TECHNICAL UNIVERSITY OF DENMARK

MASTER THESIS

MODELLING A RADIANT FLOOR SYSTEM WITH PHASE CHANGE MATERIAL USING A BUILDING SIMULATION TOOL: ANALYSIS OF A FLOOR HEATING SYSTEM

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ABSTRACT

In this project, the performance of Phase Change Material (PCM) gypsum wallboard was evaluated in a residential building in Denmark which uses radiant floor as heating system. Different EnergyPlus simulations were carried out to know which melting temperature range leads to the lowest heating demand and total energy consumption. Besides, the location of the PCM, above or below the heating system, was also considered. Different parameters were considered in this study: (1) varying the temperature of the water from the radiant floor; (2) varying the flow from the radiant floor; (3) varying the melting point of the PCM and (4) varying the amount of PCM. After analyzing the first three parameters, a melting point of 23ºC-24ºC will be considered as it leads to the lowest heating demand and energy consumption. Finally, the addition of more layers of PCM wallboard leads to 17.9% - 22.2% heating demand savings for constant flow and variable flow, respectively. In the other side, 15.6% - 13.4% energy consumption savings for constant flow and variable flow, respectively.

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CHAPTER 1: INTRODUCTION

1.1. Introduction to the thesis

We live in a world where the global warming is increasing day by day. The Earth has been getting warmer, and glaciers have been melting, for many years. As a consequence of global warming, it is expected that hot days will become hotter and more frequent, with fewer cool days in the future [1]. Furthermore, the quantities of greenhouse gases, especially carbon dioxide (CO_2) are increasing in the atmosphere, contributing to global warming. These changes will affect building energy consumption, especially through changes in cooling demand. Furthermore, many parts of the world are facing an energy crisis, and therefore, there is a need to find a solution to face these changes.

Growing focus on combating global warming and the use of renewables has led to enhanced development and research in phase change materials (PCM), among other materials. The traditional concept of refrigeration and air conditioning must give up the step to emerging new technologies, such as solid-state refrigeration and phase change materials, which could substitute vapor compression refrigeration cycle [2]. This type of refrigeration is based on the caloric effect detected in some ferrocaloric solid materials. This method of refrigeration is done by the nature of the driving field which could be electric or magnetic, among others. Furthermore, thermal energy storage is essential to match production and demand, and therefore to provide heat or cold to the consumers when required independently. Several ways exist to fulfil this requirement in buildings. The most prominent modes of thermal energy storage (TES) are: (1) hot water tank storage; (2) gravel-water pit storage; (3) aquifer storage; and (4) borehole storage. But there are more compact and efficient TES technologies, such as the use of a latent heat storage using phase change materials.

According to the IEA (International Energy Agency, [3]), the energy demand in buildings have been increasing for the last years in 1.8% annually, this rise leads to an increase in the greenhouse gas emissions in 24% [4]. Even though, the speed of energy intensity has fallen in recent years, from around 2% in 2015 which have been the result of energy policies progress, the evolution of building energy codes is not keeping up with rapid growth in emerging economies. Heating, ventilation and air conditioning (HVAC) systems are the most relevant energy services in buildings and account for 60% of the total energy consumed in buildings [1], this is because it is crucial to assure thermal comfort as its influence to occupants' health and it also affects directly to the occupants' mood. For example, in office buildings, if there is no thermal comfort and the person is feeling too hot or too cold, then his/her productivity will decrease. On the contrary, working in optimal conditions enables us to think and work better [5]. Since

HVAC systems represent a large part of the total energy consumption in buildings therefore an effort must be made to reduce the CO_2 emissions and the energy consumptions.

The most common way to reduce the energy consumption in buildings is by reducing the heat transfer rate between indoor and outdoor environment by incorporating high quality thermal insulation and construction materials into building envelopes [6]. Another way to approach this reduction is to increase the efficiency in HVAC systems, nevertheless energy efficiency improvements should not be limited to these approaches. Increasing the building's thermal inertia is also a good way to reduce the energy consumption for heating and cooling because it reduces the indoor temperature fluctuations and helps to maintain the thermal comfort range.

One way to increase the thermal inertial is by using PCM because it undergoes phase change at temperatures within the thermal comfort range and it works as a thermal energy storage system. PCM are discerned from other traditional thermally materials as they store energy in the form of latent heat by changing phase between solid and liquid phase, instead of storing energy as sensible heat. The advantage of latent heat storage over sensible heat storage is the large energy storage capacity per volume. The PCM can be implemented in many applications in residential buildings in order to reduce the thermal load in the building, to smooth and reduce the heating demand. These applications include, solar water heating, space heating/cooling and waste heat recovery, among others [7].

1.2. Research objectives

The objective of this project is to implement PCM in a residential building, which uses radiant floor for heating system, to obtain larger efficiencies and a lower heating demand. This building is located in Denmark; thus, the project will be focused in lowering the heating demand, the energy consumption and obtaining larger efficiencies. This project will not be focused in the cooling demand as the location of the building it is in a cold climate.

Several simulations will be performed using EnergyPlus, in which the influence of varying many parameters will be simulated in order to determine the potential of incorporating PCM in a residential building. These parameters are: (1) varying the temperature of the water from the radiant floor; (2) varying the flow from the radiant floor; (3) varying the melting point of the PCM and (4) varying the amount of PCM.

The physical properties of different PCM materials will be found from literature. These properties will be used for dimensioning the PCM in the EnergyPlus model. In order to identify the effects of the PCM in the residential building, a study will be done by comparing two identical houses throughout the EnergyPlus simulations, one with PCM and one without PCM.

The PCM will be introduced in the building by installing gypsum wallboards (1.25x2 m with a width of 0.0125m) manufactured by Knauf [8]. Each wallboard contains around 5 kg_{PCM}, which represents a mass ratio of approximately 18%. This wallboard contains Micronal DS-5040-X manufactured by BASF, it consists of microencapsulate paraffin phase change material (whose characteristics will be explained in more detail in **CHAPTER 2: THEORETICAL BACKGROUND OF THE PCM**) with a size of 5 µm. Therefore, in order to cover the whole floor surface of the zones more than one wallboard must be installed. For the West and East zone which have a floor surface of 37.16 m^2 it is necessary to install 14 wallboards, in the other side for the North zone which has a floor surface of 55.74 m^2 it is necessary to install 22 wallboards. Hence, with a wallboard width of 0.1 m (8 layers), West and East zone will have an amount of 560 kg_{PCM}, and North zone will have an amount of 880 kg_{PCM}.

In section **4.4 Description of the PCM** a detail description on how the PCM is introduced in the program will be explained.

1.3. Thesis outline

This project is divided in the following sections:

1. Chapter 2: Characteristics of the PCM and theoretical background, *page 12*.
2. Chapter 3: Description of the building and location, *page 22*.
3. Chapter 4: Description of the materials and important characteristics implemented in EnergyPlus, such as the radiant floor and how to implement the PCM, *page 24*.
4. Chapter 5: Description and simulations of the different scenarios, *page 41*.
5. Chapter 6: Conclusions, *page 57*.

1.4. EnergyPlus program

EnergyPlus is a building energy simulation program that architects, engineers and researched use to model both energy consumption for heating, cooling, ventilations, lighting and plug; and it also models, process load and water use in buildings. It is based on two other programs: DOE-2 and BLAST. EnergyPlus is a free, open-source program and some of the features and capabilities are [9]:

a) Integrated, simultaneous solutions of thermal zone conditions and HVAC system response.
b) Heat balance-based solutions of radiant and convective effects that produce surface temperatures thermal comfort and condensation calculations.
c) Combined heat and mass transfer model that accounts for air movement between zones.

Nowadays, there are many commercial software that can simulate PCM, for example: BLAST, Energy-10, HAP, HEED, IES, TRNSYS, etc. The most popular ones are EnergyPlus, ESP-r and TRNSYS [10]. In order to replace real experiments, which are expensive and time consuming, to study the effects of incorporating PCM in buildings, dynamic simulations will be done using EnergyPlus version 8.8.

Since April 2007, EnergyPlus presents the capability of modelling PCM which has been facilitated with the introduction of a conduction finite difference solution algorithm which will be explained in more detail in section **4.2 Heat transfer problem.**

CHAPTER 2: THEORETICAL BACKGROUND OF THE PCM

2.1. Overview of the phase change material PCM

In buildings, the 60% of the energy consumed is due to cooling and heating systems and ventilation [1]. Furthermore, the PCM is a promising alternative for the battery thermal management (which include air cooling and liquid cooling) for lithium-ion batteries for electric vehicles due to its complex system and high investment and maintenance cost. The PCM where chosen because its capacity of absorb and release heat during the phase change transition. Therefore, PCM based on battery thermal management are easier to maintain and its cheaper [11]. Besides this application, the PCMs can be also used in tanks coupled with heat pumps with the goal of increasing heat storage in the same accumulation volume. The combine use of heat pumps and PCMs offers several benefits, particularly, it can reduce the size of the buffer tanks for storing thermal energy, prevent the oversizing of heat pumps or detach thermal energy production consumption [12].

On one hand, an efficient way to increase the thermal inertia of buildings, can be done by using passive cooling strategies [13]. The high density of the PCM for thermal storage can be efficiently employed for this purpose. PCMs can absorb heat energy from inside (creating a cooling effect) and release energy to the environment during a reversible cooling process. Hence, passive cooling systems are essential for sustainable building concepts because they encompass the mitigation of energy consumption and GHG emissions. The application of PCMs can be found in several industries, such as, solar cooling, solar power plants and space industry, among others [1].

In the other hand, controlling the thermal behavior of batteries is an essential point to improve the performance of the electric vehicles. These batteries must work within a strict temperature range for a correct behavior, which is why the use of PCM is a good choice. This material can absorb a large quantity of heat generated by the battery without changing the temperature itself. The disadvantage that this material faces is its low thermal conductivity. However, many researchers have introduced thermal conductivity improvement material into PCM like graphite, metal foam and carbon fiber [14].

This project will only focus on PCMs to increase the thermal inertia of buildings even though there are more applications where PCMs are a good choice, for example, in transportation and electronic [15].

2.2. State of the art

A review of the different types of PCM attainable will be discussed, as well as its application in real life (commercial products) and the requirements of the material to be used as a PCM. There is a wide variety of phase change materials available with different thermo-physical properties that affect their efficiency. Therefore, it also affects the contribution of the thermal comfort and the reduction of the heating, ventilation and air cooling (HVAC) loads in buildings, another important characteristic that affect to this reduction are the climate conditions [16].

As mentioned before, around the 60 % of the energy consumed in building is due to cooling and heating demand and ventilation, for this reason the energy efficiency relies on building envelopes and HCV systems [1]. The application of Thermal Energy Storage systems (TES) help to decrease this demand [17].

TES systems, also known as heat and cold storage, allows the storage of energy in form of heat or cold to be used at a later time [18]. These systems involve three principal steps: thermal charging, thermal storing and thermal discharging, where the storage is the most important one.

There are several methods for reversible storage of heat and cold [17], including sensible heat (i.e., the heat stored in a temperature increase in the material), latent heat (i.e., the heat reserved or released when the phase changes via temperature variation in controlled conditions) and chemical reactions (heat is absorb, if the reaction is endothermic; heat is released if the reaction is exothermic)[18]. The most common method to reserve heat is sensible heat, where water is the most commonly used as storage material, as it has the highest heating capacity at ambient temperatures among other compounds. Latent heat storage it is also used. The most obvious example is the conversion of water to ice. Finally, the amount of heat stored (ΔQ) using chemical reactions can be easily calculated as follow [17]:

$$\Delta Q = \Delta H = m * \Delta h \qquad \text{(eq.1)}$$

Where:

m = *mass flow rate,* $\frac{kg}{s}$

Δh = *enthalpy variation* $\frac{kJ}{kg}$

PCM Selection criteria

Two basic and important requirements for the selection of the PCM are a suitable phase change material and a large melting enthalpy. Besides these two requirements that must be fulfilled in order to store and release heat at all, there are more requirements for most applications. Several factors that should to be considered are shown in Table 1 [19].

Table 1. PCM Types Include Paraffin Waxes, Non-Paraffin Organics, Hydrated Salts, and Metallics. Source: Advanced Cooling Technologies.

Property or Characteristic	Paraffin Wax	Non-Paraffin Organics	Hydrated Salts	Metallics
Heat of Fusion	High	High	High	Med.
Thermal Conductivity	Very Low	Low	High	Very High
Melt Temperature (°C)	-20 to 100+	5 to 120+	0 to 100+	150 to 800+
Latent Heat (kJ/kg)	200 to 280	90 to 250	60 to 300	25 to 100
Corrosive	Non-Corrosive	Mildly Corrosive	Corrosive	Varies
Economics	$$	$$$ to $$$$	$	$$ to $$$
Thermal Cycling	Stable	Elevated Temperature Can Cause Decomposition	Unstable over Repeated Cycles	Stable
Weight	Medium	Medium	Light	Heavy

The requirements needed for the selection of the PCM can be divided as follows [21], [22]:

1. Physical, regarding the storage and release of heat:
    a. Suitable phase change temperature.
    b. Large phase change enthalpy.
    c. Cycling stability, which means, the use of the material as many times as required by the application for the storage and release of heat. It varies from one to several thousand cycles depending on the application.
    One of the main problems that the PCM faces is the phase separation the PCM consists of several compounds. If the PCM faces this separation, the heat storage will be affected significantly because the capacity of storage the heat will be lower.

d. Little subcooling (also called supercooling) in order to guarantee the melting and solidification process in a narrow temperature range.

   This is the effect that a temperature right below the melting point has to be reached, until a material begins to solidify and release heat. If this temperature is not reached, the PCM will not solidify and thus, only store sensible heat.

e. Good thermal conductivity will strongly depend on the application and the design of the storage.

2. Technical, regarding the construction of a storage.
   a. Low vapor pressure in order to reduce the necessity of mechanical stability of the recipient of the PCM.
   b. Chemical stability to assure a long lifetime of the PCM.
   c. Compatibility with other materials of the vessel and surroundings.
   d. Safety restrictions (non-toxic, non-inflammable, etc.)
3. Economic.
   a. Low price in order to be competitive with other types of materials and/or methods of heat and cold supply without storage.
   b. Eco-friendly, environmental reasons.

Usually, it is not common to find a material that fulfills all the requirements mentioned above. Therefore, different strategies have been developed to deal with these problems [18], which are explained below.

1. Phase change separation, means when two or more component system separates into different phases when it is heated above its melting point and then solidify again below the melting temperature, due to gravitation the phase with higher density will sink to the bottom and the phase with lower density will raise to the top. Hence, the original composition is changed. This phenomenon happens because the melting temperature of the components are different.

   The problem with this phenomenon is that it can reduce the storage density, meaning, that the latent heat of solidification can usually not be released completely. To get rid of this problem can be used the artificial mixing but the main disadvantage is that it requires equipment, another solution will be to use diffusion processes for homogenization, but it is only efficient in small scales. Another solution would be to increase the viscosity of the PCM, due to high viscosity, different phases cannot separate until the whole PCM is solid.

2. Subcooling. Many PCM do not solidify upon cooling below the melting point but start crystallization right after the melting temperature. During the extraction of heat, the latent heat is not released when then melting temperature is reached due to subcooling, if nucleation does not happen, then it could be a serious problem for technical application as only sensible heat would be stored. The most common approach to get rid of subcooling on the level of the PCM is to add special additives, also called nucleator, to the PCM to cause heterogeneous nucleation.

3. Prevention of the leakage and improvement heat transfer. There are two ways to prevent the leakage of liquid PCM during the phase change process, firstly by form stable PCM which are fabricated by impregnating functional PCM into porous supporting materials which are expected to give mechanical strength to the composite [23]. Another way to prevent the leakage is to encapsulate the PCM, there are two ways: micro and macro encapsulation. In addition, the encapsulation method helps to improve the heat transfer and it adds mechanical stability [18].

1. Improve of the mechanical stability and thermal conductivity. The improvement of the thermal conductivity of the PCM is done by introducing conductive metallic and carbon-based nanoparticles, metallic foams and encapsulation of PCM [24]. In addition, ceramic granules and tiles which can be impregnated to form a composite material can improve the mechanical stability [18].

Classification of the PCM

Phase change materials can be classified according to their composition in **¡Error! La autoreferencia al marcador no es válida.** [25]. There is a wide variety of PCMs available with different melting points and characteristics. The most common classifications are organic, inorganic and eutectic. Even though PCMs can be classified into three states (solid-solid, solid-liquid, liquid-gas) [26], only the solid liquid can be used for building cooling or heating because the other categories have technical limitations[27].

Table 2. PCM Classification according to their composition. Source: [28]

PCM Type	Composition
ORGANIC	PARAFFIN COMPOUNDS
	Compounds without PARAFFIN
INORGANIC	Hydrated salts
	METALLIC
EUTECTICS	ORGANIC - ORGANIC
	ORGANIC - INORGANIC
	INORGANIC - INORGANIC

1. Organic PCM. has got a good latent heat capacity, appropriate phase-transition temperature and stable physical and chemical characteristics. Despite this, this type of PCM has low thermal conductivity which limits their application in practice.

   This type of PCM can be paraffin or non-paraffin:

   a. Paraffin: Can release a large amount of thermal energy.
   b. Non-paraffin: The most considered for thermal storage applications, but one limitation that has is its high inflammability.
2. Inorganic PCM. Even though it has a higher heat of fusion per unit mass in comparison with the organic PCM, its lack of thermal stability and the super cooling phase segregation cover its advantages.
3. Eutectic PCM: This type of PCM consist in the combination of at least two other PCM (organic and/or inorganic PCM)

In many cases, except for some applications of water-ice, PCMs need to be encapsulated in order to hold the liquid phase and to avoid contact of the PCMs with the environment. Besides, the surface of the capsule acts like a heat transfer surface and in some cases, the encapsulation can add mechanical stability to a construction element. Thus, another classification of this material can be according to the size of the capsules [18] [29][30]:

1. MicroPCM. Microencapsulation can be defined as the process of surrounding one substance to another at very limited scale, producing capsules ranging from less than one micron to several hundred microns in size. They provide a solution to the increasing consumer demand for improved energy efficiency and thermal regulation. The PCM substance is typically a paraffin or fatty ester acid that absorbs and releases heat in order to maintain a defined temperature

2. MacroPCM are spherical capsules of a larger size (3-5 mm) containing high concentrations of phase change materials. These materials were originally developed for use in cooling vests and clothing. They regulate body temperature of individuals working in hot environments, such as soldiers in missions in the desert. The macroPCM absorbs heat excess and allows the user for a longer time in a more comfortable temperature.

PCM Selection process

The PCM selection process is essential to choose the optimal material for specific applications. The melting temperature and phase change enthalpy of existing PCMs are shown in Figure 1. From the point of melting temperature, for the latent heat storage, the potential PCMs are paraffin, fatty acids, salt hydrates and eutectic mixtures. To be a desirable material used in latent heat storage systems, the following criteria need to be met: thermodynamic, kinetic, chemical and economic properties, as shown in Table 3 [31].

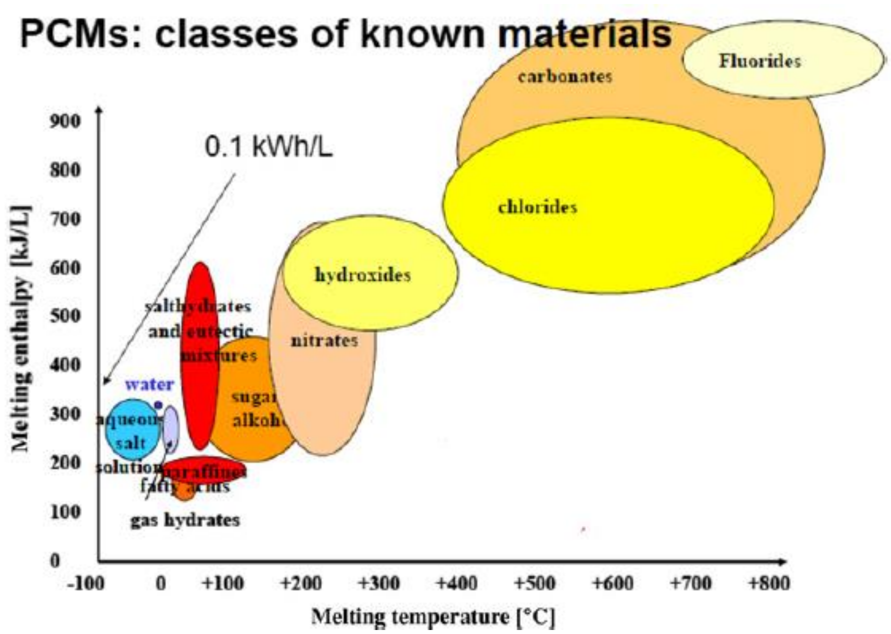

Figure 1. Melting temperature and phase change enthalpy for existing PCM. Source: [32].

Table 3. Selection criteria. Source: [26]

Thermodynamic properties	(1) Melting temperature in desired range (2) High latent heat of fusion per unit volume (3) High thermal conductivity (4) High specific heat and high density (5) Small volume changes on phase transformation and small vapor pressure at operating temperatures to reduce the containment problems (6) Congruent melting
Kinetic properties	(1) High nucleation rate to avoid super cooling (2) High rate of crystal growth to meet demands of heat recovery from the storage system
Chemical properties	(1) Complete reversible freezing/melting cycle (2) Chemical stability (3) No degradation after a large number of freezing/ melting cycle (4) No corrosiveness (5) No toxic, no flammable and no explosive material
Economic properties	(1) Effective cost (2) Large-scale availabilities

Commercial PCM

The availability of commercial PCMs, PCMs composite materials (this is produced to improve at least one of PCM properties or to improve the heat storage capacity of another material) and encapsulated PCMs is crucial to the development and commercialization of PCM applications.

The reason is that from a customer's point of view, only commercial PCMs, PCMs composite materials and encapsulated PCMs have defined properties, a warranty, a fixed price, and can be delivered in each time. From a supplier point of view, the size of the potential market of a PCM, PCM composite, or encapsulated PCM is also important. Both views determine what is commercially available. Commercial PCMs and PCM composite materials must fulfill harder requirements in their development than encapsulated materials in order to be used for thermal storage for building applications [18].

Usually, it is necessary that the main properties of PCMs are well documented. For this reason, a standard control of the product quality has to be done by the ZAE BAYERN and the FhG-ISE [33]. Since spring 2007, the quality label (Figure 2) will indicate that a PCM product has been tested according to this standard.

Figure 2. Quality label for PCM. Source: RAL [34].

The number of commercial PCMs, PCMs composite materials, and encapsulated PCMs is growing from year to year. Therefore, it is not possible to give a complete description of all available commercial products. In the following, some commercial products available are listed.

1. PCM. Currently, more than 50 PCMs are commercially available. Figure 3 shows an overview of the phase change temperature and enthalpy per mass and volume of these commercial PCMs. Most commercial PCMs are based on materials from the classes of the salt hydrates, paraffins and eutectic water-salt solutions, even though they are not identical with these materials. For example, in the case of salt hydrates, often another nucleator is added. In the case of paraffins, mix paraffins are used because the pure ones are expensive.

   The price of commercial PCM varies from 0.5 €/kg to 10 €/kg which affects the economic applications of the PCMs.

