AN ASSESSMENT OF COMMERCIAL STIRLING ENGINES FOR TRI-GENERATION SYSTEMS

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Rezumat. In lucrare se face o analiza a beneficiilor si limitarilor utilizarii motoarelor Stirling ca motoare primare in sistemele de trigenerare. Motoarele Stirling au randamentul termic cel mai ridicat, urmate de motoarele cu ardere interna. Motoarele Stirling utizeaza o sursa exterioara de caldura, ceea ce simplifica designul, micsoreaza nivelul de zgomot si vibratii si permite folosirea mai multor tipuri de combustibili. Aceste aspecte fac din motorul Stirling o alternativa la motorul cu ardere interna.
Cuvinte cheie: trigenerare, motor Stirling, randamente, costuri.

Abstract. In this paper an analysis is made from the point of view of benefits and limitations of the Stirling engines as prime movers in micro –CCHP systems. The thermal efficiency is better for micro-CCHP systems with Stirling engines followed by reciprocating engines. Stirling engines use an external heat source, which simplifies design, minimizes noise and vibration, and allow multi-fuel use. These features make the Stirling engine a promising alternative to the internal combustion engine.
Keywords: trigeneration, Stirling engine, efficiency, costs.

1. INTRODUCTION

The trigeneration concept refers to the simultaneous production of mechanical power (usually converted to electricity), heat (at low and high temperatures) and cooling (using heat at high temperature) using only one source of primary energy [14]. This source is represented by fossil fuels or by some appropriate types of renewable energy sources (biomass, biogas, solar energy, etc).

Trigeneration or combined heat, cool and electricity systems (CCHP systems) represent a concept that involves the production of both electricity and useful thermal energy in one operation, thereby utilizing fuel more efficiently than if the desired products were produced separately [1, 12]. The requirements of cogeneration may be met in many ways ranging from steam and gas turbines to fuel cells and Stirling engines.

Reduced fuel use naturally reduces combustion emissions [3]. Today's small-scale CHP systems already provide heat, cooling and electricity at nearly twice the fuel efficiency of separate heat and power based on power remote plants, electric chilling, and onsite hot water and space heating. CHP is an extremely efficient way of producing usable heat and electricity simultaneously at the point of use, offering an economic and environmentally friendly alternative for meeting thermal and electrical demands in many public sector applications [4].
In a CCHP system, useful heat is delivered at a relatively high temperature, which results in less electricity being generated [5].

The balance of heat and electricity output is optimised to meet the particular site requirements.

Using a renewably fueled micro-CCHP, a negative CO_2 balance can be created in comparison with heating by fossil fuel and pulling electricity from a fossil fuel burning electrical utility [6].

Generally, CCHP (Combined Cooling, Heating and Power, i.e. tri-generation, (figure 1) indicates large-scale technologies that contain both improved conventional approaches, like steam turbines, reciprocating engines, combustion turbines and electric chillers, as well as relatively new technologies such as fuel cells, micro turbines, Stirling engines, absorption chillers and dehumidifiers [8].

Although steam turbine, reciprocating internal combustion engine and gas turbine that can be

considered as the conventional prime movers still make up most of the gross capacity being installed, micro gas turbine, Stirling engine and fuel cells present a promising future for prime movers in CCHP system [9].

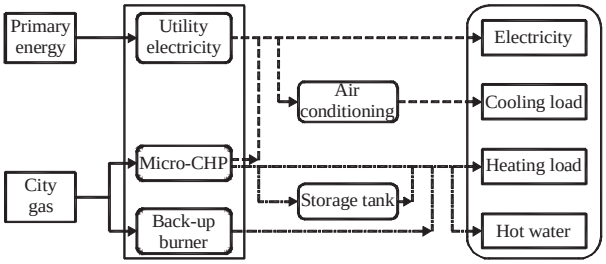

Fig. 1. *Structure of a residential micro-CCHP system* [4].

