A combined heat and power (CHP) plant consisting of a microturbine and a Stirling engine

Y A Antipov, S V Smirnov, P P Oshchepkov and H S Khalife
Peoples’ Friendship University of Russia, Miklukho-Maklaya street bld. 6, Moscow, 117198, Russia

E-mail: hassan.khalife.rudn@gmail.com

Abstract. Modern industrial development of governments is largely determined by the condition of the power industry. Nowadays, the energy policy of governments is focused on the improvement of highly efficient combined heat and power (CHP) plants, to conserve fossil fuels and achieve higher output power. The application of gas turbines and heat recovery systems is considered a promising method of increasing the overall efficiency of the power plant. In this article, a microturbine was considered as the prime mover in a CHP plant, while the exhaust gases were used to power a Stirling engine, and consequently generating additional power and heat, increasing the overall efficiency of the power plant. Also, the advantages and disadvantages of the Stirling engine were briefly discussed. Moreover, two general configuration schemes and a calculation method of the CHP plant have been developed. Finally, the results of utilizing the exhaust gases of a microturbine and a Stirling engine were presented.

1. Introduction
A major goal for several governments is building effective power plants since the energy sector plays a significant role in economic growth. Energy policies target generating more output with less fuel, and this can be accomplished by actualizing methods to increase the overall efficiency. One notable method is cogeneration, an energy-efficient technology that generates electricity and captures the heat that would otherwise be wasted to provide useful thermal energy—such as steam or hot water—that can be utilized for heating, cooling, domestic hot water, and industrial processes.

One of the important advantages of CHP plants is their high thermal efficiency. CHP plants have higher thermal efficiencies (60-80%) when compared to fossil-fuel power plants (33%). Another advantage is related to their positive ecological impact. CHP plants utilize exhaust heat producing the same output energy with less fuel, and since less fuel is combusted, harmful emissions such as carbon dioxide and others (CO₂, NOₓ and SO₂) are reduced, causing less damage to the environment. The positive economic impact is also one of the advantages, where the high efficiency of CHP plants saves a significant amount of money [1].

In this article, a CHP plant consisting of a microturbine and a Stirling engine was considered. The exhaust gases (EG) of the microturbine were utilized to power a Stirling engine. The main function of the Stirling engine in the developed CHP plant is to generate additional electricity along with the microturbine. In addition, network water is heated by the utilized EG of the microturbine, and consequently, increasing the overall thermal efficiency of the power plant.
The objective of this article is to present a general configuration scheme of a CHP plant developed by the authors, and a calculation method of the CHP plant based on a microturbine and a Stirling engine.

2. Methods and calculation

As mentioned earlier, the CHP plant considered consisted of a microturbine and a Stirling engine. The microturbine generated most of the electricity, then the heat energy of the EG (up to 35% of the heat of the burned fuel leaves with the exhaust gases [2]) was used to heat the Stirling engine’s working fluid and generate additional power.

Microturbines are small-scale gas turbines whose power ranges from 15 to 300 kW. Their basic working principle is based on the Brayton open-cycle. However, microturbines have several distinct features, such as operation speed, easy installation method, compact size, low maintenance, simple operability, type of bearings, low NOX emissions, and typically a recuperator [3]. Microturbines are usually used at locations far from main power grids, as well as backup generators during emergencies, voltage surges, or other disturbances. [4,5] The microturbine considered in this article was manufactured by Capstone and its main parameters are presented in table 1 [6].

Table 1. The main parameters of the microturbine.

| Parameter                  | Symbol | Value |
|----------------------------|--------|-------|
| Output power               | \( N_{mt} \) | 200 kW |
| Exhaust gas temperature   | \( T_{EG1} \) | 280 C  |
| Exhaust gas flow rate     | \( G_{EG} \) | 1.3 kg/s  |
| Electrical efficiency     | \( \eta_e \) | 30% |
| Supplied thermal energy   | \( W_{equiv} \) | 600 kW |

The Stirling engine was invented by Robert Stirling in 1816. The engine received a little attention and was not used commercially at that time. In recent years, the interest in the Stirling engine has been renewed, especially with the increased environmental concern and interest in renewable energy technologies [7,8].

