Stirling Engine in Residential Systems Based on Renewable Energy

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Abstract: - The paper presents a review regarding the use of Stirling engine in residential systems based on renewable energy. In general, the reciprocating engines and Stirling engines have better performances for micro-CHP systems compared with other prime movers as RC, micro-turbine and fuel cell. The Stirling cycle engine can use different types of renewable sources of energy including biomass, solar and geothermal energy. These features make the Stirling engine a promising alternative to the internal combustion engine.

Key-Words: - Stirling engine, Micro-cogeneration, Residential, Renewable energy.

1 Introduction

Generally, CCHP (Combined Cooling, Heat and Power, i.e. tri-generation) 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 [1].

CHP (Combined Heat and Power, i.e. cogeneration) is an engineering concept involving 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 [2,3].

Recent development of CCHP systems is generally related to the emergence of DER (distributed/ decentralized energy resources) - a novel technical concept in energy supply [4]. DER is defined as an electricity-generation system located in or near user facilities, which provides electrical and thermal energy simultaneously to meet local users in top-priority. DER can be divided into two major sections [4]:

i. High-efficiency CHP or CCHP systems in industry and buildings, using prime mover technologies as reciprocating engines, gas turbines, micro-turbines, steam turbines, Stirling engines and fuel cells.
ii. On-site renewable energy systems with energy recycling technologies, including photovoltaic and biomass systems, on-site wind and water turbine generators, and other low-energy content combustibles from various processes.

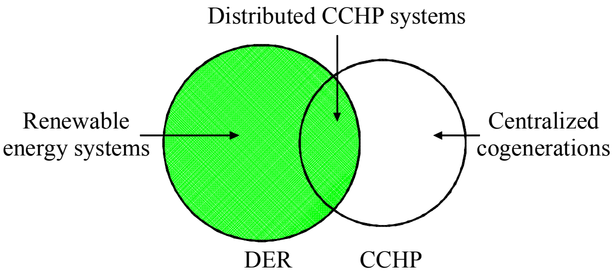

Fig. 1. Categories of CCHP and DER [4].

Due to the relationship between traditional CHP and novel DER (Fig. 1), CCHP systems are classified into two categories [4]:

1. Traditional large-scale CCHP applications (predominantly CHP systems without cooling options) in centralized power plants or large industries.
2. Relatively small capacity distributed CCHP units with advanced prime mover and thermally activated technologies to meet multiple energy demands in commercial, institutional, residential and small industrial sections.

Residential cogeneration, also termed micro-cogeneration or micro combined heat and power (Micro-CHP), is an emerging technology with the potential to provide energy efficiency and environmental benefits by reducing primary energy consumption and associated greenhouse gas emissions [5].

Successful development of a micro-CHP system for residential applications has the potential to provide significant benefits to users, customers, manufacturers and suppliers of such systems and, in general, to the nation as a whole [6].

The environmental benefits offered by CHP can assist public sector energy, estates and facilities managers to meet CO_2 emission reduction targets, such as the Kyoto Protocol and Agenda 21. Compared to generators which lack the system for utilizing waste heat, co-generation can reduce CO_2 emissions up to 30%; with a renewably fueled micro-CHP, 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 [7].

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 cell present a promising future for prime movers in CCHP system [8].

For small-scale CHP systems using biomass as fuel, Stirling engines are a promising solution for installations with nominal electric capacities between 10 and 150 kW [9]. Stirling-cycle engines have been also identified as a promising technology for the conversion of concentrated solar energy into usable electrical power [10], thus potentially eliminating the need for combustion of a fuel [4].

This paper presents a review regarding the use of Stirling engine in residential systems based on renewable energy with bringing forward the benefits and limitations of this type of prime mover.

2 Prime movers

A prime mover in a micro-CHP system (Fig. 2) generates electricity and the waste heat is recovered downstream [6]. This section describes four micro-CHP prime movers. Each technology faces numerous challenges detailed in the following [3]. The prime movers to be evaluated include:

- reciprocating engines;
- Stirling engines;
- micro steam and gas turbines;
- fuel cell systems.

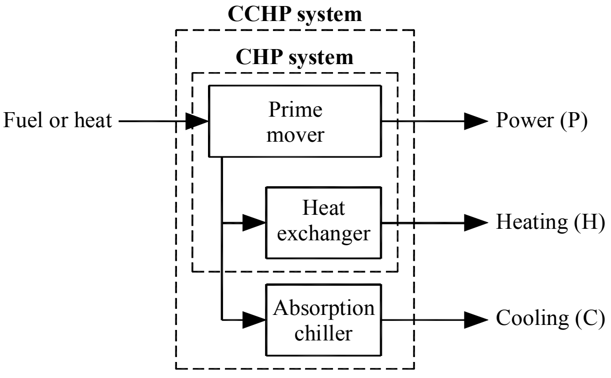

Fig. 2. A schematic representation of a CCHP system (adapted from [11]).

