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# Free cooling based phase change material for domestic buildings in hot arid climate

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*Abstract: Free cooling based phase change materials (FCPCM) are promising sustainable technologies which could be used to store the cold energy available during summer nights in a sufficient latent heat storage for later utilisation during the daytime. This current work aims to evaluate the feasibility of FCPCM technology in hot arid regions where the cooling demand is dominant during most of the year round. Energy-Plus simulation engine was used to predict the cooling load of a selected case study in order to size the capacity of the storage medium. The flat-plate PCM panel storage system has been developed and assessed using computational fluid dynamics (CFD) modeling utilising ANSYS FLUENT. The influence of operating conditions on the system performance was discussed through studying the solidification and melting process characterisation of the PCM. The results indicate that the proposed system is capable of reducing the cooling load substantially and the temperature of air supplied by the system is well maintained within the summer comfort zone between 298.65 and 303.15 K under the case study climate for up to 14.5 hours during the discharging period.*

*Keywords: Free cooling; Phase change material (PCM); Building cooling; hot arid climate, CFD analysis*

# 1. INTRODUCTION

The global annual consumption of all forms of primary energy has increased more than ten-fold during the past century reaching to around 451 Exajoules in the year 2002 (Boyle, 2004: p.6). Thus, a significant awareness towards energy consumption in buildings as a dominant contributor to the global energy use than the industry and transportation sectors has begun increased nowadays. Most of the energy in buildings is consumed by the HVAC systems to maintain the thermal comfort, therefore, sustainable and abundant alternatives are highly required to replace or rather to diminish depending on these conventional systems.

Buildings in hot arid climate (A typical of Khartoum – Sudan) feature high indoor temperatures above the comfort zone most of the year. In such regions, the ambient air temperature in summer is extremely high throughout the daytime exceeding 40°C while at night it can be as low as 20°C. Admittance of this cold energy into interior spaces is a passive way of cooling buildings. However, limited availability of this source required an existence of thermal energy storage (TES) medium to keep cooling during the unavailability period of the day. Storing the nocturnal cold energy in a sufficient TES unit is referred to in the literature as free cooling, which takes place by either increasing the temperature of a sensible heat storage (SHS) substance or by altering a physical phase of a Latent heat storage (LHS) substance (Zalba et al., 2004, Hasnain, 1998). According to Raj and Velraj (2010), free cooling incorporated LHS systems performs efficiently in locations with diurnal temperature variation range between 12 and 15 K.

Substances operated for LHS are recognised as phase change materials (PCMs) which can be defined as substances that store and release latent heat as they undergo a phase change by rearranging their microstructure (Riffat et al., 2013). The use of PCM for TES systems is highly desirable to maintain the indoor thermal comfort over the other SHS as PCMs possess a high energy storage capacity and able to absorb and release heat at a narrow temperature range (Pasupathy et al., 2008, Fernandez et al., 2010, Regin et al., 2008). The aims of the present article are; to assess the feasibility of free cooling technology under the extremely hot and arid climate conditions, and to evaluates how the proposed flat plate PCM storage system based free cooling is capable of providing thermal comfort and reducing the energy consumption in domestic buildings in hot and arid climate through investigation of melting and solidification behaviour of the PCM.

# 2. EVALUATION OF FREE COOLING FEASIBILITY IN HOT ARID CLIMATE OF KHARTOUM

In order to determine to what extent the natural cold energy available at night in hot arid climate is capable of providing all day thermal comfort inside domestic buildings; the human thermal comfort, weather conditions, and thermal performance of current houses are discussed considering Khartoum as a case study location as follows;

## 2.1. Identification of human thermal comfort

Studying thermal comfort of buildings is crucial as it represents the basis for assessing the applicability limits of the passive design strategies such as the free cooling technology considered in the present application as comfort temperature range is directly associated with the selection of the appropriate PCM transformation temperature.

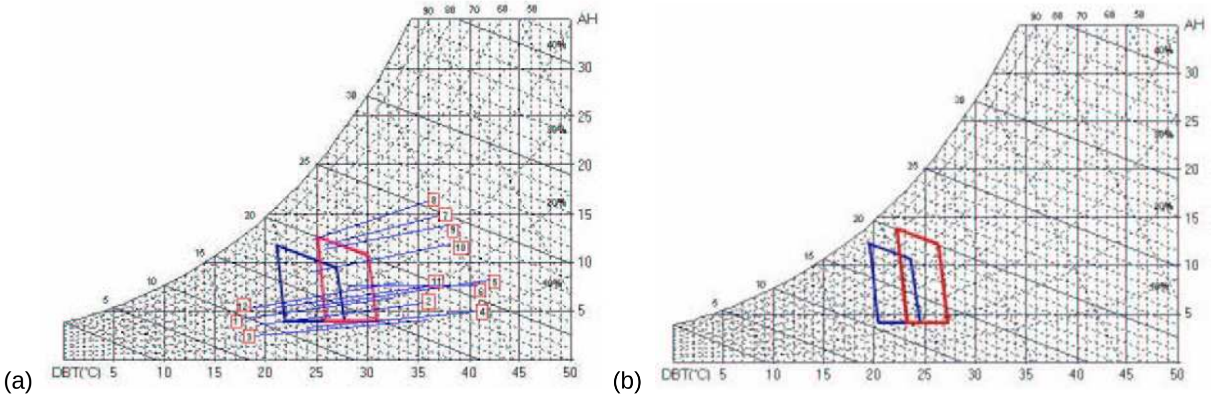

*Figure 1: Comfort zone for Khartoum city; winter (blue) and summer (red); (a) demarcated by Merghani (2001), and (b) recommended by ASHRAE standards.*