Stirling engines advantages include quiet operation, fuel flexibility, eco-friendly, and efficient. The uncertainty over the future availability of fossil fuels and the damage caused by burning fossil fuels on the environment is pushing towards finding new sources of energy. The Stirling engine is one of the power generation options for use with renewable sources of energy, since the engine operates through a closed thermodynamic cycle that can operate using any heat source.

However, several disadvantages affect the wide commercial use of Stirling engines nowadays. First, and most importantly, the high cost of production, due to the use of materials that should withstand high temperature and pressure conditions. Second, low power-to-weight ratio, compared to internal combustion engines. Last but not least, the hazardous working conditions inside the engine, depending on the working fluid used.

Nowadays, the development of new materials, primarily composite materials, and the reduction of their cost is causing several breakthroughs in the development of new Stirling engines, such as the free-piston Stirling engine. Also, the use of neutral working gases, such as helium or nitrogen, or without the use of conventional lubricants, would make the engine operate in less dangerous conditions. The modern technological development in the world will lead to an increase the demand of the Stirling engine in various fields sooner or later [9]. In this work, the “SOLO Stirling 161” engine was chosen and its main parameters are presented in table 2 [10].
**Table 2.** The main parameters of the Stirling engine.

| Parameter                                | Symbol | Value       |
|------------------------------------------|--------|-------------|
| Number of cylinders                      | $z$    | 2           |
| Bore diameter                            | $d$    | 0.068 m     |
| Working stroke                           | $S$    | 0.044 m     |
| Working volume of the expansion cylinder  | $V_{SE}$ | $160 \cdot 10^{-6}$ m³ |
| Working volume of the compression cylinder| $V_{SC}$ | $160 \cdot 10^{-6}$ m³ |
| Total dead volume                        | $V_D$  | $1 \cdot 10^{-4}$ m³ |
| Maximum pressure                         | $P_{max}$ | 15 MPa     |
| Maximum cycle temperature                | $T_E$  | 650 C       |
| Minimum cycle temperature                | $T_C$  | 30 C        |
| Rotation frequency                       | $n$    | 30 s⁻¹      |
| Working fluid                            | $-$    | Helium      |
| Phase angle                              | $\alpha$ | 90°        |

In the proposed general configuration scheme shown in figure 1, the EG of the microturbine are not only utilized to heat the Stirling engine, but also to heat the network water [11]. Accordingly, the CHP plant’s efficiency would increase, as well as the output power.

![Figure 1. General configuration scheme of the CHP plant. C-Compressor; CC-Combustion chamber; T- Turbine; EG- Exhaust gases; HE-Heat exchanger; R-regenerator; G- Generator; CO- Cooler.](image_url)

A thermodynamic calculation was carried out according to the Schmidt analysis, to determine the main parameters of the engine. The Schmidt theory is one of the isothermal calculation methods for Stirling engines. It is the simplest method and very useful during Stirling engine development. This theory is based on the isothermal expansion and compression of an ideal gas. Although this theory
is idealized as well, it is considered more realistic than the ideal Stirling cycle. The calculation method consists of the following steps:

- Calculation of the amount of heat supplied through the heater, and rejected through the cooler, as well as the magnitude of the useful indicated work.
- Refinement of the obtained indicated power result using the Beal number.
- Calculation of the heat exchanger to determine the temperatures at the outlet of the Stirling engine.
- Calculation of the economizer to determine the flow rate of the network water.
- Formation of the heat balance of the CHP plant.
- Determination of the overall efficiency of the CHP plant.

The following basic parameters were calculated using the formulas presented in the works [12,13]:

The indicated energy \( W_i \) per cycle of the engine was calculated as follows:

\[
W_i = W_E + W_C = \frac{P_{\text{max}} \cdot \delta \cdot V_{\text{SE}} \cdot \pi \cdot \sin(\theta) \cdot \sqrt{1-\delta}}{\sqrt{1+\delta \cdot (1+\sqrt{1-\delta^2})}},
\]

(9)

Where:

\[
\theta = \arctg \left( \frac{k \cdot \sin \alpha}{\xi + k \cdot \cos \alpha} \right),
\]

(5)

\[
S = \frac{2 \cdot X \cdot \xi}{\xi + 1},
\]

(6)

\[
X = \frac{V_D}{V_{\text{SE}}},
\]

(7)

\[
\xi = \frac{T_C}{T_E},
\]

(8)

\[
\delta = \frac{\sqrt{\xi^2 + k^2 + 2 \cdot \xi \cdot k \cdot \cos \alpha}}{\xi + k + 2 \cdot S},
\]

