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Study of the regenerator constituting material influence on a gamma type Stirling engine †

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Abstract

A gamma Stirling engine with compressed air as working fluid was investigated. This engine operates at a maximum charge pressure of 10 bar, runs at a maximum rotation speed of 600 rpm and can provide 500 W of brake power on the shaft. The engine is equipped with several pressure sensors and thermocouples. This experimental study concentrates on the regenerator constituting material (porous medium). Four different materials were investigated: stainless steel, copper, aluminum and Monel 400. The obtained experimental results provide guidance to Stirling engine enhancement and selection of the appropriate regenerator material. As a conclusion, the regenerator has an important role to enhance the heat exchange and to improve Stirling engine performance, which closely depends on its constituting material.

Keywords: Brake power; Stirling engine; Thermal capacity; Thermal conductivity; Regenerator material; Optimization

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1. Introduction

Robert Stirling invented the Stirling engine in 1816. He had the brilliant idea to use a heat economizer, a regenerator, to improve his system. The regenerator is a heat exchanger formed generally of a porous medium. It separates both sources of heat, and operates as a thermal sponge which alternatively accepts and rejects heat from the working fluid. Much experimental and analytic research have been conducted to understand the phenomena of heat transfer, irreversibility, imperfect regeneration and flow friction in Stirling engine regenerators. The influence of regenerator imperfection and dead volume (dead volume in hot and cold spaces and all regenerator volume) on Stirling engine performance were studied [1, 2]. They indicated that only the dead volumes can influence the engine net work. On the other hand, they proved that engine efficiency and heat input are affected by both regenerator effectiveness and dead volumes. Ones [3] proposed an approximate analytic solution to express regenerator ineffectiveness and entropy generation rates, which can be useful to determine the optimal design of a Stirling engine regenerator. A new regenerator matrix design was proposed. It was divided into 3 sections [4]. The end sections have larger fill factors and wire diameters than the central one. Their new design improves engine efficiency from 32.9% to 33.2%. Abduljalil developed an experimental study to identify a low cost regenerator material with performance similar to those usually used [5]. They concluded that the regenerator porosity and the flow resistance considerably affect the performance of the regenerators. In fact, the very high regenerator porosity causes higher thermal relaxation loss.

Despite the numerous studies made on the Stirling engines regenerators [6-9], it is difficult to find experimental analysis of the regenerator's constituting material. In the present paper, four regenerator matrices with different materials were employed to carry out the investigation of a gamma type Stirling engine. The first matrix is made of stainless steel (S-S), which is the most commonly used regenerator material in Stirling engines. The second matrix is made of copper, which has a significant thermal conductivity. The third matrix is constituted of aluminum, which has a very low density, does not oxidize like copper and/or like steel, and can be efficiently and ecologically recycled. The last matrix is formed of Monel 400, which is a nickel-copper alloy with high strength and excellent oxidation resistance. All regenerators are experimented upon by varying the initial charge pressure and the heating tempera-

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Table 1. The Stirling engine dimensions and specifications.

Parameters	Values	Parameters	Values
Maximal rotation speed	600 rpm	Regenerator	
Working fluid	air	Outside diameter	134 mm
Crank radius	66 mm	Inside diameter	98 mm
Compression space		Height	50 mm
Diameter	80 mm	Porous media: Copper	
Height	145 mm	Porosity	90%
Expansion space		Temperature of the hot source	500°C
Diameter	95 mm	Temperature of the cold source	15°C
Height	120 mm	Compression ratio	3.5

