Estudo de um sistema de armazenamento térmico com transição de fase

Pedro Daniel Resende e Silva

2015

ABSTRACT:

The objective of this thesis is to give a district heating and cooling plant the ability to store the excess thermal energy for later use in periods of peak heat demand. So, this work includes research and consolidation of existing knowledge of thermal energy storage techniques with focus on phase change materials related subjects

The result was the elaboration of an *Excel* based simulator which permits the estimation of the service water temperature exiting the equipment and the amount of PCM in a phase, in this case solid, in a 24 hour operation cycle. The chosen equipment for the PCM implementation was a shell and tube heat exchanger, with the PCM lodged in the annular region of the tubes. A similar strategy could be used if other types of equipment are desired for study. For this, design variants of the simulator will have to be calculated for the equipment.

The simulator enabled the study of various configurations of the industrial process, some of which met the operation requirements for storage and discharge of thermal energy. For each standard heat exchanger in the case study, it will be needed 4 heat exchangers with PCM implemented in a series. Their estimated dimensions are 7 meters in length and respectively 3m, 3m, 2,8m and 2,7m. Achieving a total of 12 heat exchangers which would completely eliminate the need of auxiliary steam production for peak heat demand periods by using 24,2% of the excess heat produced by the present process.

Introduction

Energy can have many forms, like thermal, chemical, electric, and kinetic amongst others and it´s present in humanity´s everyday activities. Using data available from the *International energy Agency* [1] it´s possible to observe the growth tendency of energy consumption worldwide like shown in Fig.1

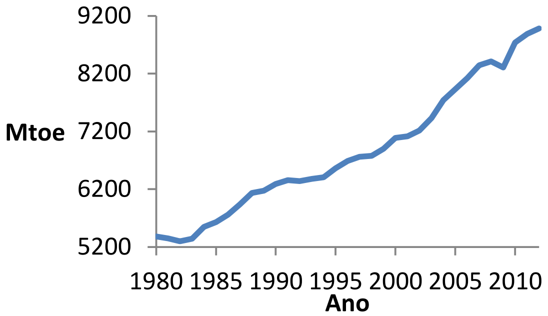
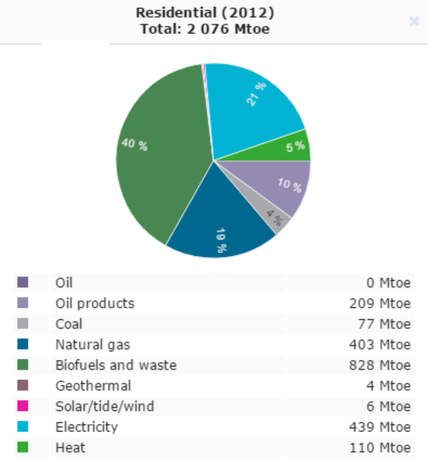


Figura 1 – Worldwide energy consumption. Data supplied by IEA [1]

The data available at the International energy Agency´s website also enables us to correlate daily lives activities with energy sources consumption, see Fig 2.

Even taking in account that it´s not possible to ascertain from which source was electricity produced, it can be inferred that fossil fuel are still heavily relied upon to meet energy demands. Also it can be considered the following: 1. Unstable Oil market; 2. Fossil fuel usage is responsible for various of environmental damage(?); 3. Ever increasing energy demand. All this contributes to the world energy crisis.

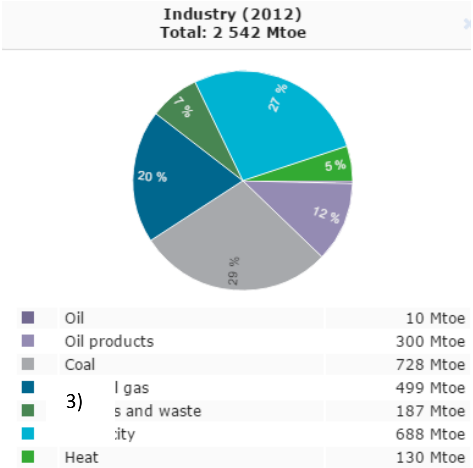
The state of affairs in this issue has led to an increasing interest in non-polluting renewable sources of energy and in efficient energy usage. This work is focused in an application that supports the latter.



