Universidad del País Vasco Euskal Herriko Unibertsitatea

Makina eta Motor Termikoak Saila
Departamento de Máquinas y Motores Térmicos

Abstract

This Ph.D. thesis deals with the integration of latent heat thermal energy storage systems in the design and operation of residential cogeneration plants.

The interest of the thesis was awoken by the current energy situation where the important role played by cogeneration has been extensively recognized. Specifically, and according to Directive 2004/8/CE, cogeneration presents a great potential for all those applications with important thermal energy consumption levels, such is the case of residential applications. However, the thermal load in this sector presents two particularities: high variability and difficulty for its prediction. Amongst the different alternatives to overcome these problems, thermal energy storage (TES) offers the possibility for improving the operation of these plants making generation and consumption independent.

Amongst the different kinds of TES, latent heat thermal energy storage (LHTES) systems offers features which make it very suitable for its integration in residential cogeneration plants. These systems use the heat exchanged during the phase change energy of the storage media (commonly referred to as PCMs) as the useful storage effect. This allows storing, for a given volume, a higher amount of heat than sensible heat TES and therefore, reducing the storage volume required for a fixed amount of thermal energy. This is especially interesting in residential sector where usually the availability of space is a problem and the development of compact systems is very important.

For the design and operation of LHTES systems, it is very important the detailed evaluation of the thermal operation and economic feasibility of the residential cogeneration plants where they are going to be integrated. A thorough analysis of the current legal and economic framework for small-scale cogeneration (100kW-1MW) in Spain is carried out, considering as well the cogeneration technologies available in the market. Amongst these technologies, nowadays internal combustion engines are the most reliable technology for their application in building plants, so this is the technology considered in this work.

Based on this information, a simulation model is developed for the evaluation of the annual operation of this kind of plants. That model allows obtaining both the energy efficiency and the economic profitability of the plant. The model has been improved allowing the inclusion of different kinds of TES systems, which are defined by its storage capacity and its mean charging and discharging power. After evaluating the thermal demand of the plant, it is determined that the discharging thermal power does not affect the annual results. This approach allows the annual simulation of cogeneration plants including different kinds of TES systems. It determines

the energy efficiency and economic feasibility (defined by its NPV) of the plant as a function of the size of the cogeneration device and the characteristics of the TES system (storage capacity and charging power).

After analyzing the available LHTES technologies, the finned-plate LHTES technology is selected as the most suitable for its implementation in residential cogeneration plants. This technology allows, by means of the definition of independent finned flat plates, adapt the power and storage capacity for different applications, offering high modularity and flexibility in the design of the system. Moreover, the prismatic geometry of the plates allows getting prismatic shapes which makes it easier its integration in boiler rooms or even in the cogeneration modules themselves. This is especially significant when compared with conventional hot water storage systems, whose storage effect is closely linked with the stratification effect, which is got by high aspect ratios.

Amongst all the PCM solutions currently available in the market, the RT60 paraffin is selected as the most suitable for the selected application. The thermophysical properties of this material were characterized by differential scanning calorimetry (DSC) obtaining the properties that govern the operation of the resulting LHTES system.

Considering these properties, the cogeneration operating conditions that allow maximizing the benefits of the LHTES system are selected. The main parameters that rule the charging and discharging process are identified and defined.

Subsequently, the importance of predicting the behavior of the LHTES system for different geometries and configurations is recognized, which makes it possible to determine the optimal configuration for different sizes of cogeneration plant. Simulation is selected as the basis for fulfilling this objective. Thus, three simulation codes of different nature are proposed: numerical code, approximated analytical code and simplified numerical code. These three models are used for the simulation of the same configuration of finned-plate LHTES system, both for charging and discharging. After comparing the results and the time required for the simulation, the simplified numerical code is selected as the most suitable for proceeding with the design and optimization process.

As part of the simulation work, a detailed analysis of the natural convection effect of the liquid phase over the solid phase is carried out with the aim of getting an expression for the effective thermal conductivity. Additionally a hydraulic model is presented which allows obtaining the pressure drop of the heat transfer fluid through the system and therefore, the required pumping electricity.