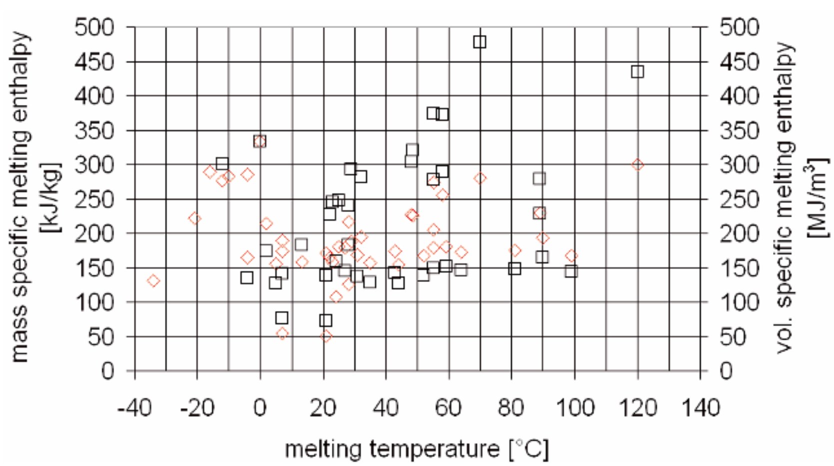

Figure 3. Phase change temperature and enthalpy per volume (□) and mass (◊) for commercial PCMs.

2. PCM composite materials. As mentioned before, this type of PCM is produced to improve at least one characteristic of the PCM. There are several ways to do it: embedding PCM in a matrix of another material or the other way around.
   a. PCM composite materials to improve handling and applicability. Paraffins as PCM are used. This type of composite has been developed and commercialized by the company

Rubitherm Technologies [35]. Figure 4 shows the compound PX and GR developed by this company. It consists of a paraffin as PCM in a polymer structure

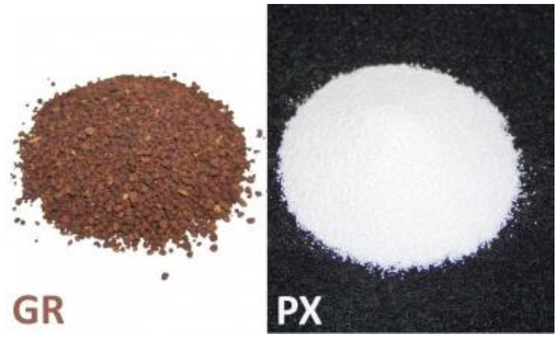

Figure 4. Composites developed and commercialized by Rubitherm Technologies. Source: Rubitherm Technologies [35]..

b. PCM composite to improve the thermal conductivity. In many applications metal or graphite is used as additive in the form of powders or fibers. The idea to use these materials was developed and patented by ZAE Bayern [33].

3. Encapsulated PCM. Encapsulated PCM can be classified, as mentioned before, according to their size in micro and microencapsulated PCM. When encapsulating a PCM, several factors must be considered such as the material of the walls which must be compatible with the PCM and the thickness of the wall must be necessary to assure the diffusion tightness.

   a. Macroencapsulation. Usually uses plastic and it can also be used with organic PCM, but special attention must be given as organic PCM can soften plastics. Another material used are foils and metal walls.

   b. Microencapsulation. This type of encapsulation is only technically feasible for organic materials. Commercial products just use paraffins. This type of PCM is sold under the name Micronal [30].

CHAPTER 3: DESCRIPTION OF THE BUILDING

The residential building under study is a house composed of three different zones, which will be explained with more detail in section **3.1 Description of the zones**. The software used to define the house geometry is 'Google SketchUp' which combined with the plugin 'Euclid' allow the connection between EnergyPlus and 'SketchUp'. In Figure 5 it is possible to see the representation of the house, which is divided in three different zones: bedrooms, living room and kitchen – dining room. In **APPENDIX 1: BUILDING DIMENSIONS** it can be found in more detail the dimensions of the house.

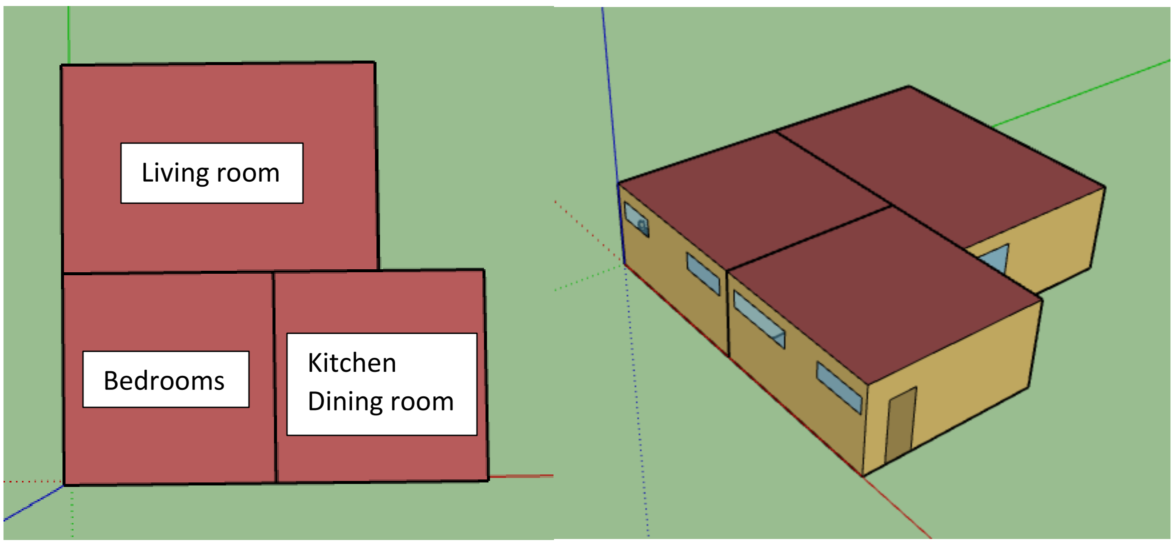

Figure 5. Representation of the building through SketchUp. Source: Own.

The house is located in Denmark and the weather file selected for the simulations is from EnergyPlus database for København. This weather data is carried out for the year 2009, where the design conditions is from ASHRAE handbook which are generated from a period of record for typically 30 years, to be representative of the chosen location and to be suitable to use in heating and cooling load calculations [36].. Figure 6 shows the exact location of the house whose parameters where taken from the weather file.

Field	Units	Obj1
Name		COPENHAGEN
Latitude	deg	55.63
Longitude	deg	12.67
Time Zone	hr	1
Elevation	m	5

Figure 6. Location of the house. Source: Google Maps and EnergyPlus screenshot.

The EnergyPlus weather file requires [37]: (1) dry bulb temperature, ^{0}C; (2) dew point temperature, ^{0}C; (3) relative humidity, %; (4) atmospheric pressure, Pa; (5) extra-terrestrial horizontal and direct normal radiation, $\frac{W.h}{m^2}$; (6) horizontal infrared radiation intensity from sky, $\frac{W.h}{m^2}$; (7) global horizontal and diffuse radiation $\frac{W.h}{m^2}$; (8) direct normal radiation, $\frac{W.h}{m^2}$; (9) global horizontal and diffuse horizontal illuminance, lux; (10) direct normal illuminance, lux; (11) zenith illuminance, $\frac{Cd}{m^2}$; (12) wind direction, deg; (13) wind speed, $\frac{m}{s}$; (14) total sky cover, %; (15) opaque sky cover, %; (16) visibility, km; (17) precipitable water, mm; (18) aerosol optical depth, %; (19) snow depth, cm; (20) days since last snow, albedo, %; (21) liquid precipitation depth, cm; and (22) liquid precipitation quantity, hour.

3.1. Description of the zones

This house is composed by three different zones named: West (bedrooms), North (living room) and East (kitchen – dining room) zone, Figure 7 . Each zone refers to a different location in the house but in order to reduce the time of each simulation, several simplifications has been considered, for example: connect different rooms in one zone and consider that the house is isolated.

a) WEST ZONE. This zone is composed by two bedrooms. One of them is for the parents (2 people) and the other one is for the child (1 person). Both rooms will be considered equals because they will have the same schedule for everything, meaning, schedules for lights and occupancy.
b) NORTH ZONE. This zone is the living room.
c) EAST ZONE. This zone is composed by the kitchen, the dining room and a bathroom. The three rooms will be considered as one zone with same schedules.

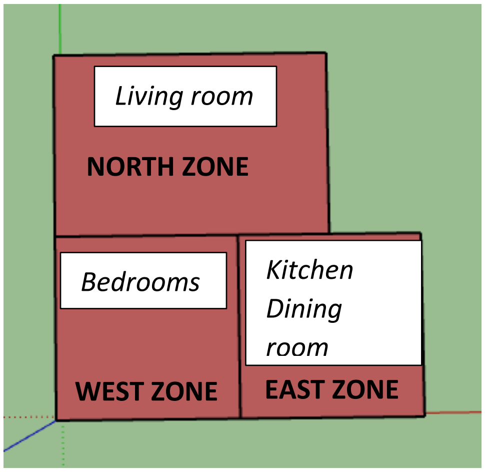

Figure 7. Description of the zones. Source: Own.

CHAPTER 4: THERMAL MODELLING

In this chapter it will be explained in detail: (1) the necessary inputs for the simulations in EnergyPlus, (2) the description of the calculation of the heating system used in the house and (3) the internal algorithm that this software uses to calculate the PCM. Thus, this chapter will be divided in:

1. General input as run period, schedules, etc.
2. Heat balance algorithm: Description on how EnergyPlus works with the PCM.
3. Material and construction.
4. Heating system: Description on how it has been calculated and how to implement it in EnergyPlus

4.1. General inputs

1. Run period. This object will vary depending on the case under study. In general, the simulation will have a run period for a whole year, from 1st January until 31st December. In this period, the total energy of the house, which is the energy consumed by the house, kWh; and the heating demand, kWh; will be obtained. Besides this run period, a one-day simulation will also be considered in order to see the behavior of the indoor temperature. The day selected will be 21st December as it is the winter solstice. Figure 8 shows a screenshot of this object.

Field	Units	Obj1
Name		Anual
Begin Month		1
Begin Day of Month		1
End Month		12
End Day of Month		31
Day of Week for Start Day		UseWeatherFile
Use Weather File Holidays and Special Days		Yes
Use Weather File Daylight Saving Period		Yes
Apply Weekend Holiday Rule		No
Use Weather File Rain Indicators		Yes
Use Weather File Snow Indicators		Yes

Figure 8. Object: Run period. Source: EnergyPlus.

2. Schedules. EnergyPlus has in its database typical schedules for different activities which will be very useful to define this input as it is difficult to estimate it for a residential building, therefore, a typical schedule for a house was selected from the database. These schedules vary from 0 to 1, where a value of 0 means no one is occupying the zone and the equipment are off, and a value of 1 means that all the people are in the zone (number of people: 3) and the equipment work at its maximum power. Figure 9 shows an example of the occupancy schedules.

The schedules must be made for different inputs as: people, light and equipment.

Obj24	Obj25	Obj26
Dining Room - Kitch	Rooms	Living room
Fraction	Fraction	Fraction
Through: 12/31	Through: 12/31	Through: 12/31
For: Weekdays	For: Weekdays	For: Weekdays
Until: 06:00	Until: 06:00	Until: 06:00
0	1	0
Until: 07:00	Until: 07:00	Until: 07:00
0	1	0
Until: 08:00	Until: 08:00	Until: 08:00
0.33	0.66	0
Until: 11:00	Until: 11:00	Until: 11:00
0.3	0	0
Until: 13:00	Until: 13:00	Until: 13:00
0	0	0.33
Until: 17:00	Until: 16:00	Until: 17:00
0	0.33	0.33
Until: 18:00	Until: 18:00	Until: 18:00
0	0.33	0.66
Until: 19:00	Until: 19:00	Until: 19:00
0	0	0.66

Figure 9. Occupancy schedule. Source: EnergyPlus Schedule Database.

a. *Object: People*. In this object is necessary to specify the number of people, as previously said, this number is 3, and the activity schedule. This last parameter means the metabolic activity that a person has when she/he is doing a specific activity. Overall, this parameter usually takes the value of 120 $\frac{W}{m^2}$. This level of activity means a generation of carbon dioxide which enters in the calculation of heating and cooling loads. People, as well as any other element with a given temperature, have heat transfer with the environment, differentiate latent and sensible fraction. Figure 10 shows the screenshot of this object.

Field	Units	Obj1	Obj2	Obj3
Name		West Zone	EAST ZONE	NORTH ZONE
Zone or ZoneList Name		West Zone	EAST ZONE	NORTH ZONE
Number of People Schedule Name		Rooms	Living room	Dining Room - Kitch
Number of People Calculation Method		people	people	people
Number of People		3	3	3
People per Zone Floor Area	person/m2			
Zone Floor Area per Person	m2/person			
Fraction Radiant		0.5	0.5	0.5
Sensible Heat Fraction				
Activity Level Schedule Name		ACTIVITY SCH	ACTIVITY SCH	ACTIVITY SCH
Carbon Dioxide Generation Rate	m3/s-W	0.0000000382	0.0000000382	0.0000000382
Enable ASHRAE 55 Comfort Warnings				
Mean Radiant Temperature Calculation		zoneaveraged	zoneaveraged	zoneaveraged
Surface Name/Angle Factor List Name				
Work Efficiency Schedule Name		WORK EFF SCH	WORK EFF SCH	WORK EFF SCH
Clothing Insulation Calculation Method		ClothingInsulationSc	ClothingInsulationSc	ClothingInsulationSc
Clothing Insulation Calculation Method S				
Clothing Insulation Schedule Name		CLOTHING SCH	CLOTHING SCH	CLOTHING SCH
Air Velocity Schedule Name		AIR VELO SCH	AIR VELO SCH	AIR VELO SCH
Thermal Comfort Model 1 Type		FANGER	FANGER	FANGER

Figure 10. Object: People. Source: EnergyPlus.

b. *Object: Lights*. In this case, the parameters needed are the lighting level and the schedule which is taken form the EnergyPlus database.

For the lighting level, LED bulbs where chosen with a power of 4 $\frac{W}{unit}$, therefore, the East and North zone has 8 light bulbs, and the West zone 4 light bulbs. Figure 11 shows the screenshot of this object.

Field	Units	Obj1	Obj2	Obj3
Name		EAST ZONE Lights	NORTH ZONE Ligh	WEST ZONE Lights
Zone or ZoneList Name		EAST ZONE	NORTH ZONE	West Zone
Schedule Name		luminaria cuartos	iluminacion comedo	iluminacion comedo
Design Level Calculation Method		LightingLevel	LightingLevel	LightingLevel
Lighting Level	W	32	32	24
Watts per Zone Floor Area	W/m2			
Watts per Person	W/persor			
Return Air Fraction		0	0	0
Fraction Radiant		0.42	0.42	0.42
Fraction Visible		0.18	0.18	0.18
Fraction Replaceable		1	1	1
End-Use Subcategory		GeneralLights	GeneralLights	GeneralLights

Figure 11. Object: Lights. Source: EnergyPlus.

c. *Object: Equipment*. The zones have different electric equipment depending on the activity that will take place in. For example, the living room (north zone) will have a television; and the kitchen (east zone) will have an oven, a fridge, a microwave, etc [31]. Figure 12 shows the screenshot of this object.

Field	Units	Obj1	Obj2
Name		EAST ZONE ElecE	North Zone
Zone or ZoneList Name		EAST ZONE	NORTH ZONE
Schedule Name		Equip Comedor Coc	Equip Comedor Coc
Design Level Calculation Method		EquipmentLevel	EquipmentLevel
Design Level	W	3250	300
Watts per Zone Floor Area	W/m2		
Watts per Person	W/person		

Figure 12. Object: Equipment. Source: EnergyPlus.

4.2. Heat transfer problem resolution

Heat transfer is the thermal energy flow due to a temperature difference. There are three types: (1) conduction, heat transfer across a medium, (2) convection, heat transfer between a surface and a moving fluid with a difference temperature, and (3) radiation, heat transfer through the form of electromagnetic radiation between two surfaces at different temperature.

The heat balance algorithm used in all cases (with PCM and without PCM) was conduction finite difference (CondFD). It was selected because its capability to handle PCM. In the other side, the surface convection algorithm selected is Thermal Analysis Research Program (TARP).

The timestep value suggested for this type of heat balance is 20. This value is used in the zone heat balance model for heat transfer and load calculations and it is the timestep to use within an hour, by means, a value of 20 directs the program to use a zone timestep of 3 minutes.

a) Surface convection algorithm: Inside and Outside. TARP algorithm was selected. This model correlates the heat transfer coefficient to the temperature difference from various orientations. Walton, an important professor of EnergyPlus developed this model by blending correlations from ASHRAE and flat plate experiments [37]. This model splits convection into forced and natural components being the total convection coefficient the sum of these two components. Figure 13 shows a screenshot of this object.

Field	Units	Obj1
Algorithm		TARP

Figure 13. Object: Surface convection algorithm. Source: EnergyPlus.

b) Conduction finite difference. Due to its iterative nature, this model has the capability to simulate materials with variable properties. This algorithm uses an implicit finite difference model where the user can choose between the fully implicit scheme and the Crank-Nicolson, which is semi-implicit. In this project, the Crank-Nicolson scheme was selected because it has a smaller error in comparison to the other scheme. This scheme is based on an Adams-Moulton solution and uses an enthalpy-temperature function to account for phase change energy accurately. In equation 1 is shown the formulation used for Crank-Nicolson scheme [32].

$$C_P \rho \Delta x \frac{T_i^{j+1}-T_i^j}{\Delta t} = \frac{1}{2}\left(k_w\left(\frac{T_{i+1}^{j+1}-T_i^{j+1}}{\Delta x}\right) + k_E\left(\frac{T_{i-1}^{j+1}-T_i^{j+1}}{\Delta x}\right) + k_W\left(\frac{T_{i+1}^{j}-T_i^{j}}{\Delta x}\right) + k_E\left(\frac{T_{i-1}^{j}-T_i^{j}}{\Delta x}\right)\right) \qquad \text{(eq. 2)}$$

Where:
T = node temperature.
i = node being modeled.
i+1 = adjacent node to interior of construction.
i-1 = adjacent node to exterior of construction.

j+1 = new time step.
j = previous time step.
Δt = calculation time step.
Δx = finite difference layer thickness.
C_P *= specific heat of the material.*
k_w *= thermal conductivity for interface between i node and i+1 node.*
k_E *= thermal conductivity for interface between i node and i-1 node.*
ρ = density of the material

Equation 2 is accompanied by another one that relates enthalpy and temperature.

$$h_i = HTF(T_i) \qquad \text{(eq. 3)}$$

Where:

HTF = enthalpy-temperature function that uses user input data. This function, which belongs to the properties of the PCM, will be described in more detail in section **4.3 Material and construction.**

In **APPENDIX 2: HEAT TRANSFER RESOLUTION** can be found more information about the heat transfer resolution problem.

4.3. Material and construction

The material inputs of the house envelope (wall, roof, floor, windows, partitions and door) and the construction layer of each envelope will be described in this section, with the exception of the PCM, the floor construction and the heating system which will be explained in section **4.4 Description of the PCM, 4.5 Description of the floor and 4.6 Heating system: Radiant floor**, respectively.

Material inputs.

All the material properties used in the house where selected from the Spanish technical code of edification, (CTE) [40], which is approved by the European legislation 2010/31/EU. The required inputs for the different materials, except for the window and the airgap which have different inputs requirements as they belong to another object; are (1) surface roughness, (2) thickness, m; (3) conductivity, $\frac{W}{m\,K}$; (4) density, $\frac{kg}{m^3}$ and (5) specific heat, $\frac{J}{kg\,K}$. In addition of the thermal absorptance, solar absorptance and visible absorptance which are optional. Figure 14 shows a screenshot of the material properties.

The window material property selected is from the EnergyPlus database as well as the airgap. Figure 15 and Figure 16 shows a screenshot of these properties.

Field	Units	Obj1	Obj2	Obj3	Obj4	Obj5	Obj6	Obj7	Obj8	Obj9	Obj10	Obj11	Obj12	Obj13
Name		Gypsum	Concrete Ext	Insulation CellGlass	Mortar	Polystyrene Floor	Concrete Floor	Concrete Roof	Insulation felt	Insulation bitumer	Wood Material	Concrete block	Double brick	Simple brick
Roughness		Smooth	MediumRough	Smooth	Rough	MediumRough	Rough	Rough	MediumSmooth	MediumSmooth	MediumSmooth	Rough	MediumRough	MediumRough
Thickness	m	0.02	0.1	0.05	0.0275	0.04	0.05	0.1	0.005	0.005	0.0254	0.25	0.07	0.04
Conductivity	W/m-K	0.4	2.3	0.05	1.8	0.029	2.3	1.65	0.05	0.23	0.15	1.788	0.432	0.432
Density	kg/m3	900	2400	19	2100	30	2400	2100	140	2420	608	1645	930	1000
Specific Heat	J/kg-K	1000	1090	850	1000	1210	1090	1090	1300	2180	1630	1000	1000	1000
Thermal Absorptance														
Solar Absorptance		0.32	0.32					0.32						
Visible Absorptance		0.32	0.32					0.32						

Figure 14. Material properties. Source: EnergyPlus.

Field	Units	Obj1
Name		Airgap
Thermal Resistance	m2-K/W	0.18

Figure 15. Airgap properties. Source: EnergyPlus

Field	Units	Obj1
Name		Clear 6mm
Optical Data Type		SpectralAverage
Window Glass Spectral Data Set Name		
Thickness	m	0.006
Solar Transmittance at Normal Incidence		0.775
Front Side Solar Reflectance at Normal Incidence		0.071
Back Side Solar Reflectance at Normal Incidence		0.071
Visible Transmittance at Normal Incidence		0.881
Front Side Visible Reflectance at Normal Incidence		0.08
Back Side Visible Reflectance at Normal Incidence		0.08
Infrared Transmittance at Normal Incidence		0
Front Side Infrared Hemispherical Emissivity		0.84
Back Side Infrared Hemispherical Emissivity		0.84
Conductivity	W/m-K	0.9

Figure 16. Window properties. Source: EnergyPlus.

Construction inputs.

In EnergyPlus the construction must be introduced from the outside layer to the inside layer. Figure 17 shows the layers for each surface, for the exception of the floor, which will be discussed below.

For a better comprehension of the order of the layers see Figure 18 and Figure 19.

Field	Units	Obj1	Obj2	Obj3	Obj4	Obj5	Obj6
Name		EXTWALL80	PARTITION06	ROOF34	WIN-CON-LIGHT	Exterior Door	Heavy Furnishings
Outside Layer		gypsum	gypsum	concrete block	Clear 6mm	wood material	wood material
Layer 2		double brick	Insulation CellGlass	mortar	Air 13mm		
Layer 3		mortar	Gypsum	Polystyrene Floor	Clear 6mm		
Layer 4		air gap		Concrete Roof			
Layer 5		mortar		air gap			
Layer 6		simple brick		gypsum			
Layer 7		gypsum					

Figure 17. Construction layers for the different surfaces. Source: EnergyPlus.

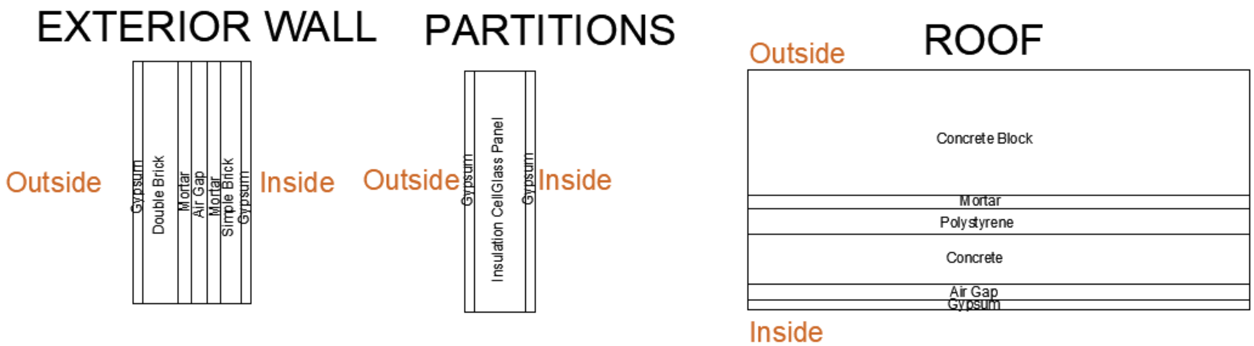

Figure 18. Construction layers for the roof, partitions and exterior wall. Source: Own

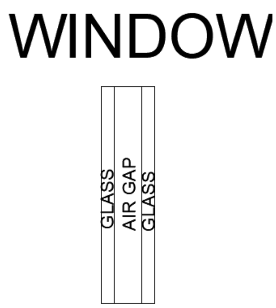

Figure 19. Window construction. Source: Own.