Residential (2012)
Total: 2 076 Mtoe

Oil	0 Mtoe
Oil products	209 Mtoe
Coal	77 Mtoe
Natural gas	403 Mtoe
Biofuels and waste	828 Mtoe
Geothermal	4 Mtoe
Solar/tide/wind	6 Mtoe
Electricity	439 Mtoe
Heat	110 Mtoe

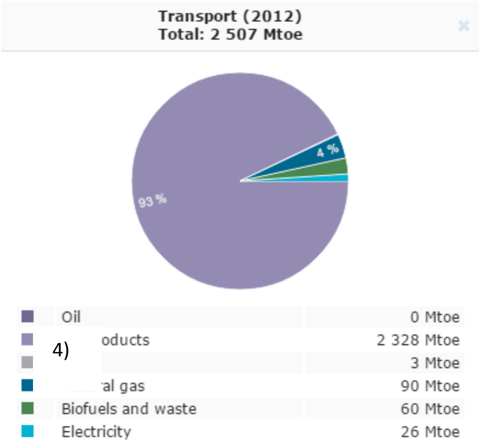
2)



Industry (2012)
Total: 2 542 Mtoe

Oil	10 Mtoe
Oil products	300 Mtoe
Coal	728 Mtoe
l gas	499 Mtoe
s and waste	187 Mtoe
:ity	688 Mtoe
Heat	130 Mtoe

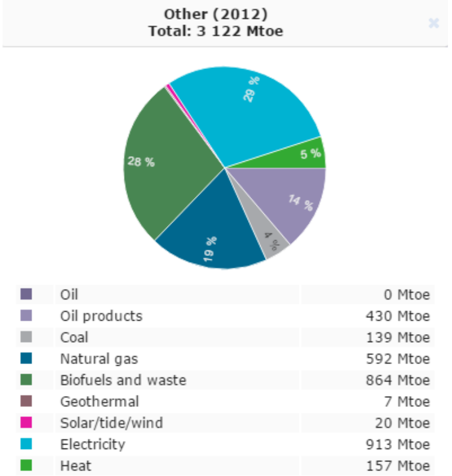
3)



Transport (2012)
Total: 2 507 Mtoe

Oil	0 Mtoe
oducts	2 328 Mtoe
	3 Mtoe
:al gas	90 Mtoe
Biofuels and waste	60 Mtoe
Electricity	26 Mtoe

4)



Other (2012)
Total: 3 122 Mtoe

Oil	0 Mtoe
Oil products	430 Mtoe
Coal	139 Mtoe
Natural gas	592 Mtoe
Biofuels and waste	864 Mtoe
Geothermal	7 Mtoe
Solar/tide/wind	20 Mtoe
Electricity	913 Mtoe
Heat	157 Mtoe

Fig 2 – Absolute and relative values of consumption of various energy sources in 1) Residential zones, 2) Industry, 3) Transport industry and 4) others sources of energy consumption like commercial zones.

One of the main drawbacks of some of renewable sources of energy is it´s fluctuation and intermittent nature. Energy storage development is a possible solution that could address this drawback. This solution consists in the storage of energy that then could be supplied as demanded to the process in question. This could be also used to address the issue of waste excess energy produced in some industrial complexes.

Some forms of energy storage are mechanical, electric, and thermal, among others. In the thermal energy storage there are three types: sensible heat, latent heat storage and thermochemical heat storage. Sensible heat storage depends on the heat capacity of the material whilst latent heat storage relies upon it´s phase transition enthalpy variation. Thermochemical storage uses the heat generated, or consumed, by a ideally totally reversible reaction.

This work focuses on thermal energy storage in latent heat form, which relies on phase change materials (PCMs) to store heat in latent form. For this the material should possess a high enthalpy change in phase transition. The higher it is, the less material is needed, in mass.

This technology has uses in various industries like electronics, textiles, and medical and even in building construction. Usually the implementation of PCM enables thermal comfort without the use of energy from the grid, lessening the need for air conditioning equipment or decreasing the thermal load in heat sensitive equipment.

The case study of this work focuses on a heat and cold production and distribution facility. The objective is to harness and store the waste heat produced in excess on low heat demand periods and use this heat on the high demand periods. Eliminating the need to fire up additional heat producing equipment to meet the peak heat demands.

PCM properties

Although almost material could theoretically function as a latent heat storage phase change material. Certain materials are more prone to be selected for this function than others because of sought after properties like those presented in the table 4.

