ASSESMENTS ABOUT CALCULATION OF THE PCM'S PHASE CHANGE TEMPERATURE IN THE CLIMATIC CONDITIONS OF ROMANIA

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Rezumat. Studiul prezintă o procedură originală pentru recomandarea temperaturii de schimbare de fază a materialelor cu schimbare de fază, bazată numai pe date climatice. Procedura a fost aplicată pentru condiţiile din România, luând în considerare pe de-o parte datele climatice recomandate de reglementările legislative din România şi pe de altă parte condiţiile climatice tipice, constând din seturi de date climatice orare provenite din măsurători multianuale. Temperatura de schimbare de fază a materialelor cu schimbare de fază este determinată astfel încât să permit atât solidificarea cât şi topirea în condiţiile variaţiei naturale a temperaturii pe timp de vară. A fost studiată influenţa pe care o prezintă asupra temperaturii de schimabare de fază atât gradul de asigurare definit conform SR 6648/1, cât şi randamentul schimbătorului de căldură regenerativ cu materiale cu schimbare de fază. Rezultatele obţinute pentru patru locaţii situate în zone climatice diferite din România, permit evidenţierea avantajelor şi limitelor metodei propuse şi au fost comparate cu diverse alte recomandări disponibile în literatură
Cuvinte cheie: Materiale cu schimbare de fază, temperatura de schimbare de fază, răcire naturală, ventilaţie.

Abstract. The study is presenting an original procedure for recommending the phase change temperature (**PCT**) of the phase change materials (**PCM**), based only on climatic data. The procedure was applied to the Romanian conditions, taking into account the climatic data recommended both by Romanian climatic regulation and the “typical meteorological year” (**TMY**), representing a set of hourly climatic data based on multiannual measurement. The **PCT** of **PCM** is determined to allow both melting and solidification of the **PCM** under the summer daily natural temperature variation. It was studied the influence of the recommended **PCT** of **PCM** of two parameters: the "level of certitude" (**LOC**) defined according to SR 6648/1, and the efficiency of the regenerative **PCM** based heat exchanger. The results obtained for four different locations in Romania situated in different climatic zones, allow to highlight the advantages and the limits of the method and were compared with results provided by different other recommendations available in literature.
Keywords: Phase change material, phase change temperature, free cooling, energy efficiency, natural ventilation.

1. INTRODUCTION

The use of Phase Change Materials (**PCM**) in the design of Heating, Ventilation and Air Conditioning (**HVAC**) systems can be an adequate answer to the request of the European Commission (**EC**) that established the energy and climatic objectives known as “20-20-20”. Comparing to 1990 the emissions of greenhouse gases must be reduced with 20%, the share of renewable energy must be 20% (modified to 25%) and the energy efficiency must be increased by 20% [1].

In the same context the Directive 2010/31/EU of the European Parliament and of the European Council is mentioning that passive cooling techniques should be applied to improve the inside conditions and the outside microclimate [2].

PCM can be successfully used to accumulate cold during the night from the ambient air and to absorb heat during the day from the fresh air introduced in the buildings [3]. For the optimal functioning of the **HVAC** systems using **PCM**, it is important to correlate the temperatures of the cold air from the night time and of the warm air from the day time with the phase change temperature (**PCT**) of the **PCM**, taking into account that the particular climatic conditions may affect the choice of the **PCM**. Changes of the **PCT** have opposite effects on the solidification and melting stages of the **PCM** [4], favoring one or the other.

Other criteria than the **PCT** for choosing the **PCM** are: the physical properties of the **PCM**, the compatibility with the housing, the environmental impact and economical aspects [5, 6].

The goal of this study is to propose a simple and original algorithm for adopting the **PCT** of the **PCM** depending only on the climatic conditions of the chosen location. The climatic data were defined based on two different sources: SR 6648/2 [7] – 14 and the “typical meteorological year” (**TMY**), representing a set of hourly climatic data based on multiannual measurement. The algorithm was applied for four locations situated in different climatic zones of Romania.

2. MATERIAL AND METHOD

The use of **PCM** for cooling inside **HVAC** systems was integrated in the general concept of “free cooling” and was proposed at the University of Zaragoza, Spain [3], based on the scheme presented in Fig. 1.

