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DESIGN AND MODELLING OF A ICE THERMAL STORAGE SYSTEM FOR AIR CONDITIONING APPLICATIONS
THE XXV COBEM

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Abstract. *In a scenario of high penetration of renewables and increasing demand for cooling due to climate change and global warming, TES (Thermal Energy Storage) plays a crucial role. Therefore, the application of design methodology to create new technologies related to air conditioning applications and energy storage can be seen as a great opportunity to innovate and bring feasible solutions to market. This work is focused specifically on the conceptual and preliminary design phases of the product development process (PDP), in order to develop and validate a concept of a thermal storage system capable to supply a 3,517 W air conditioning for 3 hours. Therefore, a number of feasible concepts were created, evaluated, and later identified the most adequate concept. Furthermore, the concept validation methodology was based on both physical and computational models. Firstly, proof of concepts were developed, in order to prove the physical phenomena involved. Furthermore, a functional scale prototype was built with a planned data acquisition. Lastly, a computational model was developed in Simcenter Amesim® environment. As a result, it was possible to compare physical and computational models, suggesting improvements to be carried to the detailed design. Also, a parameterized simulation allows to evaluate different system operation parameters and strategies. In conclusion, the research proves the effectivity of PDP for an innovative TES design, besides explore modelling and simulation field.*

Keywords: *Energy storage, air conditioning, modelling, product development process, refrigeration.*

1. INTRODUCTION

High temperatures and the intensive use of air conditioning are considered the main drivers of the increase in Brazil's electricity demand in the summer, which has been causing major power cuts due to insufficient supply to meet demand (EPE, 2015). Furthermore, according to the MME1 report (2017), the economy gained by the implementation of the summer time is diluted due to high spent of energy in air conditioning. The report affirms that the Brazilian government intends to require more efficient air conditioning systems from manufactures. However, specialists believe that this action cannot change the scenario by itself, especially if compared with technologies adopted in other countries. Moreover, ABRAVA (2014) states that in Brazil, in 2013, more than 4 million air conditioning units were marketed, with 74 % of them split type.

Therefore, in a scenario of climate change and global warming, the application of design methodology to create new technologies related to ITES (Ice Thermal Energy Storage) can be seen as a great opportunity to innovate and bring feasible solutions to market.

A previous product planning was performed, idealizing an ice battery sufficient to supply 3,517 W of refrigeration during 3 hours, with a total latent heat of 37982 kJ stored. The objective is to produce ice during offpeak time, storing it in an ice bank, and use it to cool during on-peak time, ensuring the performance needed to generate savings to a possible costumer. This work assesses a possible solution of ITES technology for wider scale integration in Brazil's commercial sector, understanding the technological aspects of the solution by developing a prototype and further modelling the system in Simcenter Amesim® to uptake the new technology created, by performing a comparation between physical and computational models.

2. LITERATURE REVIEW

2.1 Product development

The PRODIP (Integrated product development process) methodology, shown in Figure 1, is presented by Back *et al.* (2008) and provides support for companies to implement a systematic and formal procedure to execute the product development process, integrated to other business processes, in order to reach innovative and viable solutions.

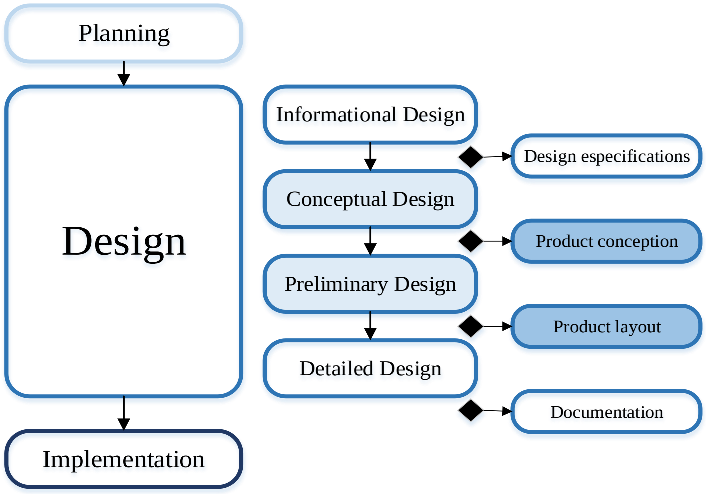

Figure 1. PRODIP methodology, source: Back *et al.* (2008)

As it can be seen, PRODIP design process is divided into four phases, as: Informational design, conceptual design, preliminary design and detailed design. This work is focused specifically in the conceptual and preliminary design, seeking for the development of a concept and a techno-economic validation of the thermal storage system.