Properties	**Criteria**	**Effects**
Thermal	Adequate Phase change Temperature	Heat transfer driving force with PCM and heat transfer fluid.
	High phase transition enthalpy	Lower volume and mass of PCM needed
	Good thermal conductivity	Faster charge and discharge processes.
Physical	High Density	Container size reduction.
	Small Volume variations.	Design and technical challenges minimization
	Low vapor pressure	
Kinetic	No supercooling	A supercooling effect of 5-10ºC could stop the heat transfer process completely and force a restart.
	Crystallization Rate	A good crystallization rate may be enough to prevent.

Case Study

The heat and cold production facility has a tri-generation process, meaning it produces electricity, heat and cold in one process. The focus of this work is in the heat production part of the process. Fig.2

The process consists of a heat exchanger in which condensing steam heats up water for heat distribution. The steam is generated in a boiler using treated water in a closed cycle.

For this thesis, it was created a consumption profile for a day long operation cycle, that could simulate a realistic consumption behavior. A high consumption results in a lower temperature of the returning water from heat distribution, which also means a higher power demanded in heat energy.

In the development of this case study, it is considered that the base heat production from the gas turbine is such that provides more heat than it´s necessary in low heat demand periods but it´s less than the demand on peak demand periods, as is shown on Fig-3.

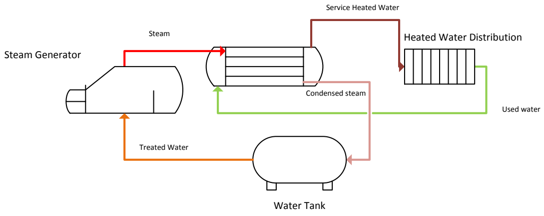


Fig 2 – Base case of the heat production and distribution process.

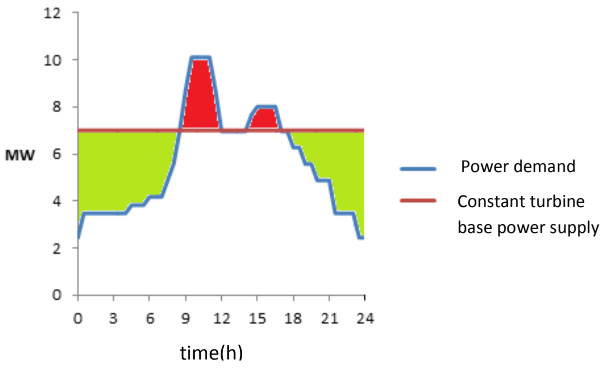


Fig 3 – Constant power supply vs Power demand

In order to reduce steam production costs, it´s desirable to eliminate the need to rely on auxiliary steam generators to meet the peak heat demands on the highlighted periods in red on Fig-3. One way to do this would be to store the excess heat produced in low heat demand periods, highlighted in green in Fig-3, and supply it as needed.

Solution Strategy

A possible strategy the implement for this case study is the use of secondary equipment with the ability to harness heat power from steam, when produced in the excess by the steam generator, and the ability to supply it as needed.

The first step needed is to know how much heat load can be supplied by the heat exchanger without PCM, including in the peak heat demand periods, in order to know how much of the main water stream is diverted to the new heat exchanger with PCM implemented.

Table-1 – Results of water load splitting between the primary and secondary heat exchangers (H.E.).

		Stream Flow (m^3/h)	**Peak Power Demand (MW)**
Case Base	Heat Exchanger	300	10,1
Energy Storage Strategy	Primary H.E. (no PCM)	207.9	7
	Secondary H.E. (PCM)	92.1	3.1
Splitting factor	30.7%		

As seen on Table-1, the water stream was split in a way that the gas turbine alone is capable of increasing the stream's temperature to the operational value for distribution. As the gas turbine has an output power of 7 MWs of heat which matches the peak demand of the reduced stream. As it is, the secondary heat exchanger will have to be able to provide the 3,1 MWs in heat to the remaining water flow, which will be supplied in full by the implemented PCM.

For this process to work, the amount of steam generated by the turbine has to be enough to heat up both streams. In table-2 is presented the excess heat provided and is compared with the heat needs of the secondary heat exchanger. The amount of heat generated by the gas turbine is originally more than enough for the total heat load of a daily operation cycle.

Table-2 Quantidades de calor trocado nos permutadores de calor operando 1 ciclo

	Total Water Mass (1 cycle, tons)	**Heat (GJ)**	**Excess/ Waste (GJ)**	
Case Base	7200	491,0	150,7	Desperdício
Primary H.E. (no PCM)	4989,3	340,2	264,6	Excesso
Secondary H.E. (PCM)	2210,7	150,8	-150,8	Requerido
Total	7200	491,0	113,8	Desperdício

The generated steam would be supplied to both heat exchangers, controlled by pressure levels, giving priority to the primary heat exchanger. In this manner, the PCM would be charged with heat during the low heat demand periods. In case of excessive pressure buildup on the process, excess heat will be released into the atmosphere with the combustion gases from the gas turbine.