4.4. Description of the PCM

In this project, Micronal PCM gypsum wallboards will be introduced, Figure 20. This wallboard is manufactured by Knauf. With this type of wallboard, it is a simple and cheap way to introduce the PCM as it does not require big interventions and installations costs. Its installation is simple as it can be glued to a wall, suspending in a ceiling or used as a wall partition. Besides, 30 kg_{PCM} gives around 1 kWh of heat storage performance. In the other side, the heat capacity of a construction that its integrated with 15 mm of PCM gypsum wallboard it is comparable to a 14 cm thick concrete wall or 36.5 cm thick of brick wall [41].

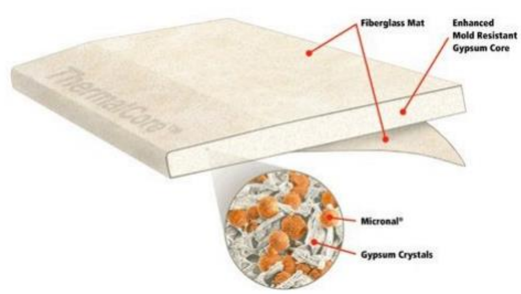

Figure 20. Example of microencapsulated PCM. Source: BASF [42].

According to [43], many factors affects the behavior of the PCM wallboard, such as:

1. PCM concentration in the wallboard. In this project this concentration is around 18%.
2. Latent heat storage per unit area. In this project, depending on the melting point the latent heat varies from 116 - 170 $\frac{kJ}{kg}$
3. Wallboard thickness. In the cases where the amount of PCM is constant, the thickness will be 0.1 m (8 layers of PCM wallboard).
4. Internal and solar gains.
5. The climatic conditions.
6. Orientations of the surfaces where the PCM is installed.
7. Location in the building. Whether it is installed in roofs, walls, floors… In this project it will be installed in the floor (above or below the heating system).

Besides PCM wallboards, there are other ways to introduce PCM in buildings, such as [44]:

1. PCM bricks.
2. PCM trombe wall.
3. PCM shutters, window blinds and translucent PCM walls.
4. PCM enhanced concrete systems and mortars.

PCM gypsum Wallboard.

Micronal PCM gypsum wallboard (Figure 21) are named ‘ComfortBoard’ and are manufactured by Knauf. They contain a PCM which is manufactured by BASF and consists of microencapsulated wax paraffin. The properties of this wallboard are: (1) height, 2 m; (2) width, 1.25 m; (3) thickness, 0.0125 m; (4) density, 825 $\frac{kg}{m^3}$; (5) amount of PCM per each wallboard, 5 kg.

Figure 21. PCM gypsum wallboard. Source: Knauf.

PCM properties

EnergyPlus can simulate PCM using CondFD (**4.2 Heat transfer problem resolution**). This object requires the introduction of the enthalpy – temperature curve, but due to the material hysteresis, the melting and freezing curve are different, Figure 22. Therefore, the average of both curves will be introduced in the program. As mentioned before (**CHAPTER 2: THEORETICAL BACKGROUND**), the PCM has a different conductivity depending on its phase, depending on if it is liquid or solid, therefore, as the manufacturer just provides one value for the thermal conductivity, it is assumed to be constant and equal in both phases with a value of 0.2 $\frac{W}{m\,K}$. Besides, the specific heat (C_p) also varies, but the algorithm chosen (CondFD) can calculate it at each iteration, using:

$$C_p = \frac{h_{i,new} - h_{i,old}}{T_{i,new} - T_{i,old}} \qquad \text{(eq. 4)}$$

Where:
$h_{i,X}$ = *new or old enthalpy of node i*
$T_{i,X}$ = *new or old temperature of node i*

The iteration scheme assures that the correct enthalpy, and therefore, the correct C_p is used in each timestep [39].

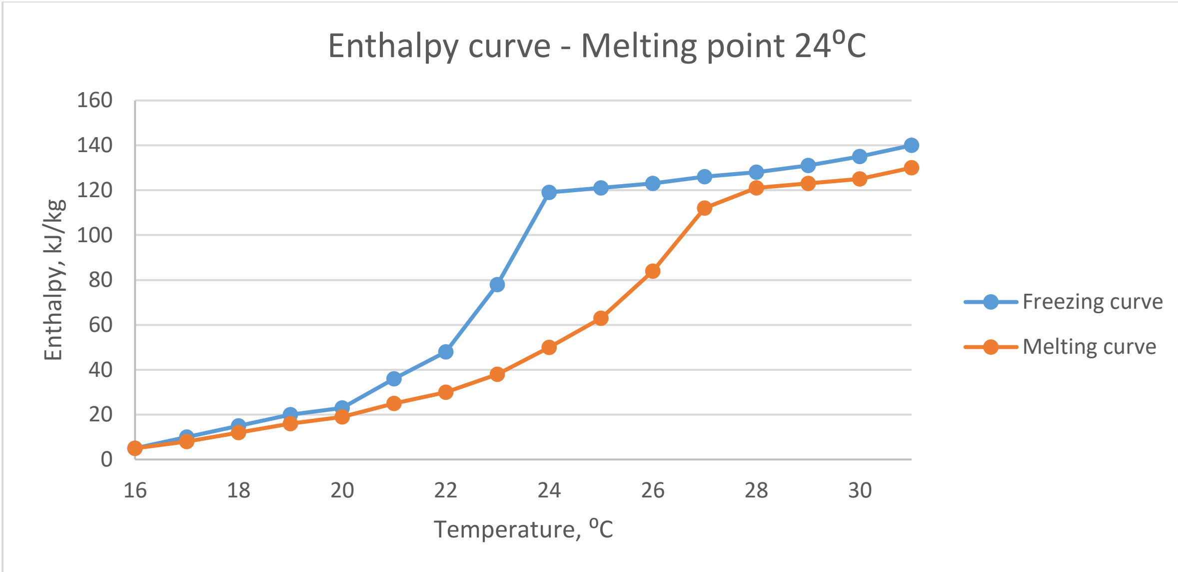

Figure 22. Enthalpy curve PCM melting point 24°C. Source: Knauf.

Figure 23 shows an example of the object used in EnergyPlus for a PCM with a melting temperature of $24^{0}C$. The field of temperature coefficient for thermal conductivity is set to 0 because the manufacturer only provides a single value for the thermal conductivity. In the case that the manufacturer provides this coefficient, the thermal conductivity is obtained using:

$$k = k_o + k_1(T_i - 20) \quad \text{(eq. 5)}$$

Where:
k_o *is the 20°C value of thermal conductivity.*
k_1 *is the change in conductivity per degree temperature difference from 20°C.*
T_i *is the temperature at each node*

Field	Units	Obj1
Name		PCMS
Temperature Coefficient for Thermal Conductivity	W/m-K2	0
Temperature 1	C	16
Enthalpy 1	J/kg	5000
Temperature 2	C	17
Enthalpy 2	J/kg	9000
Temperature 3	C	18
Enthalpy 3	J/kg	13500
Temperature 4	C	19
Enthalpy 4	J/kg	18000
Temperature 5	C	20
Enthalpy 5	J/kg	21000
Temperature 6	C	21
Enthalpy 6	J/kg	30500
Temperature 7	C	22
Enthalpy 7	J/kg	39000
Temperature 8	C	23
Enthalpy 8	J/kg	58000
Temperature 9	C	24
Enthalpy 9	J/kg	84500

Figure 23. PCM enthalpy curve. Melting point 24^{o}C. Source: EnergyPlus, data: Knauf.

PCM melting point

The manufacturer of the PCM used in this project is BASF and it produces PCM at different melting points. Therefore, the range of melting points that will be used in this project will be 22^{0}C-32^{0}C. This range of melting points have been chosen because the PCM must have a melting point between the room temperature and the water temperature of the heating system, because the PCM will start to melt when it achieves its melting point, and therefore, it leads to an absorption of heat and prevents the room temperature from rising. When the room temperature decrease, the absorbed heat gets released so, when the PCM cools down and solidifies [42].

The location of the PCM can be above or below the heating system. This, will be explained in the next sections: **4.5 Description of the floor and 4.6 Heating system: Radiant floor.**

In **APPENDIX 3: PCM ENTHALPY CURVES** it can be seen all the enthalpy curves used in EnergyPlus.

4.5. Description of the floor

As well as in section **4.3 Material and construction**, the materials of the floor where selected from the Spanish technical code of edification, (CTE) [40]. In this case, as the heating system will be installed in the floor, the object for this surface is not the same as the other surfaces. Figure 24 shows the screenshot of the floor construction. For a better comprehension of the order of the layers see **¡Error! No se encuentra el origen de la referencia.**.

The field of 'source present after layer number' relates the location of the heating source. As the radiant floor is installed within a single homogenous layer (mortar) it should be split in two layers and the source added between them. Therefore, the radiant floor is installed between layer 4 and 5. In the case where the PCM is installed, this value changes. If the PCM is installed above the heating system this value is the same, 4; but if the PCM is installed below the heating system, this value is 5, therefore the heating system will be between layer 5 and 6.

The field of 'temperature calculation requested after layer number' helps the user to calculate the temperature within the construction.

The field 'dimensions for the CTF calculation', where CTF means conduction transfer functions, refers if the calculations is done one-dimensional or two-dimensional, just for this surface.

The field 'tube spacing' defines how far in meters the hydronic tubes are spaced in the direction perpendicular to the main direction of the heat transfer.

Field	Units	Obj1
Name		Radiant Floor construction
Source Present After Layer Number		4
Temperature Calculation Requested After Layer Numbe		4
Dimensions for the CTF Calculation		2
Tube Spacing	m	0.1524
Outside Layer		Concrete block
Layer 2		Concrete floor
Layer 3		Polystyrene floor
Layer 4		mortar
Layer 5		mortar
Layer 6		Floor tile

Figure 24. Floor construction. Source: EnergyPlus.

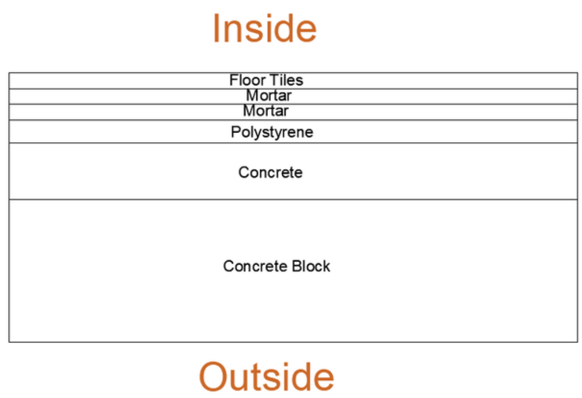

Figure 25. Floor construction. Source: Own

4.6. Heating system: Radiant floor

In this project, the heating system selected is a radiant floor which can have two configurations, variable or constant water flow. Both configurations will be simulated in order to see the behaviour of each option. Besides, the location of the PCM will also vary in both configurations (above or below the radiant floor). In **CHAPTER 5: ENERGYPLUS SIMULATIONS** a description of all the cases will be explained.

Firstly, a description on how to introduce the radiant system for both configurations will be explained and secondly, an explanation of the behaviour of the radiant system and the PCM whether it is above or below the system.

Figure 26 shows a typical configuration of a radiant floor.

Figure 26. Example of a radiant floor. Source: Google Images.

The design of the radiant floor was done according to UNE – EN – 1264 [38]. Thus, the steps that have been followed are:

1. Initial conditions. (1) thermal resistance of the floor tile, $\frac{m^2\,K}{W}$ (2) conductivity of the mortar where the radiant system is located, $\frac{W}{m\,K}$;(3) width above the tubes, m; (4) diameter of the tubes, m; (5) width of the tubes, m; and (5) conductivity of the tube, $\frac{W}{m\,K}$.
2. Limit thermal conditions.
    a. Calculation of thermal loads. This is done without any heating system and only one zone (the higher thermal load) is selected as the design zone.
    b. Maximum surface temperature: for occupied zones a maximum of 29^{o}C, for bathroom or similar (as kitchen) a maximum of 33^{o}C.
    c. Indoor temperature: For all zones 20^{o}C - 22^{o}C (design conditions).
3. Characteristics curves for different water temperatures. This curve describes the relation between the thermal emission of a system and the temperature difference between the water and the indoor temperature.
4. Calculation of the impulse water temperature and tube spacing.
5. Calculation of the return temperature.
6. Calculation of the water flow.

Variable Flow

In this configuration, the control is accomplished by throttling the hot water flow to the unit based on the radiant system controls showed in Figure 27.

In the field 'availability schedule' refers whether the radiant system can run or not during a period time. The period where the system is available is from 1st January-30th June and then from 15th July-31st December. The period between 30th June-15th July, the system is off as the house does not require any heating, previous simulations have been done to assure this period.

In the field 'temperature control type' which is related to the field 'throttling range' and 'setpoint schedule'. The control type selected is the mean air temperature of the zone.

In the field 'maximum water flow', 'hydronic tube length' and 'hydronic tube inside diameter' the different parameters where calculated using UNE-EN-1264, as previously explained.

In the field 'heating control temperature range' the radiant system throttles from 0 flow rate up to its maximum defined in 'maximum hot water flow' (for each zone). This fields requires the 'heating control temperature schedule', which defines the setpoint temperature, in order to define the response of the system. For example, if the setpoint is defined in 21^0C and the heating throttling rate is 2^0C, then between 20^0C-22^0C the flow rate is varied linearly in order to control the indoor temperature. Therefore, if the indoor temperature is at or above 22^0C the flow rate will be 0 $\frac{m^3}{s}$ and, if the temperature is at or below 20^0C the flow rate will be the maximum.

1. In this project the heating setpoint is set to 21ºC.
2. The water temperature is set to 40ºC.
3. There is no cooling system because the project is located in Denmark.

Field	Units	Obj1	Obj2	Obj3
Name		West Zone Radiant	East Zone Radiant I	North Zone Radiant
Availability Schedule Name		RADIANTSYSAVAI	RADIANTSYSAVAI	RADIANTSYSAVAI
Zone Name		West Zone	EAST ZONE	NORTH ZONE
Surface Name or Radiant Surface Group Name		Zn001:Flr001	Zn002:Flr001	Zn003:Flr001
Hydronic Tubing Inside Diameter	m	0.012	0.012	0.012
Hydronic Tubing Length	m	400	400	400
Temperature Control Type		MeanAirTemperatur	MeanAirTemperatur	MeanAirTemperatur
Heating Design Capacity Method		HeatingDesignCapa	HeatingDesignCapa	HeatingDesignCapa
Heating Design Capacity	W	autosize	autosize	autosize
Heating Design Capacity Per Floor Area	W/m2			
Fraction of Autosized Heating Design Capacity				
Maximum Hot Water Flow	m3/s	0.00008	0.00008	0.0001
Heating Water Inlet Node Name		West Zone Radiant	East Zone Radiant '	North Zone Radiant
Heating Water Outlet Node Name		West Zone Radiant	East Zone Radiant '	North Zone Radiant
Heating Control Throttling Range	deltaC	2	2	2
Heating Control Temperature Schedule Name		RADIANT HEATIN(	RADIANT HEATIN(	RADIANT HEATIN(
Cooling Design Capacity Method		CoolingDesignCapa	CoolingDesignCapa	CoolingDesignCapa
Cooling Design Capacity	W	autosize	autosize	autosize
Cooling Design Capacity Per Floor Area	W/m2			
Fraction of Autosized Cooling Design Capacity				
Maximum Cold Water Flow	m3/s	0	0	0

Figure 27. Radiant Floor - Variable flow. Source: EnergyPlus.

Constant Flow

In this configuration, the control is accomplished by schedules that will be explained below. This system differs from the variable flow in what it controls. In this case, the system keeps the flow constant via a pump and varies the water temperature sent to the radiant system. This is achieved by a mixing valve that is controlled with a sensor. It recirculates flow coming out of the system and mix it with flow from the secondary loop in order to arrive at the desire inlet temperature. There is a temperature sensor after the pump to assure the inlet temperature to the system.

Figure 28 shows the screenshot of the radiant system constant flow object.

In the field 'availability schedule', as previously said, refers whether the radiant system can run or not during a period time. The period where the system is available is from 1st January - 30th June and then from 15th July – 31st December. The period between 30th June – 15th July, the system is off as the house does not require any heating, previous simulations have been done to assure this period.

In the field 'temperature control type' which is related to the field 'control temperature' and 'Water temperature'. The control type selected is the mean air temperature of the zone.

In the field 'rated flow rate', 'hydronic tube length' and 'hydronic tube inside diameter' the different parameters where calculated using UNE-EN-1264, as previously explained.

In the field 'heating water temperature schedule name' which is related to the field 'heating control temperatures' assure the indoor temperature. The current control temperature is compared to the high and low control temperatures at each timestep. If the control temperature is above the high temperature, the system will turn off and the flow rate will be 0 $\frac{m^3}{s}$. In the other side, if the control temperature is below the low control temperature, the flow rate is set to its maximum. Finally, if the control temperature is between the high and low value the inlet water temperature is vary linearly interpolated between the high and low water temperature.

1. Water temperature is set between 40°C - 10°C.
2. Control temperature is set to 22°C - 20°C.
3. There is no cooling system because the project is located in Denmark.

Field	Units	Obj1	Obj2	Obj3
Name		West Zone Radiant	East Zone Radiant I	North Zone Radiant
Availability Schedule Name		RADIANTSYSAVAI	RADIANTSYSAVAI	RADIANTSYSAVAI
Zone Name		West Zone	EAST ZONE	NORTH ZONE
Surface Name or Radiant Surface Group Name		Zn001:Flr001	Zn002:Flr001	Zn003:Flr001
Hydronic Tubing Inside Diameter	m	0.012	0.012	0.012
Hydronic Tubing Length	m	400	400	400
Temperature Control Type		MeanAirTemperatur	MeanAirTemperatur	MeanAirTemperatur
Rated Flow Rate	m3/s	0.00008	0.00008	0.0001
Pump Flow Rate Schedule Name				
Rated Pump Head	Pa	80000	80000	60000
Rated Power Consumption	W	10	10	10
Motor Efficiency		0.87	0.87	0.87
Fraction of Motor Inefficiencies to Fluid Stream		0.1	0.1	0.1
Heating Water Inlet Node Name		West Zone Radiant	East Zone Radiant '	North Zone Radiant
Heating Water Outlet Node Name		West Zone Radiant	East Zone Radiant '	North Zone Radiant
Heating High Water Temperature Schedule Name		RADHEATHIGHWA	RADHEATHIGHWA	RADHEATHIGHWA
Heating Low Water Temperature Schedule Name		RADHEATLOWWA	RADHEATLOWWA	RADHEATLOWWA
Heating High Control Temperature Schedule Name		RADHEATHIGHCO	RADHEATHIGHCO	RADHEATHIGHCO
Heating Low Control Temperature Schedule Name		RADHEATLOWCOI	RADHEATLOWCOI	RADHEATLOWCOI

Figure 28. Radiant Floor - Constant flow. Source: EnergyPlus.

Behavior of the PCM coupled with the radiant floor

In a system without PCMs if it turns off, the surface temperature will cool rapidly, leading to a continuous operation of the boiler controller. But, installing PCMs in the system, above or below the radiant system, can keep the room warm even after the hot water supply is off because the heat energy from the hot water is stored in the PCM as latent heat.

¡Error! No se encuentra el origen de la referencia. shows the behavior of the heat flux when the PCM is located above the radiant system.

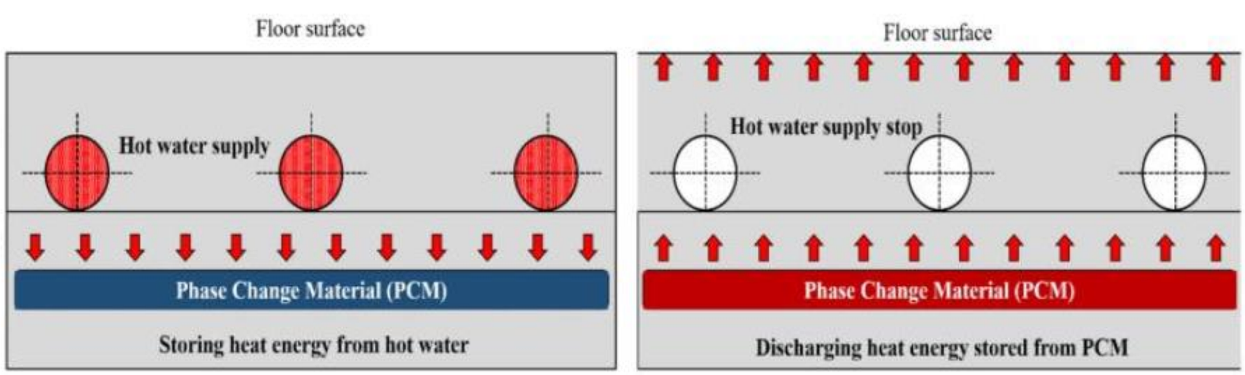

Figure 29. Heat emission from a floor heating system with PCM. Source: [39].

CHAPTER 5: ENERGYPLUS SIMULATIONS

In this chapter, the description of all the cases and the discussion of the results will be done. The results will be compared with other papers which have also used EnergyPlus as their simulation program.

In all cases, except for case 0, the melting point of the phase change material will vary from 22^0C-32^0C, in order to find out which range of melting point is the most suitable in each case and therefore know which melting temperature range leads to the lowest total energy consumption (kWh) and/or peak load for the heating demand (kW). Besides, for cases 1 and 2, the amount of PCMs installed will be the same.

The amount of PCM installed in West and East zone for cases 1 and 2 is 560 $\frac{kg_{PCM}}{zone}$ that corresponds to a 0.1 m of thickness of the PCM wallboard. In the other side, the amount of PCM installed in North zone for cases 1 and 2 is 880 kg_{PCM} that corresponds to a 0.1 m of thickness of the wallboard.

The base case is the one selected to compare it to the other cases.

1. Base case or Case 0. The house without the phase change material. It will only have the heating system.
    a. Case 0.A: Constant water flow with variation of the water temperature (40ºC - 10ºC)
    b. Case 0.B: Constant water temperature with variation of the water flow (0 $\frac{m^3}{s}$ – 0.001 $\frac{m^3}{s}$)
2. Case 1. Constant water flow (0.001 $\frac{m^3}{s}$) with variation of the water temperature (40ºC - 10ºC)
    a. Case 1.A: Location of the PCM: Below the heating system
    b. Case 1.B Location of the PCM: Above the heating system
3. Case 2. Constant water temperature (40ºC) with variation of the water flow (0 $\frac{m^3}{s}$ – 0.001 $\frac{m^3}{s}$)
    a. Case 2.A Location of the PCM: Below the heating system
    b. Case 2.B Location of the PCM: Above the heating system

Once Case 1 and 2 have been simulated and compared both options (PCM above or below the heating system) one of the locations will be selected, as well as the temperature range (melting point of the PCM), to simulate the following cases:

4. Case 3. Variation of the amount of PCM (kg) for case 1.X (one of the two configurations).
5. Case 4. Variation of the amount of PCM (kg) for case 2.X (one of the two configurations).

Each PCM wallboard has a size of 1.25x2 m with a width of 0.0125 m and 5 kg_{PCM}, therefore to cover the whole surface of the floor, 14 wallboards must be introduced in West and East zone and 22 Wallboards in North zone. The variation of the amount of PCM will be done by introducing more layers to the surface construction, meaning a variation of its thickness. Then, the simulations will be done considering 2, 4, 6, 8 and 10 layers.

