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Possibilities of the power optimization in the Stirling cogeneration engine fuelled by the natural gas

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Abstract. As the energy efficiency is at the heart of the integrated European Union energy policy, which aims to protect the environment through various research projects, the application of the Stirling engine for diffused electricity generation is one of the possible paths for low-carbon application. That is today particularly topical, just looking at the major interest paid at European level at the energy communities, also in terms of incentives and policies facilitating and supporting such initiatives. Although the tested engine V-160 runs on natural gas, its emissions can be neglected in comparison with the internal combustion engines, due to the much more favourable external combustion under the lower pressures and temperatures, as well as to the working medium, which is helium. Next step, becoming every day more and more relevant, will be using hydrogen as a clean (and green) fuel. A major advantage of the proposed engine for use in power generation is the constant speed under different loads. According to the thorough parametric analysis after 200 hours of operation of the engine at the University of Rome La Sapienza, new evidence of the possibilities of performance improvement was obtained. Compared to the Stirling engine with low temperature difference, it has a much lower Schmidt factor of about 21%, which means that a real thermodynamic efficiency of the cycle could be improved. The scope of the analysis was to determine the power that is changed due to the mass of helium and the power that is changed due to the temperature difference. Based on the experimental data, it is found that the temperature difference and the mass of the working medium have a reciprocal relationship. In such a working condition, the engine power is simultaneously increased due to the greater mass of helium, but at the same time decreased due to the decrease in the temperature difference, which is not valid for other types of Stirling engines. The resulting power can be optimized according to a new expression, presented in the paper.

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1. Introduction

The activities related to the industry and clean production primarily include the study of the applicability of the new or improved solutions [1], which can include an external combustion Stirling engine, fuelled by the natural gas. It is known that there are huge recoverable reserves of low permeability gas reservoirs amounting to 400 x 10^{12} m^3, a quantity twice as large as total proven gas reserves of 200 x 10^{12} m^3 [2]. According with the accepted scenario of the International Energy Agency [3], the percentage of gas from unconventional gas reservoirs in the total gas production should rise from today's 14% to 24% in 2035. As the country's economic objective is to ensure enough energy for its needs, many authors have attempted to determine the general empirical relationship between energy and the GDP, which could be a helpful tool in long-term national energy strategies [4, 5, 6, 7]. This research on the possibilities of the power optimization in the Stirling cogeneration is in accordance with conclusions of Naso et al. [8] upon the factors that will influence the success of Stirling engines in the future, among which the most important is the development of economic and technological issues. The originality of this paper is the investigation of the working condition under which the engine power is simultaneously increased due to the greater mass of helium and decreased due to the decrease in the temperature difference, that is resulted with a new expression for power optimization. Stirling engine cogeneration systems are being developed as power units for single family houses as an integrated CHP unit with pumps, heat exchangers, control unit etc, ready to be installed into a house. A wider vision is today particularly topical, just looking at the major interest paid at European level at the ***energy communities***, also in terms of incentives and policies facilitating and supporting such initiatives (www.enercommunities.eu) [9].

The V-160 engine [10] is a cogeneration unit with a nominal power output of 15 kWe @ 3600 rpm max (US version), and 28 kWt, named after its size, as the volume of both cylinders is equal to 160 cm^3; the maximum average working pressure is 15 MPa. It has a constant phase angle of 105°, typical for the Stirling engine of α-type (Figures 1 and 2).

Fig. 1. The V-160 Stirling engine [10].

2. Methodology

An experimental analysis has been carried out in order to check the sensitivity influence of some of the classical parameters characterizing the heat engines in general and the external combustion engines in particular. The obtained results show the peculiarity of the α-type Stirling engines, in general, and the V-160 one, in particular.
According to the technical data collected and presented together with the engine drawing in Figure 2, ten testing results of the engine experimental analysis were chosen and presented in Table 1, including next values: a) mean pressure, b) rotational speed, c) hot space temperature, d) cold space temperature, e) temperature difference, f) Schmidt cycle power, g) net power, h) break power, i) mass of the helium. Experimental data were measured at Sapienza University of Rome and the scope of the analysis and optimization of the data was to find out how much power is changed due to the mass of helium and how much due to the temperature difference.
The experimental tests were obtained in accordance with the description of the main parameters and technical data from the Figure 2. Heat is supplied with a cyclon burner fuelled with natural gas and power control is made through a mean pressure controller, so that the quantity of gas, inside the engine, can be changed with continuity [11, 12]. The pressure transducer is in the compression phase, between the compression piston and the regenerator. A complete electrical subsystem has been provided both for security and measuring. The cogeneration set is fitted with internal cooling circuit, provided with a three-speed pump and a flat plate liquid/liquid heat exchanger which is the user interface for the thermal output. An external cooling system consists of cold-water inlet and of hot-water outlet temperatures together with two thermocouples. Also, a flowmeter is provided together with a variac-contolled water pump.