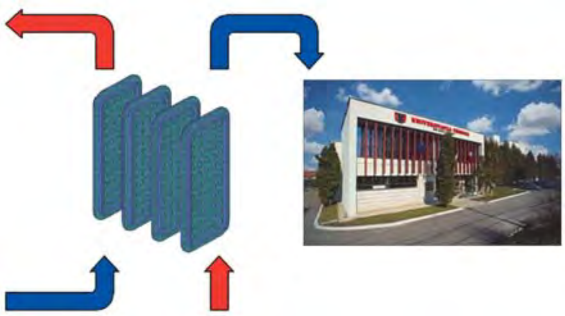


Fig.1 . *The principle of “free cooling with* ***PCM****”*

The core of the system is represented by a **PCM** based regenerative heat exchanger that accumulates cold during the night and uses it during the day.

The following recommendations for the **PCT** of the **PCM** were identified in the literature:

(**A**) (19-20) °C in temperate climate zones [8];

(**B**) (20-25) °C in temperate climate zones [3];

(**C**) Based on the following relation [9]:

$$t_{PCM} = \frac{t_{a6} + t_{a7} + t_{a8}}{3} + 2 \qquad (1)$$

where: t_{PCM} is the **PCT** of the **PCM** and $t_{a6\text{-}a8}$ are the monthly average temperatures of the summer months 6-8 (June, July and August);

(**D**) The monthly average temperature of the warmer summer month ($t_{avg,w}$ [K; °C]) [9]:

$$t_{PCM} = t_{avg,w} \qquad (2)$$

The proposed algorithm to determine the **PCT** of the **PCM** based only on climatic data is based on the thermal balances in the night time period of solidification and in the day time period of melting. The two thermal balances equations are:

$$\sum \dot{m} c_a \Delta t_{an} \Delta\tau = m_{PCM} l_s = kS\Delta t_{ms} \qquad (3)$$

$$\sum \dot{m} c_a \Delta t_{ad} \Delta\tau = m_{PCM} l_m = kS\Delta t_{mm} \qquad (4)$$

where:

- $\dot{m}_a$ [kg/s] is the mass flow rate in each of the considered period of time;
- c_a [kJ/kgK] is the specific heat of the air;
- $\Delta t_{an,d}$ [K; °C] is the air (a) temperature variation in the regenerative **PCM** based heat exchanger during the night (n) and during the day (d);
- $\Delta\tau$ = 3600 s = 1h is the considered period of time, similar during the night and during the day;
- m_{PCM} [kg] is the mass of the **PCM** in the regenerative **PCM** based heat exchanger;
- $l_s=l_m=l$ [kJ/kg] is the latent heat of solidification (s) and of melting (m);
- k [kJ/kgK] is the global heat transfer coefficient between air and the **PCM**;
- S [m^2] is the heat transfer surface between air and the **PCM**;
- $\Delta t_{ms,m}$ [K; °C] is the average logarithmic temperature difference between the air and the **PCM** during solidification (s) and melting (s).

From the thermal balances equations can be calculated the temperatures of the air at the outlet of the **PCM** based heat exchanger during the solidification (t_{aos} [K; °C]) and during the melting (t_{aom} [K; °C]), for each considered period of time:

$$t_{aos} = t_{PCM} - (t_{PCM} - t_{ais}) \cdot e^{-\frac{k \cdot S}{\dot{m}_a c_a}} \qquad (5)$$

$$t_{aom} = t_{PCM} + (t_{aim} - t_{PCM}) \cdot e^{-\frac{k \cdot S}{\dot{m}_a c_a}} \qquad (6)$$

where:

- t_{ais}; t_{aim} [K; °C] are the temperatures of the air at the inlet of the **PCM** based heat exchanger during the solidification (t_{ais}) and melting (t_{aim}) periods, in each of the one hour considered interval;
- t_{PCM} [K; °C] is the **PCT** of the **PCM**.

