Determination of Adequate Type of Stirling Engine for Cogeneration in Industrial Sector

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Abstract: In the present paper, a comparison study of three types of Stirling Engine (Alpha, Beta and Gamma) was realized for cogeneration purpose in industrial sector (cement plant). The different configurations of Stirling engine are simulated by PROSA software. Several parameters are analysed such as working gas pressure, engine speed, hot source temperature, cold source temperature and working fluid type. The results show that the Alpha Stirling engine is the best type for integration in cogeneration system purpose due to its high overall efficiency and output power, high compression ratio and low thermal losses.

1 INTRODUCTION

The depletion of fossil resources and their impact on the environment impose an energy resolution, which necessarily translates into a wide spread application of energy efficiency and massive use of renewable energies. Thus for the same comfort, we can pay less energy bill thanks to concepts optimizing the energy consumed and thus integrating the principle of energy efficiency. It is in this context that cogeneration (Combined Heat and Power, CHP) systems are integrated to improve the efficiency of industrial production processes. The Stirling Engine (SE) is a promising technology for cogeneration since it is an external combustion hot air engine, i.e. the heat required for its operation can be from multiple sources: solar energy, biomass, geothermal energy or even industrial heat waste.

Existing works in the literature have treated cogeneration with the SE only in residential building, unfortunately no work has addressed the possibility of integration SE in industrial sector for combined production of heat and electricity (CHP).

The SE is classified in three types: Alpha, Beta and Gamma, and each type is characterized by its advantages and limitations. The choice of a particular type for cogeneration requires preliminary study to be able to integrate it into the industry in an efficient way.

The aim of this work is the comparison between Stirling engine types for determination of the best configuration that deliver high output power and overall efficiency and so improve the performance of cogeneration based SE system.

2 COGENERATION SYSTEM

The World Alliance for Decentralized Energy (WADE) defines cogeneration as: «The process of producing electricity and the useful thermal energy (heat or cold) at high efficiency and close of the point of use». The idea of cogeneration is based on the fact that electricity generation releases a large amount of heat usually dissipated in the environment. For this reason, CHP techniques consist on recovering as much as possible this residual and available thermal energy.

The interest of cogeneration is the increase of production system efficiency corresponding to a more efficient use of primary energy resources. Cogeneration systems can minimize energy losses, reduce emissions and the investment price if the system is well designed. Fig.1 shows the process of cogeneration. CHP systems are distinguished from traditional systems by their high overall efficiency, Eq. (1) describes the efficiency of a traditional system and Eq. (2) presents the overall efficiency of cogeneration unit.

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$$\eta = \frac{E_{output}}{Q_{input}} \qquad (1)$$

$$\eta_{overall} = \frac{P_{output}}{Q_{input}} \qquad (2)$$

Where E_{output} is generated electrical power in KW, P_{output} is generated electrical and thermal powers in KW and Q_{input} is the fuel introduced into the system input in KW.

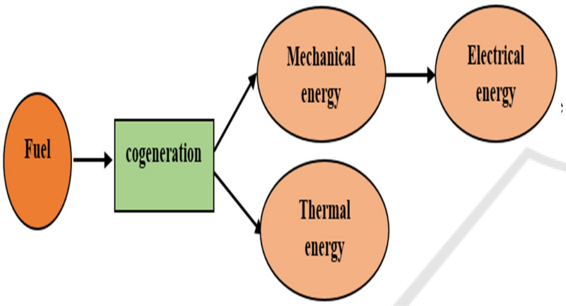

Figure 1: Cogeneration process.

3 ANALYSIS OF THE STIRLING ENGINE

3.1 Description of the Stirling Cycle

The Stirling engine (SE) is an external combustion hot air engine, it was invented by the Scottish clergyman and engineer Robert Stirling in 1816. The Stirling machine is a device that operates in a closed cycle according to a thermodynamic cycle, which in theory is described as a group of thermodynamic processes comprising two isotherms and two isochores. Fig.2 depicts the Pressure-Volume (P-V) diagram of the Stirling cycle.