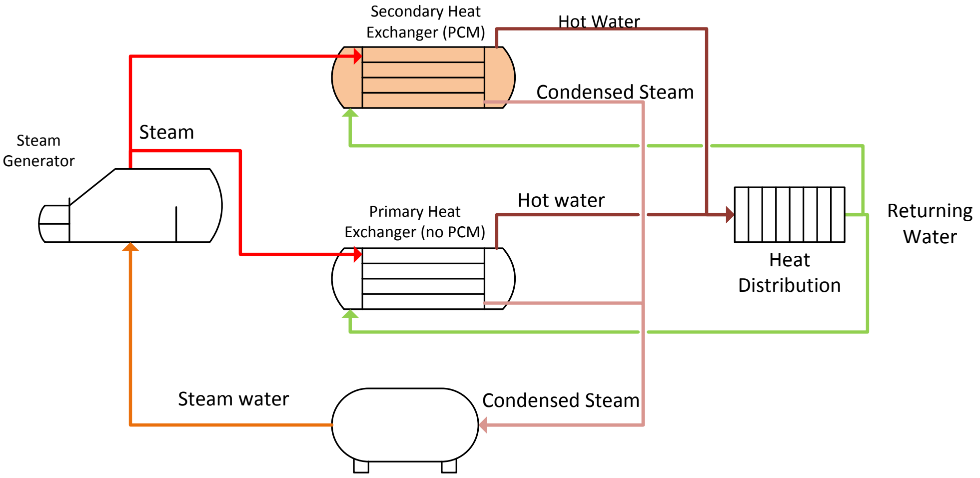


Fig 4 - Diagrama representativo do processo com PCM implementado

Choosing the PCM

In order to select which material to implement, we have to ensure that the material has a melting point temperature inside the operational range, above the hot water service temperature and below the steam condensation temperature, 100-180ºC.

Other desirable traits of a PCM are 1) high energy density; 2) no super cooling behavior; 3) Able to operate through a high number of cycles without degradation of heat storage and transfer characteristics.

The amount of PCM needed is then calculated based on the amount of heat that it has to be stored and supplied during the peak heat demand periods. Calculated through equation 1, it considers the heat power provided to the PCM during the discharging process.

$$M_{PCM} = \sum_{P=0}^{n} \frac{\int_{t_i}^{t_f} P_{descarga}(t)\,dt - \int_{t_i}^{t_f} P_{carga}(t)dt}{\Delta h_{fusão,PCM}} \quad (1)$$

There are two discharge periods are highlighted in red on Fig-1, the first being at 9:00-12:00 and the second 14:00-17:00 approximately. The totally energy required to be stored in the PCM is 36,8 GJ, which relates to values of PCM mass presented in table 4.

Considering mentioned traits, Erythritol is the most preferable PCM for the system. It features the highest energy density and has a melting point that enables a good driving force for heat transfer with both fluids. D-Mannitol could also be a good choice, but it suffers variations on its thermal properties because of polymorphic structural alterations after some operation cycles.

Table 3 – Properties of some materials that are considered for use as PCM [2].

Material	Ponto de Fusão ºC	Entalpia de Fusão kJ/kg	Densidade (kg/m^3)	Capacidade de armazenagem de calor (MJ/m^3)
Erythritol	120	339,8	1450	492,7
D-Mannitol	166-168	316,4	1520	480,9
E117 (EPS Ltd)	117	169	1450	245,1
A164 (EPS Ltd)	164	306	1500	459,0

Table 4 – Amount of heat that the PCM has to be able to supply in the discharge process and consequent results of mass needs.

Calor descarregado do PCM (GJ)	**36,8**			
Material	Melting Enthalpy kJ/kg	Heat Storage Capacity (MJ/m^3)	PCM Mass (ton)	PCM Volume (m^3)
Erythritol	339,8	492,7	108,4	74,8
D-Mannitol	316,4	480,9	116,4	76,6
E117 (EPS Ltd)	169	245,1	218,0	150,4
A164 (EPS Ltd)	306	459,0	120,4	80,3

Equipment

The equipment chosen for this process is a shell and tube heat exchanger. This equipment enables contact of the PCM with both the water circulating inside the tubes and the steam being fed to the shell side, by having the PCM applied around the tubes, like shown in Fig-5.