The parameters that have been chosen to evaluate the behavior of the PCM installed in the floor will be (1) total energy consumption, kWh; (2) heating demand, kWh; (3) indoor temperature, ^0C; and (4) the peak loads for the heating demand. Numerical values for annual simulations of (1), (2) and (4) will be shown in tables, and graphs for one-day simulations of (2) and (3) will be shown in figures. Besides these parameters, another important parameter to consider is the surface temperature of the radiant floor, which should not be more than 29^0C in all cases (except for the kitchen and bathroom which it can be up to 30^0C). The graphs for the floor surface temperature are in **¡Error! No se encuentra el origen de la referencia.**.

As mentioned before, all the simulations will be done annually (1st January – 31st December) to obtain the total energy, kWh; the heating demand, kWh; and the peak load, kW; of the house in all cases. But, in order to have a better comprehension of the behavior of the indoor temperature, ^{0}C, a one-day simulation will be done (21st December).

The different zones have almost the same behavior in indoor temperature as well as the heating demand. So, in order to not overload this report, only one zone has been selected to plot the graphs (the numerical values correspond to the entire house; total energy and heating demand, kWh; and the peak loads for heating demand, kW). The zone selected will be the West Zone, which corresponds to the bedrooms. The selection of this zone has been done due to the location, as it is south orientated. In the other side, the East zone is also orientated to the south, but people will spend less time in the kitchen (East Zone) than the bedroom and it is because of this reason that the zone selected is the West Zone.

In

APPENDIX 4: SIMULATIONS RESULTS all the graphs and tables for all the 3 zones are available for the reader.

5.1. Case 1: Constant water flow and Variation of the water temperature

4.7. In this section a brief resume of the results of the base case as well as the variation of the melting temperature for the PCM are shown in figures and tables. In section 4.5 Description of the floor

As well as in section **4.3 Material and construction**, the materials of the floor where selected from the Spanish technical code of edification, (CTE) [40]. In this case, as the heating system will be installed in the floor, the object for this surface is not the same as the other surfaces. Figure 24 shows the screenshot of the floor construction. For a better comprehension of the order of the layers see **¡Error! No se encuentra el origen de la referencia.**.

The field of 'source present after layer number' relates the location of the heating source. As the radiant floor is installed within a single homogenous layer (mortar) it should be split in two layers and the source added between them. Therefore, the radiant floor is installed between layer 4 and 5. In the case where the PCM is installed, this value changes. If the PCM is installed above the heating system this value is the same, 4; but if the PCM is installed below the heating system, this value is 5, therefore the heating system will be between layer 5 and 6.

The field of 'temperature calculation requested after layer number' helps the user to calculate the temperature within the construction.

The field 'dimensions for the CTF calculation', where CTF means conduction transfer functions, refers if the calculations is done one-dimensional or two-dimensional, just for this surface.

The field 'tube spacing' defines how far in meters the hydronic tubes are spaced in the direction perpendicular to the main direction of the heat transfer.

Field	Units	Obj1
Name		Radiant Floor construction
Source Present After Layer Number		4
Temperature Calculation Requested After Layer Numbe		4
Dimensions for the CTF Calculation		2
Tube Spacing	m	0.1524
Outside Layer		Concrete block
Layer 2		Concrete floor
Layer 3		Polystyrene floor
Layer 4		mortar
Layer 5		mortar
Layer 6		Floor tile

Figure 24. Floor construction. Source: EnergyPlus.

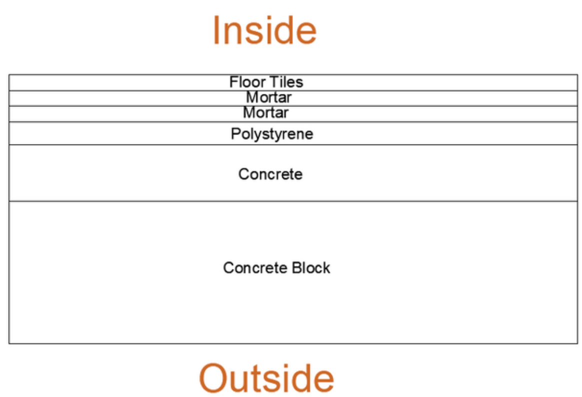

Figure 25. Floor construction. Source: Own

Heating system: Radiant floor the design values for the heating system are described.

Location of the PCM: Below the radiant system

Table 4 shows the results of the total energy consumption, heating demand and the peak load of the heating demand. For a better comprehension of the table, a graph is shown in Figure 34 and Figure 35.

Table 4. Annual simulation results -PCM Below - Constant flow. Source: Own

	BASE CASE	TMELT 22	TMELT 23	TMELT 24	TMELT 25	TMELT 26	TMELT 27	TMELT 28	TMELT 30	TMELT 32
Total energy kWh	36788.96	33556.51	33557.53	33554.17	33577.46	33590.75	33587.36	33613.33	33580.50	33554.94
District Heating kWh	31520.08	28373.35	28376.39	28379.98	28403.93	28412.86	28420.84	28444.91	28394.84	28368.90
District Heating kW	9.70	9.77	9.75	9.90	10.07	10.00	10.10	10.31	10.29	10.35

Figure 30 shows the behavior of the indoor temperature for the West Zone. The red line which correspond to the base case, differs with the other lines (different melting points for the PCM) in a maximum of 0.1788°C. The behavior of the temperature of the base case in compare with the other is almost the same. In the other side, Figure 31 shows the behavior of the heating demand which is related to the behavior of the temperature. In order to maintain the temperature, when the indoor temperature falls, the heating demand experience a rise. The peak load for the cases where the PCM is installed is lower than the base case with a maximum difference of 0.382 kW.

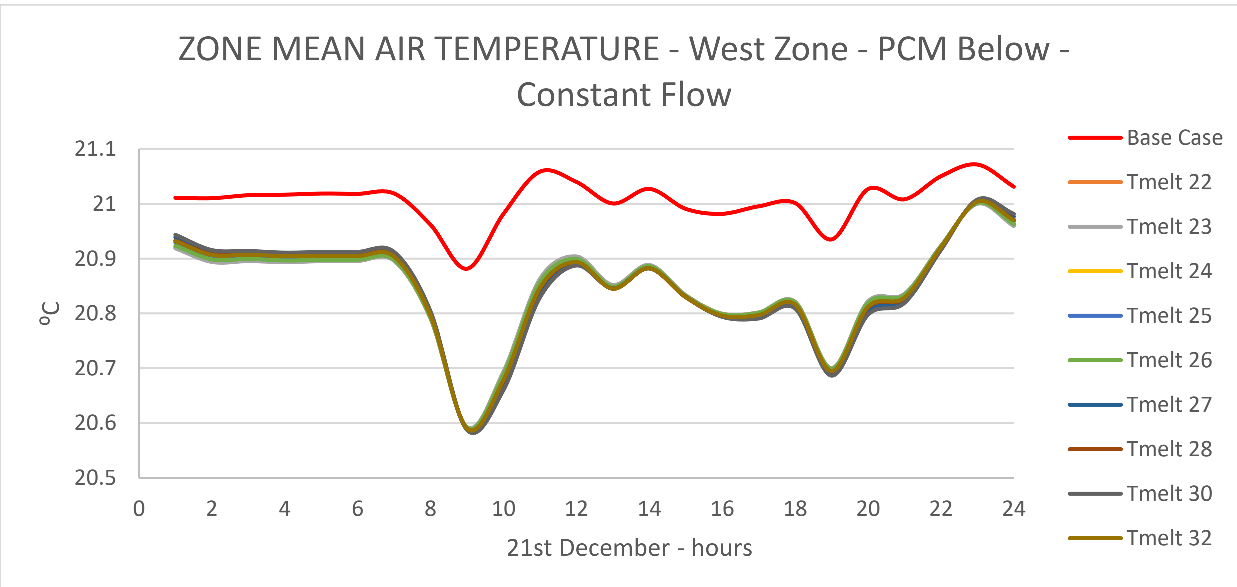

Figure 30. Zone mean air temperature - West zone - PCM Below - Constant Flow. Source: Own.

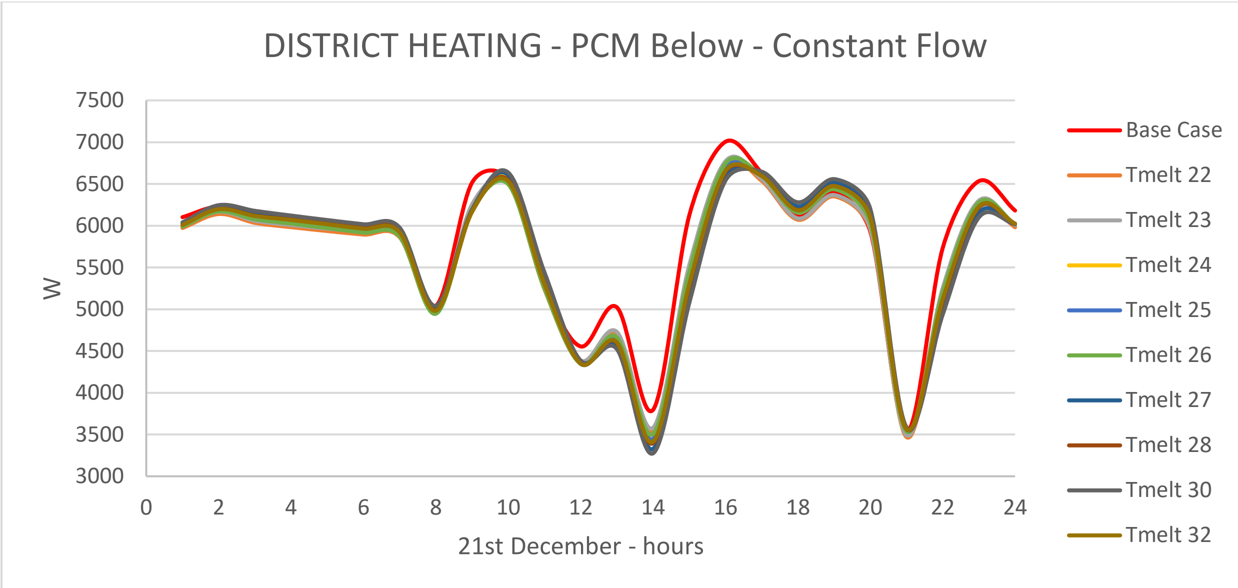

Figure 31. Heating demand - West zone - PCM below - Constant Flow. Source: Own.

Location of the PCM: Above the radiant system

Table 5 shows the results of the total energy consumption, heating demand and the peak load of the heating demand. For a better comprehension of the table, a graph is shown in Figure 34 and Figure 35.

Table 5. Annual simulation results -PCM Above - Constant water flow. Source: Own

	BASE CASE	TMELT 22	TMELT 23	TMELT 24	TMELT 25	TMELT 26	TMELT 27	TMELT 28	TMELT 30	TMELT 32
Total energy kWh	36788.96	32298.13	32281.96	32279.63	32331.35	32354.93	32312.82	32379.39	32422.07	32377.82
District Heating kWh	31520.08	27151.53	27132.15	27132	27188.9	27216.78	27168.75	27241.82	27296.16	27250.05
District Heating kW	9.7047	8.39185	8.133	8.395	8.695	9.09	8.592	9.013	9.606	9.148

Figure 32 shows the behavior of the indoor temperature for the West Zone. The red line which correspond to the base case, differs with the other lines (different melting points for the PCM) in a maximum of 0.9192^{o}C. Unlike the previous case (Figure 30), the temperature difference between the indoor temperature for the base case and the cases with PCM, is higher because of the location of the PCM. In this simulation, the PCM is located above the radiant system, therefore, due to the low thermal conductivity of the PCM it can act as an insulation to the heat flux from the radiant system that will experience a higher thermal resistance in compare to the previous case. In the other side, Figure 33 shows the behavior of the heating demand. In this case, the curve is fainter when the PCM is added to the system in compare to the base case (secondary axis) and this leads to a lower consumption of the pump.

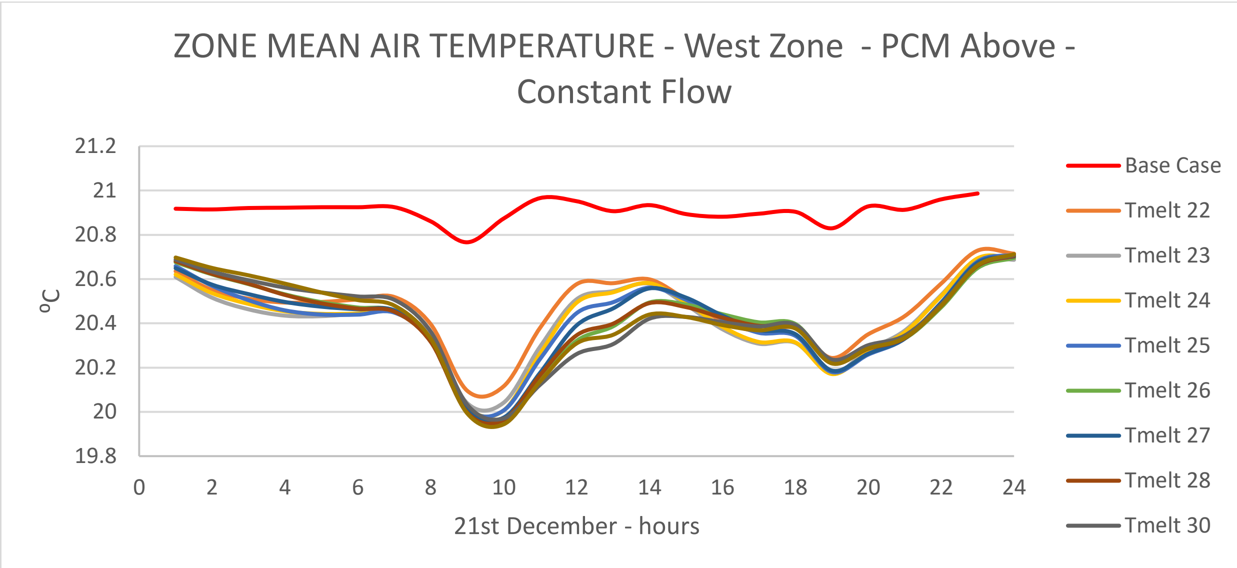

Figure 32. Zone mean air temperature - West zone - PCM above - Constant Flow. Source: Own.

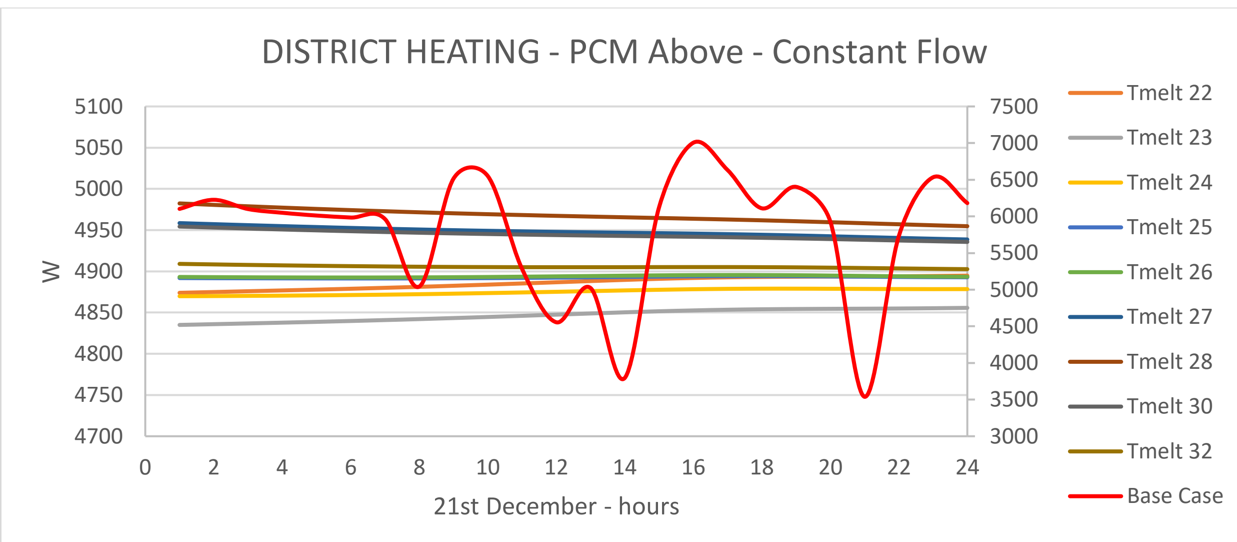

Figure 33. Heating demand - West zone - PCM above - Constant Flow. Source: Own.

Figure 34 shows the numerical results for the total energy of Table 4 and Table 5. Both configurations have got almost the same behavior and it shows a drastic fall once the PCM is installed in the house. When the PCM is located below, it represents a lower total energy in compare with the case where the PCM is located above.

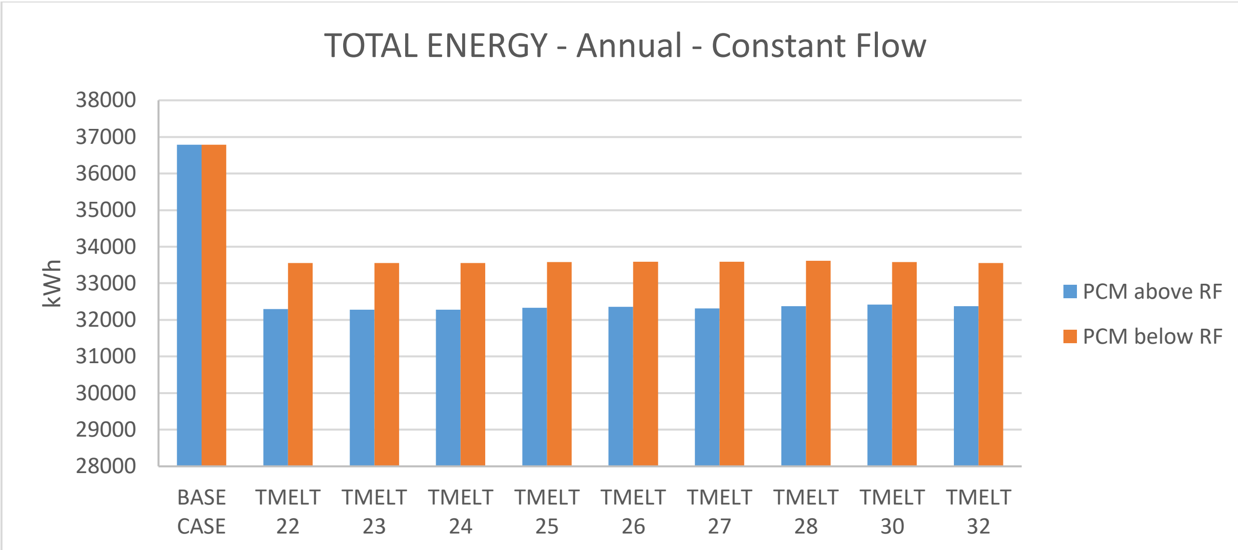

Figure 34. Total Energy - Constant Flow. Source: Own.

Figure 35 shows the peak loads of the heating demand of the numerical results from Table 4 and Table 5. The peak loads for the case where the PCM are below shows have a more stable variation than the case with PCM above. The reason of this variation is because of the water temperature which varies constantly and thus, the melting point must be between the room temperature and the water temperature.

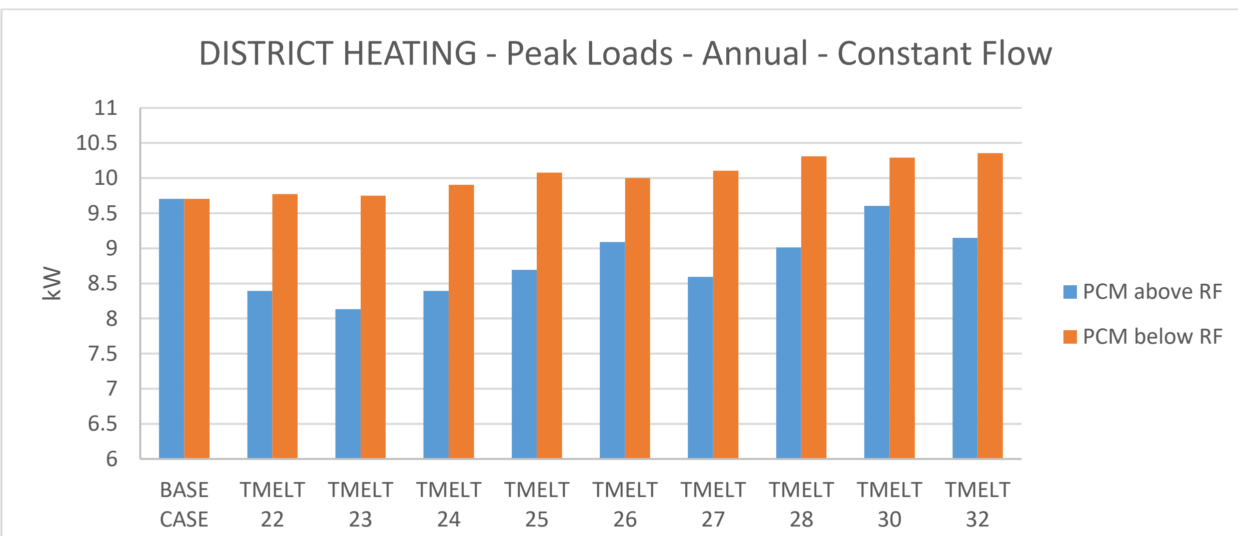

Figure 35. District Heating - Peak Loads - Constant Flow. Source: Own.

5.2. Case 2: Constant water temperature and Variation of the water flow

4.8. In this section a brief resume of the results of the base case as well as the variation of the melting temperature for the PCM are shown in figures and tables. In section 4.5 Description of the floor

As well as in section **4.3 Material and construction**, the materials of the floor where selected from the Spanish technical code of edification, (CTE) [40]. In this case, as the heating system will be installed in the floor, the object for this surface is not the same as the other surfaces. Figure 24 shows the screenshot of the floor construction. For a better comprehension of the order of the layers see **¡Error! No se encuentra el origen de la referencia.**.

The field of 'source present after layer number' relates the location of the heating source. As the radiant floor is installed within a single homogenous layer (mortar) it should be split in two layers and the source added between them. Therefore, the radiant floor is installed between layer 4 and 5. In the case where the PCM is installed, this value changes. If the PCM is installed above the heating system this value is the same, 4; but if the PCM is installed below the heating system, this value is 5, therefore the heating system will be between layer 5 and 6.

The field of 'temperature calculation requested after layer number' helps the user to calculate the temperature within the construction.

The field 'dimensions for the CTF calculation', where CTF means conduction transfer functions, refers if the calculations is done one-dimensional or two-dimensional, just for this surface.

The field 'tube spacing' defines how far in meters the hydronic tubes are spaced in the direction perpendicular to the main direction of the heat transfer.

Field	Units	Obj1
Name		Radiant Floor construction
Source Present After Layer Number		4
Temperature Calculation Requested After Layer Numbe		4
Dimensions for the CTF Calculation		2
Tube Spacing	m	0.1524
Outside Layer		Concrete block
Layer 2		Concrete floor
Layer 3		Polystyrene floor
Layer 4		mortar
Layer 5		mortar
Layer 6		Floor tile

Figure 24. Floor construction. Source: EnergyPlus.

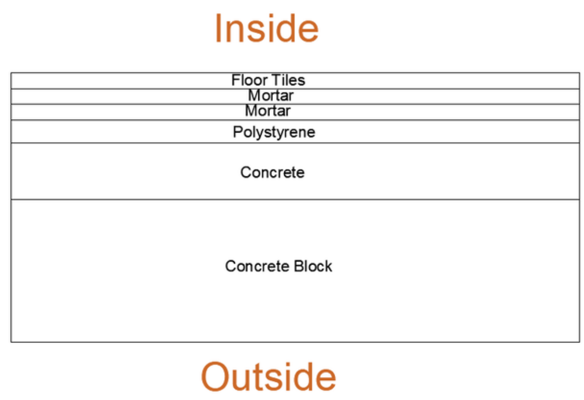

Figure 25. Floor construction. Source: Own

Heating system: Radiant floor the design values for the heating system are described.

