM wallboard stored energy equivalent to 8 cm thick concrete.

Various studies have identified PCMs as a very effective way of enhancing the thermal inertia properties of relatively small and thermally lightweight spaces [ii, iii], such as offices. As a result, they have generated increased interest and resulted in various commercial products such as DuPont Energain® and EBB PCM Clay boards, used as supplements or alternatives to gypsum plasterboards, or active systems such as the Monodraught Cool-Phase® or Trox Type FSL-B-PCM® which are ventilation units incorporating PCM. The literatures and commercial trends have shown that the application of PCMs to large spaces has been less popular. However, the growing trend of architects to design aesthetically pleasing large buildings with maximum exposure to the external environment, reduces the thermal inertia of buildings, therefore producing an excellent opportunity for the use of PCMs.

In large open indoor environments such as airports, the employed HVAC system plays a crucial part in the overall energy consumption. Air-conditioning is normally provided either through displacement diffusers or long-throw nozzles. Long-throw nozzles, as used in the International Airport in Barcelona, supply air at relatively high levels and velocities generating mixing in the space. Conversely, displacement diffusers, as employed at Heathrow Terminal 5, supply cold air at low velocities and levels. Upon reaching a heat source, the warm plume rises, displacing the air to higher regions where it is removed. The latter method is now being increasingly used for large spaces as it provides more control over the ‘to-be-conditioned’ space. In this study, air-conditioning by the displacement principle will be referred to as ‘displacement ventilation’, while air-conditioning with the long-throw nozzle will be referred to as ‘mixed ventilation’.

This study aims at numerically showing the energy saving potential of PCM tiles in an Airport terminal space, similar to London Heathrow Terminal 5 departure hall. Although Heathrow Terminal 5 is served by displacement ventilation (DV) diffusers, this study also compares the performance of the PCM tiles for a mixed ventilation (MV) system.

2.0 Numerical Considerations

In cases with large indoor spaces, the International Energy Agency (IEA) suggests that the air-flow inside the space is crucial, and recommends the use of Computational Fluid Dynamics (CFD) for performance evaluations [iv]. Multi-zonal energy simulation models and building CFD models have each been previously employed in the performance evaluation of buildings, however both tools have their advantages and limitations. Multi-zonal energy simulation tools (ES), such as TRNSYS® or EnergyPlus® comprise of one air-node in each zone, representing a fully mixed volume with uniform properties. These tools have been mainly focused on expanding the scope of building simulations by incorporating the modelling of auxiliary units such as HVAC systems, weather data files or control systems, at the expense of calculating the airflow in the space. This allowed the simulation times to be kept low. On the other hand, CFD tools such as ANSYS FLUENT® or CFX® have been focused on the accuracy and details of airflow results, at the expense of the practical aspects of building simulation tools.

In this study, the ES tool TRNSYS and the CFD tool FLUENT are dynamically coupled to investigate the energy performance of both the DV and MV systems, with respect to PCM tiles in airport buildings. The Airport airflow is reproduced in

FLUENT, while the HVAC system is simulated in TRNSYS.

TRNSYS is a modular simulation program that allows the evaluation of various energy systems, including HVAC analysis, multi-zone airflow analyses, electric power simulation, analysis of control systems, etc. The systems are defined by component ‘Types’ interlinked according to the appropriate flow of information. Each Type contains the relationships between the inputs and outputs, and the entire simulation is solved by the successive substitution method: the outputs of a Type are fed/ substituted as the inputs to another Type. A Type is called only if its inputs change during a particular time-step, and convergence is reached when the outputs vary within the tolerance limits defined by the solver

FLUENT is a general purpose CFD simulation tool, which solves the Navier-Stokes equations that define the behaviour of fluids. This requires the flow domain to be generated, discretised and solved via iterative methods. The CFD results can be of high accuracy, at the expense of high computing time and costs.

Zhai et al. [v] generally classified the coupling methods as either static or dynamic. A static coupling involves a ‘one’ or ‘two’ –step data exchange between CFD and ES, while dynamic coupling involves a continuous exchange of data at each time-step. In this study, a quasi-dynamic coupling strategy is employed, as explained in section 3.0.