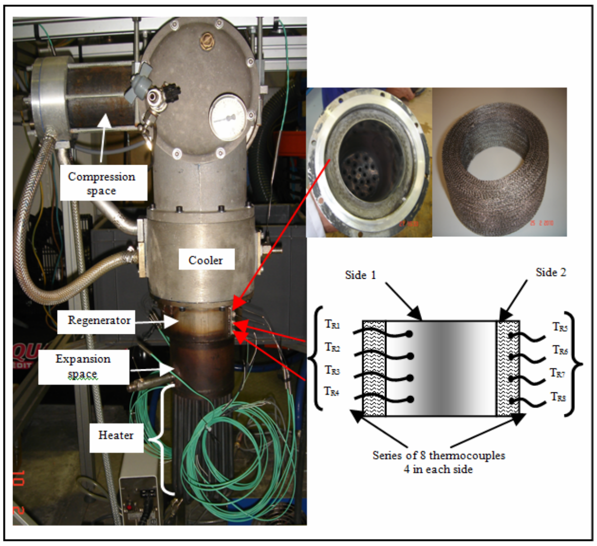

Fig. 1. Photo of the Gamma Stirling engine and its regenerator.

ture. The Stirling engine performances are calculated and drawn for every parameter variation (material, pressure, temperature).

2. Experimental apparatus

Our experiments were made on a gamma Stirling engine (Fig. 1). This engine is mainly composed of two working spaces and three heat exchangers: a heater, a cooler and a regenerator. It can provide 500 W of brake power and can reach 600 rpm as maximal rotation speed. The operating conditions and the geometrical characteristics of the studied Stirling engine are depicted in Table 1.

The engine heater is formed of 20 pipes heated up to 500°C by an electrical resistance (hot source). The cooler is formed of 225 slides divided in a cylinder which increases the exchange surface between the working fluid and the cooling water circulation (cold source). The regenerator (Fig. 1) is located between the cooler and the heater. It is constituted of a porous medium with a fixed porosity.

Table 2. Properties of all used regenerator materials.

Materials with porosity of 90%				
Proprieties	Stainless steel 304L	Copper	Aluminum	Monel 400
Density (kg.m^{-3})	7.850	8.920	2.700	8.800
Thermal capacity (J.kg^{-1}.K^{-1})	477	385	902	430
Thermal conductivity (W.m^{-1}.K^{-1})	26	390	237	22

3. Instrumentation

The local and instantaneous measured parameters are as follows: expansion and the compression pressures, cooling water flowrate, developed mechanical torque and temperatures at different locations of the engine. For the temperature measurements, type-K thermocouples with diameters of 0.5 mm, 0.25 mm and 0.0254 mm were used. These diameters are small enough that the thermocouples' thermal inertias do not mislead measurements of instantaneous temperatures. Two thermocouples were implanted upstream the expansion space and in the compression space, respectively. Another two thermocouples were used to measure the temperatures of the inlet and the outlet cooling water. Eight thermocouples were skinned symmetrically (Fig. 1) up to 1 mm inside the regenerator matrix without touching the material. They allow measurement of the working fluid temperature passing through the regenerator. The brake power produced by the Stirling engine was transmitted by a transmission belt to an alternator. The alternator was mounted on a balance plate which was used to determine the torque transmitted from the transmission belt to the alternator. Pressure transducers were installed in the compression space and the area after the expansion space. A wide range of frequency responses was chosen to ensure good instantaneous measurements of the pressures inside the working spaces. The thermocouples have ±1.1% of incertitude for the measured temperatures. The pressure transducer has 0.15% of incertitude for measured pressure and the force transducer has 0.25% N.C (nominal charge) of incertitude. Experimental data were recorded using a fast acquisition system, ADwin Pro-II. This is an external processing system with modular expansion options. All acquisitions data were coordinated by a crank angle transducer connected to the engine shaft. For every crankshaft degree, the crank angle transducer sends a transistor-transistor logic (TTL) external signal to the processor module, which performs the acquisition of all signals connected to all used modules. For every cycle, 360 acquisitions are done. For every test, 100 cycles are recorded.