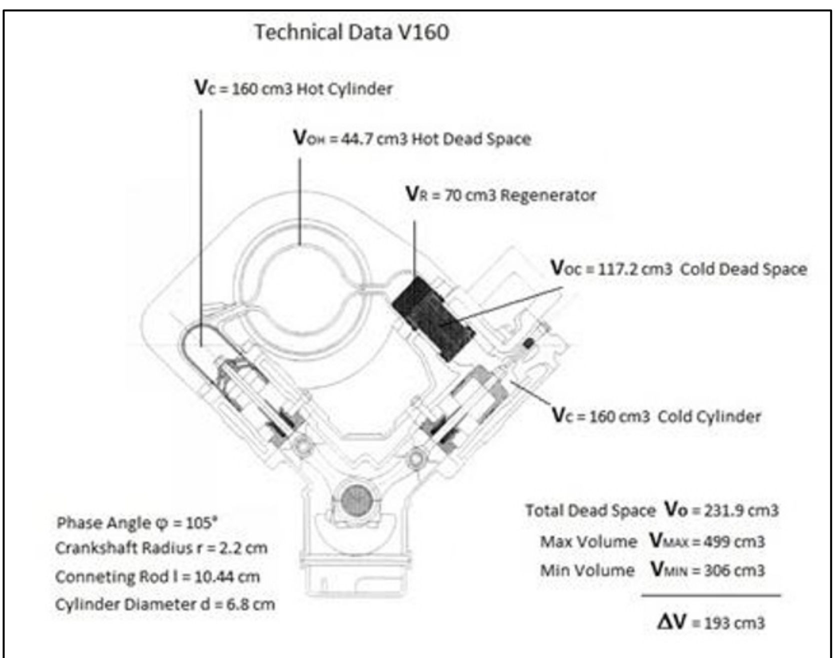

Fig. 2. Technical data of the V-160 Stirling engine [10].

Table 1. Test results.

Test number	a) p_m (MPa)	b) n (rpm)	c) T_H (K)	d) T_C (K)	e) ΔT (K)	f) P_S (W)	g) P_N (W)	h) P_B (W)	i) G (g)
1	5,92	1510	765	378,7	386,3	4750	3840	2880	2,22
2	6,68	1513	762	380,8	381,2	5343	4329	3247	2,50
3	7,6	1516	759	384,1	374,9	5990	4858	3644	2,83
4	8,36	1518	757	386,4	370,6	6477	5251	3938	3,11
5	9,12	1525	751	373,8	377,2	7252	5908	4431	3,46
6	9,95	1527	752	382,4	369,6	7801	6352	4764	3,72
7	10,75	1528	750	385,5	364,5	8321	6773	5079	4,02
8	11,51	1530	743	379,3	363,7	9061	7413	5559	4,62
9	12,23	1533	743	388,3	354,7	9218	7491	5618	4,30
10	12,57	1534	745,2	394,9	350,3	9392	7622	5716	4,63

3. Results

On the ground of the experimental data, it follows that the temperature difference and mass of the working medium are in the reciprocal proportion. In such working conditions, the engine power is simultaneously increased due to the greater mass of helium, but at the same time decreased due to the fall of temperature difference, as shown on the Figure 3.