If the efficiency (η) of the regenerative **PCM** based heat exchanger is taken into account, a relation that allows the determination of the **PCT** of the **PCM** can be obtained:

$$\eta \cdot \sum (t_{PCM} - t_{ais}) = \sum (t_{aim} - t_{PCM}) \qquad (7)$$

This equation was calculated by using a simple linear searching algorithm implemented in the function ”Goal Seek”, in Excel.

The efficiency of the regenerative **PCM** based heat exchanger, representing the percentage of the cold accumulated in the **PCM** during the night that is effectively used in the next day for cooling the fresh air, was reported to be in the range of (64.4-

75)% [10], but in this study it was considered in the range of (65…95)%.

Equation (7) will provide different **PCT** of the **PCM** for each day, meaning that choosing the day of calculation is a critical aspect.

The algorithm of calculating the **PCT** of the **PCM** is recommended to be applied for particular calculation days, depending on the "level of certitude" (**LOC**) defined as the maximum number of days from the period of summer months in which the outside air does not overpass the maximum temperature at which the cooling load is calculated (according to SR 6648/1 – 14) [11].

The period of summer months considered was: July – August and the considered **LOC** was: 80%, 90%, 95%, 98% and 100% respectively.

The day of calculation was determined based on:

(**E$_1$**) **TMY**, representing a set of hourly climatic data based on multiannual measurement.

(**E$_2$**) SR 6648/2 – 14;

SR 6648/2 – 14 indicates for a large number of locations according to the **LOC**, the outside temperature (t [K; °C]), representing t_{ais} or t_{aim} from eq. (6), depending on the day period (night – solidification; day – melting):

$$t = t_{avg} + cA_d \tag{8}$$

where:

- t_{avg} [K; °C] is the daily average temperature in the chosen location, corresponding to the considered **LOC**;
- A_d [K; °C] is the daily amplitude of the temperature variation;
- c [-] is a coefficient affecting the daily amplitude of the temperature variation.

Based on the **TMY** the day of calculation was determined by sorting the days of the summer months by the maximum daily temperature and eliminating the percentage of days calculated as the difference between 100 and the **LOC**.

Figs. 2-5 present the outside temperature for the considered locations in the summer period (01.06-31.08).

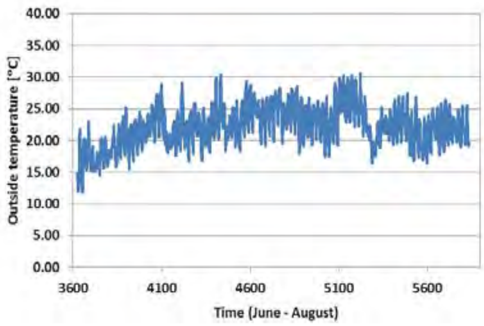


Fig. 2. *Natural temperature variation: Constanţa (Zone I)*

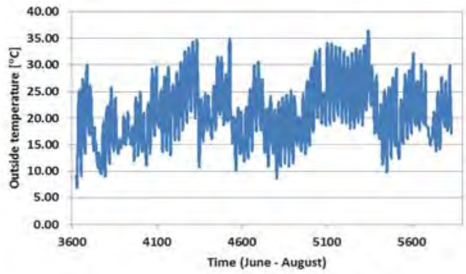


Fig. 3. *Natural temperature variation: Timişoara (Zone II)*

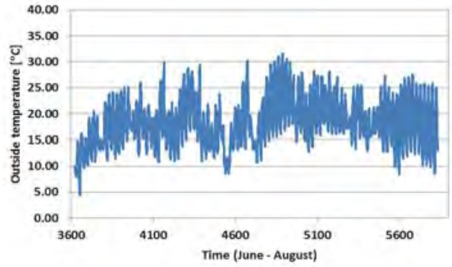


Fig. 4. *Natural temperature variation: Cluj-N. (Zone III)*

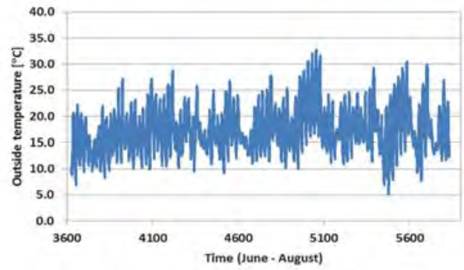


Fig. 5. *Natural temperature variation: Braşov (Zone IV)*

For the determined calculation day, the outside temperature variation must not be calculated, being available as part of the hourly data set from **TMY**.