According to Back *et al.* (2008), at the conceptual design, it is necessary to create a clear relationship between the problem inputs and outputs, in order to solve a technical issue. This is usually done by establishing the system general function and breaking into subfunctions or subsystems with lower complexity. The combination of these subfunctions provides the system functional structure. As a result, it facilitates the search for solutions. The creation of solutions can be guided by methods such as the Zwick's scheme (morphological matrix) to organize and combine with a further evaluation and selection by the Pugh Matrix.

The preliminary design starts from a chosen concept, originated from the combination of principles of solution, which at this point provides the source to work in an overall layout. At the end of this phase, the result must be a definitive layout. According to Pahl *et al.* (2007), the preliminary design differs from the concept design, because it involves a large number of corrective steps in which analysis and synthesis constantly alternate and complement each other. Moreover, at preliminary design phase, it is generally necessary several layouts so it can be evaluated simultaneously, in order to obtain information about advantages and disadvantages of each project variant. Thus, a definitive layout will be selected if verified the best relation between function, durability, production, space, costs and other aspects of the project.

By virtual simulation it is possible to recreate in a simplified mode what already exists, in order to achieve an improved design. This project uses Simcenter Amesim®, once it enhances the visual understanding of the system through a visual indication of the elements cause and effect relationship. Furthermore, the use of a virtual environment applied to multi-energy domains allows a mix of different existing libraries, such as air conditioning, twophase-flow, thermos-hydro, mechanical and electrical libraries. Allied to that, Chen (2015) brings a market-oriented product survey and affirms that mockups, prototypes and early product builds to potential users helps to obtain a feedback on functionality, usability and pricing. Therefore, the implementation of strategic prototypes at the preliminary design comes as an important condition to prove the technical feasibility and market acceptance.

2.2 Air Conditioning with and ITES System

Today, available ACs have a large variation of models, from devices capable to cool a single room to large scale systems, IEA (2018). However, despite the ACs model variation throughout the world, all of them share the same technology, the vapor compression refrigeration cycle. According to Stoecker and Jabardo (2002), vapor compression refrigeration is based on a refrigerant fluid passing through physical processes, becoming liquid, superheated, satured and wet vapor. The refrigeration cycle uses the vaporization latent heat from a given refrigerant mass flow rate, to extract a large quantity of heat. Figure 2 illustrates the operating temperatures and pressures of a R-22 AC, considering a LG™ 3,517 W model at ASHRAE rated conditions.

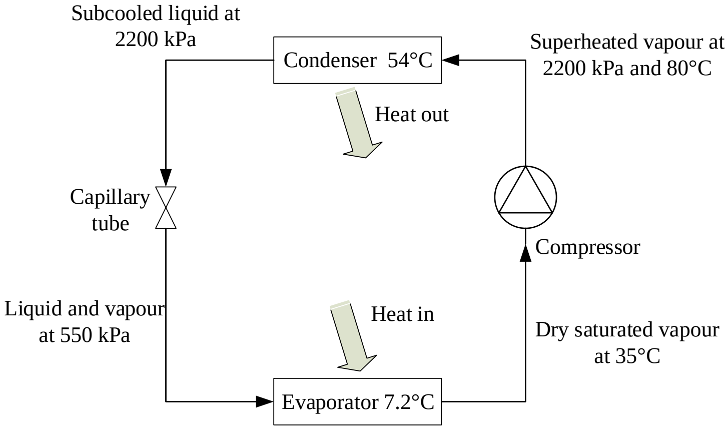

Figure 2. R-22 AC split-system at ASHRAE conditions. Adapted from LG (2014)

Although ASHRAE rated conditions fixes an evaporating temperature for air conditioning in 7.2°C, LG (2014) considers as ACs normal operation zone evaporation temperatures between -10°C and 15°C.