The area under P-V diagram presents the work obtained from the operation of SE. As the Fig.2 shows, the cycle is divided into for processes:

- Process 1-2: Isothermal compression of working fluid and release of heat to the external source.
- Process 2-3: Isochoric heating given by the regenerator to the system.
- Process 3-4: Isothermal expansion of working fluid by introduction of the heat to the engine from external source.
- Process 4-1: Isochoric cooling of the engine and absorption of heat from the regenerator.

Theoretically, the efficiency of Stirling cycle is the same as Carnot efficiency and is worth:

$$\eta_{stirling} = \frac{W_{output}}{Q_{input}} = \frac{T_h - T_l}{T_h} \qquad (3)$$

Where W_{output} is the output work in W, Q_{input} is the input heat in W and T_h, T_l are the hot and cold sources temperature respectively.

The output power of SE can be calculated approximately from the Beale formula:

$$P = 0.015 p_m f V_p \qquad (4)$$

Where P is the output power of SE in W, p_m is the mean pressure in bar, f is the frequency of the cycle in Hz and V_p is the displacement of the piston in cm^3.

The pressure of the SE is an important parameter that is used for calculating the engine work, it is as follows:

$$p = \frac{1}{\frac{V_{\exp}}{T_E} + \frac{V_{reg}}{T_{reg}} + \frac{V_{comp}}{T_C}} \qquad (5)$$

Where p is the pressure of Stirling engine, $V_{\exp}$, V_{reg} and V_{comp} are expansion, regenerator and compression space volumes respectively in m^3, T_E, T_{reg} and T_C are expansion, regenerator and compression spaces temperature in K.

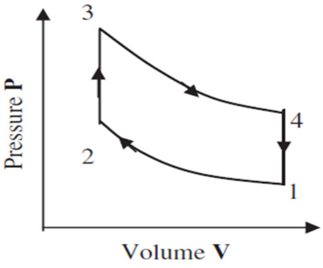

Figure 2: Stirling cycle diagram.

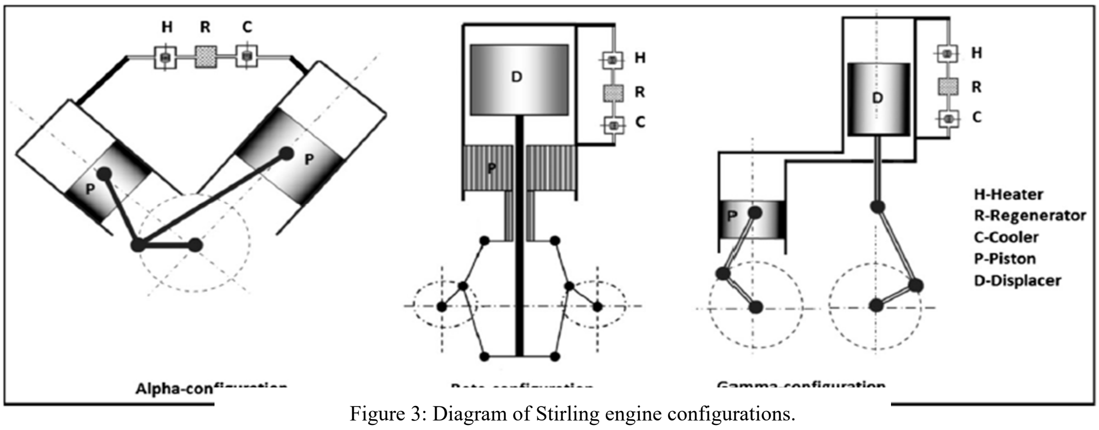

Figure 3: Diagram of Stirling engine configurations.

The SE differs from traditional engines by several advantages such:

- Multi-fuel capability.
- High efficiency.
- Low operating noise.
- Low emissions.

3.2 Classification of the Stirling Engine

As mentioned before, there are three types of SE: Alpha, Beta and Gamma, that are different by the geometric configuration of each type as illustrated in Fig.3.

