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Thermodynamic and economic optimization of a solar-powered Stirling engine for micro-cogeneration purposes

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ABSTRACT

Micro-cogeneration systems are a promising technology for improving the energy efficiency near the end user, allowing the optimal use of the primary energy sources and significant reductions in carbon emissions. Its use, still incipient, has a great potential for applications in the residential sector. This study aims to develop a methodology for the thermal-economic optimization of micro cogeneration units using Stirling engine as prime mover and concentrated solar energy as the heat source. The thermal-economic optimization was formulated considering the maximization of the annual worth from the system operation, subjected to the nonlinear thermodynamic and economic constraints. The physical model includes the limitations in the heat transfer processes and losses due to the pumping effects and the costing methodology was defined considering a purchase cost equation representative of each system component. Geometric and operational parameters were selected as decision variables. Numerical simulations were developed in MatLab® programming language and the Generalized Pattern Search optimization algorithm with MADSPositiveBasis2N was used in the determination of the optimal solution. A positive annual worth for the defined input simulation conditions and the economic analysis disclosed a system, economically attractive, with a payback period of approximately 10 years.

1. Introduction

Nowadays, several countries are developing sustainable energy policies to reduce energy consumption in buildings and to produce energy in a more efficient way. Improving energy efficiency represents a priority to all European member states and it plays an important role in ensuring the security of energy supply and greenhouse gas reduction targets [1]. The accomplishment of this target has been supported by a package of policies and frameworks. For instance, the European Energy Performance of Buildings Directive (EPBD) and its recast obliges all member states to ensure that, for new buildings with a floor area over 1000 m^2, the economic feasibility of alternative systems, such as decentralized energy supply systems based on Combined Heat and Power (CHP) or renewable energy, should be considered at the design stage [2]. The Directive also outlines that buildings should become energy producers and, by 2020, all new buildings should have nearly to zero energy requirements. In 2012, the Energy Efficiency Directive (EED – 2012/27/EU) was adopted, repealing the Energy Services Directive (ESD – 2006/32/EC), as well as, the Cogeneration Directive (2004/8/EC). This directive has to be transposed by all Member States by the beginning of June 2014. The Directive establishes a common framework of measures for the promotion of energy efficiency within the EU in order to ensure the achievement of the 20% headline target on energy efficiency in 2020, and to pave the way for further energy efficiency improvements beyond that date. According to the directive: "*High-efficiency cogeneration and district heating and cooling has significant potential for saving primary energy, which is largely untapped in the Union*". Early in 2014, the European Commission presented an energy and climate policy framework to be achieved by 2030, in which a reduction target of 40% in GHG emissions and a Renewable Energy Sources (RES) share of 27% in EU energy consumption are proposed up to 2030 [3]. These frameworks together with the recent technology developments and the recent energy consumer-producer profiles

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widened the potential of decentralized power production to small and micro-scale applications.

The development of small and micro-size on-site power plants also improves the flexibility in power generation and its potential is greatly enhanced through the combined production of heat and power to fulfil energy demands in buildings with several environmental, functional and economic advantages [4,5]. CHP systems present flexible solutions reducing both the total primary energy consumption and the overall investment costs, minimizing the distribution losses and avoiding the need for new centralized power stations or increased grid capacity. In addition, they allow for the design of systems able to meet the thermal and electrical needs of the buildings and promote the liberalization of energy markets [6–10].

Several technologies are available for residential applications, i.e. single-family dwellings (<10 kW_{el}) and multi-family (10–50 kW_{el}) applications. In this size range, the technologies suitable for cogeneration are: micro-turbine based cogeneration systems, Internal Combustion Engines (ICEs), Fuel Cells (FCs), Organic Rankine cycles (ORCs) and reciprocating external combustion Stirling engine based cogeneration systems. Small and micro-scale cogeneration systems based on Stirling engines are a promising solution for residential applications mainly because of (i) their high total efficiency, (ii) favorable ratio of thermal to electrical power, similar to a typical heat-to-electricity demand ratio of a domestic load, and (iii) low emissions, endorsed by their external and steady state combustion process.