(4)

\[
k = \frac{V_{\text{SC}}}{V_{\text{SE}}},
\]

(3)
The indicated expansion power \( L_E \), the indicated compression power \( L_C \), and the indicated power of this engine \( L_i \) were calculated using the following formulas:

\[
L_E = W_E \cdot n, \\
L_C = W_C \cdot n, \\
L_i = W_i \cdot n,
\]

To estimate the actual output power, Beal’s number was taken into consideration:

\[
P = B_e \cdot P_m \cdot f \cdot V_S,
\]

Where:
- \( B_e \) – Beal’s number;
- \( P \) – Engine’s power, W;
- \( P_m \) – Average pressure of the cycle, kPa;
- \( f \) – Cyclic frequency of engine revolutions, \( c^{-1} \);
- \( V_S \) – Total working volume \((V_{SE} + V_{SC})\) m\(^3\).

Beal’s number is a dimensionless parameter defined by Walker from the equation (13) [14].

\[
B_e = \frac{P \cdot P_m \cdot f \cdot V_S}{\text{const}},
\]

According to the available experimental data, Beal’s number is expressed using the following formula:

\[
B_e = 0.034 - 0.052 \cdot \xi,
\]

The calculated expansion power \( L_E \), allowed us to determine how much heat must be supplied to the heater of the Stirling engine from the EG released by the microturbine [15]. Knowing the amount of heat \( L_E \) necessary for the operation of the Stirling engine, it was possible to determine the EG temperature at the exit of the heater by the following formula:

\[
L_E = C_{P_{EG}} \cdot (T_{EG1} - T_{EG2}) \cdot G_{EG},
\]

Where:
- \( C_{P_{EG}} \) – EG heat capacity \( \left( C_{P_{EG}} = 1.1 \text{ kJ/(kg·K)} \right) \);
- \( T_{EG1} \) – EG temperature at the outlet of the microturbine, K;
- \( T_{EG2} \) – EG temperature at the outlet of the Stirling heater, K.

From the formula (16), the EG temperature at the exit of the heater was calculated:

\[
T_{EG2} = T_{EG1} - \frac{L_E}{G_{EG} \cdot C_{P_{EG}}},
\]

![Figure 2. Economizer scheme for heating the network water.](image-url)
The heat supply through the economizer from the EG was then determined:

\[ Q_{EGE} = G_{EG} \cdot C_{pEG} \cdot (T_{EG2} - T_{EG3}) , \]  

(18)

Where:
\( T_{EG3} \) — EG temperature at the exit from the economizer
\( Q_{EGE} \) is directed to heat the network water, and from the heat balance equation (19), the flowrate of the network water (\( G_{nw} \)) passing through the economizer was calculated:

\[ Q_{EGE} = G_{nw} \cdot C_{p_{nw}} \cdot (T_{dn} - T_m) , \]  

(19)

\[ G_{nw} = \frac{Q_{EGE}}{C_{p_{nw}} \cdot (T_{dn} - T_m)} \]  

(20)

Where:
\( C_{p_{cn}} \) — Heat capacity of the network water (\( C_{p_{cn}} = 4,19 \text{ kJ/ (kg·K)} \));
\( T_{dn} \) — Direct network water temperature, K;
\( T_m \) — Return network water temperature, K.

3. Results and discussion

The results of the calculation method described in the previous section are presented in table 3.

Table 3. The results of the calculation method.

| Parameter | Value | Unit |
|-----------|-------|------|
| \( W_E \) | 1151  | J    |
| \( W_C \) | 374   | J    |
| \( W_i \) | 777   | J    |
| \( L_E \) | 34.5  | kW   |
| \( L_C \) | -11.2 | kW   |
| \( L_i \) | 23.3  | kW   |
| \( P \)   | 10    | kW   |
| \( T_{EG2} \) | 528  | K    |
| \( Q_{EGE} \) | 297  | kW   |
| \( G_{nw} \) | 1.5  | kg/s |

Two general configuration schemes of the CHP plant were proposed, depending on consumer needs. The first scheme includes the simultaneous heating of the working fluid in the Stirling engine and network water. While the second scheme includes exclusively heating the working fluid of several Stirling engines. It is important to note that the heat rejected from the cooler of the Stirling engines can be used to heat the network water as well, moreover, the overall output power of the CHP plant would increase depending on the number of Stirling engines operating. The energy balance of the two schemes are presented in figure 3.
Figure 3. The energy balance of the two schemes: (a) Simultaneous heating of the Stirling engine and network water; (b) Exclusive heating of several Stirling engines.