2.1 Phase Change Model

Phase change basically refers to an amount of energy stored or released by a material in a specific range of temperature, in addition to the sensible energy of the material. This extra energy arises due to changes in the molecular structure of the material as it changes phase. For the purpose of thermal simulations, this is represented as heat sources or sinks in the governing energy equation.

$$\frac{\mathrm{d}}{\mathrm{dt}}\rho H = \frac{\mathrm{d}}{\mathrm{d}x_j}\left[\lambda\,\frac{\mathrm{d}T}{\mathrm{d}x_j}\right] + S_E \qquad \textbf{(1)}$$

Where:
ρ: Density (kg/m^3)
H: Enthalpy (J)
T: Temperature (K or °C)
x_j: Direction vector (-)
λ: Thermal conductivity (W/mK)
S_E: Energy source term (W/m^3)

The source term S_E is defined in Gowreesunker et al. [vi] and is obtained from experimental data. Employing this method enables the simulation of the variable enthalpy-temperature relationship and temperature hysteresis phenomena that exist when a material changes phase.

The phase change properties of the PCM tile investigated in this study is similar to a commercial PCM-Clay board, with 21% Micronal® PCM granules. This allows for an extra energy storage potential of 17kJ/kg in the temperature range of 13°C - 22°C, as described in Gowreesunker et al. [vii]

2.2 Radiation model

The Discrete Ordinates (DO) radiation model is employed to model the radiation exchange between the building surfaces. It solves the radiative heat transfer equation for a finite number of discrete solid angles, and can consider absorption and scattering properties of radiation due to the participating medium.

As described in the IEA Task 12 Report [viii], a suitable method to represent the effect of external solar radiation entering a space is by applying heat fluxes and generation rates in the building envelope in CFD. This is important to avoid the inappropriate transfer of long-wave radiation at night, which would otherwise require the non-gray modelling of radiation. As a result, all surfaces inside the building are defined as diffuse and opaque, with the transmitted solar radiation incorporated as a heat flux on the floor of the airport terminal.

$$A_{floor}\, q_{floor} = \alpha_{floor}\, G\left[\left(\tau_{glaze}\, A_{glaze}\right) + \left(\tau_{roof}\, A_{roof}\right)\right] \qquad \textbf{(2)}$$

Where:
q: Floor heat flux due to solar radiation (W/m^2)
A: Area of respective building envelopes (m^2)
G: External solar irradiation (W/m^2)
τ: Solar transmittance of building envelopes (-)
α: Solar absorptance of building envelopes (-)

The radiation properties of the materials are given in Table 1. The night-sky long wave radiation exchange is calculated based on the emissivity of the external surface of the building envelope and the night sky temperature calculated from Type 69b in TRNSYS.

2.3 CFD Model

The airport geometry is modelled as 2D where both the air and solid domains (glazing, floor and roof) are meshed. The latter domains are meshed so that the thermal inertia of the building can be considered. The floor comprises of either normal tiles or PCM tiles. The glazing and roof are externally bounded to the ambient by convection and radiation conditions, while the floor external surface is adiabatic. The external convection heat transfer coefficient is 25 W/m^{2}K. The inlets are defined by constant 'mass flow inlets' of 0.5 kg/s and 0.8 kg/s, for DV and MV respectively. The returns are defined as constant 'outwards-mass flow inlets', with the same total mass flow rate as the inlets in order to abide by the conservation of mass. Each square (0.25m^2; height of 1m) mimics the internal occupancy heat gains, bounded by uniform heat fluxes defined in Figure 3. The inlet size of the DV diffuser is 2m high and the return size is 4m high, while the MV inlet size is 0.36m and return size is 0.45m each.

