

GLOBAL DESIGN AND OPTIMIZATION OF A MEMBRANE MICRO STIRLING GENERATOR

Fabien Formosa*

SYMME - Université de Savoie BP 80439- 74944 ANNECY LE VIEUX CEDEX – FRANCE

*Presenting Author: fabien.formosa@univ-savoie.fr

Abstract: The development of a microStirling engine would provide an innovative solution for power generation. Its simplicity, high efficiency and the opportunity to use inverted cycle are great assets. Sliding pistons are replaced by flexural diaphragms. By doing this, dead volumes may be reduced consequently enhancing the performances. An iterative coupled thermodynamic-dynamic model is used to perform design optimization. As a representative test case, a 100 mm³ displacement microgenerator theoretically produces 1.5 W at 680 Hz with 12% overall efficiency (48% of the Carnot efficiency). The estimated power density of 0.18 W/cc can be increased with higher pressure and frequency.

Keywords: microStirling, design

INTRODUCTION

Micro thermal devices have become a new development area as a mean of taking advantage of the high energy densities of liquid or gaseous fuels [1]. Yet, the miniaturization approaches of existing efficient macroscale power generation systems are constrained by the limited availability of viable manufacturing processes. Design of microminiaturized technological components especially joints and seals, represents most of the development on micromachines. Moreover, because of planar architecture and heat transfer, microscale internal combustion engines are far less efficient than their macroscale counterparts.

As a close thermodynamic cycle and using an external heat source, the Stirling cycle could overcome some of these problems. The free piston mechanical arrangement without any mechanical linkages between moving parts, appears to be well suited for scaling down.

Similitude theory has been used as a design guideline to define the critical dimensions of a micro engine [2]. Thereby, for a given displacement V_{sw} and required output power target P_o , the swept volumes, chambers spaces and geometrical characteristics of heat exchangers and regenerator can be defined from a macro scale reference engine. This strategy has been performed from the NASA RE-1000 Stirling engine optimized for maximum efficiency. Thus, a first set of parameters can be drawn.

Classical sliding pistons are replaced by flexural diaphragm which suppresses any sliding friction. Each of the related chambers has a high aspect ratio (width to thickness) which provides enhanced the heat transfer effects. As a consequence, heater and cooler may be suppressed in the proposed microStirling design. The total dead volume of the micro engine can then be reduced which allows better efficiency. Although, a planar architecture allows efficient heat transfer from the external source to the internal

chambers of the engine, the thermal insulation between the hot and cold parts could become a critical deadlock and a major loss as well. This point will be addressed in the design.

An iterative global semi analytical model of the coupled thermodynamic-dynamic behavior of the engine is used to perform design optimization. The effects of the constituent parts of the engine: two diaphragms, heat exchangers and electromagnetic convertor are modeled. Fluid flow is induced by diaphragm flexion which leads to unconventional heat exchanger configuration. No usual correlation can be used and CFD computations are then performed to determine the heat transfer as well as pressure loss coefficients.

In a first part, the general architecture and operation principle are presented. Then, its performances are analyzed and the effects of the operating frequency and mean pressure are pointed out for air and helium used as working gas. Maximal pressure has been limited to 10 bars for mechanical constraint purpose. The same is true for the higher temperature source amounted to 400°C. The effects of the regenerator characteristics and the conduction losses are studied and a set of optimal parameters is proposed. In a third part, the used modeling strategy is presented.

GLOBAL STRUCTURE AND OPERATION PRINCIPLE

Structure description

The axisymmetrical architecture of the proposed microStirling is shown in Fig. 1. A multi-layer stack encloses micro channels, mechanical and electromechanical components. The moving parts namely the compression and expansion diaphragms (part 6 and 7a-b in Fig. 1) are flexible planar structures. They delineate two chambers at the hot (11) and cold side (1, 2, 3, 4) of the engine respectively. The pressurized working fluid then flows back and

forth through the regenerator (10) between the aforementioned chambers.

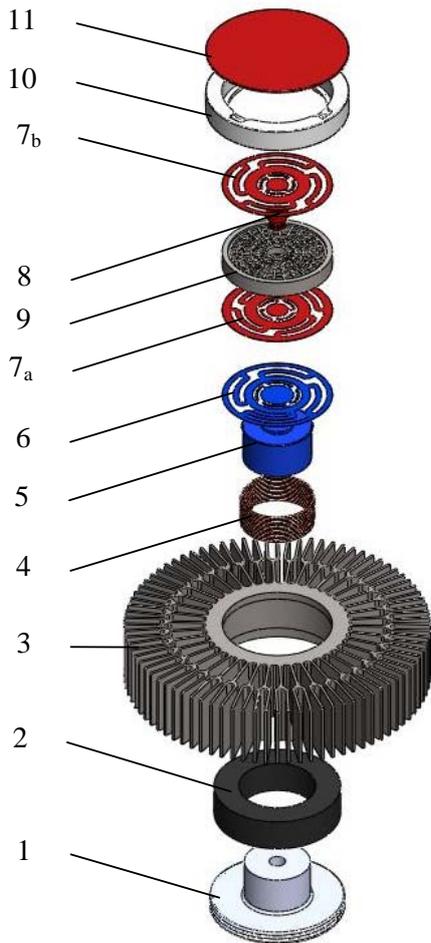


Fig. 1: MicroStirling generator architecture.