Figure 3 (b) implies that the electrical efficiency ($\eta_e$) of the entire power plant can be increased as the number of the Stirling engines increases, and was calculated using the following formula:

$$\eta_e = \frac{N_{mt} + mP}{W_{eqv}},$$

Where:
- $m$ - The number of Stirling engines.

The electrical efficiency of the power plant without a Stirling engine is 33%, however, if one to five Stirling engines are operating, the electric efficiency of the power plant would increase from 35% to 41.6%. Moreover, the overall thermal efficiency of the CHP plant would increase up to 80-90%, when network water is heated from the EG of the microturbine.

4. Conclusions

CHP plants are becoming more popular in the energy sector due to their attractive attributes, not only due to their high efficiencies but also due to their positive contribution to the environment. Human needs are growing every year, especially energy demands. This puts a huge obstacle in front of engineers to find new methods that would satisfy the increasing demands of energy while taking into consideration the catastrophic effects on the environment. CHP plants appear to be one of the engineering solutions to increasing human energy needs, that would cause minimal damage to the ecosystem, compared to other power plants.

This paper presents a CHP plant consisting of a microturbine and a Stirling, and a calculation method of the power plant. The main highlights of this paper are as follows:

- Two general configuration schemes of the CHP plant, depending on consumer needs. One includes the simultaneous heating the Stirling engine and network water, while the second scheme includes exclusively heating of the Stirling engine, while the heat rejected by the cooler of the Stirling engine can also be utilized to heat the network water;
- Up to 50 kW of additional electrical power is generated by the Stirling engines connected to the CHP plant, which is about 25% of the overall output power of the microturbine;
The electric efficiency of the CHP plant can be increased from 35% to 41.6%, depending on the number of Stirling engines operating;

The maximum utilization of the EG from the microturbine to power the Stirling engine and heat the network water would increase the thermal efficiency of the power plant up to 80-90%.

Acknowledgments
This work was prepared with the support of the RUDN University Program “5-100”.

References
[1] 2015 Combined Heat and Power (CHP) Partnership epa
[2] Pilavachi P A 2002 Mini- and micro-gas turbines for combined heat and power Applied Thermal Engineering 22 2003-4
[3] Nascimento M, de L, Santos E, Gomes E, Goulart F, Gutierrez E and Miranda R 2013 Micro Gas Turbine Engine A Review
[4] Thu K, Saha B B, Chua K J and Bui T D 2016 Thermodynamic analysis on the part-load performance of a microturbine system for micro/mini-CHP applications Applied Energy 178 600-8
[5] Gimelli A and Sannino R 2017 Thermodynamic model validation of Capstone C30 micro gas turbine Energy Procedia 126 955-62
[6] Capstone c200s engine datasheet C200S: Capstone Turbine Corporation (CPST)
[7] Wills J A and Bello-Ochende T 2017 Exergy Analysis and Optimization of an Alpha Type Stirling Engine Using the Implicit Filtering Algorithm Front. Mech. Eng. 3
[8] Stolyarov S and Stolayrov A 2017 Stirling Generators: Challenges and Opportunities Russian Electrical Engineering 88 778-82
[9] Thombare D G and Verma S K 2008 Technological development in the Stirling cycle engines Renewable and Sustainable Energy Reviews 12 1-38
[10] Demonstration Stirling Engine based Micro-CHP with ultra-low emissions- SGC
[11] Thombare D 2008 Stirling Engine Micro-CHP System Encyclopedia of Materials: Science and Technology 1-8
[12] Belozertsev V, Goshkalev A, Nekrasova A and Shimanov A 2015 Methods of calculation and experimental studies of thermal Stirling machines (Samara, Russia: SSAU)
[13] Walker G 1980 Stirling Engines (Clarendon Press)
[14] Gaponenko A M and Kagramanova A A 2018 Analysis of the Stirling engine in the Schmidt approximation J. Phys.: Conf. Ser. 1111 012019
[15] Tsvetkov F and Grigorev B 2008 Problem Book on Heat and Mass Transfer: Study Guide (Moscow, Russia: MEI)