Typical ACs use electric energy to provide cooling. However, Ice Thermal Energy Storage (ITES), which is the application of water-ice as a phase change material (PCM) in a latent heat system, can be integrated to the system in order to provide the same amount of energy for cooling, once the temperature of phase exchange of ice to water is at 0°C. Thus, applying energy storage allows to play a decisive role in the integration of renewable energy and flexibility of smart grids.

According to Arcuri *et al.* (2016), Brazil experiences an increase of energy demand, especially because of the steady increase of air conditioning use. Despite of the potential of Brazilian market to energy conservation in AC systems, currently there is only one manufacturer of ITES systems in Brazil, the Alpina CALMAC®, designed to attend large ACs, such as commercial buildings, shopping malls and supermarkets (20-1000TR). Therefore, there is still a gap in Brazilian's market to be attended by an energy storage solution capable to integrate most part of the ACs. Furthermore, the combination of working principles can generate a design to attend this market, especially because energy storage applied to small scale air conditioning remains an open field.

3. CONCEPT DEVELOPMENT

According to Dias *et al.* (2011), one method to obtain a function structure is a global function. From a global function, which is the main task the system will execute, it is possible to better understand the energy, signal and material involved in the process. Thus, Figure 3 presents the system global function, where the thicker line indicates the energy transformation, the middle line indicates the material transformation and the dotted line indicates signal transformation. The vertical lines indicate the external inputs.

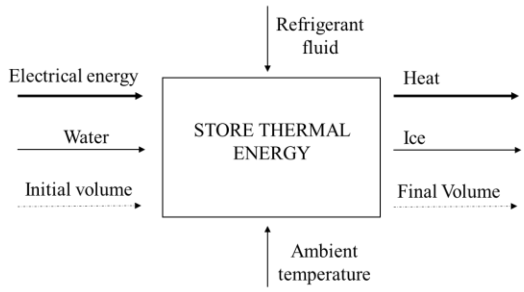

Figure 4. Global function

As can be seen, "store thermal energy" represents the main function of an "ice battery". Thus, there is energy transformation where is firstly considered electrical energy as energy input, necessary to remove heat from water. By understanding the basic functioning of the system in design, the global function can be divided in subfunctions, with less complexity. Using this technique to this problem, from the main function, it was identified the necessity of three subfunctions, which were further broken in elementary functions. The result is a function tree with three levels of functions, illustrated in Figure 4.

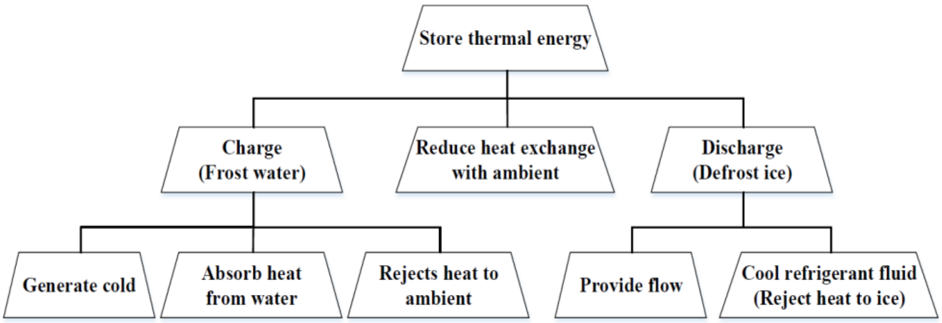

Figure 4. Function tree of an ice thermal storage system

From the lower level functions, is possible to search and apply working principles for the design of the ice battery. Therefore, a methodology was previously established utilizing morphological matrix, in order to create a number of different solutions. In the sequence, by performing two rounds of Pugh matrix evaluation, it was possible to identify the most adequate concept for the global function "store thermal energy" for AC application, shown in Figure 5. This step marks the end of the conceptual design phase and the beginning of preliminary design. Thus, the design process is continued with a better investigation of the most adequate concept, validating and optimizing it.