4. Results and discussion

During our experiments, the Stirling engine was experimented upon with different regenerators, and the same experimental conditions are seated for each test. Table 2 reca-

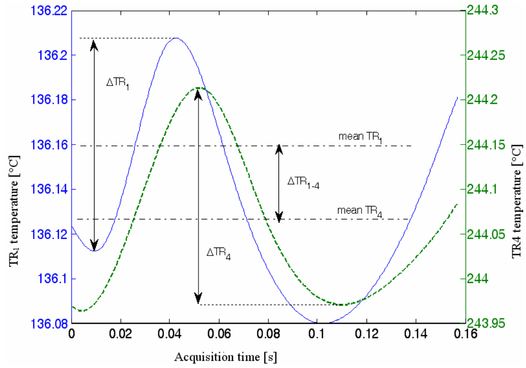

Fig. 2. Working fluid temperature evolution vs. acquisition time for a copper matrix.

pitulates the different regenerator materials that were used and their respective characteristics.

As explained in the literature, the working fluid crosses the regenerator twice in each Stirling cycle. Let's consider that the working fluid flow direction is from the cooler to the heater, passing through the regenerator. The heated regenerator matrix discharges the storage heat to the cold working fluid during half of the crankshaft cycle (half of a period). During the reverse flow direction (working fluid flowing from the heater to the cooler), the regenerator matrix is heated by the hot working fluid during the second half of the crankshaft cycle.

The heat quantity accepted or rejected by the regenerator matrix is represented by the peak to peak temperature given by the TR_1 and TR_4 thermocouples. The difference between the mean temperatures given by these TR_1 and TR_4 thermocouples represents the temperature gradient between both regenerator sides. It can be seen in Fig. 2 that the temperature of the working fluid in the regenerator increases in the first half cycle until a maximum value, then this temperature decreases during the second half cycle until a temperature close to that of the cold source. The Stirling engine regenerator has two roles. The first one is to act as a thermal sponge (ΔTR_1 and ΔTR_4) and the second is to form a thermal barrier between both heat sources ($\Delta TR_{1\text{-}4}$).

The "heat storage" character of a Stirling engine regenerator is defined by the heat capacity of its constituting material. The amount of heat stored by each regenerator increases with its heat capacity. Its "thermal barrier" character is represented by its thermal conductivity, and the gradient of temperature between its two sides (warm side and cold side) decreases with the thermal conductivity of the constituting material.

Fig. 3(a) represents the specific heat capacity of all experimented material and the variations of the working fluid temperature. It can be seen that the working fluid temperature increases about 1.4°C when it passes through the copper regenerator (from the cold side to the warm side of the engine). Thus, this regenerator provides the maximum quantity of heat to the working fluid. The aluminum regenerator allows a minimal amount of heat transfer to the working fluid. Fig. 3(b) shows that the stainless steel regenerator has the highest gradi-

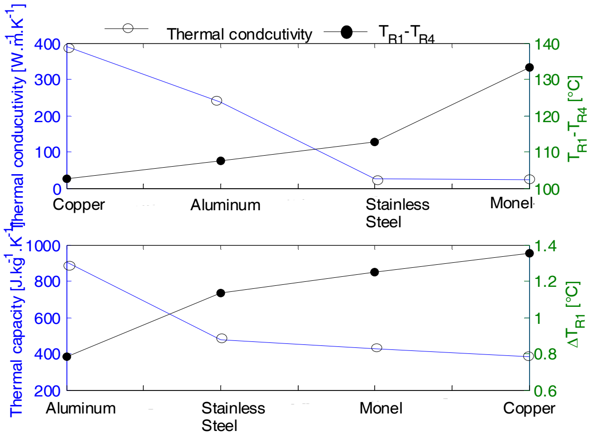

Fig. 3. (a) Working fluid gradient temperatures given by the thermocouples TR_1 for all studied materials; (b) Working fluid gradient temperature between the thermocouples TR_1 and TR_4.

