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Study of temperature distribution in a Stirling engine regenerator

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ABSTRACT

A gamma Stirling engine is studied in this paper. A special care was accorded to the instrumentation of this engine and especially the instrumentation of the regenerator. A preliminarily set of experimental measurement reveals a difference of temperature between both regenerator sides. A second set of experiments was proposed to detect the influence of this phenomenon on Stirling engine performances. The asymmetry of heat transfer inside the Stirling engine regenerator's is one of the important phenomenons which consume a part of the produced energy. Two experiments are made to find out the causes of this asymmetry. In order to know the influence of the different operation parameters on this new phenomenon the experimental design method is adopted. The experimental design is an alternative to identify the parameters sets allowing optimal Stirling engine performances. A central composite rotatable design was adopted for minimizing the asymmetry of temperature between both regenerator sides and maximizes the engine brake power. The selected four independent parameters are: heating temperature (300 °C–500 °C), initial filling pressure (3 bar–8 bar), cooling water flow rate (0.2 l/m–3 l/min) and operation time (4–20 min after study regime). The four adopted factors are experimentally varied. The results show that the heating temperature is the most significant factor for the studied phenomenon. The major damages caused by this phenomenon will be presented too.

1. Introduction

The optimization of Stirling engine performances is one of the priorities of the related researchers in the past several years. So, many experimental and analytic studies were done to understand phenomena of heat transfer [1], irreversibility [2], imperfect regeneration and flow friction [3] in Stirling engine. The performance of such engines is very sensible to its geometrical [4–7] and operation conditions [6–10].

The temperature distribution in Stirling engine is different from a compartment to another. The most important variations are observed in the regenerator (porous media, complicated heat exchange, heated and cooled at the same time). Temperature distribution is a determinant parameter to the regenerator effectiveness. The regenerator is also the seat of an important part of thermal losses recorded in a Stirling engine [11]. The most considered losses are lost by pressure drop, power lost by external and internal conduction and the regenerator ineffectiveness. Tlili et al. [11] showed that the power loss observed in the Stirling regenerator are about 86% of the total engine losses.

Popescu et al. [2] propose a finite time thermodynamic optimization of a Stirling engine based on endo and exo-irreversible cycle. They conclude that the internal irreversibilities are due to the internal conductance of the plant and to the non-adiabatic regenerator (drops of 30% of engine performances). The external irreversibilities are due to the linear interactions between the heat sources and the working fluids at finite temperature gaps.

The regenerator parameters have been the subject of several experimental and analytical investigations. The regenerator effectiveness was one of the decision variables used in the Multi-objective evolutionary algorithms developed by Ahmadi et al. [12]. They proposed an optimal Pareto frontier in objectives spaces. Chen et al. [13] built a prototype helium-charged twin-power piston c-type Stirling engine. Some of its geometrical and operational parameters were investigated by a numerical model. They found that regeneration effectiveness had the most prominent effect on efficiency, while engine speed had the greatest effect on the engine power within the range of the engine speed. Cheng et al. [14] developed and tested a beta-type 300-W Stirling engine. The engine parameters are insured in a non-ideal adiabatic model to predict its performances. Using a 120 wire mesh regenerator, the shaft power of the engine reaches 390 W at 1400 rpm with 1.21-kW input heat transfer rate (32.2% thermal efficiency). Kato and baba

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Nomenclature

b_0	constant coefficient
b_j	linear coefficients
b_{ii}	quadratic coefficients
b_{ij}	second order interaction coefficients
$\dot{m}$	cooling water flowrate
N	total number of experiments
P_i	initial filling pressure
Q	degrees of freedom
T	temperature
T_h	heating temperature
T_{op}	operation time
$\Delta T_{\exp}$	experimental difference of temperature between both regenerator sides
ΔT_{pr}	difference of temperature between both regenerator side obtained from the predicted model
U_i	experimental response
$U_i(0)$	value of U_i in the middle
ΔU_i	maximum variation of U_i
W	diagonal matrix
X	level matrix of independent variable
x_i	coded values of the factor or regression coefficient
x_{cp}	independent variable real value at the center point
X^*	average value of x_i
Δx_i	the step change of the real value corresponding to a variation of a unit for the dimensionless value of the variable i
Y	vector of observation
Y_{mod}	predicted response
Y^*	average value of Y