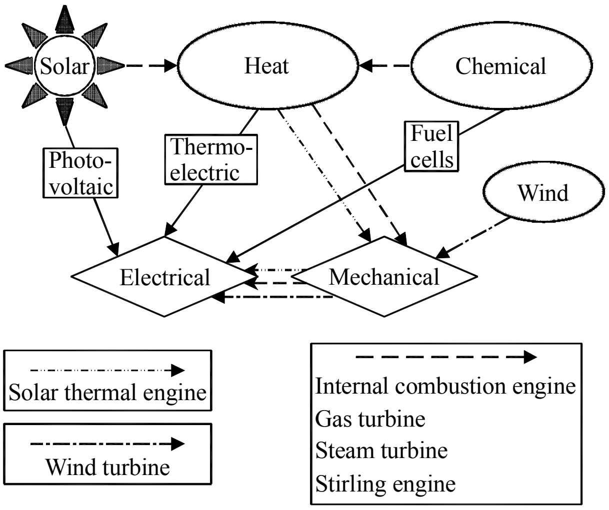

Fig. 3. The relation between different energy sources and prime mover technologies [6].

The diagram in Fig. 3 shows the relation between different energy sources (including renewable) and thermal prime mover technologies.

2.1 Reciprocating engines

In micro-CHP systems with reciprocating engines, the conventional internal combustion engines (ICE) are coupled with a generator and heat exchangers to recover the heat of the exhaust gas and the cooling water and oil [3,15].

For micro-CHP applications, typically, spark ignition engines are used [13], due to their heat recovery system producing up to 160°C hot water or 20 bar steam output compared to diesel engines where the temperature is often lower, usually 85°C maximum [14].

Reciprocating engines have several advantages for micro-CHP [6,12,15]:

- It is a mature and well-understood technology.
- It can be designed for different fuels including gasoline, diesel, natural gas or landfill gas, etc.
- The efficiency of the ICE is around 25-45%, which is higher than current Stirling engines.
- A short startup time than external combustion engines.

Some limitations of ICE are [6,12]:

- Frequent maintenance.
- Noise and emissions are two issues for the reciprocating engines. The NO_x emissions of small engines are fairly low, but still higher than the other technologies'.

2.2 Stirling engines

Compared to conventional internal combustion engine, Stirling engine is an external combustion device [3,4], where the heat is generated externally in a separate combustion chamber [12].

The Stirling engine itself is a heat recovery device, like the steam turbine [3]. Two types of Stirling engines show potential for residential cogeneration – kinematic Stirling and free-piston Stirling [16].

Stirling engines have several advantages for micro-CHP [3,6,16,17,18]:

- The Stirling engines can be operated on a wide variety of fuels, including all fossil fuels, biomass, solar, geothermal, and nuclear energy.
- 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.
- 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%. On heating the working medium to 90°C, the total efficiency of a micro-CHP with Stirling engine is 95%.

The major disadvantages of the Stirling engines include [6]:

- 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 [13] being under development for deployment in residential CHP applications [19].

2.3 Rankine cycle engine and micro gas turbines

Typical Rankine cycle (RC) systems are in the order of MW or above, but some small scale systems have capacity as low as 50 kWe [6]. The RC for micro-CHP is less expensive than most other prime mover technologies and is likely to be a competitive prime mover technology. There haven't been any RC engines in commercial sales for micro-CHP and more testing data are needed to really evaluate this promising technology [6].

The major disadvantage of the RC engines is that the efficiency is low (around 10%) [6].

Micro gas turbines are small gas turbines belonging to the group of turbo machines up to an electric power output of 300 kWe [12]. The electric capacity of current micro-turbines, usually 25 kW or above, is too high to be in a residential micro-CHP unit [6]. Research is ongoing for systems with capacities less than 25 kW, e.g. 1 and 10 kW, which will be suitable for the single-family residential buildings [20].

For cogeneration applications, an overall efficiency of 80% and above can be achieved [20]. However, in the lower power ranges, reciprocating ICE have higher efficiency.

Micro-turbines offer a number of advantages when compared to reciprocating internal combustion engine based cogeneration systems [6,20]:

- Fast response.
- Compact size, low weight and lower noise.
- Lower NO_x emission.
- Low maintenance requirements.

Micro-turbines can use different fuels, including natural gas, hydrogen, propane or diesel and other biobased liquid and gas fuels [6,20].