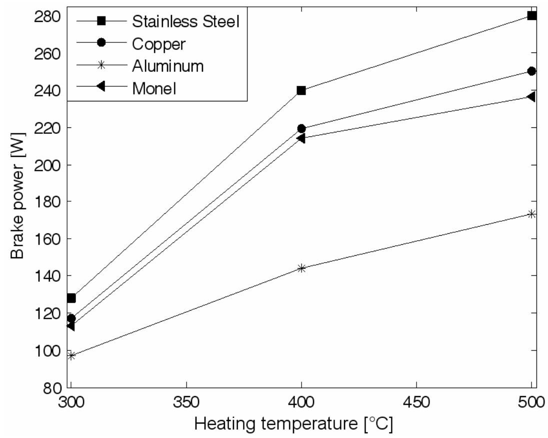

Fig. 4. Stirling engine brake power for the different regenerator materials for all experimented temperatures.

ent of temperature between the two regenerator sides and the aluminum regenerator has the lowest gradient.

An increase of initial charge pressure in the Stirling engine simultaneously increases the working fluid mass, density and velocity, consequently increasing the amount of work produced by the engine. The increase of heating temperature increases the working fluid temperature as well as the gradient of temperature between both sources of heat.

In the following section, the experiments were conducted at 300°C, 400°C and 500°C for the heating temperature and 3 bar, 5 bar and 8 bar for the initial charge pressure.

At constant heating temperature (T_H=400°C), respective variations of brake power with the charge pressure and the regenerator materials are illustrated in Fig. 4. It is shown that the brake power increases with the initial charge pressure for all studied regenerator materials. The stainless steel regenerator produced the best brake power (about 308 W for P_i = 8 bar). The aluminum regenerator generates the worst brake power (about 203 W for P_i = 8 bar).

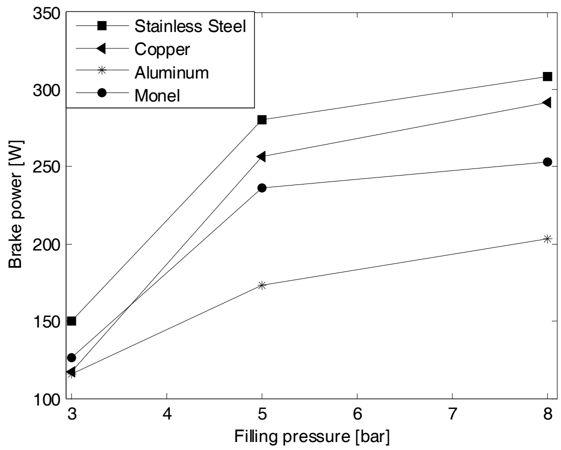

Fig. 5. Stirling engine brake power for the different regenerator materials for all experimented charge pressures.

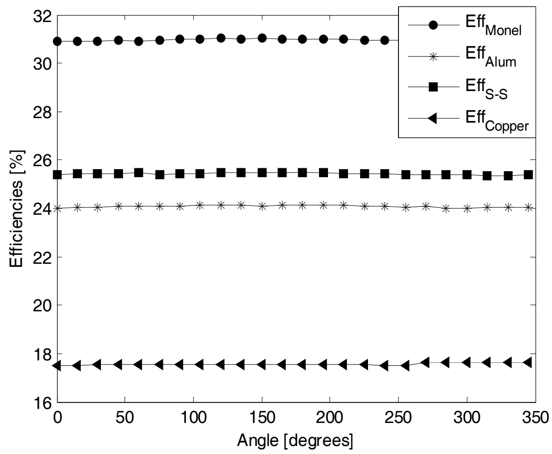

Fig. 7. Regenerator's efficiencies vs. acquisition time.

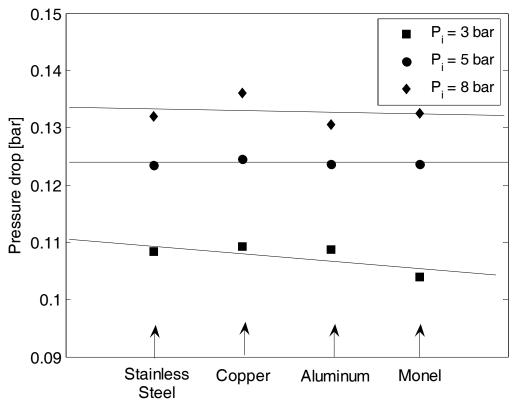

Fig. 6. Pressure drop obtained for all studied materials and for different initial charge pressures.