Greeks symbols

α	critical value of Pareto chart
β	regression vector coefficients
μ	mean value of the x variables
σ	standard deviation

[15] proposed an experimental method for regenerator evaluation. They concluded that the efficiency of the regenerator depends on the difference of temperature of the working fluid on the hot side and on the cold side and the pressure fluctuation. Chen et al. [16] noticed that the operating temperature ratio dependent on the thermal resistance of heating and cooling spaces, the regenerator effectiveness, the working fluid mass and the engine speed. Glushenkov et al. [17] proposed a thermodynamic analysis based on a heated regenerator. The developed thermodynamic model incorporates non-ideal features of the cycle, such as specific regenerator efficiency, dead volumes and other geometrical parameters. The model shows that the energy efficiency is highly sensitive to regenerator performance. Ahmadi et al. [18], optimize a solar-powered high temperature differential Stirling engine with multiple criteria. The volumetric ratio and the regenerator effectiveness effects on the final selected solution were studied and it was found that a final optimal solution with higher values of objectives (thermal efficiency and output power) could be achieved if these parameters were increased. Kato et al. [19] presented an empirical estimation of Stirling engine regenerator efficiency. The regenerator efficiency is calculated as a function of the temperature fluctuation in the regenerator and the temperature fluctuation of cold side working fluid. They showed that these two parameters are positively correlated with the regenerator loss. Cheng and Yu [20] proposed a more realist model to study beta-type Stirling engines. Their model took into consideration the temperature difference between the working gas and the external heat source, pressure drop in the regenerator, and regenerator effectiveness. Formosa and Despesse [21] included dead volume, imperfect regenerator, and external and internal thermal transfers in their analytical model that could be used to analyze Stirling. Chen et al. [22] experimentally studied the effects of several regenerator parameters on the overall performance of Stirling engine. They incorporated a moving regenerator in their engine. The parameters investigated include regenerator matrix material, matrices arrangement, matrix wire diameter, and fill factor. Anderson et al. [23] concluded that the convective heat transfer is the dominate heat transfer mechanism between regenerator matrices and working gas. Regenerator heat transfer rate is a very crucial factor to regenerator effectiveness especially at high engine speed when the time for heat transfer is very short in each cycle. Therefore, a regenerator with low heat transfer rate will perform poorly at high engine speed even though it has large heat capacity. Gheith et al. [24] experimented a gamma type Stirling engine with different regenerator materials (Cooper, Aluminum, Stainless Steel and Monel 400). The obtained experimental results provide guidance to Stirling engine enhancement and selection of the appropriate regenerator constituting material. The Monel 400 and the stainless steel regenerators present an acceptable thermal efficiency and do not oxidize. Tavakolpour et al. [25] studied numerically a LTD (Low Temperature Difference) Stirling engine. They found that the energy losses in the regenerator are due to temperature oscillation and heat conduction caused by the alternating gas flow and steep temperature gradient throughout the regenerator and found that the engine's thermal efficiency resulted from the regenerator efficiency of 1.0 at ideal conditions the is 0.069 whereas for the regenerator efficiency of zero, is about 0.0122. The use of an efficient regenerator increases six times the engine thermal efficiency.

The experimentation of Stirling engine is always made by classical way (univariate study) [25–30]. The investigation by such method requires a higher number of experiments for exploring the whole experimental domain. It is time consuming and does not depict the complete effect of each parameter in the response (Stirling engine performances).

To reduce these disadvantages during experimental studies, especially for study involving several variables factors, the experimental design methodology seems to be adequate to avoid such inconvenient.

The experimental design methodology is not a new technique it was developed by Fisher in 1952 [31] and applied first in agronomy. –This method presents several advantages over the conventional one:

- Decrease the number of test performed to scan the entire field of study.
- Possibility to study a large number of factors at a time.
- Detect single or double interactions between the studied factors, [32].
- Modeling the studied responses.
- Determining optimal results [31].

The aim of this paper is to study a new loss which dissipates a part of Stirling engine performances. Detailed descriptions of the experimental set-up as well as its corresponding metrology are presented.