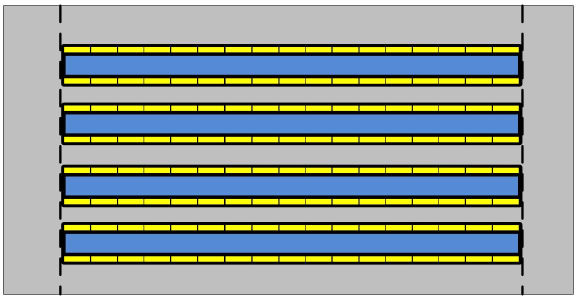


Fig 5 – PCM implementation schematic for a shell and tube heat exchanger.

In this study, it´s considered that the PCM adheres to the inner tube as it solidifies creating a PCM layer on it. The thickness of this layer will increase or decrease according to the ongoing process, being either the charging or discharging of the PCM. Both processes are illustrated in Fig-6 and Fig-7.

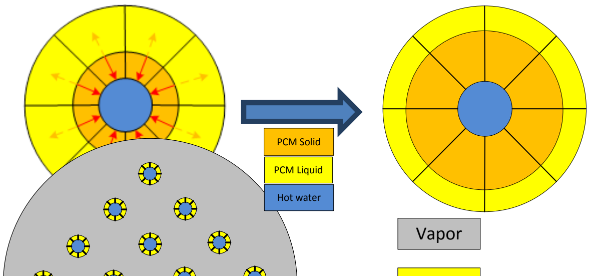


Fig 6 – Discharging process of PCM illustration

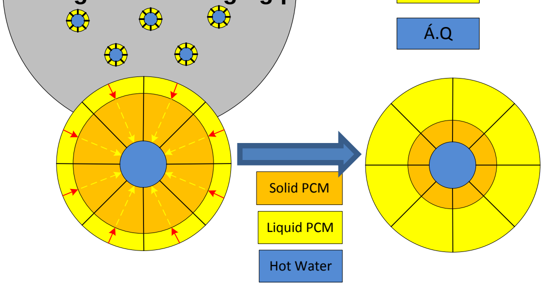


Fig 7 – Charging process of the PCM illustration.

Modelization

The variants that the model has to be able to estimate are the service water temperature exiting the heat exchanger, T_f, and the amount of thermal energy still available expressed in PCM mass in solid state, *Ws*. For this, we it was used the following diferrential equations

$$\frac{dT_f}{dt} = \frac{Q_e C_p (T_e - T_f) + UA_{interior}(T_{pcm} - T_f)}{V_t \rho C_p} \quad (2)$$

$$\frac{dWs}{dt} = \frac{Q_{exchanged}}{\Delta h_{melting,PCM}} \quad (3)$$

The PCM temperature used in Equation 2, T_{PCM}, is the PCM melting point temperature, assuming that there is no temperature gradient in the PCM for the heat balance.

The total amount of heat exchanged with the PCM, heating water and steam is then expressed by the variation of PCM mass in solid state in Equation 3. $Q_{exchanged}$ is then calculated following Equation 4.

$$Q_{exchanged} = UA_{interior}(T_{PCM} - T_f) + UA_{exterior}(T_{PCM} - T_{Steam.}) \quad (4)$$

The global heat transfer coefficient, U, and the heat transfer area, A, are calculated with the Equation 5, which says the total heat transfer resistance is the sum of the partial resistances in heat transfer through conduction, convection and fouling.

$$\frac{1}{UA} = \frac{1}{h_i A_i} + \frac{\ln\left(\frac{d_o}{d_i}\right)}{2k\pi L} + \frac{1}{h_o A_o} + R_{f,i} + R_{f,o} \quad (5)$$

Steam feed to the heat exchanger

$$\frac{dM_{Steam}}{dt} = \frac{Pot_{excess} - UA_{exterior}\Delta T}{\Delta h_{vap}} \quad (18)$$

Results

Model testing of the charge and discharge process

The model underwent a test through the study of the charge and discharge process of the PCM. The PCM thickness layer was defined with 0.7 meters in order to be able to visualize the changes in melting rate of PCM. The thermal properties used for PCM were from vacuum treated Erythritol with Nickel. In the charging process, the PCM receives heat from steam and it´s considered no heat loss to the water flow, and the PCM starts completely in the solid state.