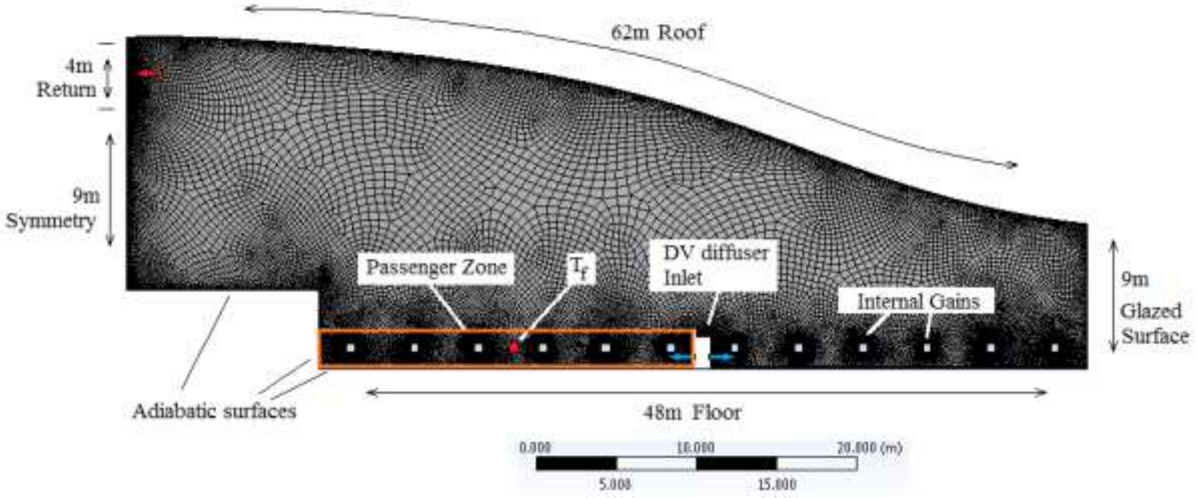

Figure 1 – Displacement Ventilation (DV) CFD model

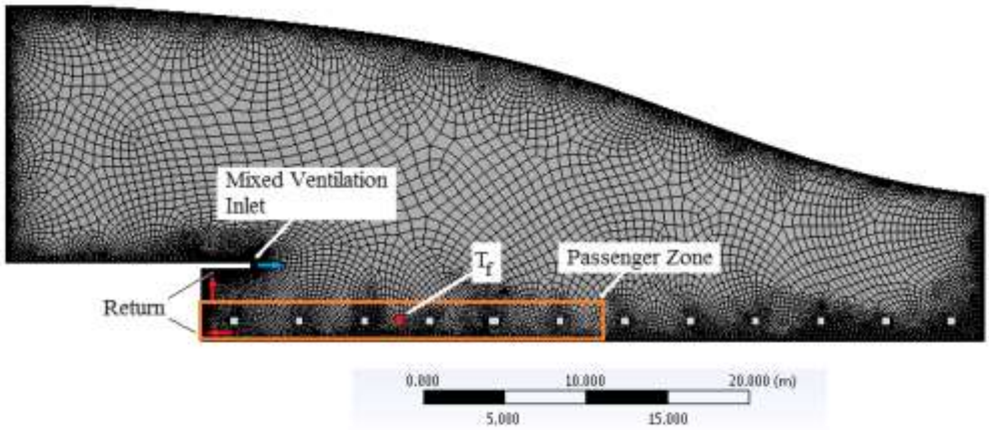

Figure 2 – Mixed Ventilation (MV) CFD model

With reference to Figures 1 and 2, the mesh is designed using the in-built ANSYS® design modeller meshing algorithm, and consists of mainly hexahedral cells. The air domain is made of unstructured mesh, with a cell size of 5cm and growth rate of 1.1 at the internal gains; a cell size of 10cm and growth rate of 1.05 at the envelope surfaces; and a cell size at the inlet and outlet of 6cm. The mesh gradually increases towards the bulk of the air domain producing a maximum cell size of 75cm. The roof, glazing and floor domains are made of structured hexahedral cells ranging from 3 to 10cm. The RNG k-ε turbulence model, the SIMPLE algorithm and the body-force weighted discretisation schemes are used in this model. The maximum allowable time-step is 360s, producing an error of <0.5°C and <0.15m/s. This model was obtained following an L_2 norm convergence study for the mesh and time step.

This geometry is similar to Heathrow Terminal 5 departure hall. The passenger zone spans half the floor area with a height of 2m. For the purpose of this study, the temperature T_f in the conditioned zone is monitored and used as feedback for the HVAC control system in TRNSYS. The building material properties are given in Table 1 (Note: Kirchhoff's law is applied to the radiation properties, i.e. $\varepsilon = \alpha$).

	Thickness (mm)	ρ (kg/m^3)	λ (W/mK)	c_p (J/kgK)	ε_{ext}	ε_{int}	τ
PCM Floor Tiles	13	1430	0.2	1240	-	0.5	-
Normal Floor Tiles	13	1700	0.8	850	-	0.5	-
Glazing	30	140	0.03	840	0.16	0.2	0.5
Roof	30	140	0.03	840	0.16	0.2	0.01

Table 1 – Material properties from CIBSE [ix] and Manufacturer

The internal occupancy heat gain in an airport environment is highly non-uniform, varying with the time of day. The following heat gains, adapted from the works of Parker et al. [x], described in Figure 3 is implemented in this study.