3. RESULTS AND DISCUSSIONS

The algorithm for determining the **PCT** of the **PCM** was implemented in Excel and applied for the following locations situated in different climatic zones of Romania:

- Constanţa in climatic zone I;
- Timişoara in climatic zone II;
- Cluj-Napoca in climatic zone III;
- Braşov in climatic zone IV.

The daily average temperatures for the considered locations and **LOC**, based on SR 6648/2 are presented in Table I.

Table I
The daily average temperatures [°C]

LOC	Constanţa A_d=4°C	Timişoara A_d=7°C	Cluj-N. A_d=6°C	Braşov A_d=7°C
80%	23.9	23.6	21.1	19.6
90%	24.8	24.7	22.2	20.7
95%	25.6	25.6	23.0	21.6
98%	26.5	26.7	24.0	22.7
100%	29.0	29.0	28.0	26.0

The calculation days based on the **TMY**, for the same locations are presented in Table II.

Table II
The calculation days based on TMY

LOC	Constanţa	Timişoara	Cluj-N.	Braşov
80%	18 Jul	07 Aug	26 Jul	30 Aug
90%	03 Aug	04 Aug	20 Jul	20 Aug
95%	04 Aug	02 Aug	14 Jul	28 Jul
98%	02 Aug	01 Aug	24 Jul	31 Jul
100%	06 Aug	11 Aug	23 Jul	30 Jul

There are differences between the daily temperatures variations calculated based on SR 6648/2 and **TMY**, respectively. An example of differences between the daily temperatures variations determined by the two methods is presented in Fig. 6.

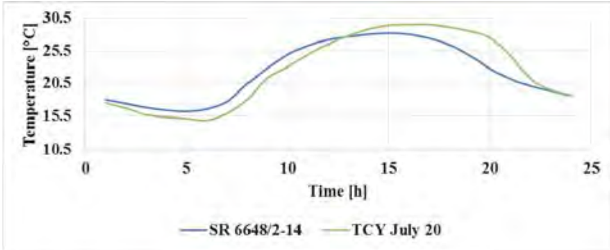


Fig. 6. *Differences between daily temperatures variations*

Since according to the presented method, the **PCT** of the **PCM** is depending on the natural temperature variation and efficiency of the regenerative **PCM** based heat exchanger, it is clear that the differences in the considered temperature variations will be reflected in differences in the values of the **PCT** of the **PCM**.

The calculated **PCT** of the **PCM** for the chosen locations, **LOC** and efficiencies of the regenerative **PCM** based heat exchanger are presented in Fig. 7 together with literature data.