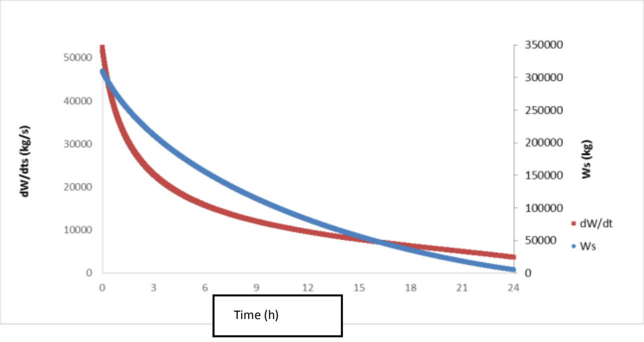


Fig 8 - PCM charge process, solidification rate and solid mass of PCM throughout the operation cycle, 1 day.

It´s possible to observe in figure 8 that the PCM melting rate decreases along with amount of liquid PCM. This happens because of the increasing distance between the outer tube surface and the frontier between the solid and liquid phases of the PCM, which translates into an increasing resistance in heat transfer through conduction. As it can be observed, it decreases 50% in 2 hours and 15 minutes and hits de 75% reduction mark at around 8 hours of operation.

Using the same design parameters and thermal properties, the simulation was again executed for the discharge process with the only difference being is the starting state of the PCM that is now liquid. The discharge test process assumes only heat transfer between the PCM and the water stream flowing inside the inner tube, with no heat gains from steam in the shell tube.

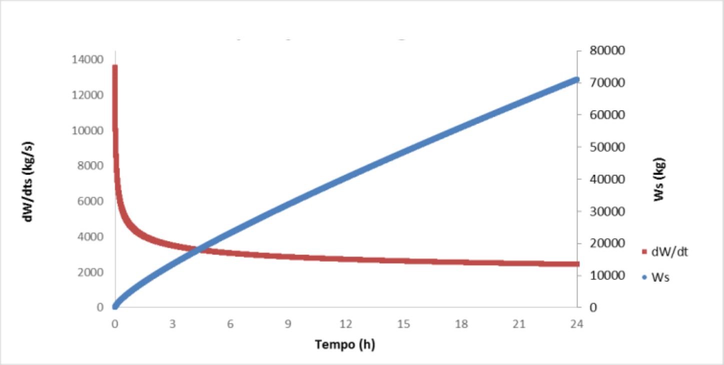


Fig 9 - PCM discharge process, solidification rate and solid mass of PCM throughout the operation cycle, 1 day.

In this operation, a solid layer of PCM deposits and sticks to the inner tube wall. As the layer increases, the heat transfer through conduction increases as well. The steep decrease of the solidification rate in the first hour of operation reflects the layer formation. As it can be observed in the Figure 9, the solidification rate decreases 50% in just 10 minutes and reaches a 75% reduction in 3 hours and 30 minutes.

Taking in account that the amount of heat exchanged is directly proportional to the amount of PCM that undergoes phase transition. The fact that the charging process has a higher melting rate when the PCM is discharged is a favorable behavior for the current strategy proposal. In contrast, there´s a steep decrease on solidification rate throughout the discharge process is an indication that the PCM will transfer less heat to the water in the high demand periods.

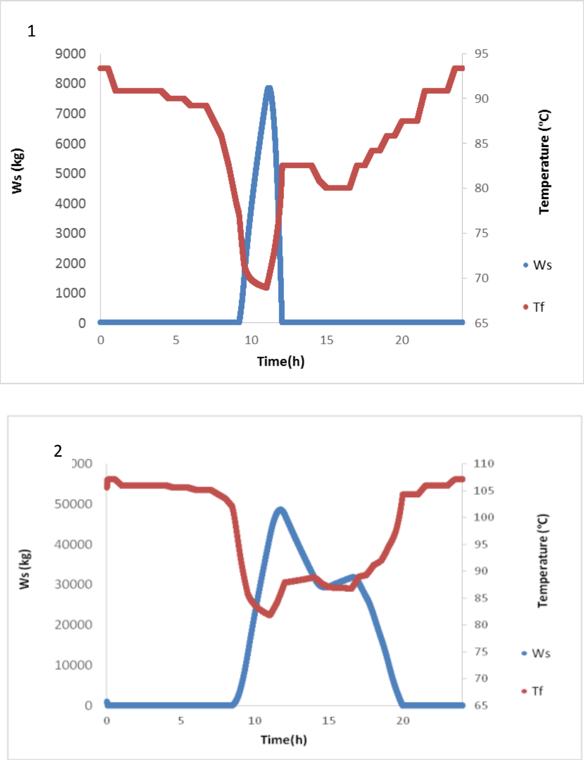


Fig 10 - Estimation of outlet water temperature of the secondary heat exchanger when using 1) Pure Erythritol and 2) Erythritol + Nickel

Heat exchanger with PCM operation

The proposed strategy operation was then simulated, utilizing the thermal properties of Nickel treated Erythritol and pure Erythritol for comparison.

