THERMODYNAMIC ANALYSIS OF A STIRLING ENGINE USED AS PRIME MOVER IN A CCHP BIOMASS SYSTEM

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Rezumat. Motorul cu ciclu Stirling poate folosi diferite tipuri de resurse regenerabile de energie incluzând biomasa, energia solară şi geotermală. Aceste caracteristici fac din motorul Stirling o aleternativă promiţătoare la motorul cu ardere internă. Această lucrare prezintă problema evaluării performanţei şi eficienţei motorului Stirling utilizând combustibili regenerabili (paleţi), intr-o microcentrală de răcire şi încălzitre a unui sistem de trigenerare, pentru o reşedinţă domestică.
Cuvinte cheie: sistem de trigenerare, motor Stirling, combustibili regenerabili, biomasă, paleţi de lemn.

Abstract*:* 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. The paper presents the problem of energy performance and efficiency evaluation of the Stirling prime mover using renewable fuels (pellets), in a micro scale combined cooling, heating and power (mCCHP) trigeneration system, for a domestic residence.
Keywords*:* Trigeneration system, Stirling engine, renewable fuels, biomass, wood – pellets.

1. INTRODUCTION

Fossil fuels such as petroleum, coal, and natural gas have become limited resources. In addition, global warming due to carbon dioxide (CO2) emission has become a serious environmental issue, in recent years. Since current living and economical standards depend strongly on fossil energy sources, it is necessary to realize a new technology that utilizes biomass as a source of energy. Climate change and limited fossil resources call for a reduction of non - renewable primary energy input and greenhouse gas (GHG) emissions by 50 to 80 % by 2050 [1]. One possible developmental path is decentralization of the electricity system. Distributed power generation in small, decentralized units is expected to help in reducing emissions and saving grid capacity, while also providing opportunities for renewable energy. It could thus form a constituent part of a more sustainable future. This vision of decentralized, and often autonomous, technological systems has been often replicated and has also been applied to energy systems. 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). Since biomass is the only carbon-based renewable fuel, its application becomes more and more important for climate protection [15]. One objective of trigeneration systems is the diversification of energy sources, especially use of renewable ones, accordingly to the geographical location.

2. MICRO CCHP SYSTEMS

A comparison of residential micro CCHP technologies focused on prime mover, made versus separate heat and power, where the needed separate heat and power (SHP), indicates that the overall system efficiency has the best value for Stirling micro-CCHP technology as well as for thermal/electric ratio [2, 12]. One of the most recent and promising alternatives for the biomass use are the m-CCHP (Combined Cooling, Heating and Power small-scale <1 MWe) plants. In such systems, there are no important resources requirements and the seasonal efficiency of the conversion is increased thanks to the high efficiency of the overall system and the large operation period. A CCHP system (figure 1) indicates large-scale technologies that contain both improved conventional approaches, like steam turbines, engines, combustion turbines and electric chillers, as well as relatively new technologies such as fuel cells, micro turbines, Stirling engines, absorption chillers and dehumidifiers [14]. 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.

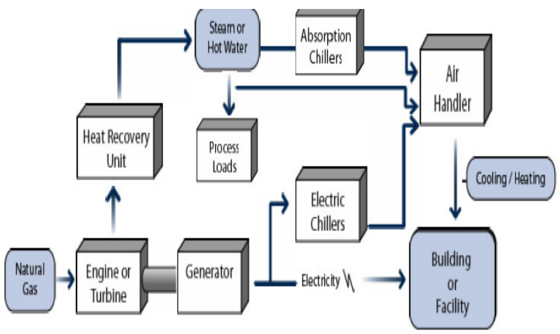

Fig. 1. A micro - CCHP concept

The trigeneration technology is a very good solution to supply energy to the building sector (residential houses, offices, hotels) [2].