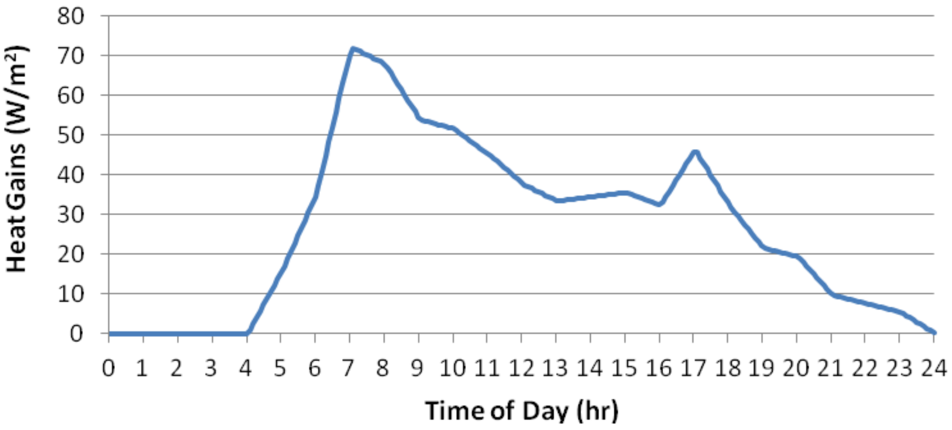

Figure 3 - Occupancy heat gains applied to CFD model

Figure 3 shows that peak heat loads occur at 07:00 and 17:00, and because of the operating hours of an airport, the internal gains spread between 04:00 and 24:00. The HVAC system is therefore only operational during the occupied hours, and turned off for the 4hrs during the night, when the airport is closed.

3.0 Coupled Model

In this quasi dynamic coupled simulation, the HVAC system is simulated in TRNSYS while the building and PCM are simulated in FLUENT, as schematically shown in Figure 4.

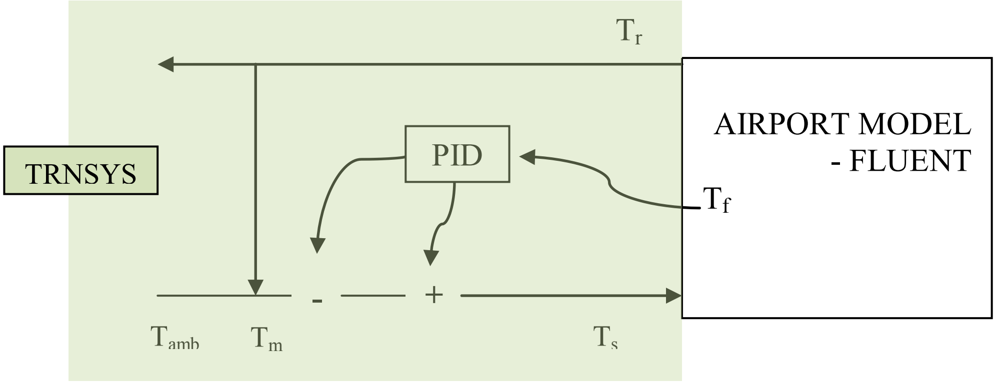

Figure 4 – Schematic of AC unit

The comfort temperature range is taken to be 18-23 °C [ix], and the PID set point temperature is 21°C. The PID operates either heating or cooling, thus affecting T_s, based on the feedback temperature T_f.

- For 18°C ≤ T_f ≤ 23°C; the PID produces T_s at 21°C, the optimum comfort temperature.
- For T_f > 23°C; the PID calculates a lower supply temperature T_s to satisfy the cooling load.
- For T_f < 18°C; the PID calculates a higher supply temperature T_s to satisfy the heating load.

The HVAC is a constant air volume system, whereby the fresh air flow rate is 0.2kg/s [ix] with a total flow rate of 0.5kg/s and 0.8kg/s for the DV and MV cases, respectively. Hence the mixing ratio of fresh air (T_{amb}) and return air (T_r) is constant throughout the simulation. The lower mass flow rate for DV is due to the smaller effective area to be conditioned. The integral, derivative and gain constants of the PID are 0.1hr, 0.1hr and 10% respectively. These parameters are maintained for both the DV and MV cases, and for all seasons.

The quasi dynamic coupling process employed, refers to the exchange of data whereby CFD receives the outputs from the current ES time-step (t^{th}), and returns the results to the ES for the next $(t+1)^{th}$ time-step, as shown in Figure 5.