In order to get the displayed results on Fig 10 and Table 5, the design parameters of heat exchanger where adjusted until it was possible to guarantee through the simulator a full day cycle of operation with T_f within service parameters. As it was already mentioned, the Nickel treated Erythritol is able to transfer more heat through conduction than it´s pure counterpart and that´s also observable by comparing fig 10 and 11. The resulting design parameters of the heat exchanger are presented in the following table 11

Table 5 – Heat exchanger design parameters. The design variables adjusted are highlighter with brackets.

	Caudal (m3/h)	Tmáx (ºC)	Tmin (ºC)
Pure Erythritol			
Primary Heat Exchanger	207,9	95	95
Secondary Heat Exchanger	92,1	93	93
Resulting Stream	300,0	87,0	94.4
Erythritol + Nickel			
Primary Heat Exchanger	207,9	95	95
Secondary Heat Exchanger	92,1	107	80
Resulting Stream	300,0	98,7	90,4

Table 6 – Heat exchanger design parameters. The design variables adjusted are highlighter with brackets.

Heat Exchanger					
Inner Tube			Outer Tube		
[Lenght/per pass]	7	m	**Total Length**	56	m
Total tube length	56	m	**Diameter**	0,22	m
[Diameter]	0,03	m	**Heat Transfer Area**	38,7	m2
Heat Transfer Area (per tube)	5,3	m2	**Total Heat transfer Area**	774,1	m2
Total Heat Transfer Area	105,6	m2	**[PCM thickness]**	0,09	m
Tube section Area	0,000707	m2			
Shell Side					
Total Tube Lenght	1120	m	**[Tube Passes]**	8	
Water Flow per Tube	4,6	m3/h	**Shell side Diamater**	5,51	m
Flow speed	1,81	m/s	**Shell side Free Volume**	124,5	m3
[Number of tubes per pass]	20	tubos	**PCM Volume**	41,8	m3
			Total Number of tubes	160	

The dimensions of such heat exchanger are too big for it to be feasible. This led to the decision to divide the load through a number of heat exchangers. A successful configuration consists in the setup of 4 heat exchangers in a serial Fig 12.

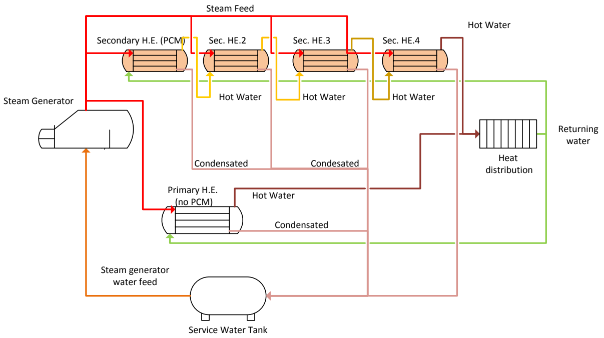


Figura 12 - Schematic illustrating the process with 4 heat exchangers in a serial configuration supporting a primary heat exchanger.

The temperature of the resulting stream from the heating process is kept within service parameters as seen on table 12.

Tabela 7 - Temperaturas resultantes da mistura do caudal principal com o caudal auxiliar aquecido pelo PCM

	Flow (m^3/hr)	**T_{max} (ºC)**	**T_{min} (ºC)**
Primary Heat Exchanger	207,9	95	95
Secondary Heat Exchanger	92,1	107,8	80,9
Resulting Stream	300,0	98,9	90,7

Conclusions

The objective of this thesis is to find a way to give a district heating and cooling plant the ability to store the excess thermal energy for use in periods of peak heat demand. The final feasible configuration from the engineering point of view consists of creating a secondary heating circuit using 4 heat exchangers in a serial configuration, with thermal energy storage through PCMs, to heat 30.7% of the total water flow.

From the 152 GJs of excess heat energy, 36.8 GJs are used to charge the PCM in the secondary heat exchangers, enabling heat production operation without using auxiliary equipment to meet the needs in high heat demand periods.