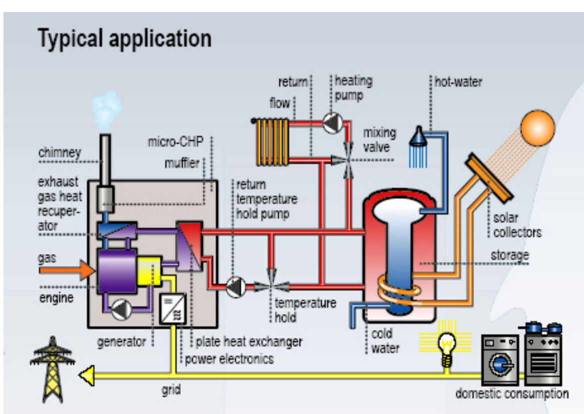

Fig. 2. Schematic mCCHP

The proposed micro-CCHP systems comprise a prime mover, which generates electricity, and the heat recovery and utilization components which use the heat rejected by the prime mover provide space heating, hot water, and cooling [7].

3. A PRIME MOVER STIRLING ENGINE

Since the invention of Robert Stirling in 1816, the Stirling cycle engines have always been of great importance for the engineers to generate mechanical or electrical power more efficiently or to reduce the energy consumption of the refrigeration devices [5, 11]. Stirling engines can be used for primary power generation and as a bottoming cycle utilizing waste heat for power generation. The most outstanding feature of the Stirling engine is its ability to work at low temperatures, and thus it can use low temperature energy sources that are widespread in nature: the hot water from flat solar collectors, geothermal water, and hot industrial wastes. Stirling engine can also use all fossil fuels and biomass, to realize an environmentally friendly electrical energy production. Compared to conventional internal combustion engine, Stirling engine is an external combustion device [13]. It produces power by an external heat source and not by explosive internal combustion. Stirling engines closely couple a burner to a heater-head heat exchanger that induces harmonic oscillations in a piston inside a hermetically sealed container [10, 11]. The Stirling engine itself is a heat recovery device, like the steam turbine [6]. Two types of Stirling engines show potential for residential trigeneration: – kinematic Stirling and free-piston Stirling [3,5, 11]. The free-piston Stirling has fewer moving parts, does not need for a lubricant, it has low maintenance costs and a longer life. The theoretical efficiency of the Stirling engine is equal to that of the Carnot engine, which is the highest possible of all heat engines. Stirling engines generally are small in size, ranging from 1-25 kW although some can be up to 500 kW [11, 13]. The Stirling engines are 15-30% efficient in converting heat energy to electricity, with many reporting a range of 25 to 30% [12]. The efficiency of modern Stirling generators is more than 40% [7]. Stirling engines are expected to run 50000 hours between overhauls, and free-piston Stirling engines may last up to 100000 hours [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 [6].

3.1. MATHEMATICAL MODEL ANALYSIS OF STIRLING ENGINE

In the ideal Stirling engine cycle, a working gas is alternately heated and cooled as it is compressed and expanded [11].

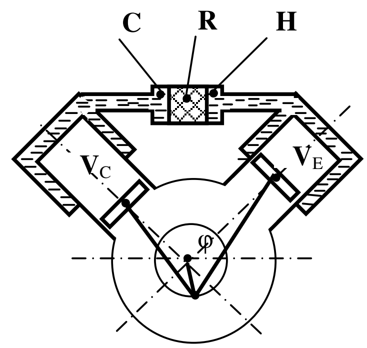

Fig. 3. VE – expansion volume, VC – compression volume, H – heater, C – chiller, R – regenerator

The ideal Stirling cycle combines four processes, two constant-temperature processes and two constant-volume processes (figure 3) [11]. The study presents the thermodynamic analysis of a Stirling engine with two separate V cylinders [11]. Two pistons generate the compression and the expansion spaces and the regenerator is on the connecting pipe between the two variable volumes (figure 4).

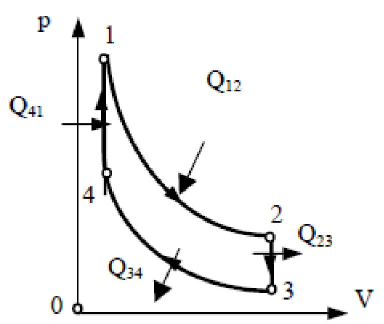

Fig. 4.

3.1.1. Volumes

Compression and expansion instantaneous volumes are defined according to crankshaft angle [11].