Location of the PCM: Below the radiant system

Table 6 shows the results of the total energy consumption, heating demand and the peak load of the heating demand. For a better comprehension of the table, a graph is shown in Figure 40 and Figure 41.

Table 6. Annual simulation results -PCM Below - Variable water flow. Source: Own.

	BASE CASE	TMELT 22	TMELT 23	TMELT 24	TMELT 25	TMELT 26	TMELT 27	TMELT 28	TMELT 30	TMELT 32
Total energy kWh	29112.94	28388.42	28393.09	28370.48	28390.28	28409.35	28389.65	28417.6	28406.85	28387.8
District Heating kWh	24543.91	23827.1	23831.7	23809.3	23828.86	23847.75	23828.2	23855.84	23845.3	23826.49
District Heating kW	7.34104	7.39354	7.4005	7.46482	7.458	7.466	7.54753	7.53003	7.62255	7.508

Figure 36 shows the behavior of the indoor temperature for the West Zone. The red line which correspond to the base case, differs with the other lines (different melting points for the PCM) in a maximum of 0.0154^{o}C. In the other side, Figure 37 shows the heating demand and even though the behavior is more or less the same, the peak loads for the cases where the PCM are installed are lower with a maximum difference of 0.237 kW.

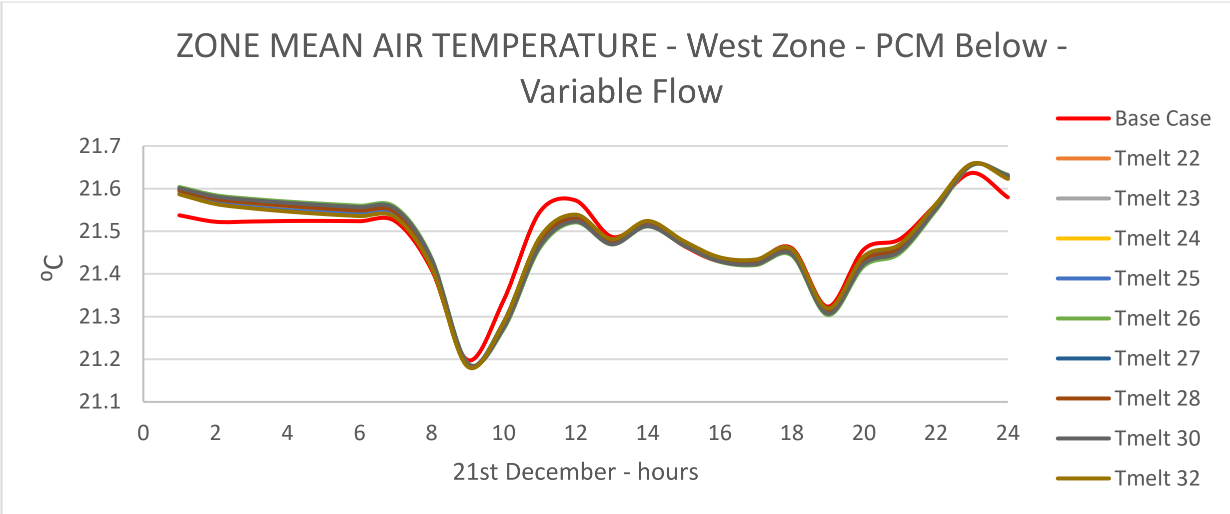

Figure 36. Zone mean air temperature - West zone - PCM Below - Variable Flow. Source: Own.

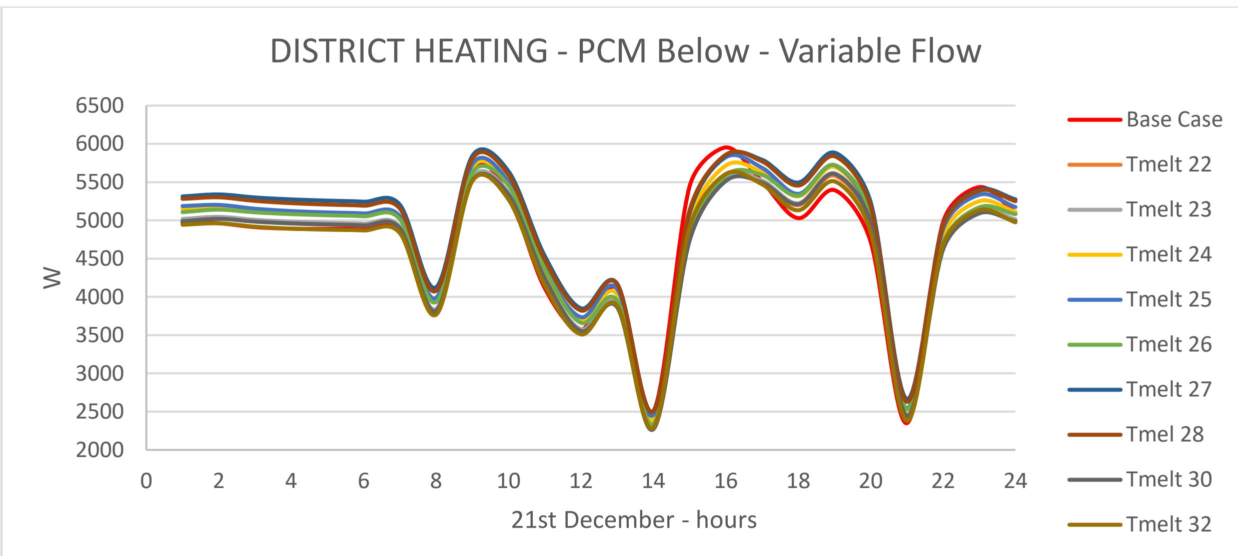

Figure 37. Heating demand - West zone - PCM below - Variable Flow. Source: Own.

Location of the PCM: Above the radiant system

Table 7 shows the results of the total energy consumption, heating demand and the peak load of the heating demand. For a better comprehension of the table, a graph is shown in Figure 40 and Figure 41.

Table 7. Annual simulation results -PCM Above - Variable water flow. Source: Own.

	BASE CASE	TMELT 22	TMELT 23	TMELT 24	TMELT 25	TMELT 26	TMELT 27	TMELT 28	TMELT 30	TMELT 32
Total energy kWh	29112.94	26193.2	26199.09	26176.14	26184.33	26216.74	26179.43	26204.12	26262.9	26241.08

District Heating kWh	24543.91	20359.28	20365.23	20342.42	20349.42	20379.88	20345.22	20368.04	20423.07	20402.62
District Heating kW	7.34104	4.963	4.957	4.984	5.0158	5.14	5.115	5.375	5.437	5.2628

Figure 38 shows the behavior of the indoor temperature for the West Zone. The red line which correspond to the base case, differs with the other lines (different melting points for the PCM) in a maximum of 0.3938ºC. Just like Figure 32, the temperature difference between the base case and the cases with PCM is higher because of the location of this material. In the same way, in Figure 33, the curve is fainter when the PCM is added to the system in compare to the base case (secondary axis) and this leads to a lower consumption of the pump. Unlike Figure 39, the heating demand curve presents more variation because the temperature of the water is constant and when the indoor temperature drops, the consumption of the heating demand undergoes a rise.

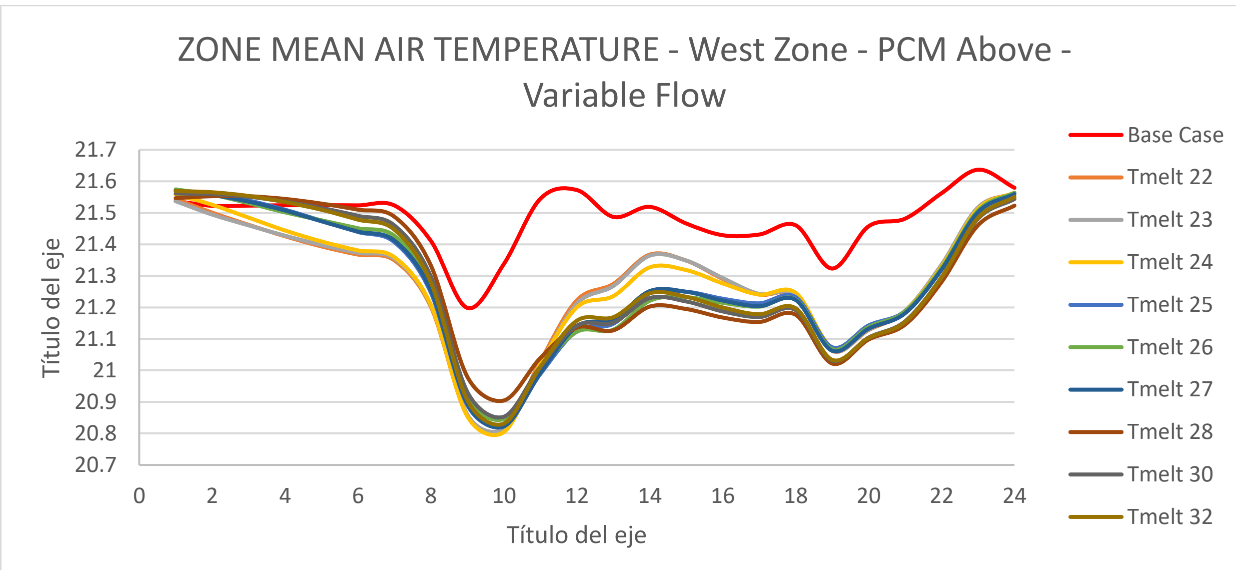

Figure 38. Zone mean air temperature - West zone - PCM Above - Variable Flow. Source: Own.

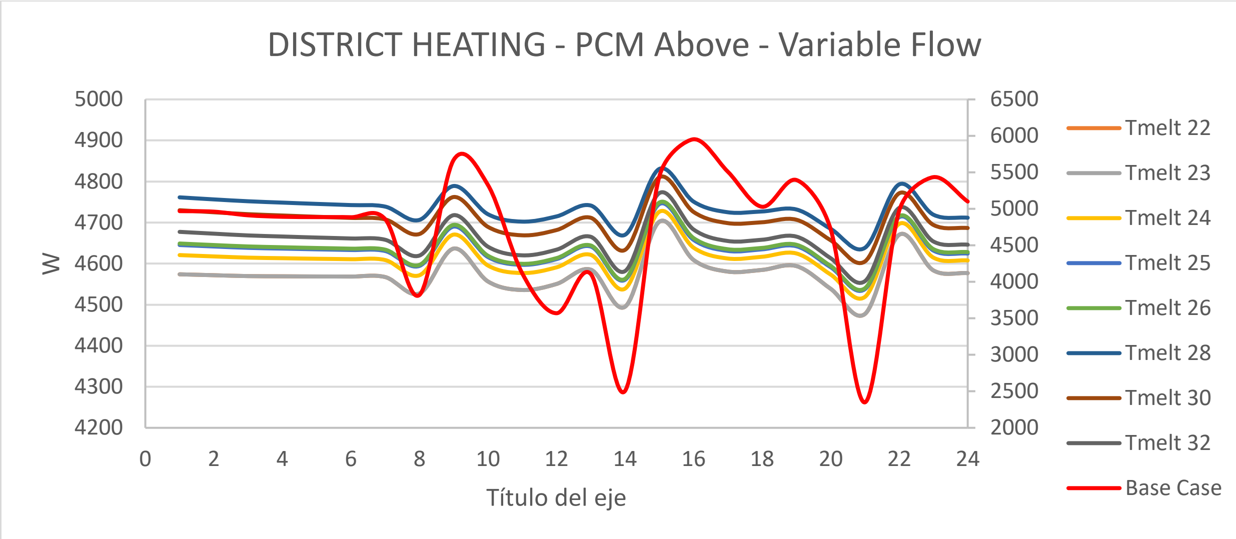

Figure 39. Heating demand - West zone - PCM Above - Variable Flow. Source: Own.

Finally, Figure 40 shows the numerical results of Table 6 and Table 7. Both configurations have got almost the same behavior, but in compare with Figure 34, the difference of the total energy between the configurations are higher. In the same way, in Figure 41, the peak loads for the case where the PCM is below the heating system is higher.

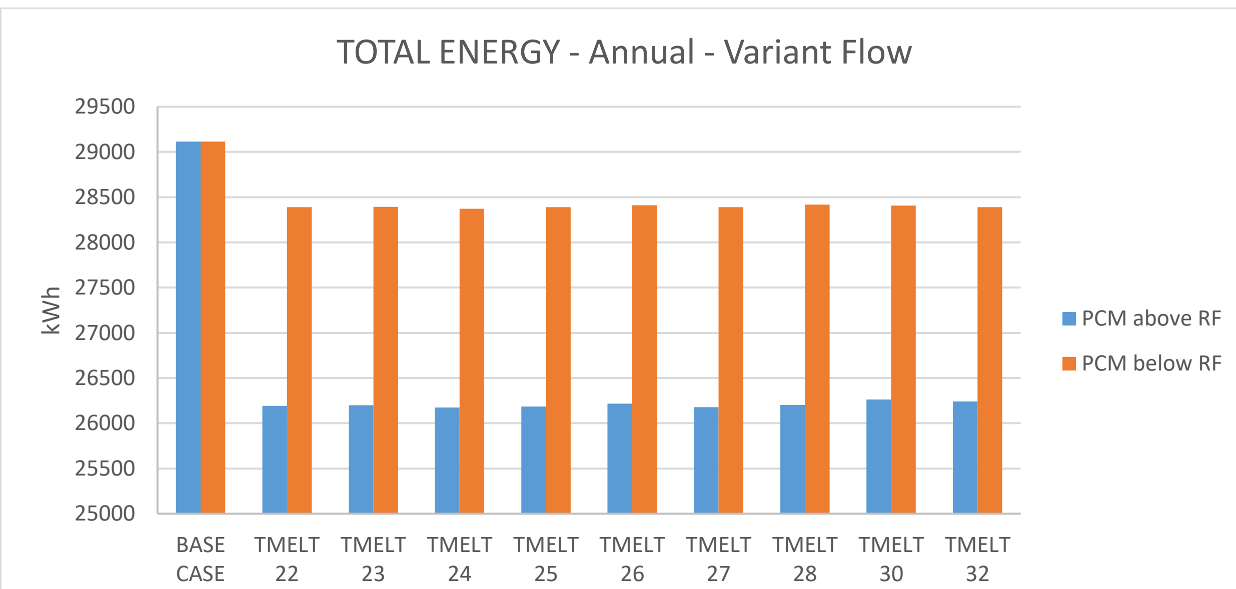

Figure 40. Total Energy - Variable Flow. Source: Own.

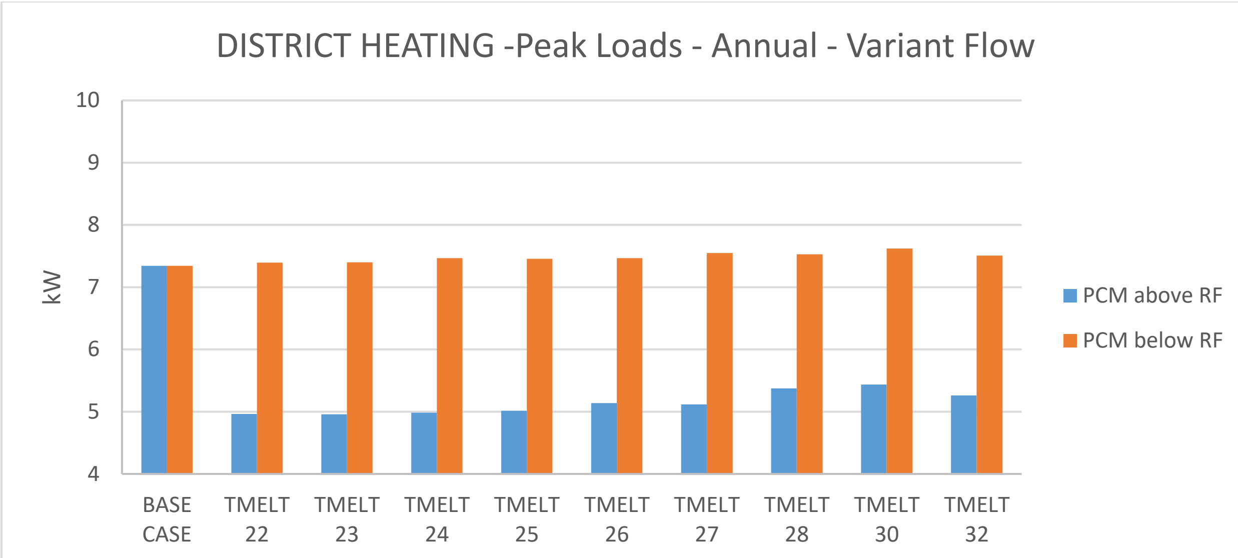

Figure 41. District Heating - Peak Loads - Variable Flow. Source: Own.

5.3. Discussion Case 1 and Case 2

To sum up case 1 and 2, both total energy consumption and the peak loads for both cases represent a higher value when the PCM is installed below the heating system. Therefore, both peak loads and total energy can be drastically reduced when introducing PCM above and shifted to nighttime when the electricity costs are lower. Despite this, the indoor temperature and the heating demand represents a fainter variation for the case where the PCM is above and the temperature of the PCM is preserved for a longer time after the heating is stopped and thus, it leads to economic savings.

As the location 'above' the heating systems leads to a lower total energy and peak load, it will be the one selected for the next cases.

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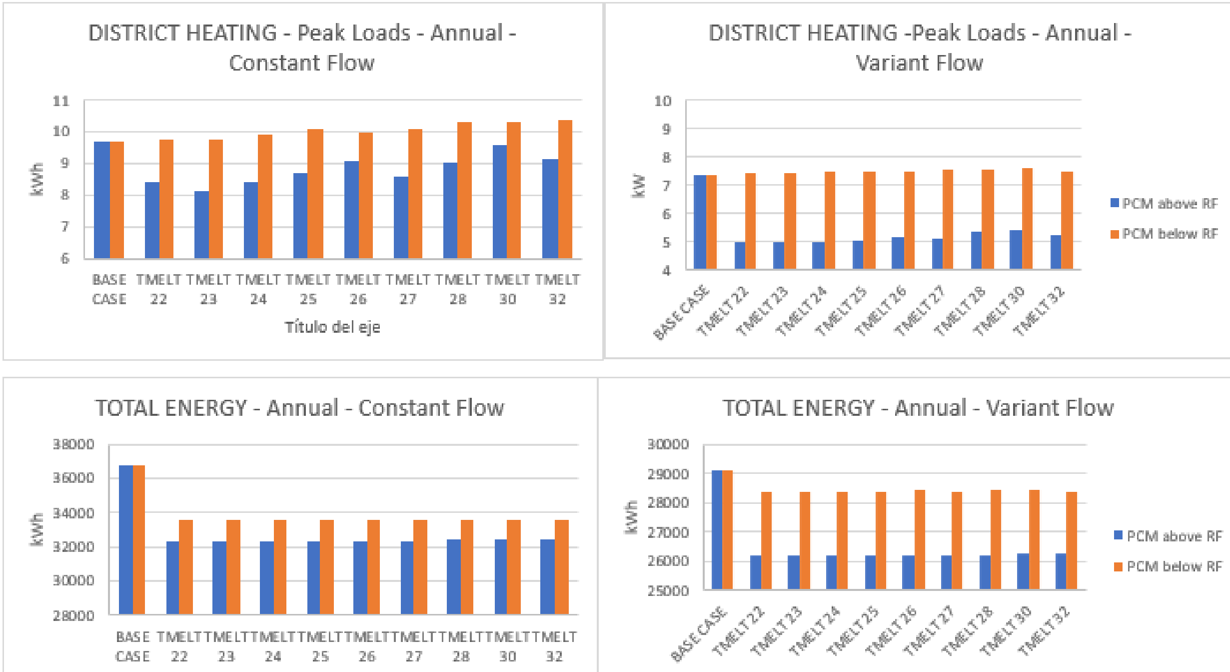

Figure 42. Resume of the results for case 1 and 2. Source: Own.

Focusing in Figure 42, the minimum values for total energy and heating demand where chosen in order to obtain the range of melting point that suits both parameters. Thus:

1. <u>Constant Flow</u>. A minimum total energy consumption of 32279.63 kWh that corresponds to 24^0C melting point. A minimum peak load of 8.133 kW that corresponds to 23^0C melting point.
2. <u>Variant Flow</u>. A minimum total energy consumption of 26176.10 kWh that corresponds to 24^0C melting point. A minimum peak load of 4.957 kW that corresponds to 23^0C melting point.

Finally, the melting temperature range chosen for the next cases are 23ºC - 24ºC.

5.4. Case 3: Variation of the amount of PCM for case 1

In this case, a variation of the amount of PCM will be simulated for the case where the heating system has constant flow. This variation, as previously said, will be done through the number of layers installed in the floor construction between the heating system and the floor tile.

Figure 43 shows the variation of the total energy consumption as introducing more layers of the PCM wallboard. In compare with the base case (red bar), the percentage of savings of the total energy consumption that can be achieved with 10 layers is 15.66%. In the other side, the percentage of savings of the heating demand (Figure 44) that can be achieved with 10 layers is 17.9% which is more or less the same quantity for the savings in peak loads (17.66% - Figure 45).

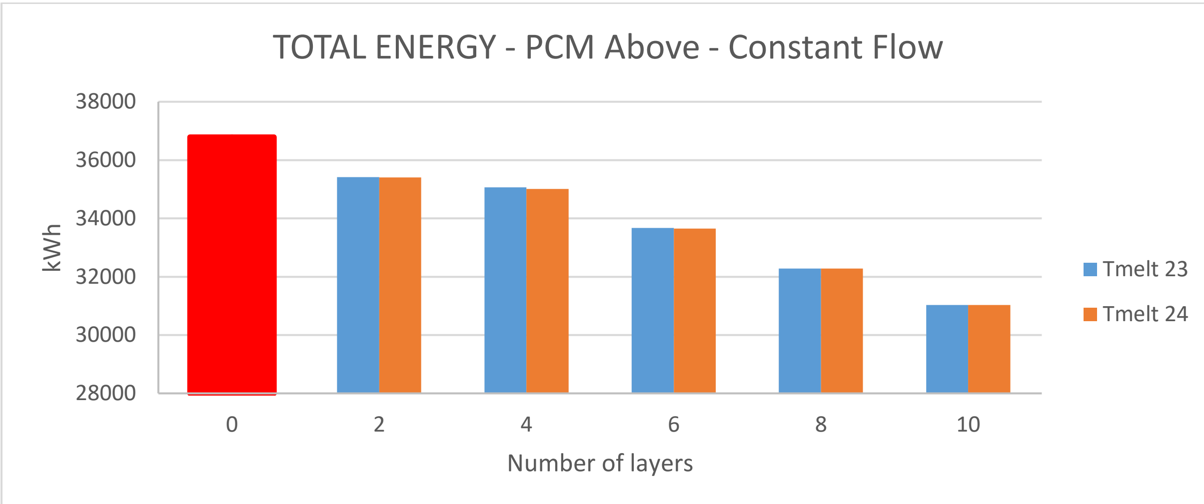

Figure 43. Total Energy - PCM Above - Constant Flow. Variation of the amount of PCM. Source: Own.