The Alpha configuration has two pistons in hot and cold cylinders respectively, it is a V-shape formed by two pistons that are joined at the same point on a crankshaft. The working fluid is moved between the two pistons. A heater, regenerator and cooler are grouped in series. The Alpha type can be joined with a configuration of multiple cylinders, hence a high power output can be reached, which is adaptable with motorized machines.

The Beta configuration possesses a single cylinder containing both a power piston and a displacer that moves the working gas between the cold and hot ends. This configuration is used with a rhombic drive in general in order to keep the phase angle difference between the power and displacer pistons, but they may be joined on a crankshaft. Beta type has less technical problems than the other types because the power piston is away from the hot fluid.

The Gamma configuration has two separated cylinders like Alpha configuration, but it possesses a piston and displacer as the same as the Beta type, and the pistons are joined in parallel on a crankshaft. This configuration produces lower compression ratio as the compression space is split up between the two cylinders, but it is mechanically simpler than the other configurations.

3.3 Application of the Stirling Engine for Cogeneration in Cement Plants

Cement plants are a major source of heat ejection that is lost in the air without any exploitation. In this study, we are interested in the recovery of thermal losses ejected by the process of clinker (cement component) cooling leaving the kiln of cement plants.

The hot air generated from the cooling will be recovered using a heat exchanger to be the heat source of the SE which will simultaneously produce electricity and heat for cogeneration purpose.

The specifications and operating conditions of the SE types used in this study are summarized in Table 1.

4 RESULTS AND DISCUSSION

4.1 Effect of Pressure

The pressure parameter has an important influence on the operation of SE since it contributes on the displacement of the working gas.

Table 1: Technical specifications of Stirling engine.

Parameters	Values
Pressure (bar)	350
Hot source temperature (˚C)	1110
Cold source temperature (˚C)	61
Engine speed (rpm)	1500
Matrix outer diameter (mm)	104.24
Length of the cooler pipes (mm)	220
Number of the cooler pipes (-)	161
Length of the heater pipes (mm)	246.3
Number of the heater pipes (-)	80

Fig.4 shows the pressure impact on the overall efficiency, i.e. thermal and electrical efficiencies, for the three types of SE. It is seen that the overall efficiency increase as the pressure increase and reach the values of 71.27 %, 72.46 % and 72.61 % for Beta, Gamma and Alpha types respectively for 500 bar value. The increase of overall efficiency for all the types is due to the fact that the area under the P-V diagram becomes larger at higher pressure which is equal to power output. Hence the SE will produce more power and it efficiency will increase. The Alpha exceeds the other types in terms of overall efficiency because it has a high compression ratio and its pressure drop are low.

Fig.5 illustrates the influence of pressure on the thermal power. It is shown that Gamma configuration can produce more thermal power compared to the other types. This is because Gamma type has more heat losses so the cogeneration based SE system recovers these thermal losses to generate thermal power. However, the Alpha type produce more electrical power so its overall efficiency is higher than Beta and Gamma types as it is depicted in Fig.4.

4.2 Effect of Hot Temperature

The electrical efficiency for all SE types can be improved when the temperature of hot source rises, as displayed in Fig.6, and reaches maximum values of 50.88 %, 41.79 % and 40.32 for Alpha, Beta and Gamma respectively at 1500 ˚C. It is due to the Carnot efficiency equation which reveals that the increase of hot temperature will improve the efficiency, hence the output power will also increase.

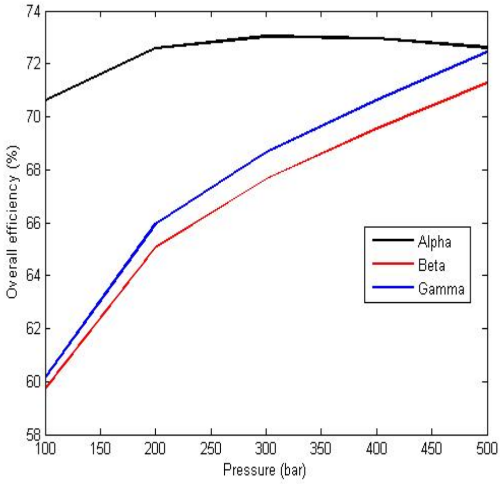

Figure 4: Effect of pressure on overall efficiency.