The major disadvantages of this technology include the high cost, relatively shorter life and high O&M cost [6]. The efficiency of micro-turbines is not very high, although this is enough or more than enough for residential micro-CHP because of the high thermal/electric load ratio.

2.4 Fuel cell

Fuel cells are electrochemical energy converters similar to primary batteries [12]. Fuel cell micro-CHP systems are either based on the low temperature proton exchange membrane fuel cell (PEMFC) which operate at about 80°C, or on high temperature solid oxide fuel cells (SOFC) working at around 800 - 1000°C [3,12].

Fuel cells normally run on hydrogen, but can also be used with natural gas or other fuels by external or internal reforming [5].

Fuel cells have several benefits [3,5,6]:

- Higher efficiency, up to 45% electric.
- Emissions are essentially absent producing negligible amounts of pollution.
- The fuel cells are very quiet.

Fuel cells are still in the R&D stage [13]. The major problem of fuel cells is the short lifetime of the membrane [6], and their cost is very high [3,6].

There are no fuel cell based micro-CHP systems commercially available at this moment [3,6].

3 Evaluation of prime movers

A comparison of residential micro CHP technologies related on prime mover can be made versus separate heat and power (SHP) [3]. Table 1 shows by which factor micro-CHP efficiencies exceed those of separate heat and power. The needed SHP was calculated to match 1 unit of fuel into each of

Table 1. Comparison of the main residential micro-CHP technologies to SHP [3].

1 kW unit	Electric η_e (%)	Thermal η_t (%)	Temperature range	System η (%)	T/E	SHP/CHP fuel
PEM Fuel Cell	29	46	80 - 100°C hot water	76	1.59	1.59
SOFC Fuel Cell	27	45	80 - 1000°C* hot water-high quality steam	82	1.67	1.51
IC Engine	25	56	90 - 120°C hot water, low-grade steam	81	2.24	1.59
Stirling engine	14	75	80 - 700°C* hot water-med. quality steam	89	5.36	1.48

*Depending on recuperation

η is the symbol used for thermodynamic efficiency calculated at higher heating value.

the four micro-CHP technologies. The data from Table 1 indicate that the overall system efficiency has the best value for Stirling micro-CHP technology as well as for themal/electric ratio.

The various prime mover technologies described previously are evaluated using the metrics and weighting factors [6]. The weighting factors are assigned subjectively and are intended to provide a relative measure of the importance of each metric with respect to application in a CHP system. The weighted scores are shown in Fig. 4. It can be seen that the reciprocating engines and the Stirling engines have higher scores, suggesting that they are more appropriate for the micro-CHP.

An assessment of micro-CHP can be made on environment impact basis, regarding the annual CO_2 savings for micro-CHP prime movers compared to grid electricity and boiler alternatives [21]. The best CO_2 savings are obtained for 1 kWe gas engine micro-CHP, followed by 1 kWe Stirling/ Rankine engine (low efficiency) micro-CHP.

The evaluation of micro-CHP prime mover technologies showed that, in general, the reciprocating engines and Stirling engines have better performances for micro-CHP systems compared with other prime movers as RC, micro-turbine and fuel cell.

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.

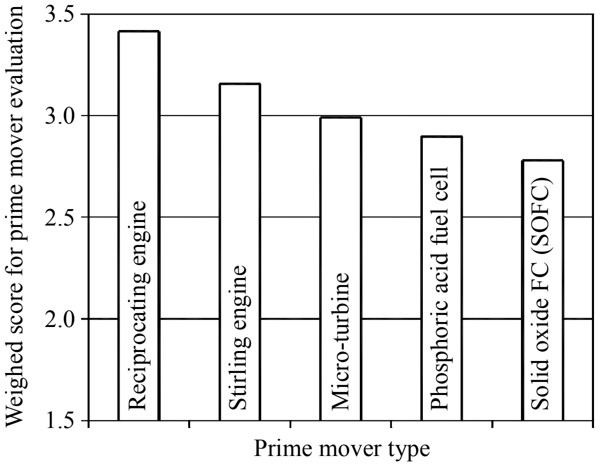

Fig. 4. The weighted scores for evaluation of different micro-CHP prime movers (adapted from [3]).

4 Stirling engine operating on renewable energy sources

The Stirling cycle engine can use different types of renewable sources of energy including biomass, solar and geothermal energy [22].

4.1 Biomass

Biomass needs to undergo several processes so that it can be widely used as a source of energy [23]. These processes will transform its accumulated energy (carbon and hydrogen) into solid, liquid and gaseous fuels. Fig. 5 displays the details of three kinds of conversion processes: physical, thermochemical and biological.

The problems concerning utilisation of biomass fuels in connection with a Stirling engine are concentrated on transferring the heat from the combustion of the fuel into the working gas [9]. The temperature must be high in order to obtain an acceptable specific power output and efficiency, and the heat exchanger must be designed so that problems with fouling are minimised.