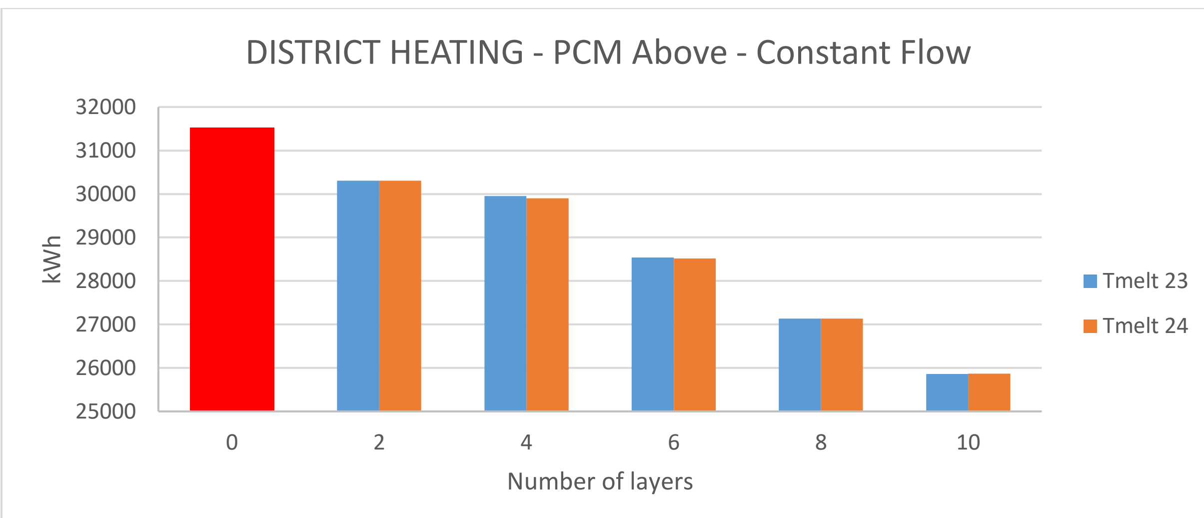

Figure 44. Heating demand - PCM Above - Constant Flow. Variation of the amount of PCM. Source: Own.

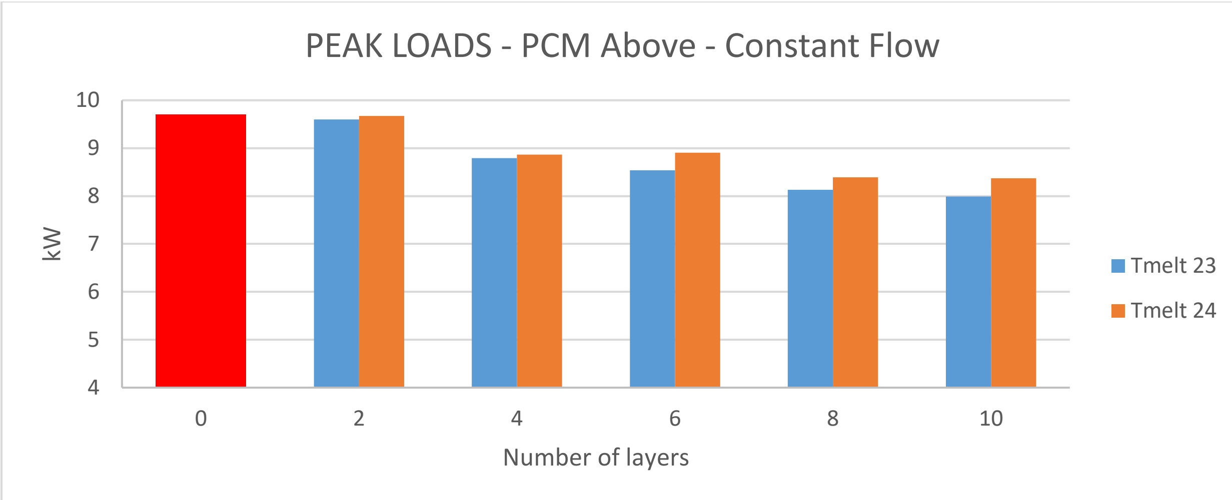

Figure 45. Peak loads - PCM Above - Constant Flow. Variation of the amount of PCM. Source: Own.

5.5. Case 4: Variation of the amount of PCM for case 2

In this case, a variation of the amount of PCM will be simulated for the case where the heating system has variant flow. This variation, as previously said, will be done through the number of layers installed in the floor construction between the heating system and the floor tile.

Figure 46 shows the variation of the total energy as introducing the PCM wallboards. In this case a saving percentage of 13.42% of the total energy is achieved with 10 layers in compare with the base case (red bar). In the other side, 22.2% of heating demand can be saved by adding 10 layers and 35% of the peak load in compare with the base case.

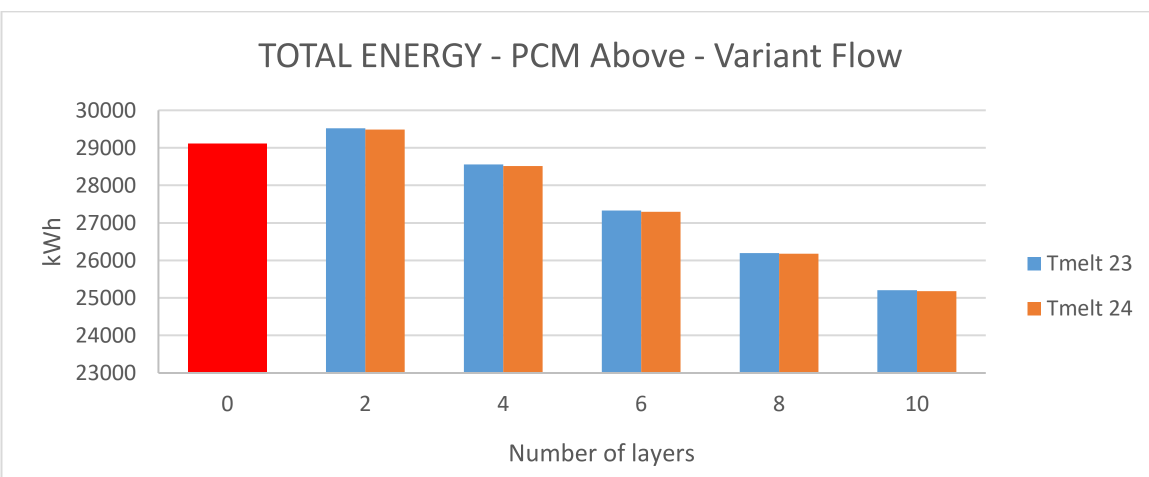

Figure 46. Total Energy - PCM Above - Variant Flow. Variation of the amount of PCM. Source: Own.

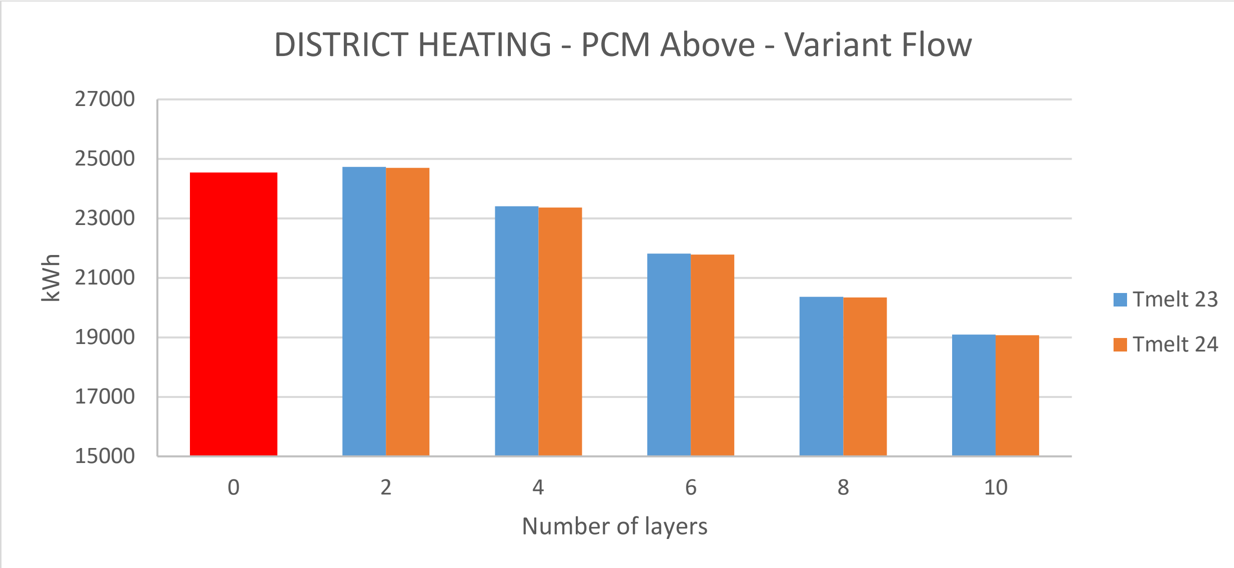

Figure 47. Heating Demand - PCM Above - Variant Flow. Variation of the amount of PCM. Source: Own.

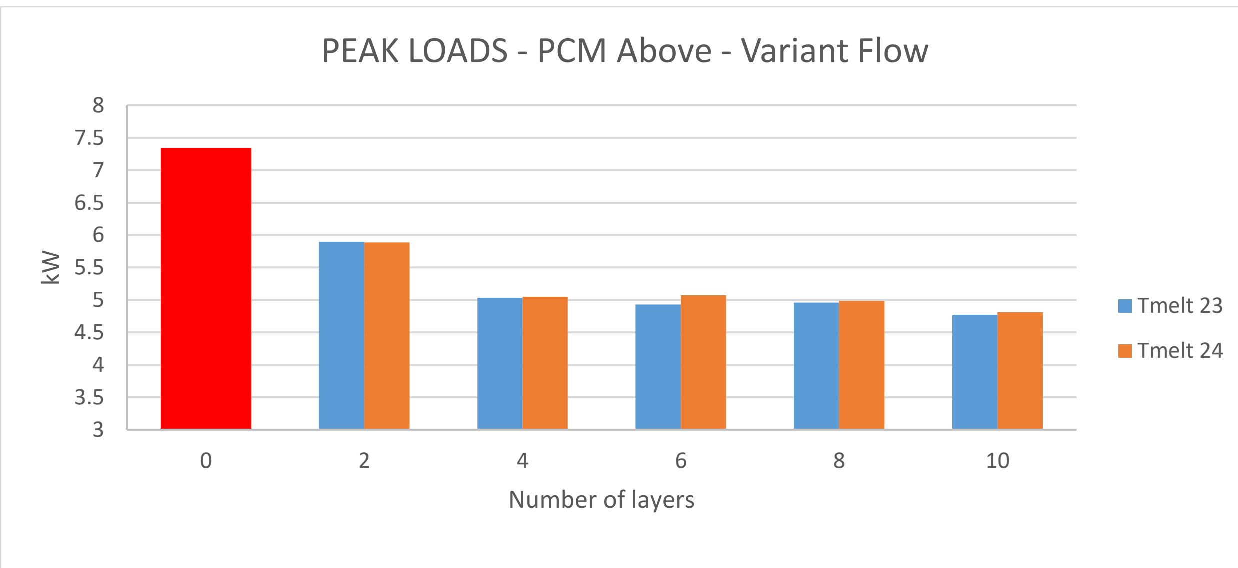

Figure 48. Peak loads - PCM Above - Constant Flow. Variation of the amount of PCM. Source: Own

5.6. Discussion Case 3 and 4

Figure 49 resumes the results of cases 3 and 4, where the melting points of 23ºC-24ºC have got approximately the same results, varying as maximum in 4%.

Focusing in case 3 and compare it with the base case (red bar) a maximum saving of 15.6% of the total energy can be achieved by adding 10 layers, but by adding 8 layers this saving is 12.25%. In the other side, by adding 10 layers the savings in heating demand is 17.9% and for 8 layers is 13.92%. In the case of the peak loads, 10 layers equals to 17.66% of savings and 8 layers equals to 16.19% of savings.

Focusing in case 4 and compare it with the base case (red bar) a maximum saving of 13.4% of the total energy can be achieved by adding 10 layers, but by adding 8 layers this saving is 10%. In the other side, by adding 10 layers the savings in heating demand is 22.2% and for 8 layers is 17.02%. In the case of the peak loads, 10 layers equals to 35% of savings and 8 layers equals to 32.4% of savings.

Therefore, in both cases, as the percentage of savings is approximately the same for 10 and 8 layers, and adding more layers means more costs to the installation, then, 8 layers of PCM wallboard would be the ideal.

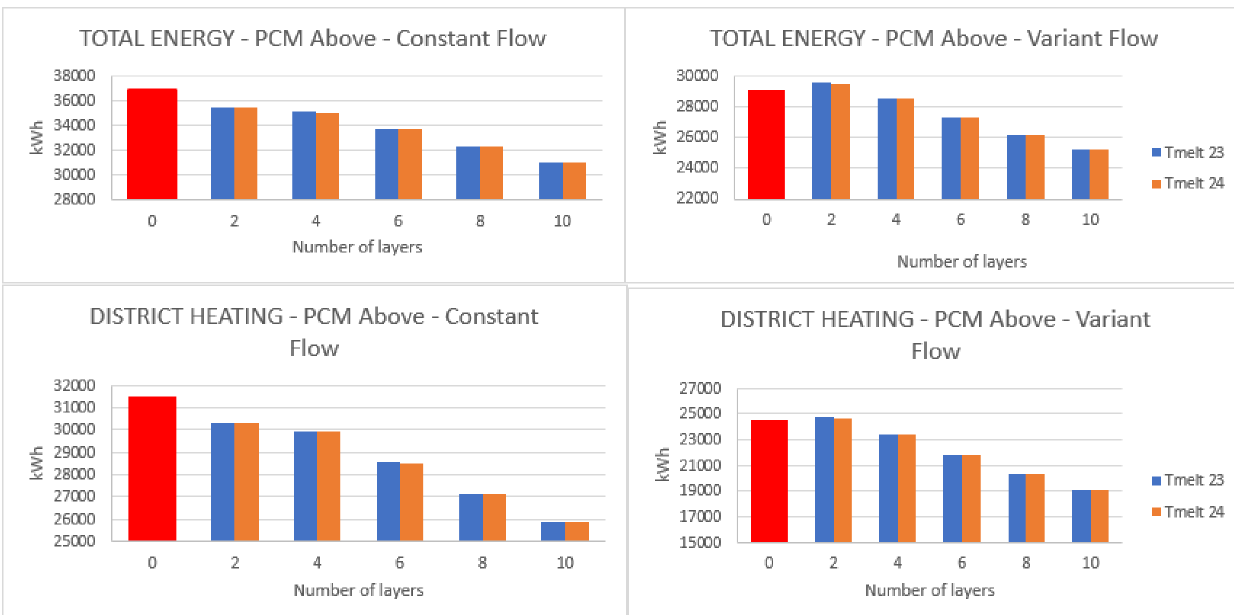

Figure 49. Resume of the results for case 3 and 4. Source: Own.

CHAPTER 6: CONCLUSIONS

In this study, PCM was incorporated to a residential building in Denmark, that uses radiant floor as a heating system, in order to figure out the PCM melting temperature range that reaches the lowest heating demand and total energy consumption. Once obtained this range, different simulations will be done by varying the amount of PCM in order to know how it affects the total energy consumption and the heating demand. Finally, a percentage of savings is identified for the mentioned parameters in compare with the base case (without PCM).

1. The melting point range that reaches the lowest heating demand and total energy consumption for case 1 and 2 is 23^0C-24^0C.
    a. According to [46] the melting point that reaches an indoor temperature of 22^0C, a floor surface of 28^0C-30^0C was set at 35^0C-45^0C. The location of the building is in South Korea and the PCM used id n-paraffin PCM (RT-44 Rubitherm).
    b. [47] Obtains a temperature range of 26^0C-30^0C. The PCM selected is Micronal PCM which is the raw material of Smartboard 26. The PCM is in walls and roof.
    c. [48] Obtains a melting range of 27^0C-29^0C. The PCM selected is paraffin Energain.
    d. [49] States that the optimum melting temperature range depends strongly on the climate, where normally in cooling dominant climates PCM temperature is around 24^0C-26^0C.
2. The results in case 3 and 4 show that by adding PCM to the floor the indoor temperature is reduce by up to 0.9192^0C (for case 3, location of the PCM above) without introducing another type of ventilation and/or cooling system.
    a. This is in accordance with [47] where the indoor temperature is reduce by up to 1.2^0C.
3. Case 3 achieved a heating demand savings of 17.9% and total energy consumption savings of 15.6%. In the other side, case 4 achieved a heating demand savings of 22.2% and total energy consumption savings of 13.4%.
    a. According to [50] which uses approximately the same initial values for the heating systems achieves a total energy savings of 17.7% and 20.5% for a water temperature of 35.6^{o}C.
    b. [48] Achieves energy savings of 32%.

Finally, the results show that the use of PCM in the floor coupled with a radiant floor heating system can reduce both, total energy consumption and the heating demand; besides, the indoor temperature can be reduced by up to 0. 9192^{0}C. In the other side, the variation of the amount of PCM show a large reduction in heating demand by up to 22.2%, furthermore, in the case of the radiant floor with variable flow shows lower heating demand and total energy consumption in compare with the base case.

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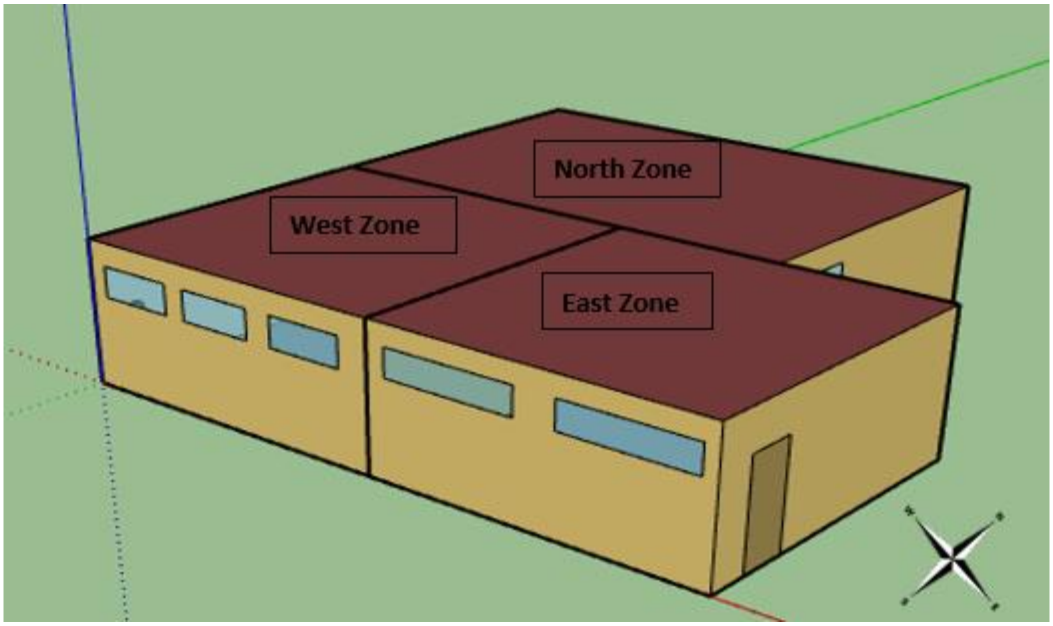
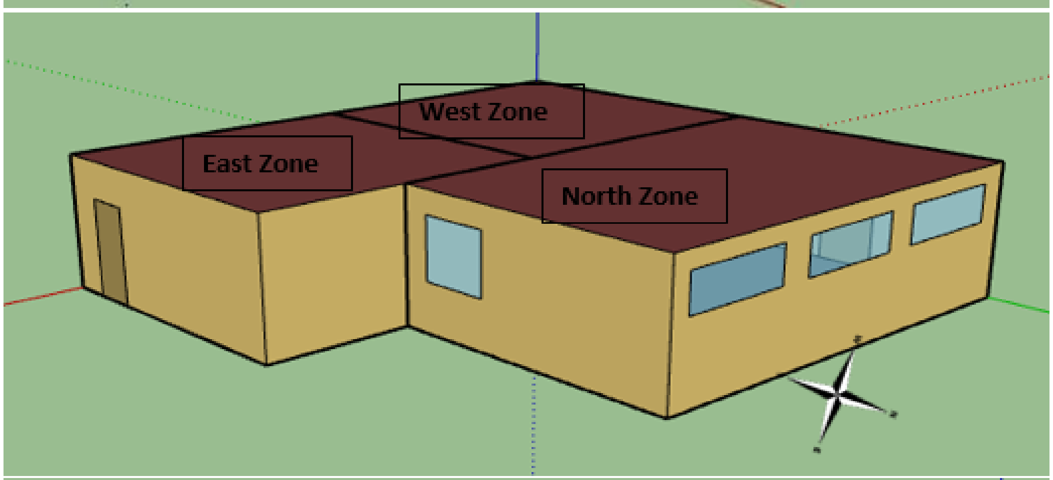
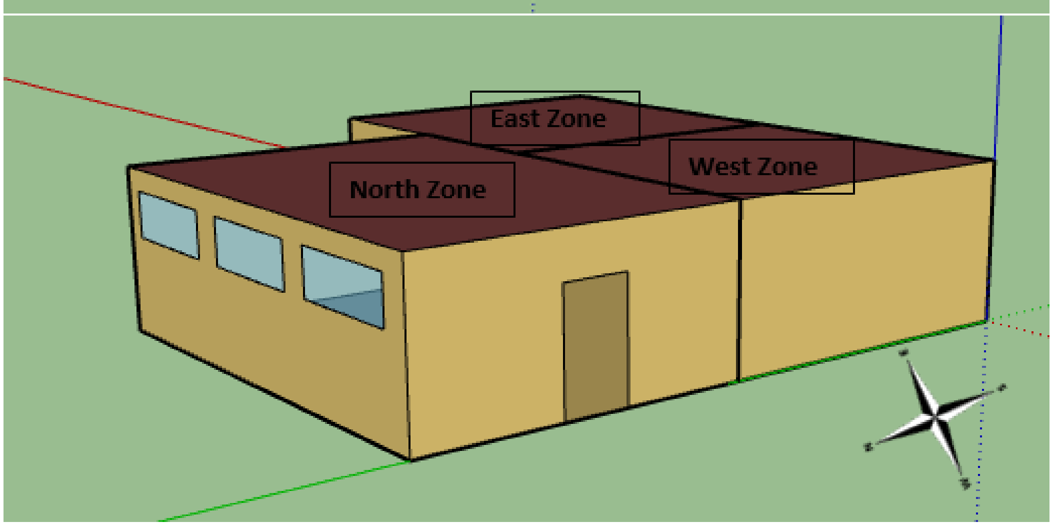
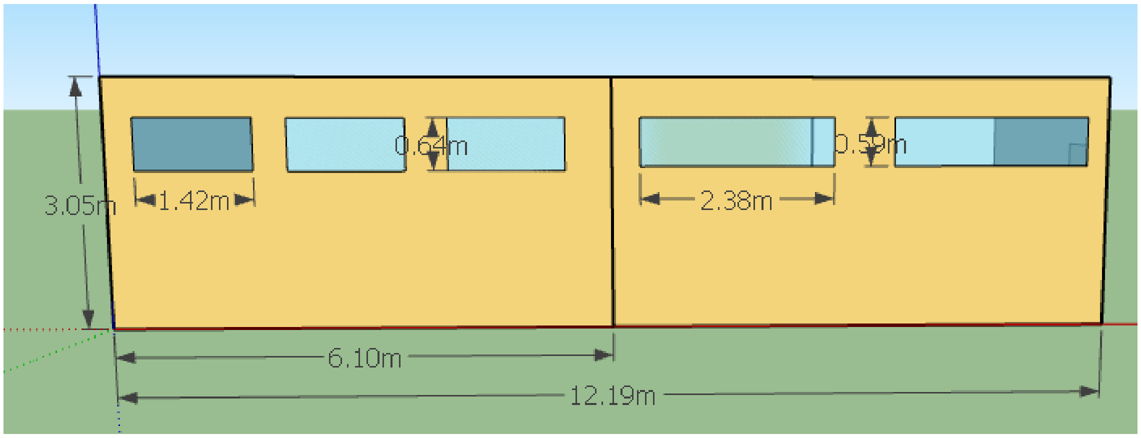
APPENDIX 1: BUILDING DIMENSIONS





