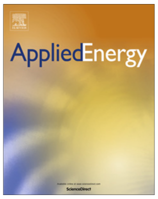
Applied Energy 139 (2015) 272–280

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy



Determination of adequate regenerator for a Gamma-type Stirling engine

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HIGHLIGHTS

- A Gamma-Stirling engine is investigated to optimize its operation.
- A stainless steel of a porosity of 85% was used as material for the regenerator.
- Asymmetry of heat transfer inside regenerator's consumes a part of produced energy.
- Central composite rotatable design was adopted to minimize this phenomenon.
- The heating temperature is a most significant factor in the study.

ARTICLE INFO

Article history:
Received 24 July 2013
Received in revised form 20 October 2014
Accepted 11 November 2014

Keywords:
Stirling engine
Regenerator
Constituting material
Porosity
Optimization

ABSTRACT

This paper deals with an optimization of the Stirling engine regenerator's. Firstly, different materials are experimented (Stainless Steel, Copper, aluminum and Monel 400). The engine performances and the state of each material after 15 h of use are considered. The Stainless steel was the material that best satisfies these two conditions. Five regenerators in stainless steel with different porosities were manufactured and experimented (95%, 90%, 85%, 80% and 75%). Porosity that gives the best trade-off between maximizing the engine brake power, maximizing the heat transfer and minimizing the pressure drops, was retained. Thus, the regenerator in stainless steel with porosity of 85% was considered as the most suitable matrix maximizing the Stirling engine performances and minimizing heat and friction losses.

1. Introduction

Stirling engine regenerators are very complex to modeling and to designing. It will require a large number of equations to describe their thermodynamic operation. Since it is a balancing act of several factors, some researches have proposed the best regenerator qualities [1–4] allowing optimal Stirling engine performances. It must have:

- High thermal capacity to minimize temperature variation [5],
- high thermal conductivity to minimize temperature gradients [6],
- large surface area to minimize temperature differences between the regenerator and the working fluid [7],
- small dead volume with dense matrix to maximize pressure variation [7,8a,b],
- a highly porous matrix with minimum resistance to flow [9,10].

Evidently, it is impossible to satisfy all these properties at one time; thus any regenerator must be a compromise [3].

Chen et al. [11] has demonstrated that the insertion of a metallic matrix helps the system to become more stable to possible disturbances in the mass flow rate supply of hot fluid. Timoumi et al. [12] studied the performances of a Stirling engine regenerator for porosity ranging from 0.6112 to 0.9122 by varying its corresponding wire mesh from 0.0090 to 0.0035. The decrease in mesh porosity leads to the highest friction factor and pressure drop. In spite of the higher pressure drop we have better power and thermal efficiency because we have better heat transfer. Chang and Yang [13] studied a Ross Yoke drive engine for solar applications. They proposed a detailed analysis of the influence of the regenerator parameters on the engine performances. An increase in matrices

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http://dx.doi.org/10.1016/j.apenergy.2014.11.011
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Nomenclature

E	engine efficiency, 3.227
r	compression degree
T	temperature, °C
P	pressure, bar
Vol	volume, m^3
V	engine speed, RPM
N	Stirling engine speed, rpm
Subscript	
C	Carnot
Cold	cold side
Hot	hot side
w-input	water input circuit
w-output	water output circuit
i	initial filling pressure
com	compression space
Exp	expansion space
R1, R2, R3, R4	position of thermocouples on regenerator side 1
R5, R6, R7, R8	position of thermocouples on regenerator side 2

porosity leads to the friction factor increases and the pressure drop loss decrease. A selection of a small wire diameter meshes may reduce the pressure drop for high porosity matrix. The regenerator effectiveness can be manipulated by varying wire diameter and wire length, which in turn changes the wetted surface area.