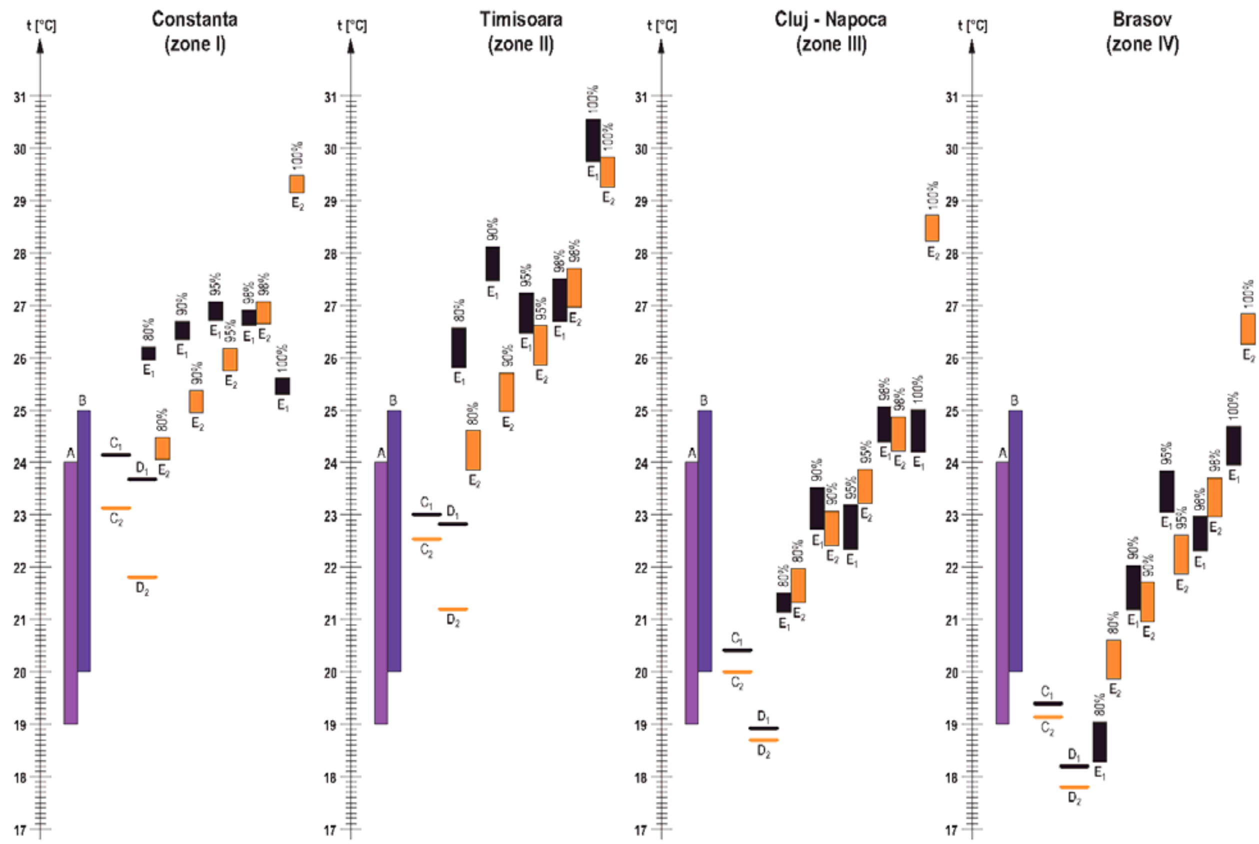
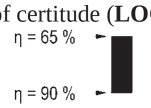


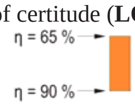
Fig. 7. *The calculated **PCT** of the **PCM** together with the values recommended by the literature*
*(**A**) – According to [8]; (**B**) – According to [3];*
*(**C**) – According to eq. (1) [9] and **TMY** (**C_1**) or according to eq. (1) [9] and SR 6648/2 (**C_2**);*
*(**D**) – According to eq. (2) [9] and **TMY** (**D_1**) or according to eq. (2) [9] and SR 6648/2 (**D_2**);*
*(**E**) – According to the proposed method and **TMY** (**E_1**) or according to the proposed method and SR 6648/2 (**E_2**).*

Level of certitude (**LOC**) [%]



E_1
PCT of the **PCM** (t_{PCM})
according to the (**TMY**)

Level of certitude (**LOC**) [%]



E_2
PCT of the **PCM** (t_{PCM})
according to the national regulation (SR 6648/2)

*The influence of the **LOC** is as follows:*

- If the **PCT** of the **PCM** is calculated based on the national legal regulations, the recommended **PCT** of the **PCM** is increasing along with the **LOC** for all the chosen locations.
- The general trend is similar when the **PCT** of the **PCM** is calculated based on the **TMY**, but due to the real variation of the daily temperature, some exceptions occur for all the chosen locations.

The influence of the climatic zone is as follows:

- The warmer the climatic zone, the lower the global range of variation of the calculated **PCT** of the **PCM**. The same conclusion is valid irrespective if the calculations are based on the national legal regulations or the **TMY**, but it is clearer if the calculations are based on the **TMY**.
- Generally, the warmer the climatic zone the higher the calculated **PCT** of the **PCM**, with the exception of Constanţa, which is in the climatic zone I (the warmer), but where the influence of the sea is affecting the results by decreasing the calculated **PCT** of the **PCM**. For Constanţa the results are between those obtained for Timişoara in the climatic zone II and Cluj-Napoca in the climatic zone III.
- To confirm the influence of the climatic zone on the calculation of the **PCT** of the **PCM**, the study should be extended to other locations situated in the climatic zone I, but not influenced by the sea. The proposed location for extending the study is Bucharest, the capital of Romania.