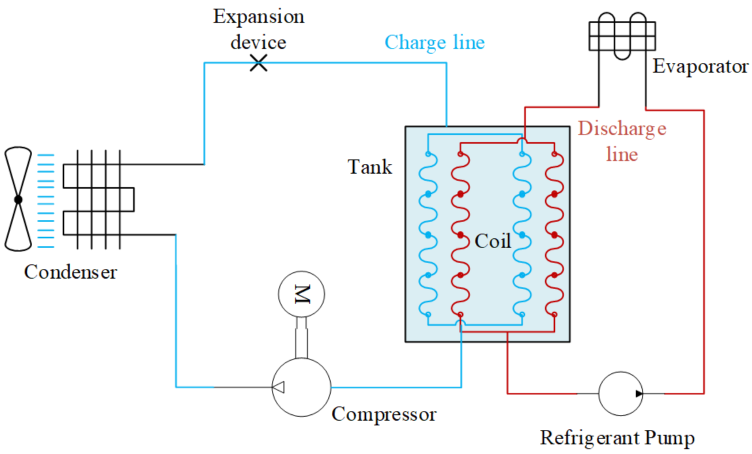

Figure 5. Function tree of an ice thermal storage system

As shown, the best evaluated concept is a vapor compression cycle with two separated coils, where one, named charge line, freezes the water while a second line, named discharge line, is linked with a refrigerant pump and AC evaporator, melting the ice. The main advantages of this concept where is aspects such as economic feasibility, innovation, maintainability, technical feasibility and operability. One of the strong reasons for that is the fact that two separated coils consist in two separated systems, simplifying the operation as a whole, despite the additional coil requires a more complex manufacturing process.

4. CONCEPT VALIDATION

The start of preliminary design is the concept of a technical product. From this stage, the design is developed in accordance with technical and economic criteria, seeking for details that can lead directly to production. Modelling methodology is then explored, in order to create evidence, which validates the proposed design. Moreover, concept validation is divided in two steps: Prototyping and Computational modelling.

4.1 Prototyping

The prototyping phase started with proofs of concept, to prove the technical feasibility of the discharge and charge mode, to further develop a prototype with all system functions integrated. As presented in Figure 4, an ice thermal storage system is divided in two general modes: charge and discharge. The discharge mode was the first to be tested and validated, because it was considered the most critical part. Since the two-phase flow operates near the fluid saturation point and therefore remains a risk to pump reliability, regarding the possibility of a dry pump operation. Subsequently, a second proof of concept was built and tested for the charge mode, with the intention to validate a no conventional evaporation unit, into the water.

According to Chen (2015), once proved the technology efficacy, the goal is "to bring to life" an integrated lookslike and work-like prototype. Therefore, at this stage, the intention is to test both operation modes of the ice battery together, providing a full understanding of the product requirements necessary, within an adequate cost.

Thus, the prototype design was based on the already acquired components, as shown in Figure 6. The design requirements specify three hours supply for 3,517 W AC, which would require 125 L of water becoming ice. However, the polystyrene tank has volume maximum volume of 60 L and the acquired evaporator has a capacity of 2,638 W. Therefore, the water volume planned was 44 L, which is equivalent to 14,243 kJ stored, sufficient to supply 1.5 hours of a 2,638 W AC evaporator. Moreover, according to EMBRACO™ (2015), at a condensing temperature of 45°C and evaporating temperature of -5 °C, the acquired condensing unit has a cooling capacity around 733 W (ASHRAE test conditions). Thus, it must create the ice block in approximately 6 hours.