2. STIRLING ENGINES

Compared to conventional internal combustion engine, Stirling engine is an external combustion device [5, 18], where the heat is generated externally in a separate combustion chamber [15]. The cycle medium, generally helium or hydrogen is not exchanged during each cycle, but within the device, while the energy driving the cycle is applied externally.

The Stirling engine itself is a heat recovery device, like the steam turbine [5]. Two types of Stirling engines show potential for residential cogeneration – kinematic Stirling and free-piston Stirling [2]. The free-piston Stirling does away with mechanical linkages, resulting in fewer moving parts, no need for a lubricant, low maintenance costs, and a longer life [5]. Kinematic Stirling engines are typically larger than their free-piston counterparts [20]. Electric capacities for kinematic Stirling units are between 5-500 kW, while the capacities for free-piston units are between 0.01 and 25 kW.

Due to the nature of external combustion, the Stirling engines can be operated on a wide variety of fuels, including all fossil fuels (e.g. natural gas [11]), biomass (biomass can be used many ways, including direct combustion, two-stage combustion, and (the cleanest) with a gasifer), solar, geothermal, and nuclear energy [5, 3]. The combustion can be controlled relatively easily and the emissions have the potential to be very low. The noise of the Stirling engine is lower than that of the IC engines [3].

The maintenance is also supposed to be low and the life is usually long.

The Stirling engines are 15-30% efficient in converting heat energy to electricity, with many reporting a range of 25 to 30% [2]. The goal is to increase the performance to the mid-30% range. The efficiency of modern Stirling generators is more than 40% [12].

On heating the working medium to 90°C, the total efficiency of a micro-CCHP with Stirling engine is 95% [5, 12]. Cogeneration systems based on natural-gas Stirling engines permit 40% reduction in fuel consumption relative to centralized power systems [12]. The cost of 1 kWh of power from a cogeneration system is 3–4 times less than for centralized power systems, and the heat generated is essentially free.

Stirling engines are more efficient than internal combustion engines in cogeneration systems on account of their thermal balance, i.e., the difference between the heat extracted by the spent gases and the heat extracted by the coolant liquid [12]. For Stirling engines, this difference is 30%. Taking account of their high efficiency, this permits the creation of compact and highly efficient cogeneration units.

A great advantage for the Stirling engine is that, in a micro-CCHP, the heat from the burner that is not used by the Stirling engine can be readily used for hot water and space heating [3].

The major disadvantages of the Stirling engines include [3]:

- The high cost;
- The engine needs a few minutes to warm up;
- Durability of certain parts is still an issue.

Stirling engines are in between demonstration phases and marketing [16] being under development for deployment in residential CHP applications [13]. There are still field trials being carried out; but initial commercial products are already defined and on the verge of series production [16].

There are more than 20 Stirling engine manufacturers worldwide [3]. Currently Stirling engines have been used in various applications, which include residential [3, 17, 14]. But the total Stirling engine market is rather small [3].

2.1. Benefits and limitations of Stirling engines

Because a micro-CCHP system is an important investment, in order to identify the most appropriate micro-CHP technology for a residential application, various cogeneration technologies listed above can be compared based on different criteria.

Generally are used three main groups of criteria

- thermodynamic performance;

- economic profitability;
- environmental parameters.

The Stirling engine itself is a heat recovery device, like the steam turbine [12].

Two types of Stirling engines show potential for residential cogeneration – kinematic Stirling and free-piston Stirling [15].

The free-piston Stirling does away with mechanical linkages, resulting in fewer moving parts, no need for a lubricant, low maintenance costs, and a longer life [2].

The piston power is delivered directly by an integral permanent magnet linear alternator to produce alternating current power at any desired voltage. Stirling engines have been demonstrated at power levels up to 150 kW, but the new free piston flexure-bearing versions are best suited to power levels below 10 kW – well suited to residential applications. On the other hand, the combustion system—comprising a heater head, and air preheat systems – does tend to be relatively sophisticated. Like the steam turbine, Stirling engines can be used with heat recovery as an additional cycle for one of the other prime movers. Because a continuous combustion burner powers them, their emissions are quite low. Recent data shows NO_x emissions of less than 10ppm from an uncontrolled Stirling generator.