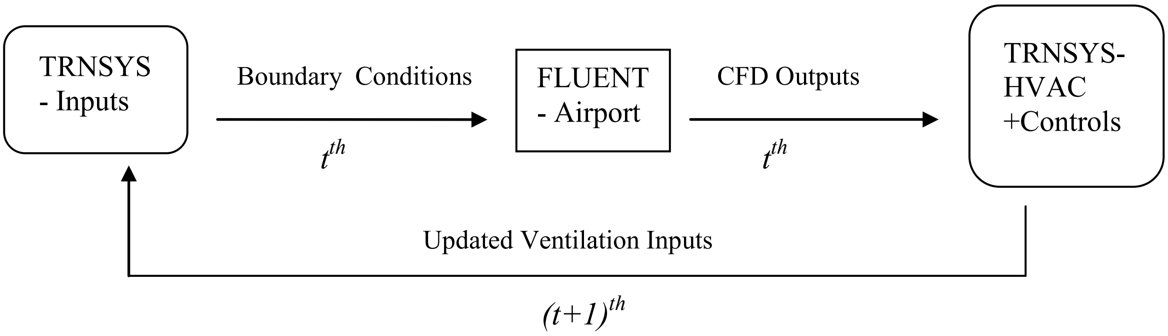

Figure 5 – Flow of information in TRNSYS-FLUENT quasi-dynamic Coupling

The 'inputs' to FLUENT from TRNSYS at time t^{th}, comprise of the external weather data (T_{amb} & Solar insolation), heat gains and ventilation supply air temperature, used as boundary conditions in the airport. The 'outputs' from FLUENT at t^{th} are then passed to the control system (PID) which influences the AC system in order to send the appropriate, ‘updated ventilation temperature’ at *(t+1)*th to complete the information loop. The ‘outputs’ are the feedback temperature (T_f) for the PID controller and the appropriate temperature for the HVAC system return air (T_r).

4.0 Results – DV Case

The simulation cases are divided into three distinct weather conditions (summer, winter and intermediate) for the London Heathrow area, of 100hrs each. This is done because of the large simulation times required by the CFD tool. The simulations are done with PCM tiles and with normal tiles in order to portray the energy differences. The computing time for each season was 14 hrs.

Figures 6 show the air distribution inside the terminal space with a displacement AC system. In cooling mode, the effect of temperature stratification is clearly observed in the space, with a temperature difference of ≈5.5°C from the floor to the top of the building. This effect is important as it allows the separation of the conditioned zone from the rest of the space, and also reduces heat gains from the top surfaces because of the higher temperatures. In heating mode, this effect is destroyed. The airflow is then more mixed, with a lateral stratification effect produced due to the geometry of the space and the location of the inlet and outlet.