*Table 1: Summer and winter comfort temperature for Khartoum city available in the literature.*

| | ASHRAE | ISO | Merghani (2001) |
|---|---|---|---|
| Summer | 23.3-27.2°C | 23-26ºC | 25.5-30.9ºC |
| Winter | 20.6-24.4ºC | 20-24ºC | 21.5-27.5ºC |

Merghani (2001) determined the comfort temperature and demarcated the local comfort zone for Khartoum city based on the findings of his major observation study and a fieldwork survey on thermal comfort in residential buildings. The monthly climate data of Khartoum and the local comfort zone achieved by Merghani (2001) are shown in Figure 1 along with that recommended by ASHRAE standards, and the comfort temperature was also compared to that recommended by the international standards (ISO / ASHRAE) in Table 1.

It appears from the psychometric chart in Figure 1a that people feel comfortable in summer within the temperature limit of 25.5 to around 30ºC and a relative humidity range 20% to 60%, while the comfort zone in winter months extends from 21.5 to 27.5ºC and between a relative humidity 20% to 70%, noting that, both comfort zones are based on 80% sedentary conditions. It is also clear from Figure 1 and Table 1 that the new comfort zone achieved by Merghani (2001) is more expanded to involve temperatures that considered uncomfortable by ASHRAE and ISO standards and includes more realistic humidity level lower than that proposed in ASHRAE. Accordingly, the comfort temperature boundaries that provided in (Merghani, 2001) will be adopted for this study.

## 2.2. Analysis of the weather data

According to (Raj and Velraj, 2010, Zalba et al., 2004), the successful application of the free cooling technology can be climatically realised in the presence of suitable diurnal temperature variation larger than 12 K, and when the ambient air temperatures are within or below the PCM melting temperature range during the charging time. Khartoum is one of the hottest and sunniest cities in the world which locates at a latitude of 15° 6´N and a longitude of 32° 55´E (Oliver, 1965). The climate data for Khartoum during the period of 1961-2000 analysed in this work were obtained from Khartoum (CIV/MIL) station which is available at the World Metrological Organisation (WMO). Khartoum generally features a hot desert climate characterised by a very long dry season lasts for 9 months October to June, and the other three months (July to September) are the rainy season where occasional precipitations and dust storms are present. The city essentially experiences the dominant qualities of dry regions with very hot summers and warm dry winters.

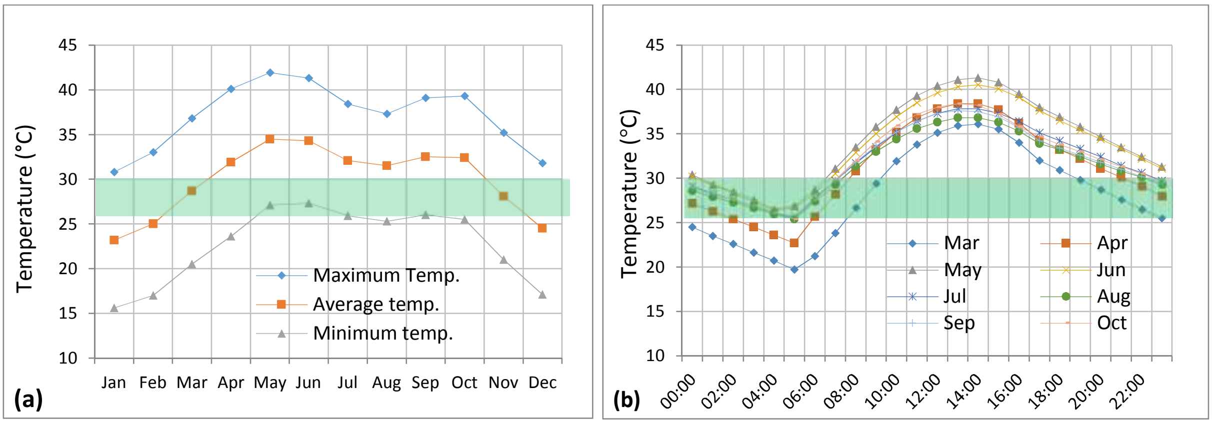

*Figure 2: Temperature data for the site of Khartoum, obtained from Khartoum (CIV/MIL) station; (a) Monthly average dry bulb temperature and, (b) monthly diurnal average temperature at hourly scale for summer months.*

Figure 2a illustrates the mean monthly data of dry bulb temperature recorded in Khartoum for the duration of 1961-2000 along with the comfort temperature limit determined by Merghani (2001). It is clear that there is a large diurnal temperature variation around 15 K throughout the whole year. According to the mean maximum ambient temperature pattern, months extending from April to September and months from November to February represent the two main seasonal patterns summer and winter respectively, whereas, March and October are transitional months (Oliver, 1965). Therefore, the overheating period should be considered lasting for eight months including the transitional months where a significant need for cooling exists.