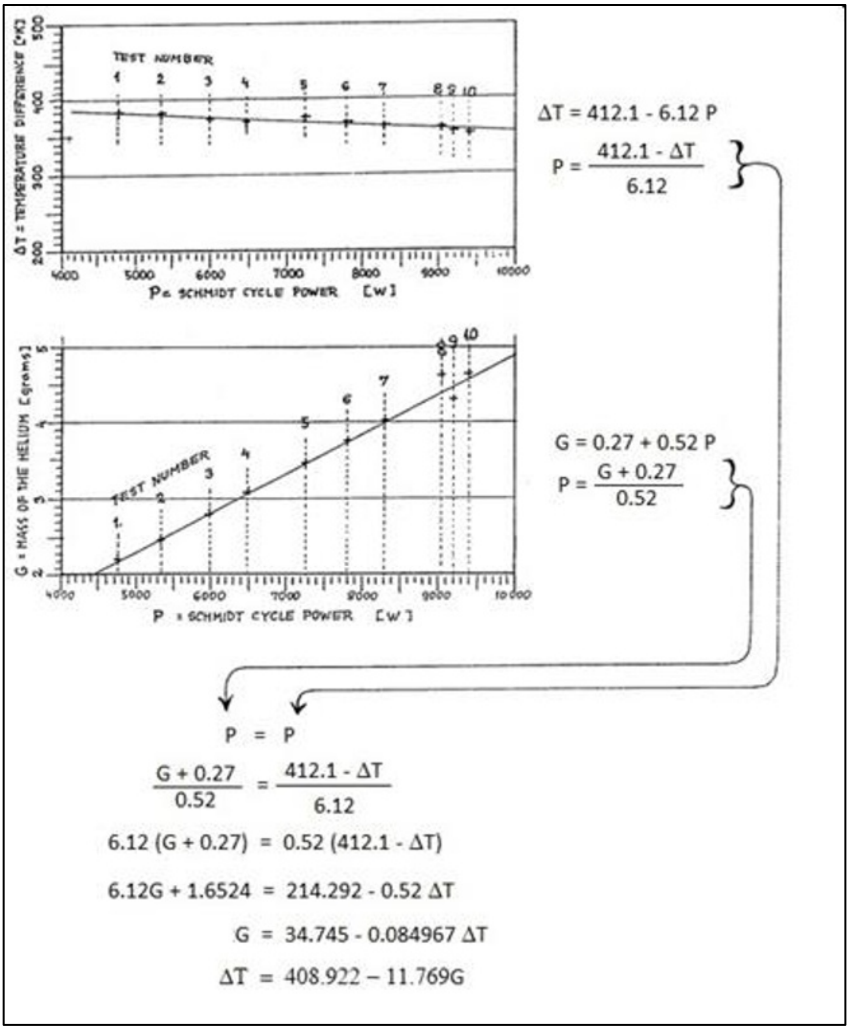

Fig. 3. Common influence of the helium mass and temperature difference.

Temperature difference, as well as greater mass of the working medium cause a higher engine power. This common rule is valid for just any Stirling engine, except for V-160 motor, where temperature difference decreases when the mass of helium is increased. When all the ten cycles, belonging to ten subsequent tests from the Table 1, are presented one over the other in the p,V-diagram (Figure 4), the resulting engine power can be deduced according to the mathematical procedure (Equation 1).

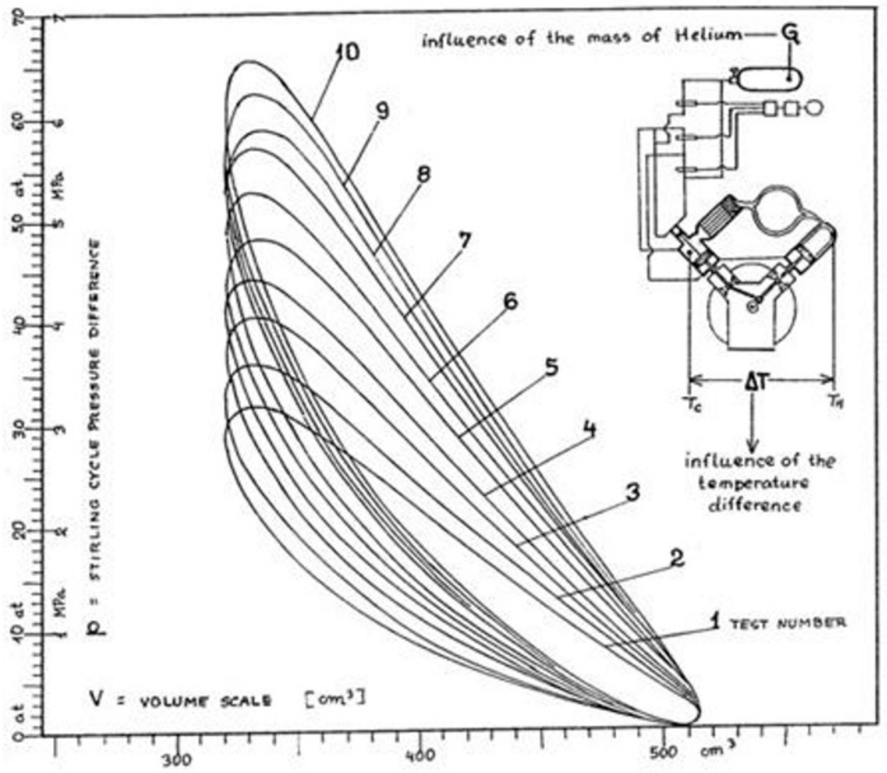

Fig. 4. p,V- diagram of ten cycles based on the selected test results from Table 1.