*The influence of the efficiency of the regenerative **PCM** based heat exchanger is as follows*:

- The higher the efficiency of the regenerative **PCM** based heat exchanger, the lower the calculated **PCT** of the **PCM**. This conclusion is similar and without any doubt, irrespective if the calculations are based on the national legal regulations or the **TMY**.

The influence of the considered reference of the climatic data is as follows:

- The calculation of the **PCT** of the **PCM** based on national legal regulations provides uniform distribution of the results depending on the **LOC**, for all chosen locations, but generally provides higher range of variations, equivalent with lower global precision, for the calculated **PCT** of the **PCM**.
- The calculation of the **PCT** of the **PCM** based on **TMY** provides uneven distribution of the results depending on the **LOC**, due to the uneven real daily temperature variations, but provides lower range of variations, equivalent with higher global precision, for the calculated **PCT** of the **PCM**.

The comparative analysis of the results, with the recommendations available in the literature is as follows:

- The recommended values labeled (**A**) and (**B**) provide a larger range of variation for the **PCT** of the **PCM** than the ones labeled (**C**) and (**D**).
- For the locations in the climatic zones I and II, the recommended values labeled (**A**) and (**B**) provide **PCT** of the **PCM** in the same range with the ones labeled (**C**) and (**D**).
- For the locations in the climatic zones III and IV, the recommended values labeled (**A**) and (**B**) provide higher **PCT** of the **PCM** than the ones labeled (**C**) and (**D**).
- The **PCT** of the **PCM** obtained with the proposed method, labeled ($\mathbf{E_1}$) and ($\mathbf{E_2}$) are generally higher that those labeled (**C**) and (**D**).
- The **PCT** of the **PCM** obtained with the proposed method, labeled ($\mathbf{E_1}$) and ($\mathbf{E_2}$) are generally within the same range as the ones labeled (**A**) and (**B**), only for the colder zones corresponding with the Romanian zones III and IV. Thus proving that the recommended values (**A**) and (**B**) are not valid for warmer zones (I, II).

The advantages and the limits of the proposed method are as follows:

- The proposed method provides the **PCT** of the **PCM** in better agreement with the climatic zones than the recommendations available in the literature.
- The proposed method provides, the **PCT** of the **PCM**, based on the **TMY** with a lower range of variation, equivalent to a better precision, than the proposed method provides, based on national climatic regulations (SR 6648/2).
- The proposed method provides, the **PCT** of the **PCM**, based on the **TMY** with a lower precision depending on the **LOC**, than the proposed method provides based on national climatic regulations (SR 6648/2). This limit is due to the real and uneven variation of the outside temperature provided by the **TMY**.

- The obtained **PCT** of the **PCM** for the locations situated in warm climatic zones of Romania, are very high, in the range of (24-30.5) °C, suggesting that in the climatic zones I and II of Romania the **PCM** are not suitable to be used in **HVAC** with fresh air applications.
- The obtained **PCT** of the **PCM** for locations in the colder climatic zones III and IV of Romania are in good agreement with the recommendations in the literature and suggests that **PCM** are suitable to be used in **HVAC** with fresh air applications for lower **LOC** values. The maximum **LOC** suggested by the authors for fresh air applications with **PCM** is of (80-90) %, corresponding to **PCT** of the **PCM** lower than 24 °C.

4. CONCLUSION

The proposed method proved to be able to provide the **PCT** of the **PCM** for different locations situated in different climatic zones in Romania.

The obtained results are capable of better fitting the local climatic conditions than the general recommendations in the literature.

Based on the **PCT** of the **PCM** provided by the proposed method, it was concluded that in the warm climatic zones I and II of Romania the **PCM** are not suitable for **HVAC** applications.

However the **PCM** are suitable for the colder climatic zones III and IV of Romania.

The maximum **LOC** suggested to be considered in such applications is of (80-90) % corresponding to **PCT** of the **PCM** lower than 24 °C.

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