The monthly diurnal average temperature in Figure 2b shows that the mean minimum outside temperatures in the summer and transitional months (March to October) are well within and below the comfort level by few degrees most of the time. This indicates the availability of cool night air which can directly be used for instantaneous cooling besides accumulating the cooling energy in appropriate thermal storage to cool the hot daytime hours when the average maximums range between 37.9°C and 41.3°C. Furthermore, the temperature pattern indicates that May, June, and July are the hottest months in Khartoum. Thus, sizing of cooling systems and all calculations must be carried out considering weather conditions of these months. However, the ambient air temperature for some periods at night during some summer months can be slightly higher than the comfort upper limit; this low variation minimises the solidification process in the required time and thereby the cooling energy stored. In such cases, it would be beneficial to further cool down the air by other passive methods before being circulated through the PCM storage.

### 2.3. Case study analysis

Most of the modern houses in Khartoum have almost a similar layout for the indoor spaces but a different outer skin design. The adopted house was chosen from one of the major housing developments in Khartoum named Elyasmeen residence. It can be considered a typical for the modern houses in Khartoum which experience a higher energy consumption compared to other housing typologies. The house occupies about 463 m² and comprises two main storeys. A model for the prototype house was created in the DesignBuilder software in order to perform the thermal performance analysis. The building orientation was set to face the exact north direction and no external obstructions are considered. The model contains 19 thermal zones in addition to a number of non-thermal zones to accommodate the shading elements. A photo of the selected house and the model tested in DesignBuilder software using EnergyPlus simulation engine is shown in Figure 3.

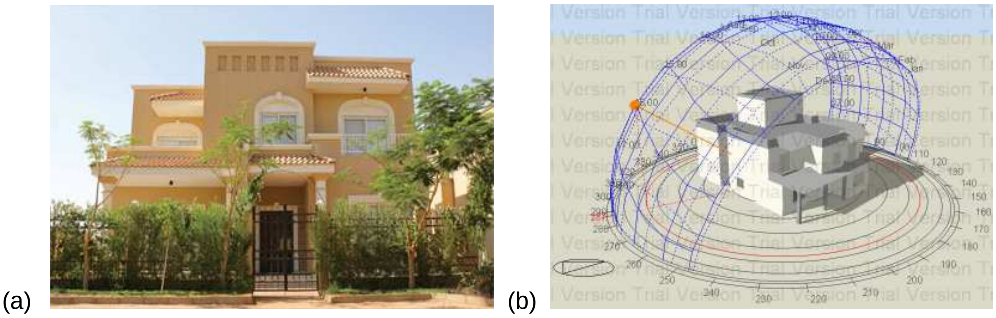
(a) (b)

*Figure 3: (a) Photo of the selected case study house, (b) modeled geometry in DesignBuilder software.*

The utilised weather file was compared to measured weather data (1961-2000) by Khartoum (CIV/MIL) station and an excellent agreement was observed. In the case of internal loads and environmental comfort controls, the data used for occupancy and metabolic settings (activity and clothes) were assumed based on the living behaviour inside houses in Khartoum. The HVAC thermostat set-points were set to 21.5ºC and 30°C for cooling and heating respectively based on the comfort zone of Khartoum. The RH humidification and dehumidification set points were set to 20% and 60% respectively. The air infiltration was set to a constant rate of 0.3 ac/h scheduled as always on. Natural ventilation was controlled according to the occupancy schedule by opening about 50% of the windows and internal doors area. The required luminance level and the minimum fresh air for each space were set according to CIBSE guide. The construction materials were set according to that commonly applied to the current housing constructions in Khartoum using plastered masonry brick for external walls, cast concrete slab directly attached to earth for the ground floor, cast concrete slab for internal floor and flat roof, and single glazing for windows.