- Instantaneous expansion volume:

$$V_E = V_{EM}(1+\cos\alpha)/2 \tag{1}$$

- Instantaneous compression volume:

$$V_{C_1} = k \cdot V_{DM}[1+\cos(\alpha-\varphi)]/2 \tag{2}$$

α – rotation angle of the crankshaft

φ – angle between cylinders; usually, $\varphi = 90^0$

- Overall instantaneous volume:

$$V_T = V_E + V_C = V_{EM}\begin{bmatrix} 1+k+\cos\alpha + \\ +k\cos(\alpha-\varphi) \end{bmatrix}/2 \tag{3}$$

- Maximum overall volume:

$$V_{TM} = V_{EM} + V_{CM} = (1+k)V_{EM} \tag{4}$$

- Constant “dead” volume:

$$V_M = XV_{EM} \tag{5}$$

3.1.2. Pressures

The total gas mass is the sum of instantaneous mass of the considered volumes [11]:

$$m_T = \frac{pV_{EM}}{2RT_E}(1+\cos\alpha) + \frac{k}{2}\frac{pV_{EM}}{RT_C}[1+\cos(\alpha-\varphi)] + \frac{pV_M}{RT_M} \tag{6}$$

Using the notations [11]:

$$K = 2\frac{RT_C}{V_{EM}}m_T = ct. \quad S = X\frac{T_C}{T_M} = \frac{2x\tau}{1+\tau} \tag{7}$$

Relation (6) becomes:

$$\frac{K}{p} = \tau(1+\cos\alpha) + k(1+\cos(\alpha-\varphi)) + 2S \tag{8}$$

We use the notations:

$$A = \left(k^2+\tau^2+2k\tau\cos\varphi\right)^{1/2}, \quad B = \tau+k+2S \tag{9}$$

$$C = A/B \qquad \theta = \mathrm{arctg}(k\sin\varphi(\tau+k\cos\varphi)) \tag{10}$$

$$\tau = T_C/T_E, \quad k = V_{CM}/V_{EM} \tag{11}$$

And the instantaneous pressure is:

$$p = \overline{K}\,(1+C\cos(\alpha-\tau))/B \tag{12}$$

- Average pressure is:

$$p_a = \int_0^{2\pi} p\,d(\alpha-\theta) = \sqrt{p_{min}p_{max}} = p_{max}\sqrt{\frac{1-C}{1+C}} \tag{13}$$

Where:

$$p_{min} = \overline{K}(1+C)/B \qquad (14)$$

$$p_{max} = \overline{K}(1-C)/B \qquad (15)$$

$$p = p_a\left(1-C^2\right)^{1/2}/[1+C(\alpha-\theta)] \qquad (16)$$

3.1.3. Energy Analysis

The expansion heat $Q_E>0$ and compression heat $Q_C<0$ are considered to be isothermal and they are equal to the work [11].

- At the expansion space:

$$Q_E = W_E = \int_0^{2\pi} p dV_E = \pi p_a V_E C\sin\theta / \left[1+\left(1-C^2\right)^{1/2}\right] \qquad (17)$$

- At the compression space:

$$Q_C = W_C = -\int_0^{2\pi} p dV_C = \pi p_a k V_C C\sin(\theta-\varphi) / \left[1+\left(1-C^2\right)^{1/2}\right] \qquad (18)$$

- Exchange heat ratio:

$$Q_C / Q_E = -\tau \qquad (19)$$

- Overall work of the cycle:

$$W_T = W_E + W_C = (1-\tau) Q_E \qquad (20)$$

3.1.4. Efficiency Of Stirling Cycle

- Stirling engine cycle efficiency is [11]:

$$\eta = \frac{W_T}{Q_E} = 1-\tau = 1-\frac{T_C}{T_E} = \eta_{max} \qquad (21)$$

3.1.5. Mass Of The Agent

The mass of the agent in Stirling engine is obtained from relation (1), (2) and (16) [11].

- Instantaneous mass in expansion space:

$$m_E = \frac{1}{2}\frac{p_a V_{EM}}{RT_E}\frac{(1+\cos\alpha)\left(1-C^2\right)^{1/2}}{1+C\cos(\alpha-\theta_1)} \qquad (22)$$

- Instantaneous mass in compression space:

$$m_C = \frac{k}{2}\frac{p_a V_{EM}}{RT_C}\frac{(1+\cos(\alpha-\varphi))\left(1-C^2\right)^{1/2}}{1+C\cos(\alpha-\varphi)} \qquad (23)$$