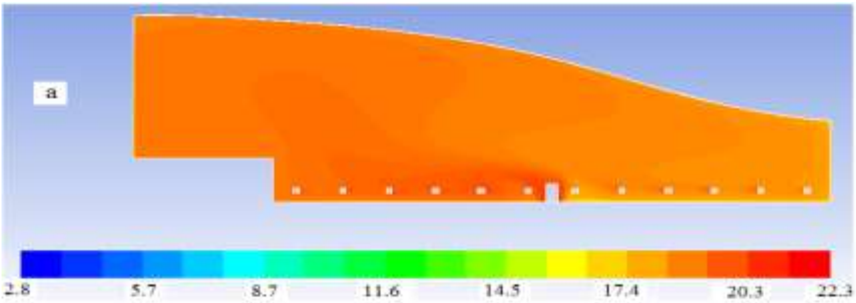

Figure 6(a) – Temperatures for DV in heating mode

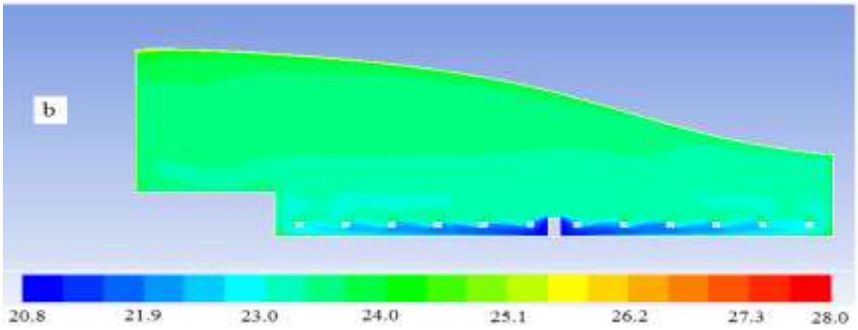

Figure 6(b) – Temperatures for DV in cooling mode

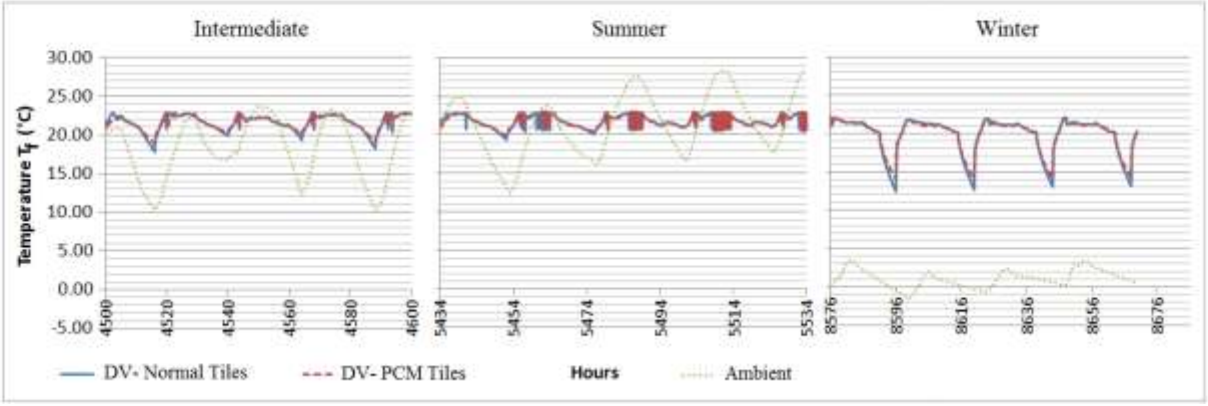

Figure 7 – Feedback / Zone (T_f) and Ambient temperatures for the DV case

Figure 7 shows that under the current control strategy used, the DV system is able to satisfy the comfort conditions (18-23°C) in the conditioned area for all seasons during the occupied hours. The low temperatures in winter are during the night time when the airport is closed and the HVAC system is turned off. The addition of the PCM tiles does not impact the temperature trend in the conditioned zone significantly during the winter period, but a slight shift of the temperature peaks is observed for the summer and intermediate periods, compared to the use of normal tiles. The energy implications are discussed in section 6.0.

5.0 Results – MV Case

Similar to the DV case, the simulations are done under the same weather conditions and with the same control strategy for the mixed ventilation (MV) case. The computing time for each season was 15.3 hrs.