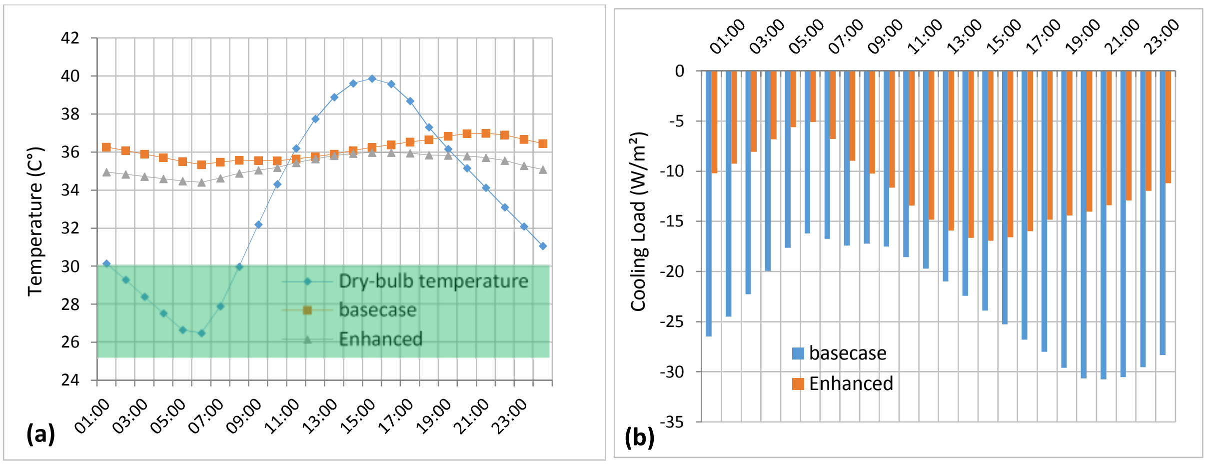

*Figure 4: (a) Indoor air temperature and (b) the associated hourly cooling load of the hottest room on a typical summer day.*

The results were obtained for the model under the existing conditions and when some enhancements have been applied using insulation for the roof and external walls. The PCM energy storage was designed to serve a single standard room of an area 16 m² in and the room with a maximum cooling load in the enhanced design case was selected. The capacity was determined based on the overall cooling load of discharging hours in an average day of the hottest months (May to July) as shown in Figure 4b. It is clear from the figure that a TES unit with a cooling capacity around 253.313 and 468.14 W/m² is needed to meet a cooling demand of 19 hours on an average summer day to bring the indoor temperature down from around 36°C to below the upper limit of the comfort zone (30°C). For the current study, the TES system capacity was sized according to the enhanced room cooling load.

Based on the observations from the aforementioned discussion on weather data, thermal comfort conditions and predicted cooling load of a selected case study represents modern houses in hot arid climate of Khartoum, it can be stated that the available large diurnal variation and the low night temperatures within and below the comfort level throughout the year generally indicate the possibility of harnessing the free cooling strategy most of the year-round in the meant location and in such type of buildings.

## 3. DESCRIPTION OF THE TES UNIT

PCMs for free cooling requirements should be selected so the temperature of exit air from the system will be within the thermal comfort range during the discharging period, and in the same way, allowing maximum and quick PCM solidification during charging period (Yanbing et al., 2003). Thus, PCMs with a melting temperature within the summer comfort limit of 25.5-30°C can be appropriate for hot and arid regions such as Khartoum. Several available commercial PCMs including; RT28HC, SP29Eu (Rubitherm GmbH), A28, A29, S27, E27 (EPS Ltd.), ClimSel C28 (Climator), TM29T (TEAP), and HC 29 (PLUS) seem to be the most appropriate PCMs for the diurnal temperature variation of summer period in Khartoum that shown in Figure 2b. For this study, the RT28HC paraffin PCM was selected as it possesses an acceptable phase change temperature compatible with both the available charging temperatures on the location and the identified thermal comfort range, besides, it has the highest latent heat of fusion. Technical specifications of the selected RT28HC PCM given by the manufacturer are presented in Table 2.

*Table 2: Thermo-physical properties of the RT28HC PCM, (Rubitherm)*

| Property | Value |
|---|---|
| Phase change temperature range | 27-29°C |
| Heat storage capacity (latent+ sensible heat between 21-36°C) | 250 kJ/kg ± 7.5% |
| Specific heat (both phases) | 2 kJ/kg.K |
| Thermal Conductivity (both phases) | 0.2 W/m.K |
| Density (solid at 15°C) | 880 kg/m³ |
| Density (liquid at 40°C) | 770 kg/m³ |

The flat plate PCM module configuration was selected as it provides a flexible surface area to volume ratio and it allows easy control of air passages between the PCM plates to vary the air mass flow. An aluminium container module with overall dimensions 1.80 m × 0.60 m × 0.01 m was suggested. 8 PCM modules containing about 59.68 kg were utilised to fulfil a maximum cooling energy of 4.50 kWh. The modules are stacked over each other with an air gap of 15 mm in between and the outer casing is considered entirely insulated (Figure 5).

## 4. COMPUTATIONAL METHODOLOGY

The thermal performance of the proposed cooling system was assessed via a CFD modelling using ANSYS software. The modelled and meshed geometry was exported to ANSYS/FLUENT for setting and solving the fluid flow and the heat transfer problem including the phase change. The schematic of the 2D model including boundary conditions is illustrated in Figure 5. For the current study, the air and PCM domains are considered incompressible, and the problem is transient and two-dimensional. The thermo-physical properties of the air were considered constant. The specific heat, dynamic viscosity and heat conductivity of the PCM were considered similar for both phases, while the density variation has been calculated using the piecewise-linear method available in Fluent. The velocity and temperature of the inlet air are constant and heat losses to the surroundings are neglected.