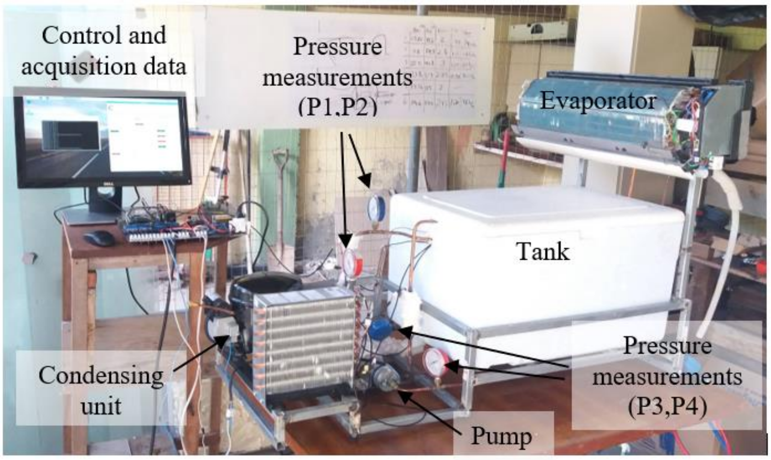

Figure 6. Ice battery prototype

As can be seen, a test bench was designed in order to settle all elements and provide a better arrangement, such it presents the pump in a lower level than the tank. Also, a remote control and acquisition data system were implemented, since there is an interest in connecting the equipment to the internet. Inside the tank pass both lines, where the condensing unit acts removing heat and freezing water, and the pump and evaporator acts adding heat and melting ice.

4.2 Computational model

The simulation aims to model the system with the prototype parameters, to further evaluate different system operation parameters and strategies, in order to obtain an optimized design. Therefore, once having experimental results, it is possible to parametrize the simulation, creating a very concise model, and then dimensioning and optimizating the design through a cheaper and faster path.

Figure 7 brings a model scheme logic, where it is possible to observe that the component representing water (PCM) has both discharge and charge systems (modelled and validated separately) and the losses of energy to environment actuating on it by exchanging heat.

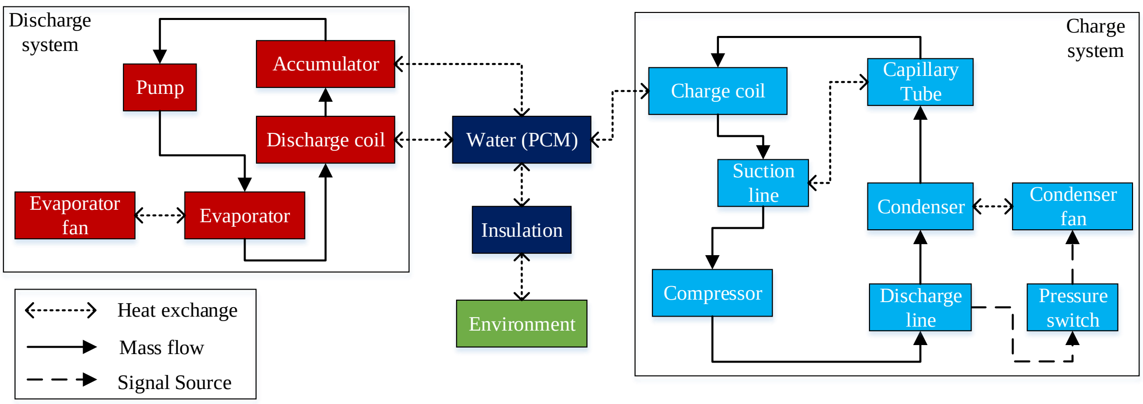

Figure 7. Full model representation in simulation

As can be seen, the charge system is configured with a pressure switch actuating on condenser fan in order to evaluate the influence of a high-pressure output control. Also, a heat exchange between capillary tube and suction line was placed, because it can increase the cycle performance by reducing the refrigerant quality at evaporator inlet. The full model visualization in Simcenter Amesim®, as well as components specifications are presented in Arcuri (2019).

5. RESULTS

The results presentation is divided in charge mode comparison and discharge mode comparison, in order to observe the main aspects of each physical phenomena. Then, a system validation is presented with power consumption comparison between all equipment modes.

5.1 Charge system

The charge mode operation consists in a refrigeration cycle performed by the condensing unit with its evaporation inside the tank. In order to better identify the divergences in refrigeration cycles, table 1 presents the main properties of the prototype and simulation refrigeration cycle, in the complete charge mode test. The cooling capacity of prototype cycle is based on total energy accumulated over the tank water level. Besides both systems cycle properties, the table also brings values of a called “reference” cycle.