- Instantaneous mass in regenerator dead space:

$$m_M = X\frac{p_a V_{EM}}{RT_M}\frac{\left(1-C^2\right)^{1/2}}{1+C\ \ \cos(\alpha-\theta\ )} \qquad (24)$$

Total mass is the sum of instantaneous mass of considered volumes. Using relations (22)…(24), and α = 0, it results:

$$m_T = \frac{p_a T_{EM}}{RT_C}\frac{\left(1-C^2\right)^{1/2}}{1+C\cos\theta}[\tau+k(1+\cos\varphi)/2+S] \qquad (25)$$

3.1.6. Dimensionless Heat Parameters

In order to compare mCCHP systems two dimensionless parameters are considered [11]:

- Overall expansion input heat related to total mass:

$$\overline{Q}_E^m = \frac{Q_E}{m_T RT_C} = \frac{\pi C\sin\theta(1+C\cos\theta)}{(1-C)^{1/2}\left[1+\left(1-C^2\right)^{1/2}\right][\tau+k(1+\cos\varphi)/2+S]} \qquad (26)$$

- Overall expansion input heat related to maximum pressure of the cycle:

$$\overline{Q}_E^{max} = \frac{Q_E}{p_{max} V_{TM}} = = \frac{\pi C \sin\theta \left(1 - C^2\right)^{1/2}}{(1+C)^2 \left[1 + \left(1 - C^2\right)^{1/2}\right](1+k)} \quad (27)$$

- Dimensionless overall work:

$$\overline{W}_T = (1 - \tau)\overline{Q}_E \quad (28)$$

The overall work of the cycle W_T depends of some parameters: τ, k, X and φ. [11].

Usually, the following values are considered:

$T_C = 300$ K, $T_E = 300 - 1700$ K, X = 0 - 2

k = 0.80 $\varphi = 100^0$

4. A CASE STUDY

The development of sustainable energy systems for the future is the combined production of electricity heating and cooling in small units that are directly embedded in the buildings where the heat, cold and electricity are to be used. Implementation in the experimental building on the University "Dunărea de Jos" of Galaţi campus of a mCCHP experimental system, using renewable energy available in the South-Eastern region of Romania and meet the specific climatic conditions, has the purpose to validate the theoretical developments and to provide the basis for the generalization of results for the entire region. Therefore, after a brief overview of the South Eastern region of Romania

- Climatic conditions of the region, and
- Energy resources, especially renewable ones, available in the region

were identified and analyzed.

The climatic parameters that influence the construction of a building are temperature, humidity, wind speed and sunshine.

From the analysis of statistical data about these parameters the climatic conditions for space heating and the specific heat needed were determined.

From the analysis of urban and rural conditions for space heating and the potential of renewable energy in the South-Eastern region it was identified the type of renewable energy that can be used to achieve a mCCHP system, namely biomass pellets and solar panels.

The simplified model of the residence meets the current standards for a living area and space volume needed for a 4-member family while keeping the particulars of the South East region of Romania.

For a good choice of the system to be implemented by the 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 in the South East of Romania – 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.

At the basis of this project lies the integration of Stirling engine (fueled with wood- pellets) with an electric generator and their interfacing with an electronic module that has a programmed logical (IT) for monitoring, protection and control (MPCS).

In this case, we choose the Stirling engine (figure 5) from Sunmachine (Germany) with characteristics:
- Stirling engine 2 single acting - pistons in V type arrangements
- Wood pellets as fuel
- Electrical output capacity: 1.5 – 3 [kW]
- Thermal output capacity: 4.5 – 10 [kW]
- Cost of unit: 23000 €
- Specific cost of unit (€/kWe): 7670

Fig. 5. Stirling engine

Wood pellets to fuel the Stirling engine have the characteristics:
- diameter: 6 mm
- length: 4 - 15 mm
- density: 1300 kg/m3
- humidity: 3.6 %
- ash content: 0.8 %
- calorific power: 18200 kJ/kg.

5. CONCLUSION

1. The evaluation of various micro-CCHP 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-CCHP having the best value for overall system efficiency.
2. A market study focused on producers and conversion techniques with a high development status pointed out that in the case of the micro-CCHP units with Stirling engines, there can be generated savings of 10% of the energy costs using it in existing one-family-houses.

The major disadvantage of the Stirling engines is the high cost of the equipment.

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