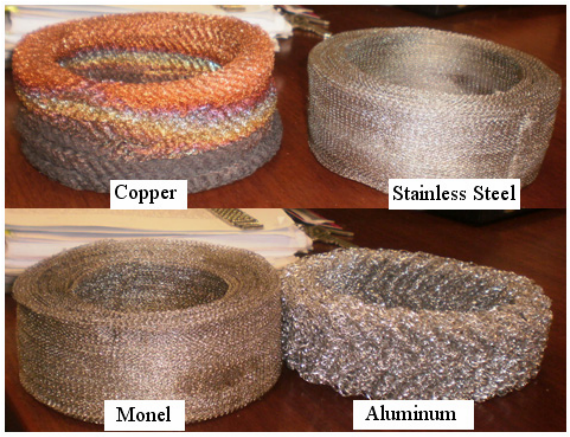

Fig. 8. Regenerator matrixes after about 15 hours of use.

For important initial charge pressure (Fig. 5), the copper regenerator generated brake power that is comparable to that of the stainless steel regenerator. However, for important heating temperature, its resulting brake power is less than that of the stainless steel regenerator. In fact, the increase of heating temperature leads to the greater loss by shuttle effect and by internal conduction due to the high thermal conductivity of the cooper.

In this study, all experimented regenerators have the same porosity of 90% (same pores volume). Thus, approximately the same pressure drop is recorded for all materials (Fig. 6). The pressure drop increases with the engine charge pressure independently of the experimented regenerator materials.

The regenerator thermal efficiency is calculated as the ratio of real heat transferred through the regenerator by the ideal heat, which must be transferred through the regenerator.

Fig. 7 represents the regenerator efficiencies vs. experimental acquisition time for the different studied materials. As can be seen, Monel 400 presents the best regenerator thermal efficiency and copper presents the worst regenerator thermal efficiency.

Fig. 8 shows all experimented regenerators after about 15 hours of use. It can be concluded that the copper matrix cannot be recommended to be used as a Stirling engine regenerator. In fact, heated at 500°C, the copper oxidizes quickly because of the working fluid (air) which contains about 21% of oxygen. This material oxidation quickly changes the physical characteristics of the copper, then leads to deterioration in heat exchange. The stainless steel and the Monel 400, used in regenerators, have good thermal efficiencies: 31% and 25.5%, respectively. These two materials do not present the problem of oxidation. The use of aluminium in a regenerator is limited by its melting temperature.

5. Conclusions

Four regenerator matrices with different constituting materials were experimented: stainless steel, copper, aluminum and Monel 400. The Monel 400 and the stainless steel regenerators present an acceptable thermal efficiency and do not oxidize. Respectively, the regenerators of stainless steel and of Monel 400 produce 300 W and 253 W of brake power for $P_i = 8$bar.

Due to its high heat capacity and thermal exchange rate, the stainless steel regenerator is shown to be the best Stirling engine regenerator compared to the other studied materials.

The use of the cooper regenerator is not recommended. In fact, the presence of oxygen in the working fluid presents a great risk of oxidation, which leads to changes in physical and thermal properties. This phenomenon decreases extremely the thermal exchanges, and consequently the brake power of the Stirling engine.

The use of a higher initial charge pressure and heating temperature leads to the increase of Stirling engine brake power and efficiency despite the increase of some losses in the engine. A good optimization of the Stirling engine can be made by making a compromise between performance and thermal and aerodynamic losses.

Acknowledgment

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Nomenclature

Alum : Aluminium
P_i : Initial charge pressure
S-S : Stainless steel
ΔT : Difference of temperatures
T_h : Heating temperature
T_{R1} : Temperature given by thermocouple 1
T_{R2} : Temperature given by thermocouple 2

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