The considered reference cycle refers to a system at test conditions of 55 °C for condensing temperature and -5 °C for evaporating temperature, as presented in EMBRACO™ (2015). From the values mentioned in catalog for pressure, condensing and evaporating temperatures, mass flow rate and power consumption, it was calculated the cycle properties considering an adiabatic expansion. It is important to mention that both tests were run with an ambient temperature of 25 °C. Therefore, the time scale presented in charts is relative to the time of physical test, in order to perform a better comparison.

Table 1. Refrigeration cycle properties

Cycle Properties	Prototype	Reference	Simulation
Mass flow (kg/h)	22.55	22.74	24.84
Power consumption (W)	460	518	541
Cooling capacity (W)	915	1121	759
COP	1.99	2.16	1.40

A resume of cycle operations is presented in Figure 8, by the pressure-enthalpy diagrams, where their performances can be better observed. Note that the poor performance of simulation cycle is explained by an incomplete condensation, as seen in point 3’, which reflects in a poor expansion and therefore less heat exchange. Also, it is possible to affirm that a subcooling in condensation of prototype cycle (3’’) could generate more stable state, avoiding the chance of flash-gas effect in expansion.

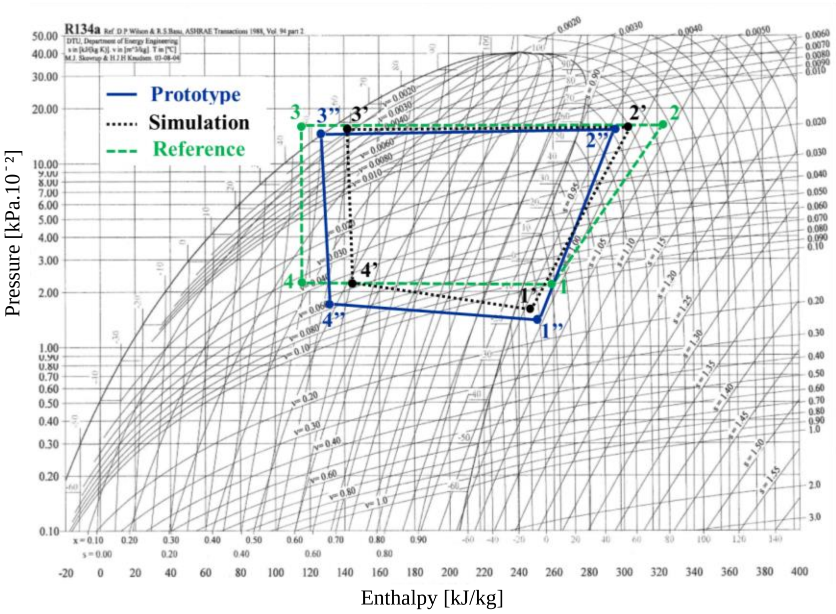

Figure 8. Pressure-enthalpy diagram for R-134a cycles

Analyzing the results above, it is noticed a divergence in condensing and evaporating temperatures of simulation, resulting in a considerable divergence in COP. The simulation cycle consumes more power and exchange less heat at evaporator, accusing a deficiency in evaporator model. Also, comparing prototype and reference cycle, it is possible to affirm that there is a converge in cycles, and the difference in COP might be expected if considered that ice formation at evaporation affected negatively the heat exchange.

5.2 Discharge System

Analogously to charge mode features, the discharge mode of the ice battery is also validated based on a comparison between physical discharge operation and simulation temperature measurements. The discharge mode test lasted 3 hours and 45 minutes, at a constant ambient temperature between 25°C and 26°C. Also, it was suspended at the moment where bubbles were observed in sight glass at pump suction, in order to protect the pump. Thus, the same conditions were set in simulation, also considering 70 % charge of the ice battery, observed by the water level measurement at physical prototype.

A comparison was made between prototype and simulation temperatures at pump suction, pump discharge and gas return, respectively, making possible the that simulation matches the behavior of the discharge cycle. Also, it can be seen a slightly difference in temperatures values, in an order of 2°C, especially in pump discharge temperature. Furthermore, Figure 9 brings a comparison between water temperature discharge cycle of prototype test and simulation.