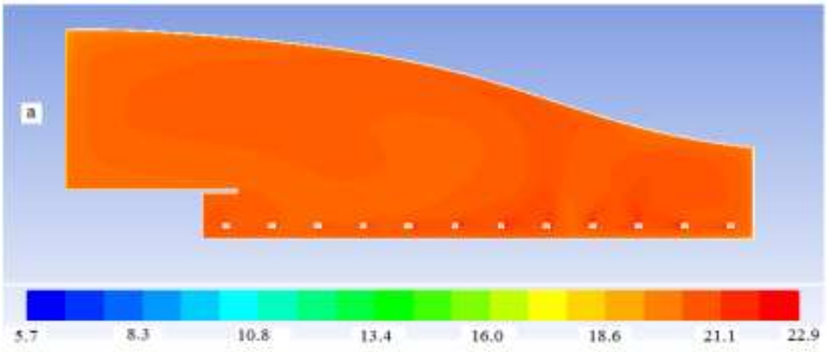

Figure 8(a) – Temperatures for MV in heating mode

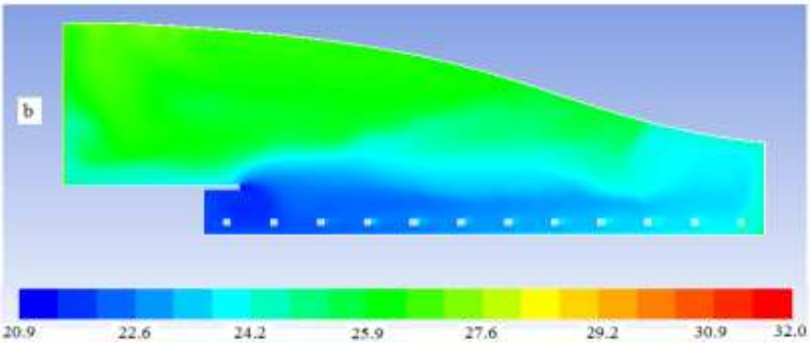

Figure 8(b) – Temperatures for MV in cooling mode

Figure 8 shows the airflow distribution in the space for the heating and cooling mode under a mixed ventilation system. During heating, the air domain is fully mixed and the underlying mixing airflow path can be observed by closely observing the temperature contours in Figure 8(a). In the cooling mode, the zone is not fully mixed and a distinction of two separate temperature zones can be observed, partly due to the geometry of the space. Nevertheless, compared to the DV system, the MV system unnecessarily conditions a much larger volume of air, leading to ventilation inefficiencies during the cooling mode.

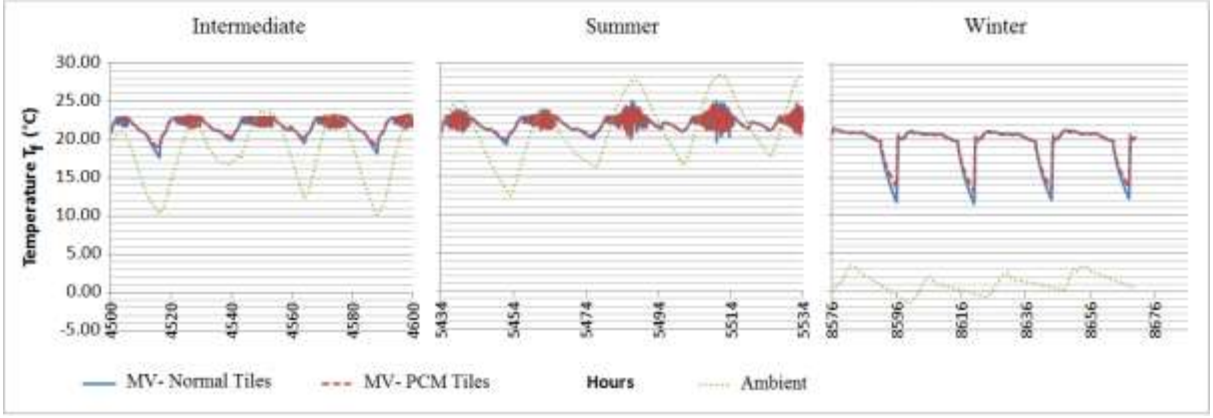

Figure 9 – Feedback / Zone (T_f) and Ambient temperatures for the MV case

The MV system is able to satisfy the comfort conditions only during the intermediate and winter season, while during summer the space overheats by ≈2°C. Similar to the DV case, the addition of the PCM tiles does not impact the zone temperature trend during the winter period occupied hours. However, during the intermediate and summer periods the peak temperatures are shifted and their frequency decreases. Furthermore, overheating during the summer is observed to decrease by ≈1°C.

6.0 Energy Impact of PCM tiles

Due to long simulation times for each simulation, it is impractical to simulate the different cases for an entire year. Alternatively, the concept of heating/cooling degree day is hereby employed to evaluate the yearly energy performance of the PCM tiles. The base temperatures used are 18°C for heating degree day (HDD) and 23°C for cooling degree day (CDD), similar to the comfort conditions in the space. The HDD and CDD for the simulated year near London Heathrow are presented in Table 2.

Base:	18 – 23 °C	
	HDD	**CDD**
Intermediate	6.66	0.12
Summer	1.69	4.13
Winter	66.35	0.00
Total	2755.82	12.43

Table 2 – Number of HDD and CDD at base temperatures of 18°C and 23°C, respectively, for each simulation period and the entire investigated year

The advantages of the concept of degree days lie in their simplicity and speed of use, as well as the possibility to easily estimate the building performance for different weather conditions. The drawback however, is that it only provides approximate results based on the assumption of average yearly conditions. It is applied in this study mainly because of the comparative nature of the results.