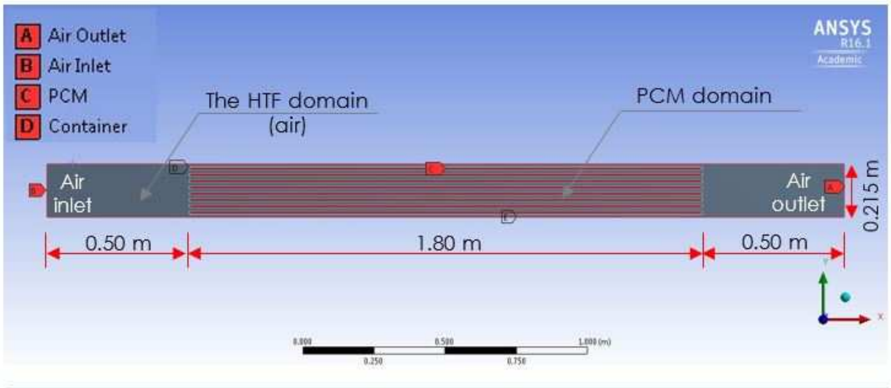

*Figure 5: Details and boundary conditions of the 2D Basecase model created in ANSYS DesignModeler.*

The air flow in the present application is turbulent. the realizable *k-ε* proposed by Shih (1995) was accepted as being highly recommended and appropriate for modelling flows such as that in this computation. Accordingly, the most widely applied Reynolds-Averaged Navier-Stokes (RANS) equations are solved in addition to the thermal energy equations as follows (FLUENT, 2013);

Continuity
$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = 0 \tag{1}$$

Momentum
$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial u_l}{\partial x_l}\right)\right] + \frac{\partial}{\partial x_j}\left(-\rho\overline{\acute{u}_i\acute{u}_j}\right) \tag{2}$$

where; $\rho$ is density of fluid, $u$ is flow velocity, $p$ is pressure, $\mu$ is fluid dynamic viscosity, and $\left(-\rho\overline{\acute{u}_i\acute{u}_j}\right)$ is the Reynolds stresses which is modelled by the selected turbulence model in order to close Equation 2.

Energy
$$\frac{\partial}{\partial t}(\rho E) + \frac{\partial}{\partial x_i}[u_i(\rho E + p)] = \frac{\partial}{\partial x_j}\left(\lambda_{eff}\frac{\partial T}{\partial x_j} + u_i(\tau_{ij})_{eff}\right) + S_h \tag{3}$$

Where; $E$ is the total energy, $\lambda_{eff}$ is the effective thermal conductivity, and $(\tau_{ij})_{eff}$ is the deviatoric tensor which is not considered as the pressure-based solver was used.

The solidification/melting model which uses an enthalpy-porosity formulation method (Voller, 1987, Voller et al., 1988, Voller and Prakash, 1987) is used by ANSYS FLUENT to solve the solidification and melting problems. In which technique, the solid-liquid front is not computed explicitly. Instead, a magnitude called the liquid fraction associated with each cell in the domain is utilised. The liquid fraction denotes the fraction of the cell volume that is in liquid form and it is calculated at each iteration, based on an enthalpy balance (Equations 4-8).

The enthalpy of the substance $(H)$ is calculated as a sum of the sensible heat $(h)$ and the latent heat$(\Delta H)$.

$$H = h + \Delta H \tag{4}$$

The sensible heat $(h)$ is calculated as function of reference enthalpy $(h_{ref})$, reference temperature $(T_{ref})$ and the specific heat at constant pressure $(c_p)$ using the following formula;

$$h = h_{ref} + \int_{T_{ref}}^{T} c_p dt \tag{5}$$

The liquid fraction $(\beta)$ can be expressed as;

$$\begin{aligned} &\beta = 0 && \text{if } T < T_{solidus} \\ &\beta = 1 && \text{if } T > T_{liquidus} \\ &\beta = \frac{T - T_{solidus}}{T_{liquidus} - T_{solidus}} && \text{if } T_{solidus} < T < T_{liquidus} \end{aligned} \tag{6}$$

The latent heat content $(\Delta H)$ can vary between 0 for a solid and the latent heat of the material $(L)$ for a liquid, thus, it can be written according to liquid fraction of the material $(\beta)$ by the given formula;

$$\Delta H = \beta L \tag{7}$$

The governing energy equation for solidification/melting model is solved using the following expression;

$$\frac{\partial}{\partial t}(\rho H) + \nabla \cdot (\rho \vec{v} H) = \nabla \cdot (K \nabla T) + S \tag{8}$$

Where; $H$ is enthalpy computed from Equation 4, $\rho$ is density, $\vec{v}$ is fluid velocity, $K$ is thermal conductivity, and $S$ is source term.

