Modelling and simulation of “Free Cooling” process applied to building construction

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Abstract. Thermal energy storage systems (TES), using phase change material (PCM) in building walls, consists a hot topic within the research community currently. In the present work, a numerical model is developed to simulate free cooling of air-PCM heat exchanger in both charging and discharging steps. The studied case is taken from experimental work. The domain consists in two parallel plates made of Paraffin as PCM, separate by a gap where air circulates. The flow and temperature can be adjusted. The goal is to calculate the temperature of the air at the outlet, in order to analyse the performance of the device. A good agreement was founded between experimental and numerical results. The analysis of the influence of the flow rate on the efficiency of the process confirms a previous works, that the heating flow rate should be higher than cooling one.

1. Introduction

One of the alternatives to decrease the energy demands is the use of thermal energy storage (TES) combined with phase change materials (PCM). In the specific conditions, PCM can absorb heat, store it and release it; improving the gap between energy supply and energy consumption [1]. This type of technique called the latent heat thermal energy storage (LHTES) is an attractive way and has taken much attention for heating and cooling purposes in buildings. Many researches and studies based on numerical simulations or experimental work were focused on the change of indoor air temperature due to installation of PCMs [2]. However, many technical tools and design improvement are required for its commercialization in the building sector. Both experimental and numerical researches have been conducted to unravel parameters influencing this kind of process. Thambidurai et al [3] pointed out that the PCM temperature range, geometry of the PCM container, inlet air temperature, encapsulation thickness and the air flow rate are the main parameters affecting the free cooling performance. The control of this last factor ensures full solidification of the PCM during the charging stage or complete melting during discharging. Arkar et al ([4]-[5]) recommended that air flow rate during the charging process should be three to four times higher than air flow rates during the discharging process. Zalba et al [6] and Saman et al [7] observed however that a higher air flow rate boosts the heat transfer rate and leads to a shortened time phase change in both steps. However while charging, if the air
temperature is not less than the subcooling temperature of the PCM, a higher air flow rate is not beneficial according to Waqas and Kumar [8].

Cold outdoor air circulates in the building via free or forced ventilation. The first type is less energy demanding, however, it is very climate dependent (it is not efficient when the wind speed is weak). The second type is more efficient because it ensures a constant ventilation of air conditioning; even if the forced ventilation needs an additional energy for the fan. In the current work we present a model to simulate the free cooling process, during the both steps. The model is validated via experimental works existing in the literature. Followed by a parametric study concerning the influence of inlet parameters (Temperature and air flow), also, the ambient conditions, on the performance of the process.

2. Studied case and assumptions
The reference case for the validation and the parametric study will be based on the experimental work done by [9], (see Figure 1).

![Figure 1](image)

The PCM slab is composed of 6 ENERGAIN®, with thermo-physical properties as summarized in [9].

| Property                        | Value       |
|---------------------------------|-------------|
| Density                         | 850 (kg/m³) |
| Thermal conductivity            | 0.2 (W/m/K) |
| Apparent heat capacity          | see figure 2|
| Melting start temperature       | 13.6°C      |
| Freezing start temperature      | 23.5°C      |
| Melting peak temperature        | 22.2°C      |
| Freezing peak temperature       | 17.8°C      |

![Figure 2](image)
Concerning air, and due to temperature range work we consider constant thermo-physical properties reported at the reference temperature 20°C. For the velocity field, we suppose that the flow is the fully developed Poiseuil regime:

\[ u(y) = \frac{3}{2} \frac{\bar{u}}{H^2} (H^2 - y^2) \]  

where \( \bar{u} \) is the mean velocity, and \( H \) is the height of the air gap. In addition, because of the small height of the PCM sample, no free convection phenomenon in the liquid state of PCM is considered.