Currently, given the exhaustion of organic-fuel reserves and the rising prices of oil and natural gas, the mass production of 3-500 kW power generators with modification of the Stirling engine for local fuel is of considerable interest [18]. Possible fuels include peat, ground coal, shale, agricultural wastes, and wood chips. Stirling engines fueled by wood chips are already in production.

Another option that may have merit is to consider fuel switching between biogas and natural gas with a Stirling engine which is a good concept applicable in the waste water treatment plants [24]. The biogas can be also obtained from the dairy facilities [25].

4.2 Solar

The most efficient solar thermal power plants on the ground are currently based on Stirling engines located at the focus of a parabolic dish solar concentrating mirror [26].

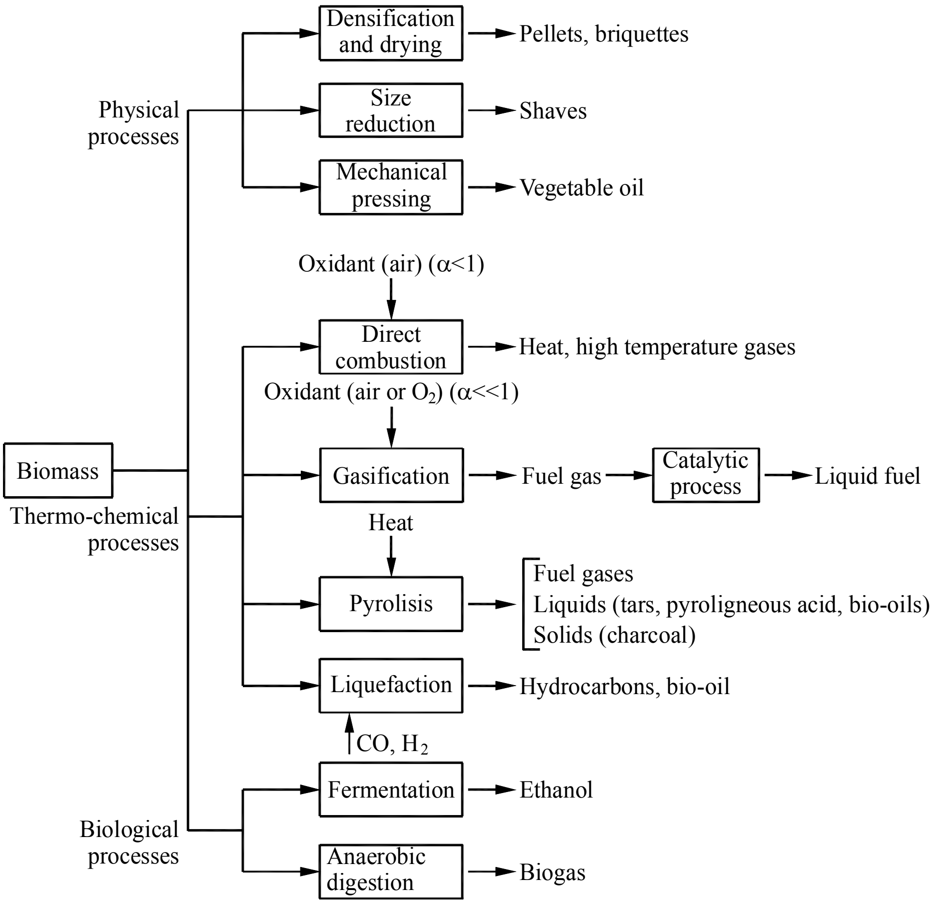

Fig. 5. Biomass energy conversion routes [21].

A dish/Stirling system comprises a parabolic dish concentrator, a thermal receiver, and a Stirling engine/generator located at the focus of the dish [27].

The size of collectors employed by today's dish/ Stirling systems ranges from approximately 7.5 m for a system which will produce 7 kWe under optimal sunshine conditions (1000 W/m^2) up to 11 m for a 25 kWe system [28]. The most efficient Stirling Dish systems have a Stirling engine with a thermal efficiency of 41% for the engine alone [26].

5 Conclusion

The assessment of residential systems regarding the prime mover technologies and the use of renewable energy these systems revealed the following:

1) In general, the reciprocating engines and Stirling engines have better performances for micro-CHP systems compared with other prime movers as RC, micro-turbine and fuel cell.
2) The Stirling cycle engine can use different types of renewable sources of energy including biomass, solar and geothermal energy.
3) Biomass needs to undergo several processes so that it can be widely used as a source of energy for Stirling engine.
4) The most efficient solar thermal power plants on the ground are currently based on Stirling engines.

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