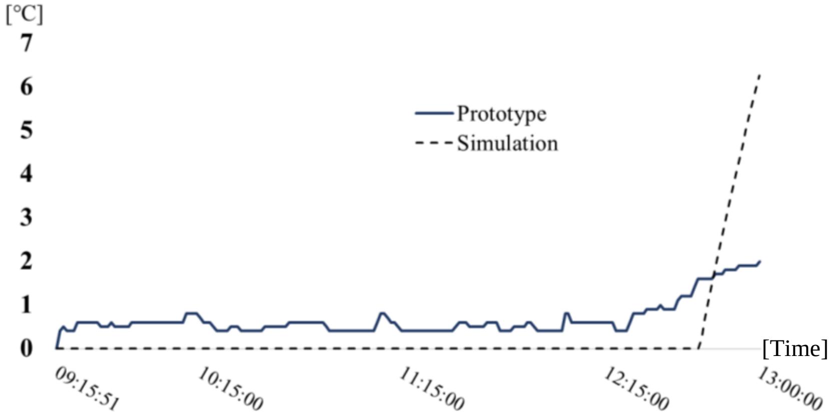

Figure 9. Water temperature in time of discharge

As evidenced, the prototype curve presents a small steady increase in water temperature just after 3 hours of operation. Simulation curve, on the other hand, presents a later increase in temperature, but with a higher slope. This contrast can be explained by a gradual ice-melting inside the tank instead of a sudden state change.

5.3 Validation

In conclusion, Figure 10 shows an experiment with Beta prototype, regarding the real power consumption in all described system modes, being those: Ice battery charge mode, Normal Air conditioning (AC) cooling and Ice battery AC cooling at Discharge mode. It is important to remember that intention of the system, using ice as the cooling device instead the AC compressor, is to reduce the instant power consumption and then generating costing benefits.

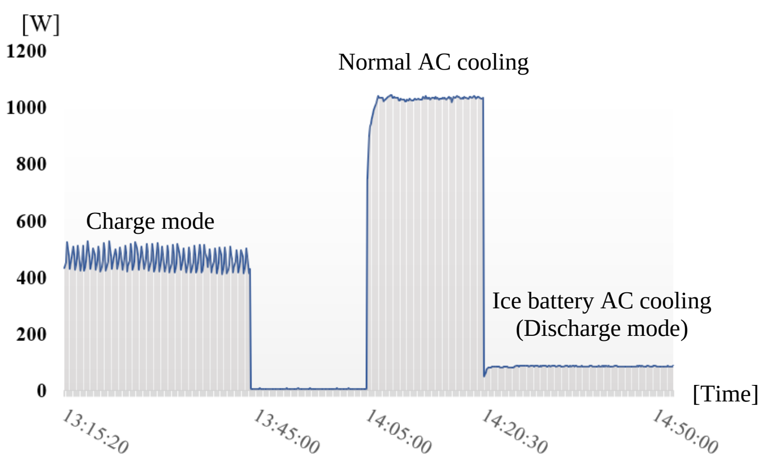

Figure 10. Power consumption of the equipment modes

As shown, the validation of equipment power consumption reduction during discharge cycle is evident, representing about 5 % of normal AC cooling power consumption. Also, it can be verified that the implementation of a pressure switch reflects at charge mode power consumption, generating an oscillation but not changing the nominal value.

6. CONCLUSION

This research aimed to assess possible solutions of ITES technology for split air conditioners, to be integrated in Brazilian commercial sector. The study has applied product development techniques through conceptual and preliminary design phases. Regarding the built prototype and simulation model, the divergence is explained mainly because of a great number of parameters, and therefore, a higher complexity to guarantee the efficacy of all adopted parameters. Although the noted divergence, simulation still predict the physical test values of cooling capacity and power consumption with a discrepancy of 17%. Moreover, convergence in physical and computational systems behavior could be observed.

Thus, it is possible to conclude that the developed model still is able to suggest improvements to be carried to PDP next phases. The next step of the product development research is evaluating the viability of implementation by developing the MVP design, exploring fields such as design for quality and design for minimum cost.

In conclusion, the proposed solution offers the possibility of implementation in Brazilian market, democratizing ITES to the masses of split air conditioners so often seen in emerging markets.

7. ACKNOWLEDGMENTS

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9. RESPONSIBILITY NOTICE

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