The governing equations of conjugate heat transfer with respect to assumptions considered in are presented in the system below:

\[
\rho_s c_{app}(T) \frac{\partial T}{\partial t} = k_s \nabla^2 T \quad \text{in}(\Omega_1)
\]

\[
\rho_f c_{pf} \frac{\partial T}{\partial t} + u(y) \cdot \nabla T = k_f \nabla^2 T \quad \text{in} (\Omega_2)
\]

With initial conditions:

\[ T_{t=0} = T_0 \]  

And boundary conditions

\[ \nabla T \cdot n = 0 \quad \text{at} \ \partial \Omega_2, (i=2,6) \]

\[ T = T_{in} \quad \text{at} \ \partial \Omega_1 \]

3. Numerical Method
Here, we used Comsol software (5.0) based on finite element method to solve the system of equations. The structured mesh (quadrilateral elements) technique was adopted, with boundary layers inflation at the air-PCM interface. The mesh consisted of 10500 elements. The time step was automatically performed by the software. At each time step, the system of equations was solved with the linear system solver (PARDISO); with fully coupled option between heat conduction and convections transfers. The apparent specific heat capacity method was adopted in heat transfer equation of PCM to take in the account the phase change phenomenon \[11\]. Results have been stored every 15 min. The model was run on a 2.7 GHz processor and a 4 Go RAMPC machine.

4. Validation
The validation of the experimental work was focused on the air temperature at the exit of the heat exchanger, for charging and discharging steps; for two flows air 240 and 330 m³/h.

![Figure 3. Comparison between model and experimental results during discharging step: 240 m³/h (left) and 330 m³/h (right)](image-url)
As can be deduced from Error! Source du renvoi introuvable., the model provides similar results to the experiments for the two processes. The average relative error doesn’t exceed 2%. And the maximum error is about 20% for all simulations.

Figure 4. Comparison between model and experimental results during charging step: 240 m3/h (left) and 330 m3/h (right)

5. Performance indicator
During thermal cycling, the key performance indicators are the charging/discharging and overall efficiencies. The charging (discharging) efficiency is the ratio of the stored (recovered) energy in the system (PCM+air) to the net input and pumping energy:

\[ \eta_{\text{Charging or discharging}} = \frac{E_{\text{stored or recovered}}}{E_{\text{net}} + E_{\text{pump}}} \]  \hspace{1cm} (7)

\[ E_{\text{stored or recovered}} = \int_{\Omega} \rho C_{p} \Delta T \Omega \times (T_{\text{final}} - T_{\text{start}}) \]  \hspace{1cm} (8)

\[ E_{\text{net}} = \int_{t_0}^{t_{\text{end}}} \int_{T_{\text{in}}}^{T_{\text{out}}} \eta C_{p} \Delta T \Omega \times dT \Omega \]  \hspace{1cm} (9)

\[ E_{\text{pump}} = \int_{0}^{t_{\text{end}}} \rho \Delta P \Omega \times \eta \Omega \times \Delta \Omega \]  \hspace{1cm} (10)

Where \( t_{\text{end}} \) is the duration of charging or discharging process.

Figure 5. Charging (left) and discharging (right) efficiency for different flow rate
Erreur ! Source du renvoi introuvable. the value of the efficiency of this kind of heat exchanger, in both regimes (charging and discharging). As can be seen, in the discharging process the flow rate reach its optimal value at the flow rate 100 m$^3$/h. However in the charging step this optimal will be at the flow rate more than 500 m$^3$/h. the same tendency was observed by [4] and [5] in here experimental works where they conclude that during charging process air flow rates of three to four times higher than air flow rates during discharging process are recommended for free cooling applications. This is due mainly to the hysteresis phenomenon of apparent heart capacity (figure 2), where the slope of the $C_{p_{app}}$ to reach the maximum (melting temperature) is more important during heating step than during cooling step.

6. Conclusion and perspectives
A model based on apparent specific heat method with hysteresis phenomenon between heating and cooling step was developed and validated in the case of air PCM heat exchanger. A good agreement between experimental and numerical value was observed, for both regimes of free cooling ie “charging and discharging”.

The parametrical study concerning the flow rate confirms the global tendency observed in the previous works. To simulate the real free cooling process mainly the charging step where the air circulate from the ambient room to heat exchanger (and not from the outdoor), a zonal model simulating the ambient temperature room should be developed and linked to the current model. On the other hand an adequate PCM should be chosen to be applied to the climate of each Moroccan region. Finally the study shows that many parameters can influence the efficiency of the heat exchanger so we believe that an inverse method is essential to optimize the efficiency of the PCM heat exchanger. And finally extending the current model of the free cooling to the “free heating” to e applied during winter season

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