The boundary conditions of the simulated problem were described in Figure 5. The inlet aperture was specified as velocity inlet with a constant velocity and temperature. The outlet aperture was set to a pressure outlet with zero Pascal gauge pressure and a temperature similar to that of inlet air. The interface between the PCM region and the air domain was set to a coupled wall boundary condition to allow heat exchange. The other channel walls were given a non-slip boundary condition and considered adiabatic. The coupled algorithm has been applied for the pressure-velocity coupling in all cases. The under-relaxation factors for; density, body forces, turbulent kinetic energy, turbulent dissipation rate, turbulent viscosity, liquid fraction, and energy remain default at 1.0, 1.0, 0.8, 0.8, 1.0, 0.9 and 1.0 respectively. The maximum iteration per time-step was set to 40 which has been found adequate for fulfilling the convergence criteria of the default residual tolerances of $10^{-3}$ for continuity, x and y velocities, and turbulence $k$-$\varepsilon$ equations, and $10^{-6}$ for energy equation. Independence tests were initially performed for a preliminary case under both transition phases in order to ensure that the solution is time and grid independent before commencing the main study. A time-step 0.1 s was selected as it was found sufficient for all charging simulations. The discharging simulations were initialized with 0.1 s time-step, and at a later simulation time it is updated to 0.01 s. Moreover, three grid element sizes 1, 2 and 3 mm were tries and a fine mesh size of 2 mm was found appropriate and therefore it is selected and kept constant for the entire analysis.

## 5. RESULTS AND DISCUSSION

For charging simulations, the initial state of the RT28HC PCM was considered a fully liquid with a temperature set to 305.15 K above its liquidus temperature by a 3.0 K. The charging air inserts the PCM heat exchanger with a certain temperature and flow rate and causes cooling of the PCM which begins to solidify. In the case of discharging, the PCM was assumed initially solid with a temperature set to 297.15 K below its solidus temperature by a 3.0 K. The discharging air of a constant temperature and flow rate causes adding heat to the PCM and hence it starts melting. The liquid fraction findings are obtained as average for the whole PCM domain and the outlet temperature as an average along the outlet aperture. The influence of operating conditions; inlet air temperature and mass flow rate; on the solidification and melting characteristics of the PCM is discussed.

### 5.1. Charging Simulation

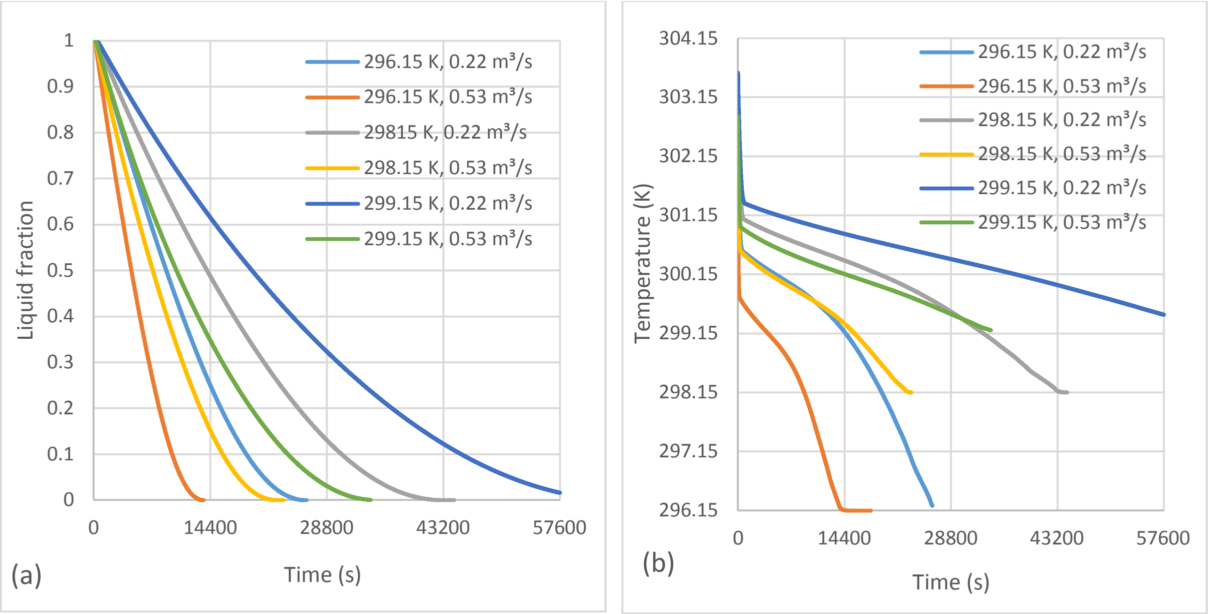

*Figure 6: Charging process; (a) mean liquid fraction on the PCM domain and (b) mean outlet air temperature for inlet air temperatures 296.15, 298.15 and 299.15 K with air flow rates 0.22 and 0.53 m³/s.*

The main target during the charging phase is to ensure full solidification of the PCM in a short time. In this study, the ambient air is used to extract the heat from the PCM. The possible time for charging is only when the ambient air temperature is below or equal to the freezing point of the selected PCM which is 300.15 K. The considered inlet air temperature was assumed based on the hourly average ambient temperatures during summer and transitional months in Khartoum that demonstrated in Figure 2b. Three inlet air temperatures were considered; 296.15 and 298.15 K in order to simulate charging during transition months (March and April), and 299.15 K which represents the prevalent average night temperature in the extremely hot conditions (May to October). For each inlet air temperature, two air mass flow rates 0.22 and 0.53 m³/s were considered.