Kinematic Stirling engines are typically larger than their free-piston counterparts [5].

Electric capacities for kinematic Stirling units are between 5-500 kW, while the capacities for free-piston units are between 0.01 and 25 kW. Stirling engine has demonstrated more than 50000 hours of continuous operation [12]. But this high level of availability applies only for the Stirling generator and does not include the heat source.

A comparison of residential micro – CCHP technologies focused on prime mover, made versus separate heat and power, where the needed separate heat and power indicates that the overall system efficiency has the best value for Stirling micro-CCHP technology as well as for thermal/electric ratio [2, 12].

Theoretically, Stirling engines should have very high availability and reliability. Service intervals of between 3500 and 5000 hours (equivalent to over one year's economic operation) are expected with a product lifetime of more than six years continuous operation

A great advantage for the Stirling engine is that, in a micro-CHP, the heat from the burner that is not used by the Stirling engine can be readily used for hot water and space heating [31].

The major disadvantages of the Stirling engines include [31]:

1) The high cost: currently the Stirling engine price is around $2000-$50000/kW.

2) The engine needs a few minutes to warm up before producing power and the engine cannot change its power quickly.

3) Durability of certain parts (shaft seal, piston rings and bearings leakage, minimization of material stress and corrosion in the high temperature region, as well as problems with abrasive particles generated at the piston rings) is still an issue.

2.2. Market analysis

There are more than 20 Stirling engine manufacturers worldwide [3]. Currently Stirling engines have been used in various applications, which include residential [1, 18], space and marine industries, and vehicles. But the total Stirling engine market is rather small.

Stand-alone Stirling engine is mainly aimed at waste heat recovery for power generation. Stirling engine based micro-CCHP has been has been under development and deployment by WhisperTech in the United Kingdom at engine capacity of 1 kW. If these Stirling micro-CCHP applications are successful, Stirling engine based micro-CCHP may see increased sales volume coming to the housing industry. Related Stirling engine technology will be improved and the cost is likely to reduce.

For a good choice of the system to be implemented by a residential project, it is necessary to know the structures, used worldwide for the energy -heat-cold production systems. Implementation of optimal solution – particular climate conditions and construction and functional particulars of buildings - calls for a comprehensive comparative analysis of the multitude of existing solutions to achieve these systems.

Precisely because of this variety, it was necessary to organize the structural-functional analysis, according to different criteria:

- according to the type of primary mover;
- according to how refrigeration cycle is carried out;
- according to the type of the electric generator employed.

3. CONCLUSIONS

1. The evaluation of various prime mover technologies by using the metrics and weighting factors showed that the reciprocating engines and the Stirling engines have higher scores, suggesting that they are more appropriate for the micro-CCHP.

2. A comparison of residential micro - CCHP technologies focused on prime mover, made versus separate heat and power, where the needed SHP was calculated to match 1 unit of fuel into each of the four micro-CCHP technologies, indicates that the overall system efficiency has the best value for Stirling micro-CCHP technology as well as for thermal/electric ratio.

3. An evaluation of five micro-CCHP systems (<5 kW) for use in residential applications, from the view point of primary energy saving and CO_2 reduction, in relation to the reference case with a gas fired combined cycle power plant, revealed that Stirling engines have the best possibilities.

4. A market study focused on producers and conversion techniques with a high development status pointed out that in the case of the micro-CHP units with Stirling engines, there can be generated savings of 10% of the energy costs using it in existing one-family-houses.

The evaluation of various micro-CHP systems, regarding the prime mover technology for producing electricity and heat for residential use, indicated that the micro-CCHP units with Stirling engines are more appropriate for the micro-CHP having the best value for overall system efficiency.

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