Heat transfer control is almost null, as there is no way to control how much heat the PCM supplies the water stream. Because the water flow speed must be kept in the range of 1-3m/s, and there is no way to affect the heat transfer area which will be constant throughout the operation. Nevertheless, the charging rate may be controlled by the steam pressure deployed in the shell side. In case of a steam pressure drop caused by condensing more steam than the amount being supplied, for example, will decrease the temperature at which steam condenses, thus decreasing heat transfer driving force.

Another drawback is the fact that the amount of heat transferred to the water stream decreases throughout the discharging process, taking in account that it´s at this point of operation that a more efficient heat transfer is desirable.

In the end, the proposed strategy is limited by the materials, stream flows, operational parameters and even heat consumption profile. The development of a heat exchanging equipment that enabled easy heat transfer area modification and/or PCM substitution with ease could help overcome the lack of versatility of the process.

This work concluded that it is theoretically possible to achieve the proposed objectives with a latent heat thermal storage system, though with a high number of restrictions and theoretical assumptions. A more hands on approach to create empiric data for heat transfer system between 3 fluids and an more detailed economic studies are necessary to assess the project´s viability.

References

[1] Sharma Atul et al, Review on thermal energy storage with phase change materials and applications, 2009.

[2] Veraj, R; Seeniraj, R.V et al 1999 Heat transfer enhancement in a latent heat storage system, solar energy Vol 65, 171-180

[3] Medrano, M; Yilmag, M.O et al, 2009 Experimental Evaluation of commercial heat exchangers for use as PCM thermal storage system, Elsevier, Applied Energy 86, 2047-2055.

[4] Zhou, D; Zhao, C.Y. et al 2012, Review on thermal energy storage with phase change materials (PCMs) in building application, Applied Energy 92, 593-605

[5] Oró, E; de Gracia, A; et al, 2012, Review on phase change materials (PCMs) for cold thermal energy storage applications, Applied Energy 99, 513-533

[6]Kenisarn, Murat; Mahkmov, Khamud, 2007, Solar energy storage using phase change materials, Renewable and Sustainable energy Reviews 11, 1913-1965

[7] Tyagi, V.V; Sharma, Atul, 2007, Review on Thermal energy storage with phase change materials and applications, Renewable and sustainable energy Reviews 13, 318-345

[8] Fan, Liwu; Khodadadi, J.M., 2011, Thermal conductivity enhancement of phase change materials for thermal energy storage; a review, Sustainable Energy Review 15, 24-46

[9] Chiu. Justin Ning-wei, 2011, Heat transfer Aspects of Using phase change material in thermal energy storage application, Estocolmo KTH School of Industrial Engineering and Management.

[10] Kakaç, S. (2002). Heat Exchangers Selection Rating and Thermal Design. New York: CRC Press.

[11] Kern, Donald Q. 1950, Process Heat Transfer, McGraw-Hill Book Company Japan Ltd., Tokyo, International Book Company

[12] Sinnot, R.K, 1999, Coulson & Richardon´s Chemical Engineering Vol 6 "Chemical Engineering Design, 3rd Edition, London, Butterworth Heinemann,

[13] Incropera F.P.; DeWitt D.P,Fundamentals of Heat and Mass Transfer, 6th Edition, 2006, Wiley

[14] Gil, Antoni; Barreneche, Camila et al, 2013, Thermal behaviour of D-mannitol when used as PCM: Compariso of results obtained by DSC and in a thermal energy storage unit at pilot plant scale, Applied Energy vol 111, 1107-1113

[15] Oya, Teppei; Nomura, Takahiro; et al, 2012, Phase change composite based on porous nickel and erythritol, Applied Thermal Engineering 40, 373-377.

[16] Jankowski, Nicholas R; McCluskey, F. Patrick; 2014,A review of phase change materials for vehicle component thermal buffering, Applied Energy vol 113, 1525-1561.

[17] Zalba, Belén; et al; 2014, Review on thermal energy storage with phase change materials, heat transfer analysis and application, Applied Thermal Engineering vol 23, 251-283.

Website

[W1] http://www.iea.org/Sankey/#?c=World&s=Balance; Novembro, 2015

[W2] http://www.climaespaco.pt; Novembro, 2015

[W3] http://www.spiraxsarco.com/Resources/Pages/Steam-Engineering-Tutorials/the-boiler-house/steam-accumulators.aspx ; Novembro, 2015

[W4] http://webbook.nist.gov/cgi/cbook.cgi?ID=C7732185&Mask=4&Type=ANTOINE&Plot=on ; Novembro, 2015