The Alpha type remains the most powerful configuration for CHP than the others, as the volumes of hot and cold sources are separated, therefore it does not release a lot of thermal losses and the input heat is used properly.

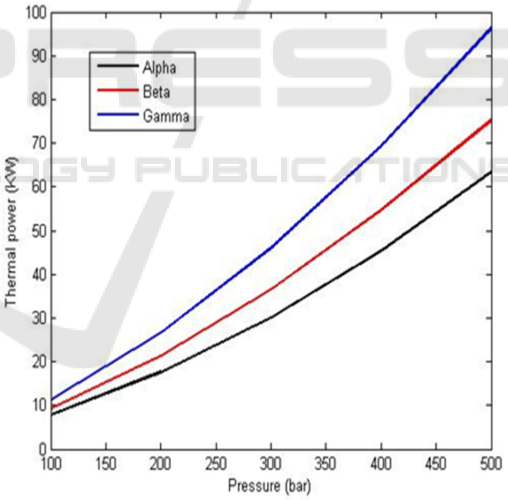

Figure 5: Effect of pressure on thermal power.

4.3 Effect of Cold Temperature

As it is depicted in Fig.7, the performance of SE decreases with the increase of the cold source unlike that of the hot source. It can be seen that the efficiency increases almost linearly for the three configurations as long as the cooling temperature decreases and reaches the values of: 46.07 %, 37.27 % and 34.45 % for Alpha, Beta, Gamma respectively at 0 ˚C.

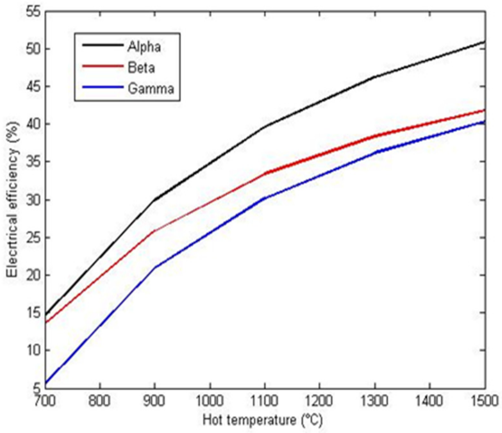

Figure 6: Effect of hot temperature on electrical efficiency.

This result is theoretically explained by the fact that it is necessary to have a large temperature difference between the hot and cold sources of the Stirling engine to optimize its performance.

The efficiency of the Alpha engine exceeds that of the other types because it is characterized by its capability to operate with a large temperature difference, which is the case of this study.

4.4 Effect of Engine Speed

Fig.8 compare the electrical power of SE with two working fluid (Helium and Air) at different engine speed values. The use of Helium as working gas improve the output power because of its low heat capacity and high thermal conductivity unlike Air.

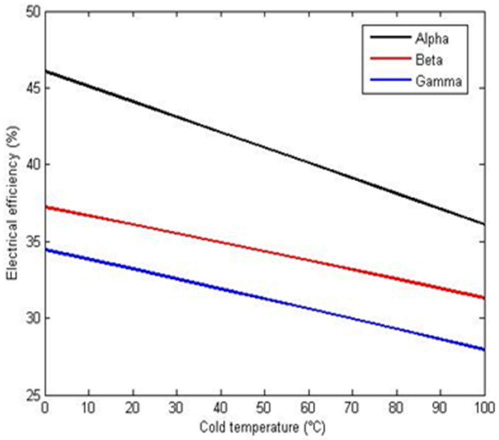

Figure 7: Effect of cold temperature on electrical efficiency.