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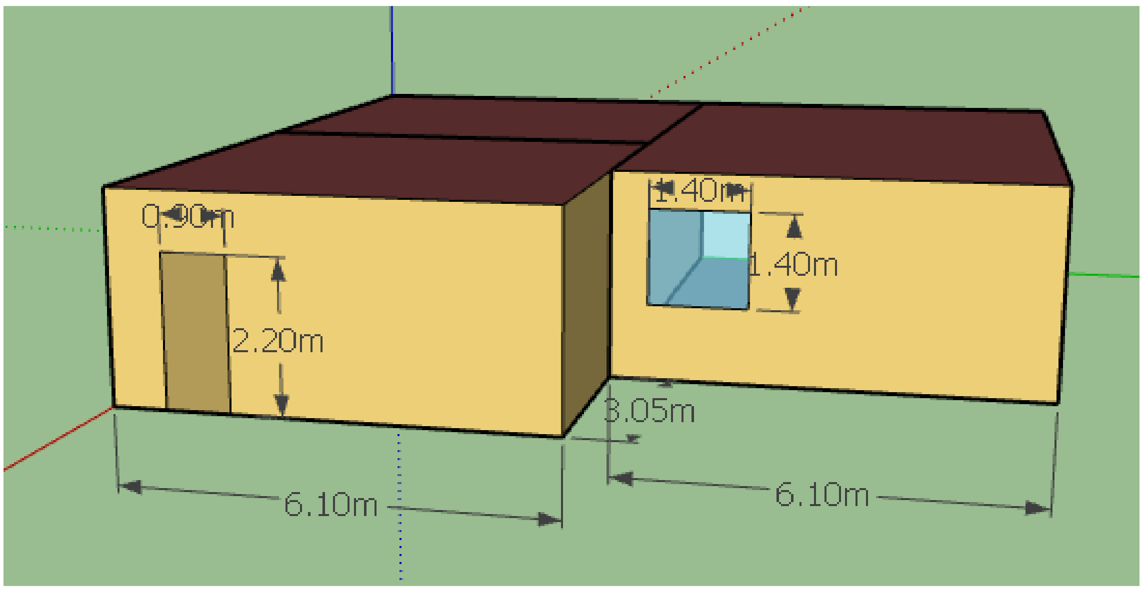
12.19m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3.05m
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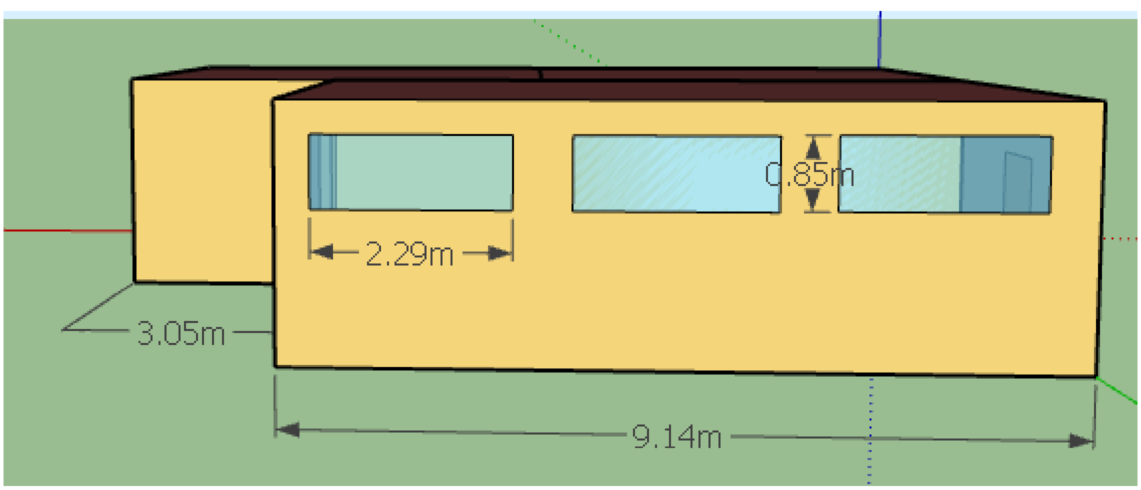
6.10m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0.85m
3.05m
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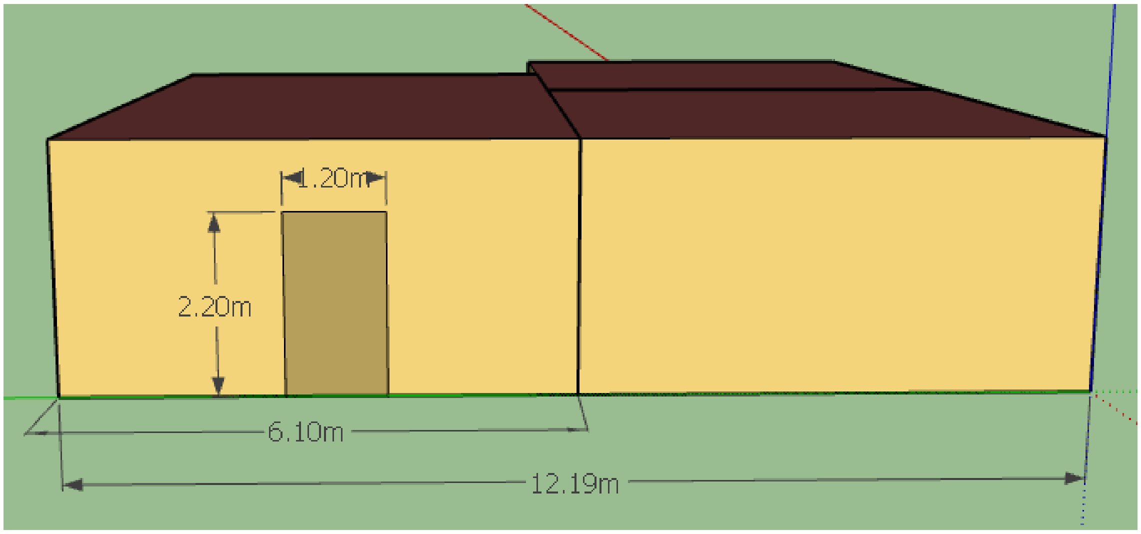

1.20m
2.20m
6.10m
12.19m

APPENDIX 2: HEAT TRANSFER RESOLUTION

For **conduction**, the equation used is ´Fourier´s Law that relates the heat flux to the temperature:

$$q'' = -k\Delta T \tag{1}$$

Where:
q'' is the local heat transfer rate per unit area, $\frac{W}{m^2}$
k is the thermal conductivity, $\frac{W}{m\,K}$
ΔT is the temperature gradient, ℃

For **convection**, the algorithm used is Thermal Analysis Research Program (TARP). In this model, the convection is split in natural (h_n) and forced (h_f) components. The sum of these components is the total convection (h_c).

$$h_c = h_f + h_n \tag{2}$$

$$h_f = 2{,}537\ W_f R_f \left(\frac{PV_z}{A}\right)^{\frac{1}{2}} \tag{3}$$

Where:
W_f = 1 for windward surfaces or 0.5 for leeward surfaces
R_f = surface roughness multiplier based on ASHRAE graphs of surface conductance and can be obtained from:

Roughness Index	Rf	Example Material
1 (Very Rough)	2.17	Stucco
2 (Rough)	1.67	Brick
3 (Medium Rough)	1.52	Concrete
4 (Medium Smooth)	1.13	Clear pine
5 (Smooth)	1.11	Smooth Plaster
6 (Very Smooth)	1.00	Glass

For the **natural convection** component, it correlates the convective heat transfer coefficient to the surface orientation and the difference between the surface and the zone air temperature.

For **conduction finite difference (CondFD)**, which is used when the PCM is implemented, uses the Crack Nicolson scheme which is semi-implicit.

For this scheme, EnergyPlus uses 4 types of nodes shown in the figure below: (1) interior surface nodes, (2) interior nodes, (3) material interface nodes and (4) external surface nodes.

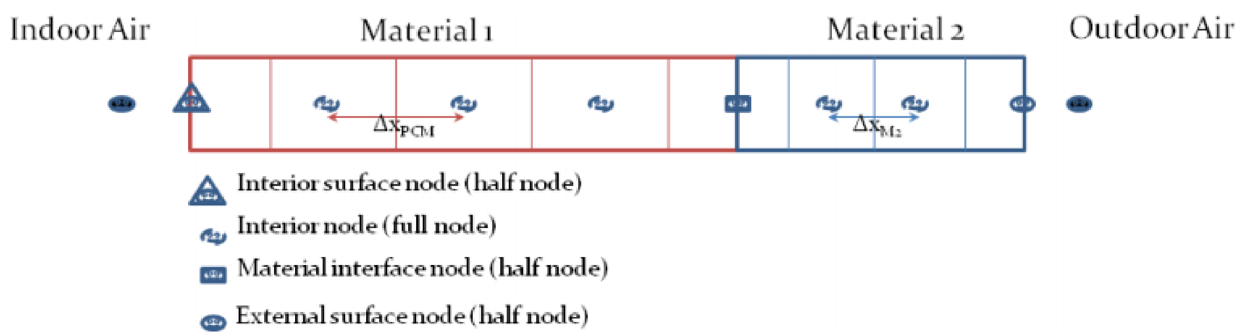


Figure 50. APPENDIX 2: Heat transfer resolution. Node depiction for CondFD. Source: EnergyPlus Engineering Reference.

The discretization of the surface (Δx) depends on the thermal conductivity of each material (α) and the time step (Δt) selected (time step = 20, meaning that the calculations are done every 3 minutes).

$$\Delta x = \sqrt{C\alpha\Delta t} \quad (4)$$

$$C = \frac{1}{Fo} \quad (5)$$

$$Fo = \frac{\alpha\Delta t}{\Delta x^2} \quad (6)$$

Where:
C = 3 (default value) space discretization
Fo = Fourier number

The number of nodes for each layer is calculated by rounding the result from dividing the length of the material layer by the result of the equation 4. After this, the discretization of the surfaces is calculated again by dividing the length of the material by the number of nodes.

Due to the iteration used in this model, the node enthalpies get updated and they are used to develop a new specific heat (C_p) when a phase change material is simulated.

$$C_p = \frac{h_{i,new} - h_{i,old}}{T_{i,new} - T_{i,old}}$$

Where:
$h_{i,X}$ *= new or old enthalpy of node i*
$T_{i,X}$ *= new or old temperature of node i*

APPENDIX 3: PCM ENTHALPY CURVES

Melting temperature = 22^{o}C

Enthalpy (J/kg)	Temperature (^{o}C)
6500	16
9000	17
15000	18
21500	19
28500	20
37500	21
73000	22
85000	23
93500	24
104000	25
115500	26
121500	27
125000	28
130000	29
134500	30
138500	31

Melting temperature = 23^{o}C

Enthalpy (J/kg)	Temperature (^{o}C)
5000	15
9000	16
13500	17
18000	18
21000	19
30500	20
39000	21
58000	22
84500	23
92000	24
103500	25
119000	26
124500	27
127000	28
130000	29
135000	30

Melting temperature = 24^{o}C

Enthalpy (J/kg)	Temperature (^{o}C)
5000	16
9000	17
13500	18
18000	19
21000	20
30500	21
39000	22
58000	23
84500	24
92000	25
103500	26
119000	27
124500	28
127000	29
130000	30
135000	31

Melting temperature = 25^{o}C

Enthalpy (J/kg)	Temperature (^{o}C)
5000	17
9000	18
13500	19
18000	20
21000	21
30500	22
39000	23
58000	24
84500	25
92000	26
103500	27
119000	28
124500	29
127000	30
130000	31
135000	32

Melting temperature = 26^{o}C

Enthalpy (J/kg)	Temperature (^{o}C)
5000	18
9000	19
13500	20
18000	21
21000	22
30500	23
39000	24
58000	25
84500	26
92000	27
103500	28
119000	29
124500	30
127000	31
130000	32
135000	33

Melting temperature = 27^{o}C

Enthalpy (J/kg)	Temperature (^{o}C)
5500	19
9500	20
14000	21
17500	22
21000	23
29000	24
49000	25
90000	26
102500	27
119000	28
147000	29
156500	30
160000	31
163500	32
166500	33
170000	34

Melting temperature = 28^{o}C

Enthalpy (J/kg)	Temperature (^{o}C)
5500	20
9500	21
14000	22
17500	23
21000	24
29000	25
49000	26
90000	27
102500	28
119000	29
147000	30
156500	31
160000	32
163500	33
166500	34
170000	35

Melting temperature = 30^{o}C

Enthalpy (J/kg)	Temperature (^{o}C)
5500	22
9500	23
14000	24
17500	25
21000	26
29000	27
49000	28
90000	29
102500	30
119000	31
147000	32
156500	33
160000	34
163500	35
166500	36
170000	37

Melting temperature = 32^{o}C

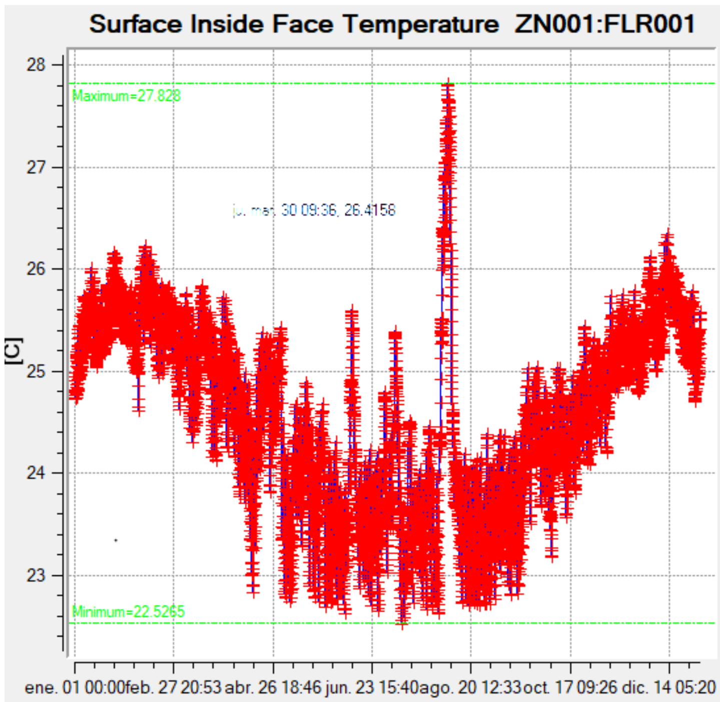
Enthalpy (J/kg)	Temperature (^{o}C)
5500	22
10000	23
17500	24
24000	25
30500	26
45000	27
75000	28
98000	29
107500	30
118000	31
136500	32
146500	33
151000	34
155000	35
157000	36
160000	37