Bangert [14] note that the regenerator effectiveness has been recognized as an important factor to Stirling engines performances. The regenerator effectiveness depends on porosity, permeability and material of the porous matrix. Temperature distribution in the regenerator can be measured to determine the regenerator effectiveness. Furthermore, the magnitude of the regenerator effectiveness is also dependent on the operating speed. Abdulrahman et al. [15] studied experimentally the influence of the foam structure (including material, porosity and permeability) on the overall performance of the Stirling engine regenerator. He proved that when the regenerator porosity increases beyond a critical point the engine performance decreases, due to increased external conduction and lack of thermal transfer with the working fluid. Rebeiro et al. [16] experimented different regenerator material: cellular ceramic substrate with regular square channels, steel "scourers" and stainless steel "wood". They tested the performances of these regenerators function of mean pressure between 0 and 10 bar. They showed that the cellular ceramics may offer an alternative to traditional regenerator materials to reduce the overall system costs. They demonstrated that the pressure drop increase with the porosity decrease and the flow resistance depends on porosity, regularity of the porous material and the nature of packing of the solid material. Gheith al. [17] studied different regenerator materials and demonstrated that the Stirling engine regenerator is very sensitive to its material characteristics. Stirling engine efficiency can be calculated in different way. The must commonly used method is the Carnot one [18–20]. An ideal Stirling cycle, consisting of two isotherms and two isochors, has thermal efficiency determined by the temperature interval between the heater and the cooler and the compression degree $r = V_{heater}/V_{Cooler}$.

$$E = \frac{T_1 - T_2}{T_1 + (T_1 + T_2)/(\gamma - 1)lnr}$$

In order to propose the most suitable regenerator (materials and porosity), different matrixes were manufactured. Firstly, four regenerators in different materials (stainless steel, copper, aluminum and Monel 400) were experimented. The most suitable material was determined. From the predetermined material, five matrixes with different porosities (95%, 90%, 85%, 80% and 75%), were manufactured and then experimented. The efficiency and the output brake power of a γ-type Stirling engine were investigated for different porosities. The most suitable regenerator (material and porosity) for the γ-type Stirling engine will be proposed. Our choice will be based on different criteria already established.

2. Experimental facility

2.1. Stirling engine set-up

The double-cylinder, γ-type Stirling engine is the ST05G of Viebach society. This engine can provide 500 W of brake power and can reach a maximum rotation speed of 600 rpm. Its main compartments and metrology are presented in Fig. 1. The engine is composed of two pistons with a draft shaft of 90°, each piston slide in one separate space. The compression space is cooled by a circuit of water and the expansion space is heated by an electrical resistance delivering a maximal power of 3.5 KW. Both pistons are linked by a classical crank-rode system. The regenerator is located between the cooler and the heater. It is constituted of a porous medium with a fixed porosity. It is an annular spaces crossed twice by the working fluid (Fig. 2).

2.2. Regenerator metrology

Type-K thermocouples with diameter of 0.5 mm, 0.25 mm and 0.0254 mm, were used. These diameters are enough small that the thermocouples thermal inertia do not mislead measurements of instantaneous temperatures. Two thermocouples were implanted respectively upstream the expansion space (T_{hot}) and in the compression space (T_{cold}). Other two thermocouples were used to measure the temperatures of the inlet ($T_{w\text{-}inp}$) and the outlet cooling water ($T_{w\text{-}out}$). Eight thermocouples were skinned symmetrically (Fig. 3) up to 1 mm inside the regenerator matrix without touching the material. They allow measurement of the working fluid temperature passing through the regenerator. Different matrixes with different material were experimented (Fig. 3). Two pressure transducers were installed in the compression space and after the expansion space. The fist one is located at the end of the compression cylinder. It is a Druck sensor comprising a membrane. It can measure a pressure up to 20 bars and gives an answer between 0 volt and 5 V. The second is placed upstream the expansion space. This sensor cannot support temperature higher than 80 °C. So it was placed after a cooling tower to decrease the temperature of the working fluid. The variation of the Stirling engine rpm is made through an electrical dissipation system. This system is constituted of 10 electrical resistances of 55 W, each one placed in parallel, in order to obtain the variation of electrical dissipation, and then the Stirling engine rpm.

3. Determination of adequate regenerator material

The Stirling engine was experimented with different regenerator's material (Table 1) at the following experimental conditions (Table 2). The first matrix is made of Stainless steel, which is the most commonly used material as Stirling engine regenerators.