Prior to proceed with the usage of the simplified numerical code for the evaluation and optimization of the finned-plate LHTES systems, it is necessary to validate such a code by means of a series of experimental tests. Therefore, the design and construction of a experimental set up is also covered by this thesis. It is designed making it versatile enough to fulfill not only the objectives of this work, but with the aim of being an experimental bench for the test of LHTES systems under several operating conditions that allow emulating heating installations of different nature (solar, heat pump, etc.). Analogously, a prototype for the testing of finned-plate type LHTES systems is designed and built for its testing in the aforementioned experimental set up. It has been designed with enough flexibility for allowing its opening and therefore, the substitution of the PCM and the inclusion of heat transfer enhancement elements.

The LHTES prototype is tested under the charging and discharging conditions selected for residential cogeneration. The experimental results are compared with those obtained from the simulation of the simplified numerical model showing very good agreement. This fact allows using the simplified numerical code confidently as a tool for design and optimization.

An optimization model for the determination of optimal finned-plate LHTES configurations for residential cogeneration plants of different size is developed. Therefore, the objective function to be maximized is selected: the NPV of the cogeneration plant that incorporates the LHTES system. It is determined that the objective function depends on the storage capacity, the mean charging power and the purchase cost of the LHTES system. With the aim of setting out the optimization procedure, it is necessary to get analytical expressions for these three functions.

The analytical expression for the storage capacity is straightforwardly obtained once the thermophysical properties of the materials and dimensions of the system are known. On the other hand, the analytical expression for the cost of the LHTES system is obtained from existing cost estimation models. Two volumes of fabrication were considered (small and big) using respectively, stainless steel and aluminum for the manufacture of the plates.

The main challenge is to obtain an analytical expression for the mean charging power. As the starting point the simplified numerical model is selected since it allows the evaluation of a large amount of different configurations at a minimum computational expense. From the results of a battery of simulations of more than 800 configurations, an accurate statistical model is obtained for the prediction of the mean charging power using multiple regression techniques for its construction. This model considers both the big and small volume of fabrication.

Once the analytical expression for NPV is obtained, the optimization process is developed, which consists of two stages: firstly the random search method is applied and secondly, Sequential Quadratic Programming methods are used for obtaining the global optimum. So, the optimal LHTES configuration is obtained for plants of different size considering both scales of fabrication.

The optimal results are compared with those obtained from the inclusion of conventional hot water TES systems considering two sizing methods: one based on the optimal storage capacity and other based on a fixed storage capacity. The economic results obtained from the conventional TES systems are better but the LHTES systems allow reducing significantly the storage volume. This makes the latter to be an interesting option (even the only one) to be considered in those applications where the volume is a limiting factor, as it is the case in many residential applications.

Finally, although the global behavior of the residential cogeneration plant with the LHTES system was evaluated by the cogeneration simulation model, the evaluation of the integral operation of all the components is approached by dynamic simulation. Therefore, by means of TRNSYS simulation software, a complete model of a 500kW cogeneration plant is presented. The dynamic simulation of two typical days is carried out: winter and summer. For both cases, the same thermal storage capacity is considered.

Then, the hourly thermal fluxes are calculated from the temperature and flow rates obtained at 6 minutes time-steps, and, for each case, the energy and exergy efficiency are determined. It is obtained that finned-plate LHTES systems offer, for a smaller storage volume, better efficiency results, which is mainly owed to the fact that they provide an easier integration and operation, reducing the needs for releasing part of the cogeneratio heat to the ambient.

Then, it can be stated that the finned-plate LHTES systems under development and optimization in this Ph.D. thesis are a very good alternative to conventional TES systems due to the next list of facts: they allow reducing the storage volume; their prismatic shape makes it easier an optimal usage of the space as well as their integration in cogeneration modules; their modular structure allows enhancing its industrial-scale production as well as adapting their storage capacity and thermal power to different applications; their integration and operation in the cogeneration plant increase the efficiency of the plant that integrates them. Nowadays, in spite of all these benefits, their current cost and characteristics makes them to be less profitable than conventional TES systems, being economically attractive only for those applications with space limitations.

In the close future, other alternative materials are being investigated as cheaper PCMs which would allow, as well, increasing the compactness of the systems. The main alternative is the use of hydrated salts. Then, the objective is to widen the number of applications where these systems can be economical alternatives to conventional TES systems.

Keywords: cogeneration, PCM, thermal energy storage, simulation, experimental, optimization, dynamic.

Doctorando: Álvaro Campos Celador
Director: José Mª Sala Lizarraga