APPENDIX 4: SIMULATIONS RESULTS

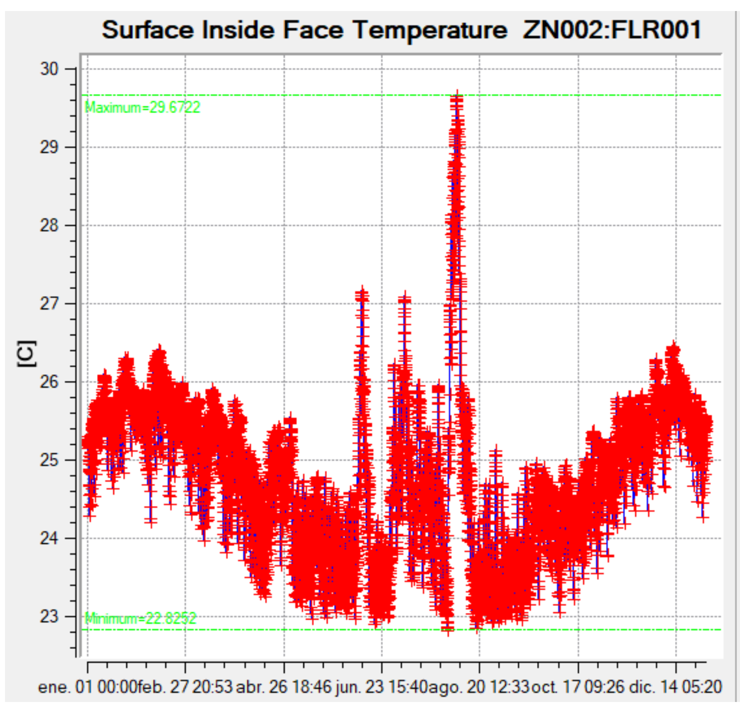
ANNUAL SIMULATION _ VARIABLE FLOW

SURFACE FLOOR TEMPERATURE

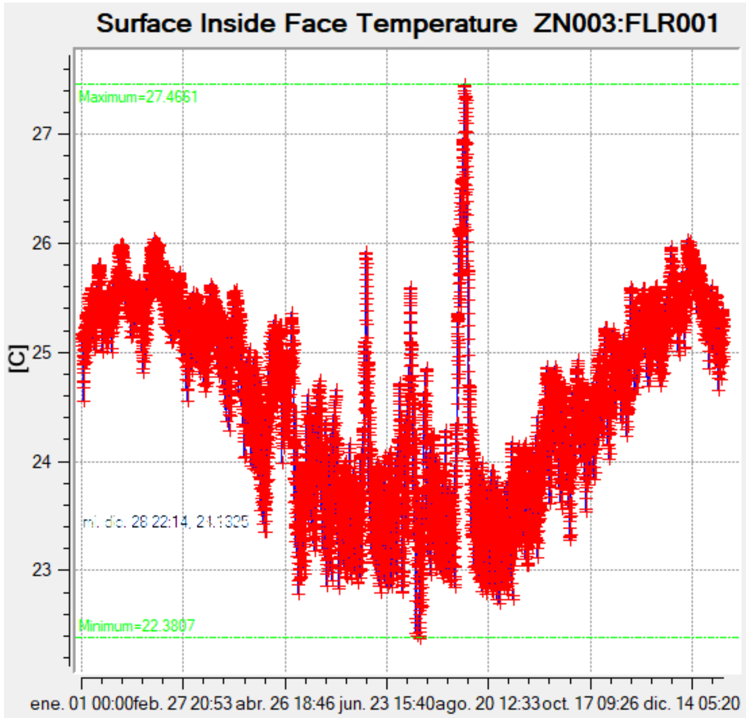
- West Zone



- East Zone

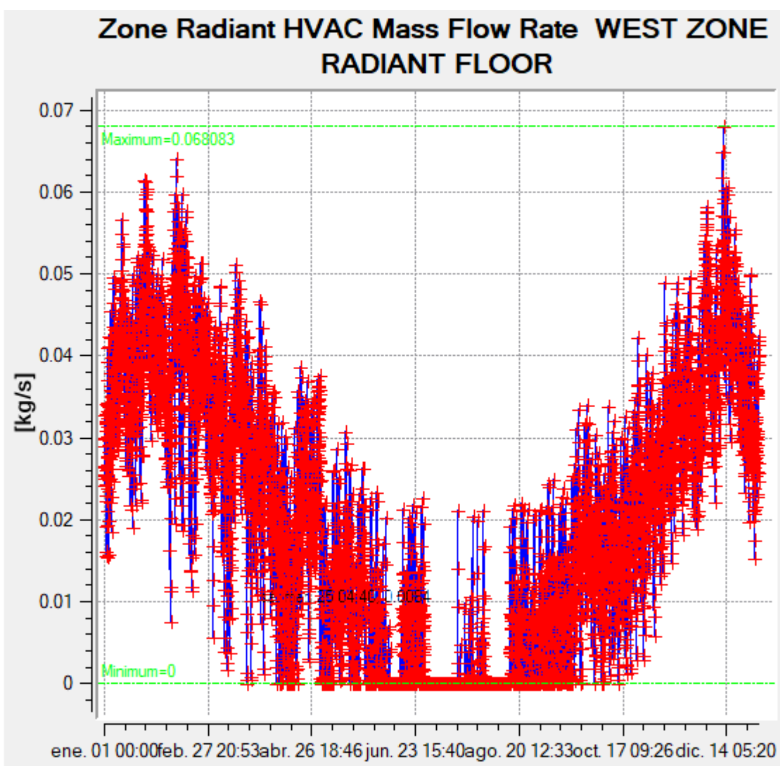


- North Zone

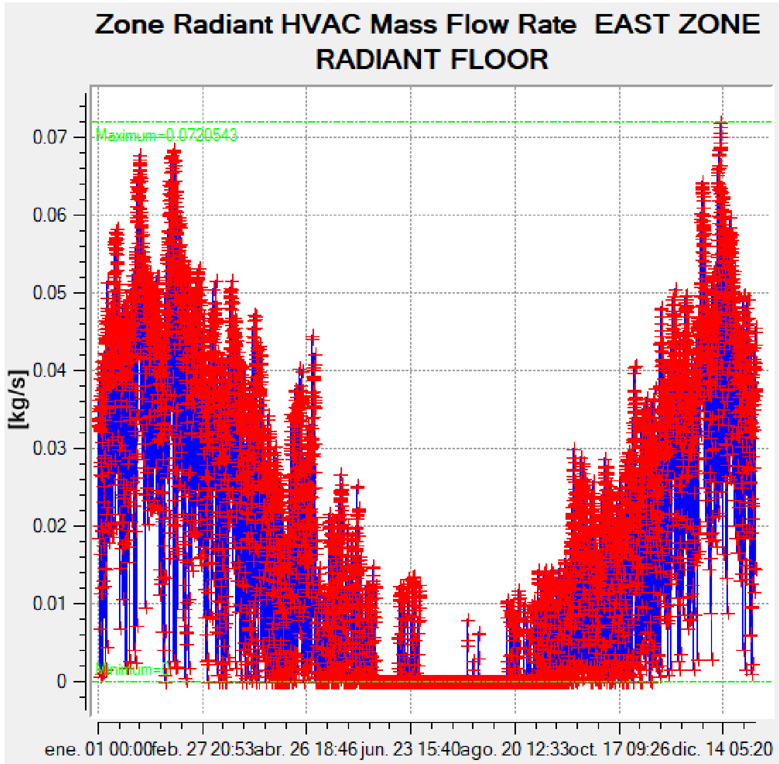


MASS FLOW RATE

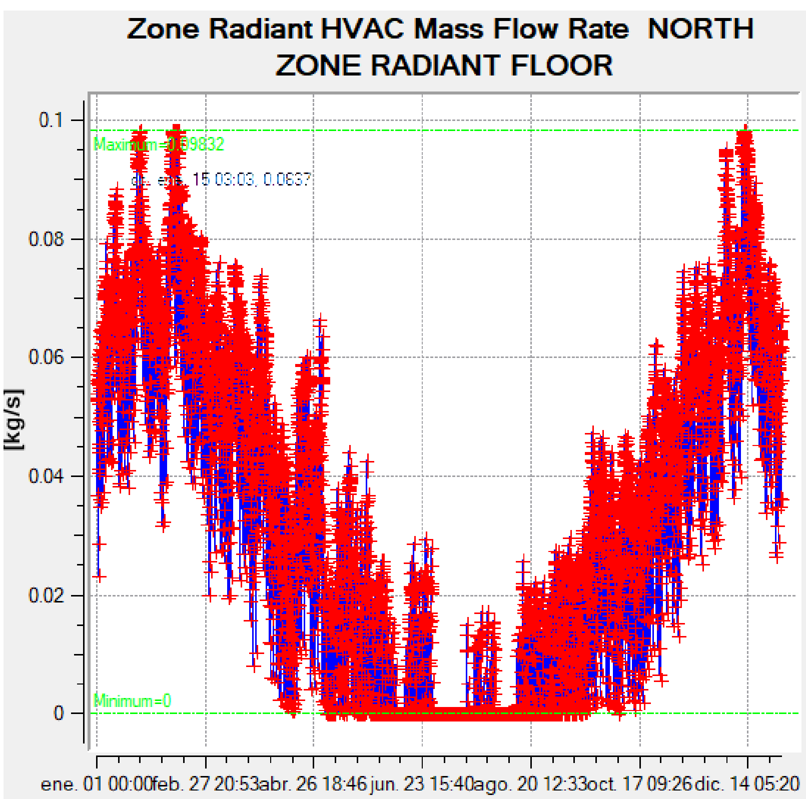
- West zone



- East zone

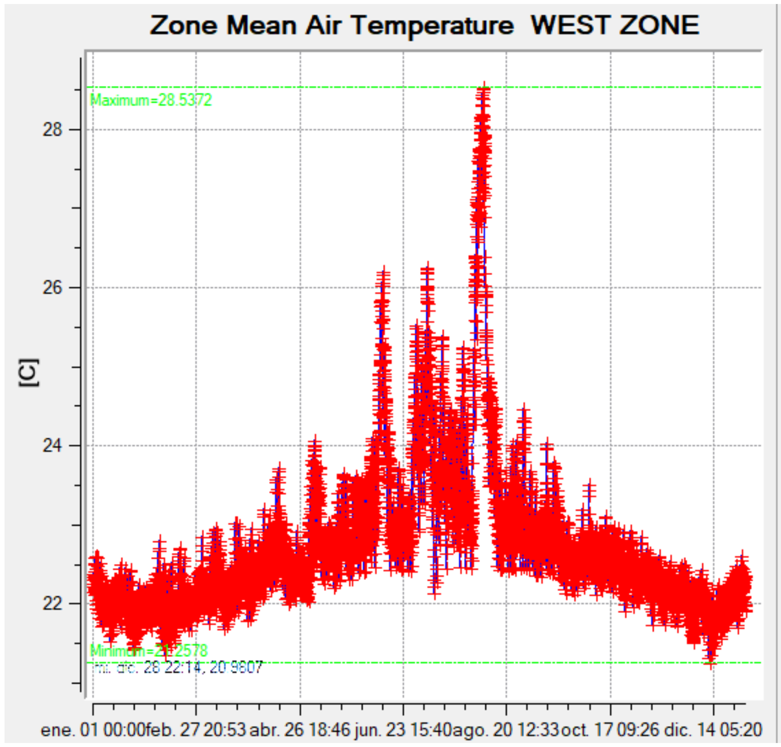


- North zone

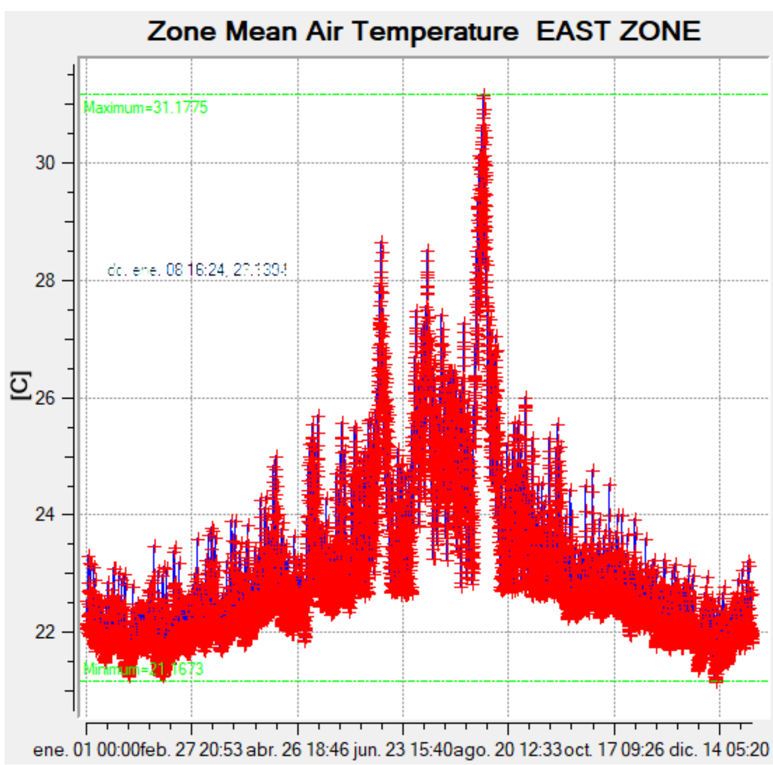


INDOOR TEMPERATURE

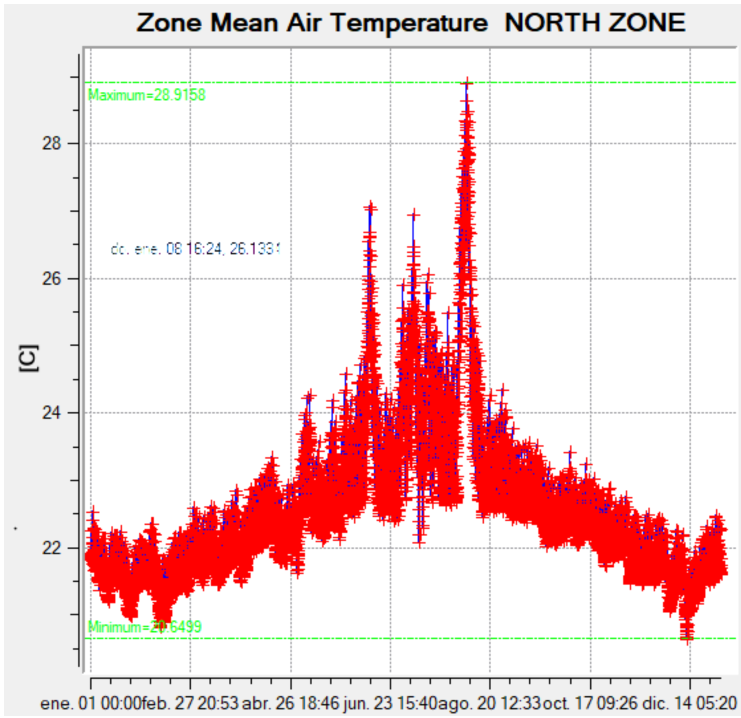
- West zone



- East zone



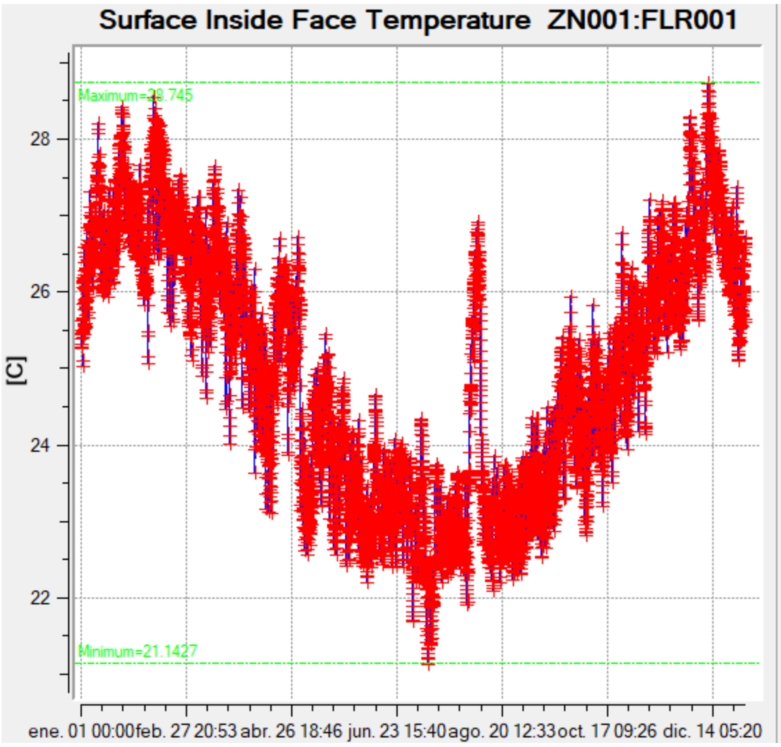
- North zone


Zone Mean Air Temperature NORTH ZONE
Maximum=28.9158
Minimum=20.6499
28
26
24
22
[C]
ene. 01 00:00
feb. 27 20:53
abr. 26 18:46
jun. 23 15:40
ago. 20 12:33
oct. 17 09:26
dic. 14 05:20

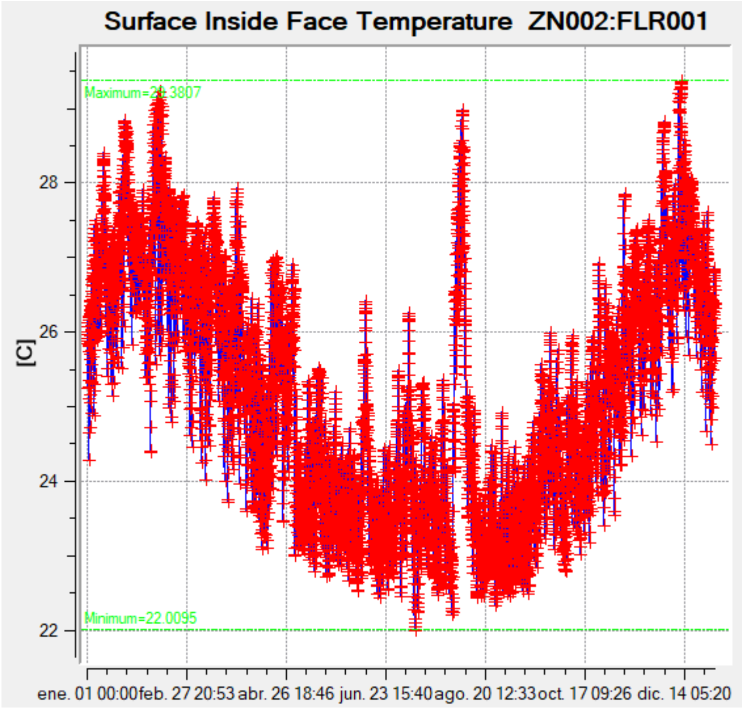
ANNUAL SIMULATION _ CONSTANT FLOW

<u>*SURFACE FLOOR TEMPERATURE*</u>

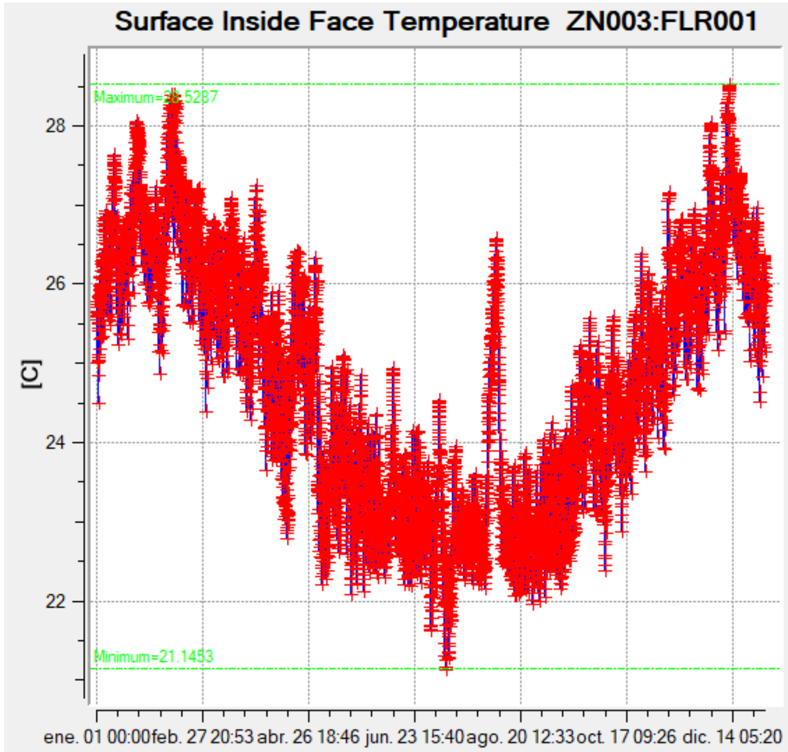
- West zone



- East zone

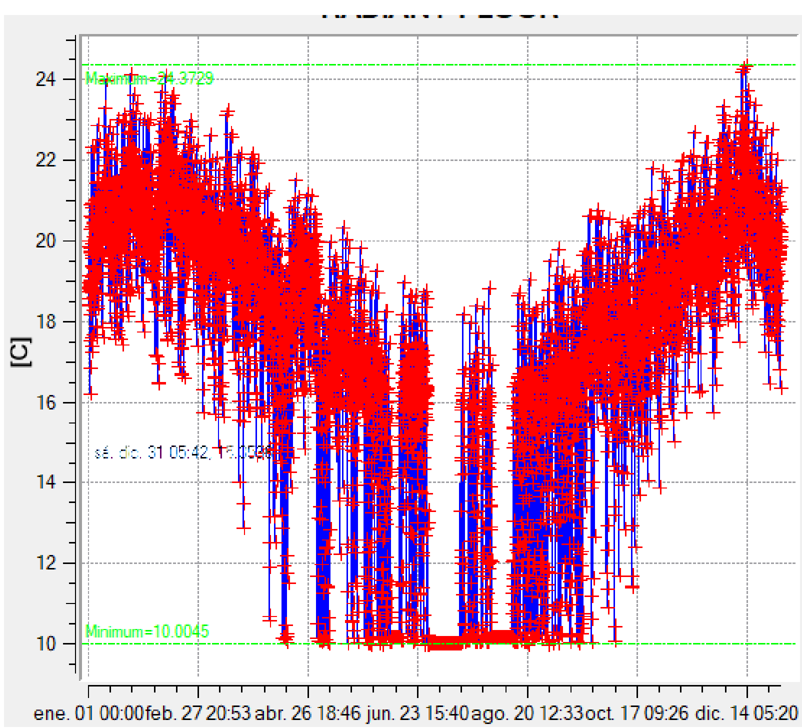


- North zone

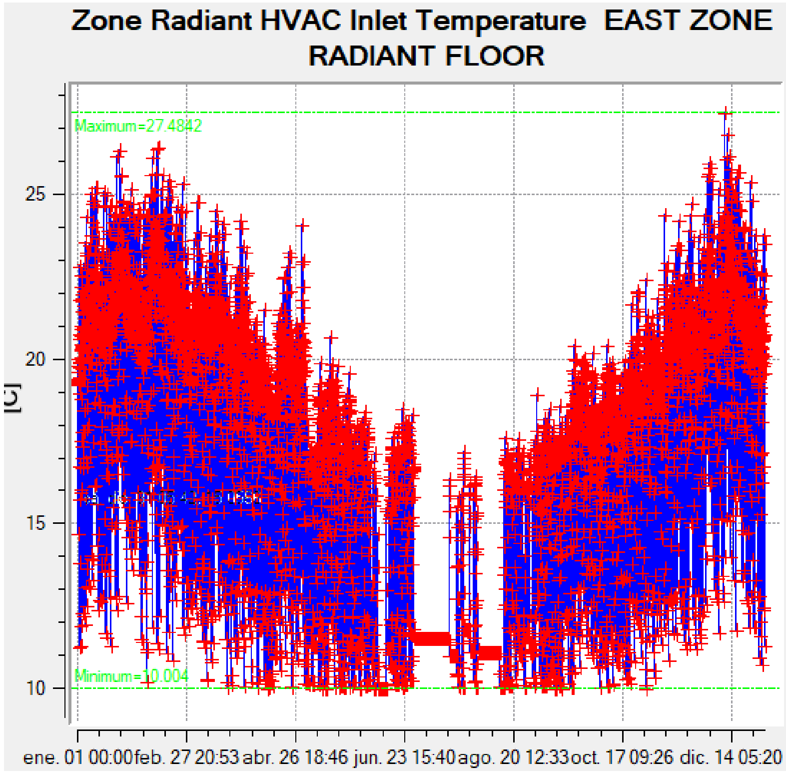


__INLET TEMPERATURE__

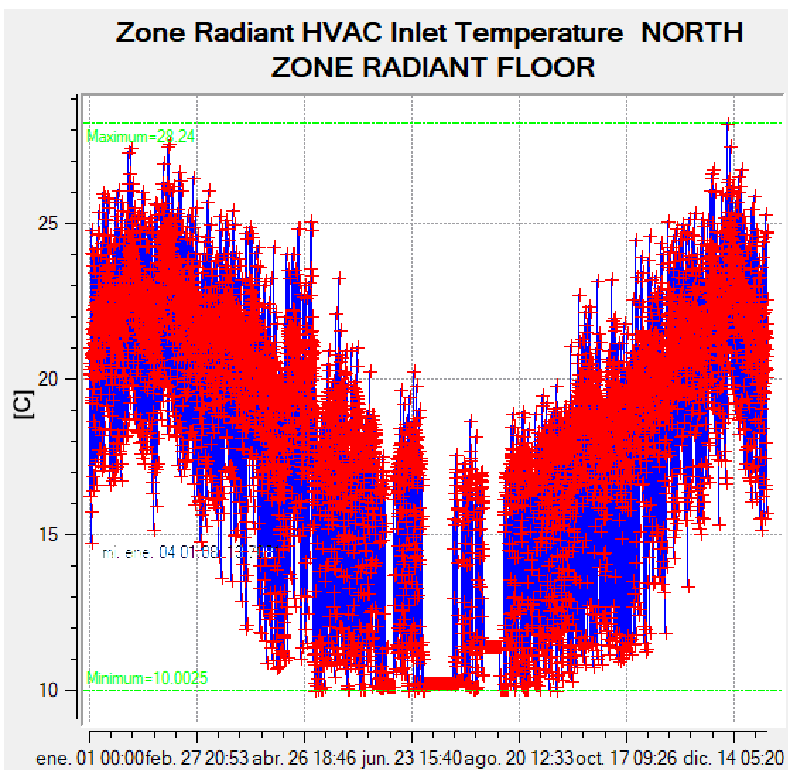
- West zone



- East zone

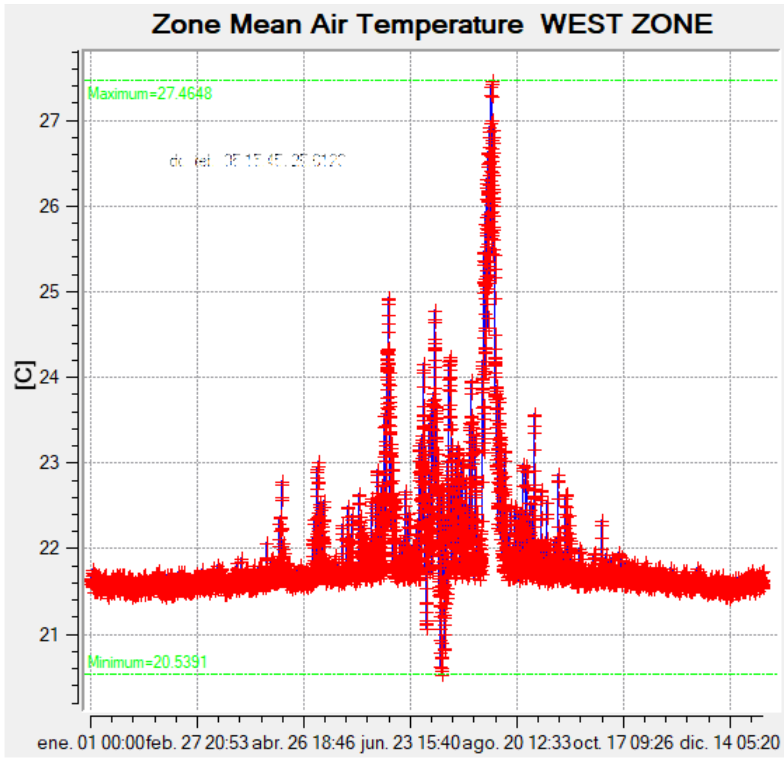


- North zone

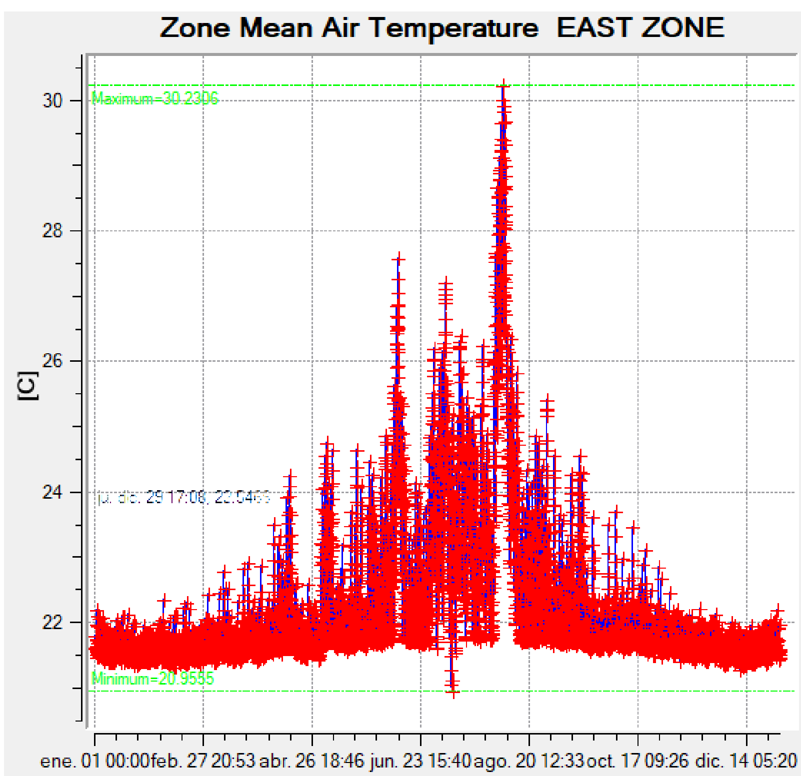


INDOOR TEMPERATURE

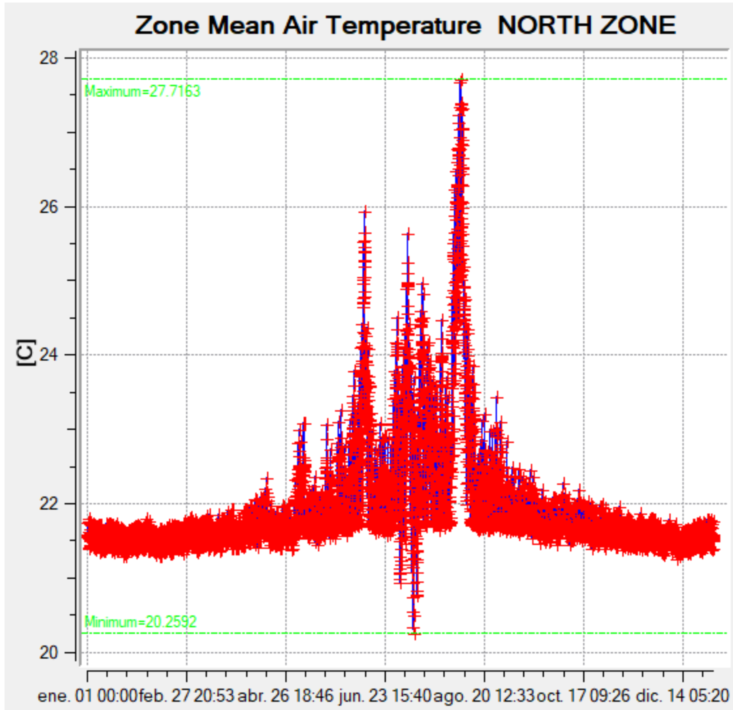
- West zone



- East zone



- North zone


Zone Mean Air Temperature NORTH ZONE
28
26
[C] 24
22
20
Maximum=27.7163
Minimum=20.2592
ene. 01 00:00
feb. 27 20:53
abr. 26 18:46
jun. 23 15:40
ago. 20 12:33
oct. 17 09:26
dic. 14 05:20