Figure 6a shows the mean liquid fraction on the PCM domain over the time for three inlet air temperatures 296.15, 298.15 and 299.15 K with air flow rates 0.22 and 0.53 m$^3$/s in a complete charging phase. It is clear that a full solidification of the PCM can be realised as early as 3.6 hours when the inlet air was introduced at 296.15 K with 0.53 m$^3$/s flow rate and up to 16 hours with a temperature of 299.15 K combined with a low mass flow of 0.22 m$^3$/s. For each inlet temperature, decreasing the mass flow rate by around 60% from 0.53 to 0.22 m$^3$/s directly increases the solidification time by almost 75 to 90%. Under the considered climate, there is a plenty of time suitable for PCM charging in the transition months lasts for 8 to 9 hours, therefore, a successful complete charging can easily be obtained with a minimum power input for fan operation. On the other hand, high flow rates are required for charging during summer months (May to July) when the average ambient temperature is around 299.15 K. However, the full solidification is difficult to be obtained in the most cases as the maximum available time for charging ranges between 3 to 5 hours only. For optimal charging performance, the inlet air temperature has to be well below the PCM solidus point associated with a maximum air flow rate to allow sufficient heat removal. Table 3 summaries the required time for obtaining a complete PCM solidification under the considered operating conditions.

*Table 3: Time required to achieve the full solidification of the PCM for the tested operating conditions.*

| | | Inlet air temperature | | |
|---|---|---|---|---|
| | | 296.15 K | 298.15 K | 299.15 K |
| Air flow rate | 0.22 m$^3$/s | 6.5 hrs. | 11.7 hrs. | 16.0 hrs. |
| | 0.53 m$^3$/s | 3.6 hrs. | 6.1 hrs. | 9.2 hrs. |

According to Figure 6b, it is noticeable that the temperature of the exit air decreases sharply at the beginning of the process (sensible cooling of the PCM). Then, the temperature drop slows gradually with the progression of time as the solid PCM component increases which results in reducing the heat exchange area between the remaining melted PCM and the cool container plate. After the PCM fully solidifies, the outlet air temperature drops significantly till equalising the inlet air temperature. For the current configuration and suggested operating conditions, the outlet temperature from the system remains within the comfort range below 303.15 K all the time except for the first 15 minutes of sensible heat removal. Yet, the flow rate may be very high to be directly admitted into an occupied space.

## 5.2. Discharging simulation

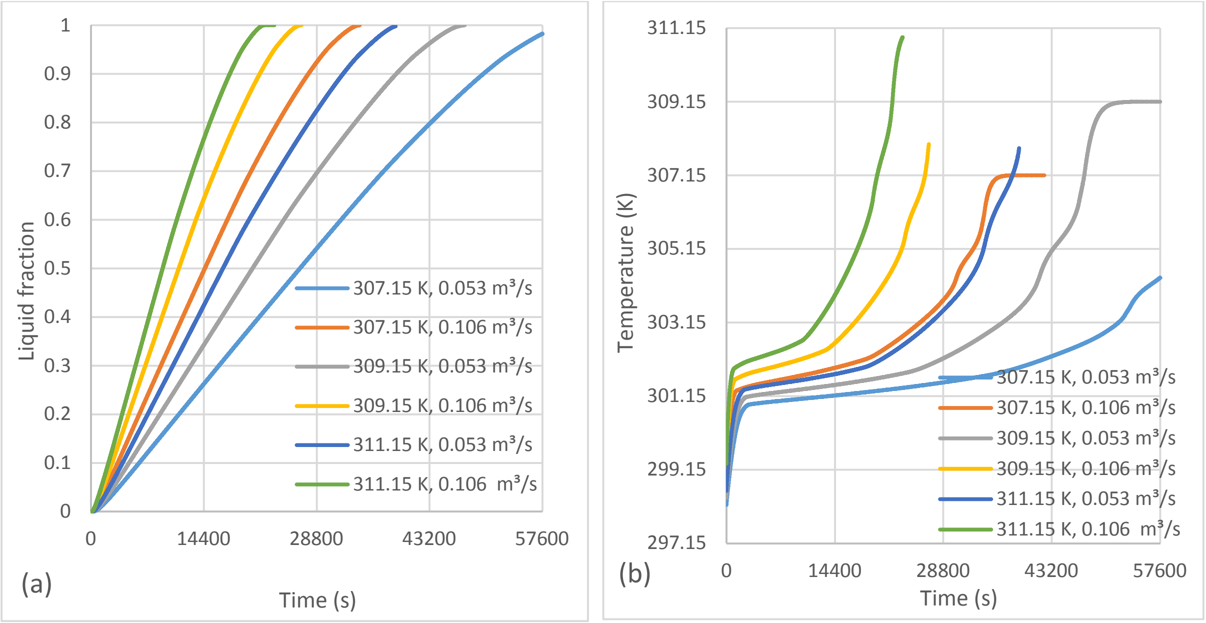

*Figure 7: Discharging process; (a) Average liquid fraction on the PCM domain and (b) mean outlet air temperature for inlet air temperatures 307.15, 309.15 and 311.15 K with air flow rates 0.053 and 0.106 m$^3$/s.*