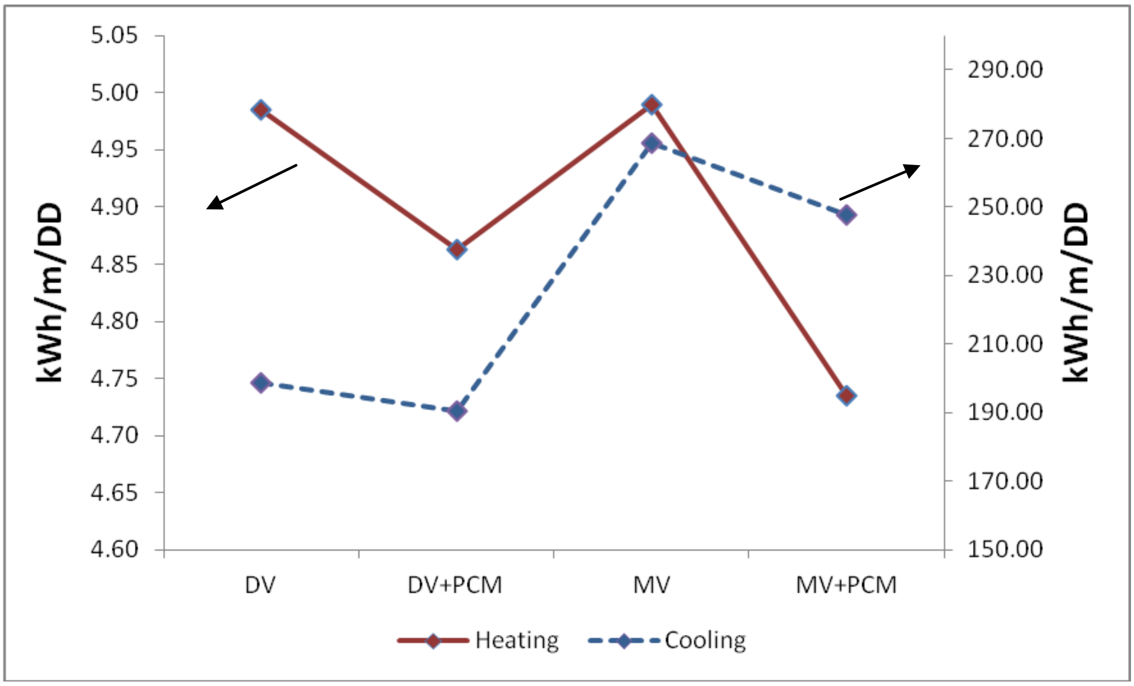

Figure 10 – Mean Yearly Energy demand per Degree Day (DD) for the 2D geometries (specific yearly energy demand)

Figure 10 shows that the effectiveness of the DV and MV air-flow ventilation systems without PCM is similar for heating applications, but significantly differs for cooling applications. In the case of heating, both the DV and MV systems mix the entire space due to buoyancy effects as shown in Figures 6(a) and 8(a), and are hence effectively behaving as the same system. On the other hand, the DV system is 35% more effective for cooling purposes compared to the MV system. This is largely due to the fact that the DV system is able to efficiently direct cooling at low levels as opposed to a larger volume by the MV system.

Applying the PCM tiles in the terminal space reduces the specific heating demand by 2% and 5%, and the specific cooling demand by 4% and 8% for the DV and MV cases, respectively. The higher impact of the PCM tiles for the MV system can be attributed to a higher convective heat transfer coefficients with the floor because of higher air mixing in the space. Overall, this corresponds to yearly energy savings of 3% and 6% for the DV and MV systems, respectively, which translates to 174 MWh/year and 379 MWh/year for a 396m long airport, such as Heathrow Terminal 5 departure hall (the length is in the perpendicular direction to Figures 6 and 8).

It is interesting to note that without the PCM tiles, the yearly energy demand for the DV and MV systems are 6419 MWh and 6767 MWh, respectively, while the addition of the tiles lowers the energy demands to 6245 MWh and 6388 MWh, respectively. The addition of the PCM tiles is therefore effectively reducing the total energy gap between the two systems. The relatively low difference in yearly energy demand between the two systems is due to the high heating degree days in the UK, where both systems heats the space due to their mixing propensity, and are thus effectively behaving as very similar systems.

7.0 Conclusions

This study considers the application of phase change thermal storage in the tiles of airport terminal buildings and operation with displacement ventilation (DV) and mixing ventilation (MV) systems. The results show that the utilisation of PCM tiles with either a DV or MV system will reduce the energy demand of the building, and will provide an improved level of thermal comfort due to reduced overheating. The research also shows that air conditioning with the DV principle is more efficient in cooling applications, but performs very similarly to the MV system in heating applications. The evaluation was done using a CFD-TRNSYS coupled simulation in order to consider both the airflow distribution within the space and the influence of HVAC control.

Acknowledgements

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