Unlike reciprocating ICEs, Stirling engines rely on an external combustion or other exterior heat-source, thus allowing the use of different primary energy sources including fossil fuels (oil derived or natural gas) and renewable energies (solar or biomass). Stirling engines are thermodynamic devices working theoretically on the Stirling cycle and using a compressible gas as working fluid, such as air, hydrogen, helium or nitrogen. Since the combustion process takes place outside the engine, the continuous combustion process make Stirling engines a smoothly technology, resulting in lower vibration, noise level and emissions when compared with the reciprocating internal combustion engines [11,12]. This technology is also characterized to have fewer moving parts, compared to other engines, low wear and long maintenance free operating periods [13]. The limitations of this technology are related with the fact that some components of the engine are manufactured with special alloys because of the high temperature and pressure conditions endured by the system. This aspect increases the production costs, requiring high investment costs. Moreover, the choice of the "ideal" gas can bring some difficulties associated with its ability to diffuse through materials. Despite these few limitative aspects of Stirling engines, this technology fulfils a number of requirements for decentralized energy conversion applications, namely, the need of reducing the fossil fuels use; the need of searching alternative ways to produce cleaner energy and the possibility of waste heat recovery [14].

More recently, a number of new Stirling engine models have been developed to improve their efficiency and open this technology to new fields of application. In the literature, there are some works concerning the optimization of Stirling engines for different scale of applications [15]. Wu et al. [16] analyzed the optimal performance of a Stirling engine. In their study, the influence of heat transfer and regeneration time on the Stirling engine cycle performance was discussed. Formosa & Despesse [17] developed an analytical thermodynamic model to study the architecture of a free-piston Stirling engine. The model integrated the analysis of the engine efficiency, the pressure drop and effectiveness of the heat exchangers. The model was validated using the whole range of the experimental data available from the General Motor GPU-3 Stirling engine prototype. The influence of the technological and operating parameters on Stirling engine performance was investigated. The results from the simplified model and the experiment data showed a reasonable correlation.

Kaushik & Kumar [18] studied the influence of irreversibility in the heat transfer process at the three heat exchangers: regenerator, cooler and heater. Ust et al. [19] introduced a new thermo-economic performance analysis based on an objective function defined as the power output per unit total cost. Boucher, Lanzetta & Nika [20] reported a theoretical study of the dynamic behavior of a dual free-piston Stirling engine coupled with an asynchronous linear alternator. The objective was the evaluation of the thermo-mechanical conditions for a stable operation of the engine. Kongtragool and Wongwises [21] investigated the effect of regenerator effectiveness and dead volume on the engine network and the heat input into the engine efficiency by using a theoretical investigation on the thermodynamic analysis of a Stirling engine. Nepveu and his co-authors [22] presented a global thermal model of the energy conversion of the 10 kW_{el} *Eurodish* dish/Stirling unit, using optical measurements to calculate the losses by parabola reflectivity. The authors also performed a thermodynamic analysis of a SOLO Stirling 161 engine. The model was divided in 32 control-volumes and equations of ideal gas, mass and energy conservation are written for each control-volume. The differential equation system was then solved, iteratively by using the MatLab programming environment. Rogdakis et al. [11] studied a Solo Stirling Engine V161 cogeneration module via a thermodynamic analysis. Calculations were conducted using different operational conditions concerning the heat load of the engine and the produced electrical power. The authors achieved good results in terms of electrical and thermal efficiencies as well as a positive primary energy saving. Asnaghi and his co-authors [23] also performed a numerical simulation and thermodynamic analysis of a SOLO 161 Solar Stirling engine. He and his co-authors considered several imperfect working conditions, pistons' dead volumes, and work losses in the simulation process. The results indicated that the increase in the heater and cooler temperature difference and the decrease in the dead volumes will lead to an increase in thermal efficiency.

Solar energy can be collected and used to provide electricity or heating and, as a clean energy source. The direct conversion of solar power into mechanical power reduces both the cost and complexity of the prime mover. Stirling engines are able to use solar energy which is a cheap source of energy [24,25]. This particular aspect increases the interest in Stirling engines due to the fact that it is more environmentally friendly than the widely used technologies.

Ahmadi et al. [26] presented the optimization of a solar-powered high temperature differential Stirling engine considering an ideal thermodynamic cycle. The problem was formulated as a multi-objective approach, applying evolutionary algorithms based on the NSGA-II algorithm and a thermal model was developed so that the output power and thermal efficiency of the solar Stirling system with finite rate of heat transfer, regenerative heat loss, conductive thermal bridging loss, finite regeneration process time and imperfect performance of the dish collector could be obtained. The solar absorber temperature and the highest and lowest temperatures of the working fluid were considered as decision variables. Duan and his co-workers [27] also presented a study regarding the multi-objective optimization of the thermodynamic Stirling engines design using the particle swarm optimization algorithm and considering a simplified isothermal cycle analysis. Most of these studies evaluating the Stirling engines for residential buildings and other micro-scale applications [28–31] are focused on the evaluation of performance parameters (e.g. power output, heat exchangers effectiveness, overall efficiency, energy dissipation