Engine Power		Influence of the mass of Helium		Influence of the temperature difference
P	**=**	$\mathbf{P_{(G)}}$	**-**	$\mathbf{P_{(\Delta T)}}$

According to the test results: $P_{(G)} = 2160 \cdot G$ $\Delta T = 408 - 11.769 \cdot G$

This expression may be reshaped into the most practical form:

$$P = 2160 \cdot G - 122\,(G - 2.22)^2 \tag{1}$$

Numerical example for the test 6 (G = 3.72 g):

$$P = 2160 \cdot 3.72 - 122\,(3.72 - 2.22)^2$$

$$P = 8035.2 - 274.5 = 7760.7\ \text{W}$$

$$P = 100\% - 3.4\% = 96.6\%$$

4. Discussion

Influence of the resulting power from the Equation 1 is more obvious when plotted in diagram where helium mass is related to do engine power (Figure 5). It is obtained by subtracting the power originating from the smaller temperature difference from the power arising from the growing mass of helium in the cycle. The specific nature of V-160 engine does not permit to present its power depending upon revolution speed, as generally used for heat engines. That's why in this research, a mass of helium, is suggested to be selected as a more suitable parameter to optimize the dependence of engine power.

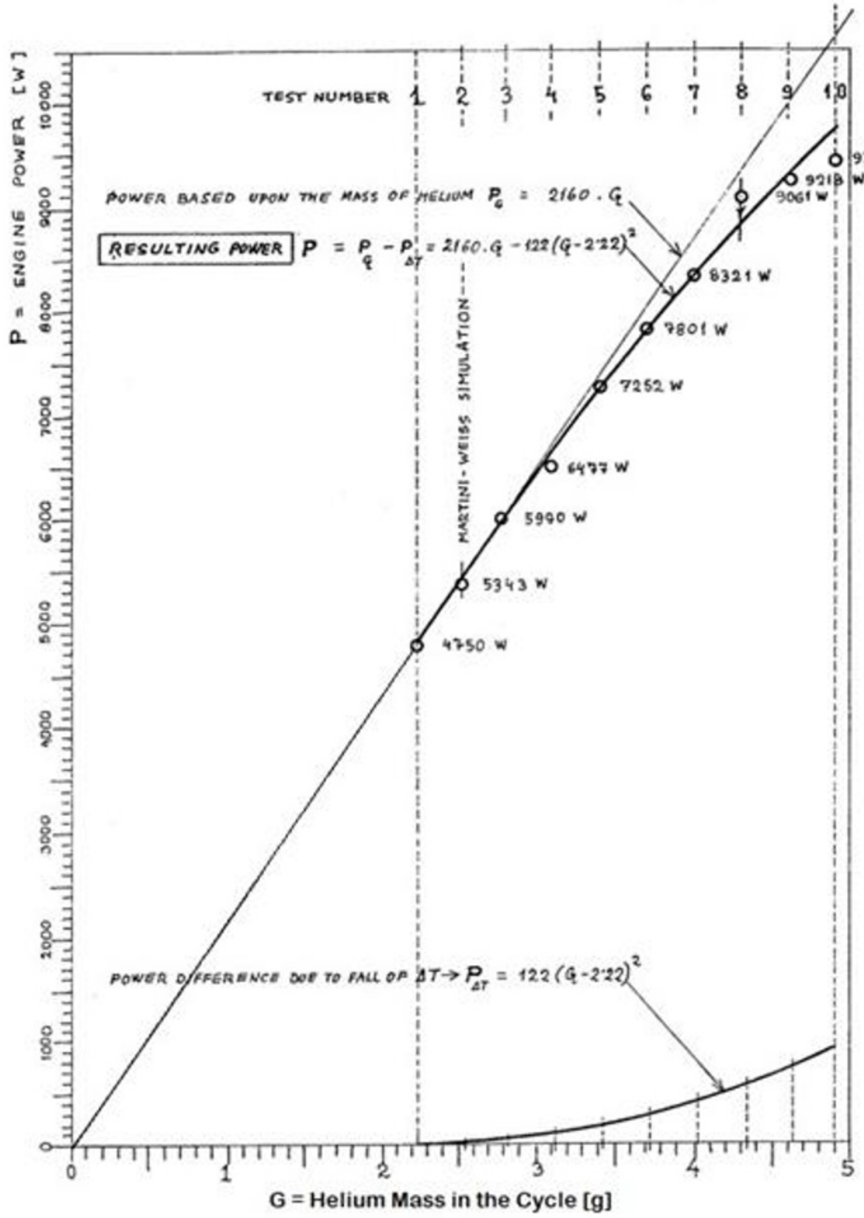

Fig. 5. Relationship between the helium mass in the cycle and the engine power.

5. Conclusion

According to the experimental data and thorough analysis of selected parameters, the new expression for engine power is deduced. As shown in the deduction of the final expression for power, two main parameters are mass of the helium and the temperature difference. It was proven the mass of helium is the main influencing parameter on the higher engine power and that the temperature difference changes only for a small percentage, being not the main reason for the increased engine power.

Nomenclature

G - mass of the helium, g
n - rotational speed, rpm
p_m - mean pressure, MPa
P_B - break power, W
P_N - net power, W
P_S - Schmidt cycle power, W
ΔT - temperature difference, K
T_C - cold space temperature, K
T_H - hot space temperature, K

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