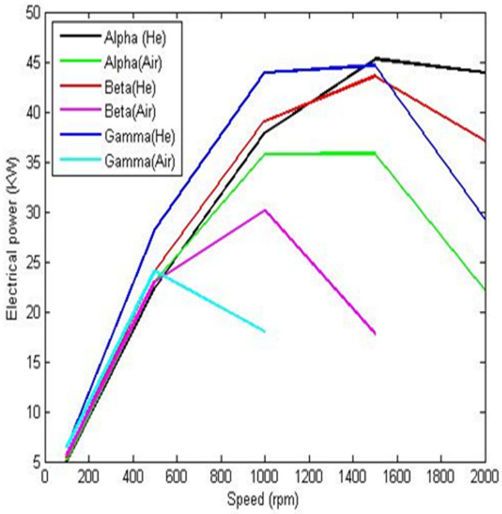

Figure 8: Effect of engine speed on electrical power.

The increase of electrical power at higher speed is due to the repetition of the P-V cycle. However, the rise of speed decreases the efficiency because of the increase of the engine friction, so the heat exchange between working gas and heat source does not happen properly.

In high engine speed values (≥ 1500 rpm), the Alpha SE provides high electrical power thanks to its low dead volume and low friction in working space.

4.5 Effect of Thermal Losses on SE Performance

In Fig.9, the thermal losses of three types of SE are given for different pressure. It is noticed that the thermal losses increase as the pressure increase. This is due to leakage of piston rings, heat leak in the conduct between the working gas and the hot source and heat losses in regenerator of the SE.

The Gamma type has great thermal losses which is owing to the no capability of this type to operate with large temperature difference. Therefore, a lot of heat input will be lost.

The Alpha SE remains the type that has the minimum of thermal losses thanks to the fact that no mixture between hot and cold working fluid is performed.

The numerical results of this work simulation are given in Table 2.

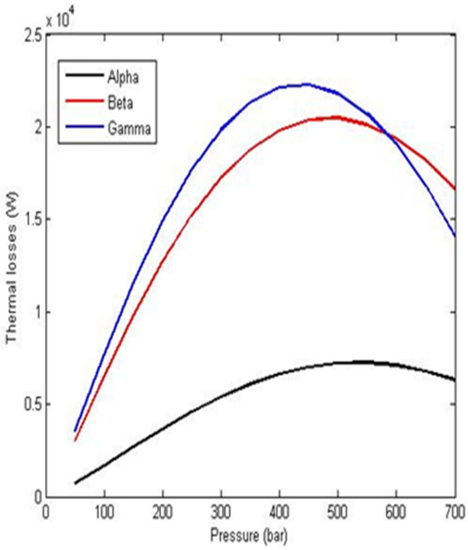

Figure 9: Thermal losses depending on the engine pressure.

Table 2: Numerical results of the comparison study

Electrical power (KW)			Electrical efficiency (%)		
Alpha	*Beta*	*Gamma*	*Alpha*	*Beta*	*Gamma*
45.29	43.57	44.61	40.01	33.68	30.53

5 CONCLUSIONS

In the present work, a comparison study between three types of Stirling engine for cogeneration purpose in industrial sector (cement plant) is carried out.

First, the influence of engine pressure on overall efficiency and thermal power respectively was analysed. The results show that Alpha type provides the best overall efficiency thanks to its large compression ratio. However, it does not provide the best thermal power.

It is also noticed that the increase of hot source temperature positively varies the efficiency of all types, as it is necessary to apply a large temperature difference between the hot and cold sources to improve the engine performances. The results show that Alpha type remains the best configuration for industrial cogeneration due to its low thermal losses, so the input heat is well used by the system.

The SE is optimized when Helium is utilized as working gas because it has a high heat transfer coefficient. It was found that the Alpha type can provide high efficiency at high speeds due to its low dead volume, hence the Stirling cycle can be repeated several times without lot of mechanical friction.

The Alpha Stirling engine can generate a great power output with high overall efficiency for industrial cogeneration (cement plant in this study), because of several advantages including high compression ratio, low dead volume, separation of hot and cold working gas spaces and capability of operation in a high temperature difference.

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