The main target during the discharging phase is to supply air into the indoor space with an acceptable flow rate and a temperature in the favourable limit for the uncomfortable hours of the day. To achieve this target, the outlet air from the storage system can be controlled via different approaches such as varying temperature and flow rate of the inlet air. The inlet temperature can be the room temperature as the outside air during the daytime seems unfeasible to be cooled to the comfort limit for a long period especially in the extremely hot conditions. A constant inlet air temperature has been used in the discharging simulation as buildings normally feature slight indoor temperature swing according to many factors including microclimate conditions, building construction, internal loads…etc. In this analysis, three different inlet temperatures are investigated to discharge the cooling energy from the PCM; 307.15 K and 309.15 which represent the average daytime room temperature on a typical summer day (Figure 4a), and 311.15 K which is can be obtained in the same room during the hottest day peak. Moreover, varying the inlet air flow is very useful in manipulating the heat transfer between the passing air and the PCM in order to maintain the comfort temperature and to fulfil various cooling demands throughout the day. However, the supplied air flow should be in line with the range accepted by occupants inside the conditioned space. Thus, two air mass flow rates 0.053 and 0.106 m³/s were considered.

The computed liquid fraction versus time for a complete discharging phase is illustrated in Figure7a. It is clear that the full melting of the PCM occurs approximately between 6 and 16 hours for the current configuration and suggested operating conditions. A low inlet air temperature coupled with a minimum flow rate required inside the space are the requirements to harness the most output from the storage system. According to Figure 7b, it is clear that the outlet air temperature increases sharply at the beginning of the process (sensible heating of the PCM). Afterwards, it continues increasing gradually until the PCM reaches the Liquidus temperature, at which point, a sharp increase takes place until the outlet temperature equalises the inlet one. The exit air temperature from the PCM heat exchanger is well within the thermal comfort limit for around 3.6 to 7.5 hours when the inlet air temperature as high as 311.15 K with a flow rate 0.053 and 0.106 m³/s respectively. For inlet temperatures 307.15 and 309.15 K which represent the indoor temperature in a well-insulated room, the comfort temperature can be maintained for around 14.5 and 10.3 hours respectively with a flow rate 0.053 m³/s. The durations at which the system supplies air within the thermal comfort range for all tested temperatures and flow rates are given in Table 4.

It should be stressed that the air flow rate has a significant influence on the system performance during the discharging phase. For each inlet temperature, decreasing the mass flow rate by 50% from 0.106 to 0.053 m³/s directly increases the melting time by almost 75% and expands the comfort time approximately to the double. Moreover, it is not necessary to achieve the complete melting of the PCM as the outlet temperature normally exceeds the upper limit of the comfort before the full melting occurs. For instance, it is needed to liquefy the PCM by only 70% to achieve the comfort temperature for all cases shown in Figure 7. This partial melting is beneficial to boost the solidification cycle by 30% and hence less fan power and charging time is needed for the system operation.

*Table 4: Comfort time maintained during the discharging phase for the tested operating conditions.*

| | | Inlet air temperature | | |
|---|---|---|---|---|
| | | 307.15 K | 309.15 K | 311.15 K |
| Air flow rate | 0.053 m³/s | 14.5 hrs. | 10.3 hrs. | 7.5 hrs. |
| | 0.106 m³/s | 7.2 hrs. | 5.0 hrs. | 3.6 hrs. |

## 6. CONCLUSIONS

Free cooling of buildings is a passive strategy aims to store the natural cold energy available at night in appropriate thermal energy storage to be extracted when it is needed. The feasibility of FCPCM technology was evaluated under a hot and arid climate of Khartoum based on the weather data, thermal comfort and predicted cooling demand in domestic buildings. It can be noted that the available large diurnal variation and the low night air temperatures within and below the comfort zone throughout the year largely indicate the possibility of harnessing the free cooling strategy most of the year-round in the considered climate. However, it should be emphasised that at some night during the extremely hot months (May to July) it is difficult to store appropriate cooling energy due to the low variation usually takes place between the solidus temperature of the PCM and the prevalent ambient air temperature in addition to the limited time available for charging. For the best performance, a PCM with a transformation temperature closer to the upper band of the summer comfort should be used in order to expand the charging period.

The introduced FCPCM system in the present study was sized to meet a cooling load of an average summer day in a typical room in domestic buildings. By controlling the flow rate, the CFD analysis indicates that the comfort temperature can be maintained day and night according to the investigated inlet temperatures.

The difference between the inlet air temperature and the liquidus or solidus temperature of the PCM plays a significant role in the heat transfer rate through the both transformation phases. A higher variation is recommended to enhance the system operation during the charging phase, while, a lower variation during the discharging period is beneficial for gradual extraction of the cold energy.

The air flow rate is a very important factor that can be manipulated to optimise the system performance. Increasing the flow rate largely accelerates the PCM solidification in a short time. On the contrary, low air flow rates are recommended for cold extraction from the PCM during the melting process considering the compatibility of the air flow supplied with the human comfort and activity inside the space. As the inlet air temperature is uncontrolled, the mass flow rate must be optimised carefully according to the instantaneous ambient temperature and the availability duration for charging in order to harness the required cooling energy at the appropriate time, hence, enhancing the COP of the system by reducing the fan power consumption.

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