Because of the pressurization of the engine, a counter pressure chamber which integrates the electromechanical converter at the cold side is defined. The same is true for the enclosed volume (9) within the bi-layer expansion diaphragm structure. Heat is supplied to the cycle from the outer surface of the device ("hot side") and removed from the opposite end through lateral fins ("cold side") to external ambient air.

Operation principle

The representative phases of the operation can be described from a reference position of the moving parts and is presented in Fig. 2 for the "engine subsystem". In Fig. 2a, the compression diaphragm (CD) is at its lowest position as the expansion diaphragm (ED) is at its highest so the volume V_C is maximal and V_E is minimal. Most of the working fluid is at lowest temperature T_L . In Fig. 2b, the upward motion of the CD induces a reduction of the total engine volume and therefore the compression of the working fluid. The subsequent temperature augmentation is balanced by heat flow at the cold side. With a downward motion of the ED the working fluid is partly forced through the regenerator. Thereby, heat

energy is provided to the fluid so it ideally emerges at the highest temperature T_U in V_E (Fig. 2c). The pressure within the engine rises as for a constant volume the temperature becomes higher. Submitted to this pressure, the CD moves to its initial position and by doing this, mechanical power can be produced and a global expansion occurs at the same time. Spring forces lead to out of phase motions of the diaphragms (Fig. 2d). The heat source provides the amount of energy to ideally keep a constant high temperature T_U during the resulting global expansion. At the end of the expansion stage the ED goes back to its initial position driving the working fluid through the regenerator again where it recovers the amount of energy harnessed by the fluid during the previous flush. In the ideal case, the fluid would V_C at the temperature T_L .

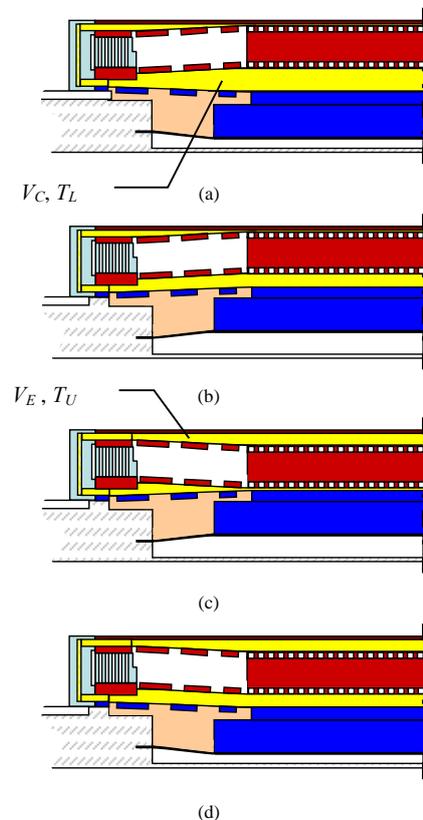


Fig. 2: Operation principle.

PREDICTED PERFORMANCES

Based on isothermal assumption, a thermodynamical-thermal model (TTM) which takes into account major losses has been developed [3]. It allows the output power to be evaluated. Losses would result from thermal conduction through the static parts of the structure as well as the central part of the expansion diaphragm (part 8 in Fig. 1). Other losses are related to viscous friction from fluid flow throughout the regenerator and micro channels ducts. CFD computation and correlation have been used to define heat transfer at the expansion and the compression chambers.

The TTM has been performed on a geometry obtained from similitude theory [2]. Main parameters are given in Table 1. Fig. 3 presents the evolution of

the mechanical output power and efficiency with respect to operating frequency for three different mean pressures.

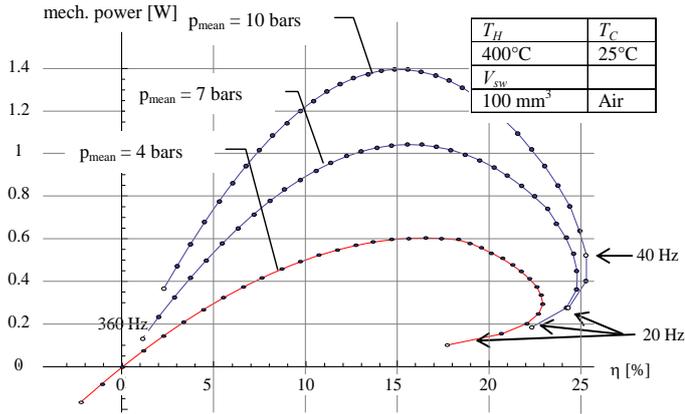


Fig. 3: Performances with respect to pressure.

Optimal efficiency and power do not occur for the same operating frequency and optimal frequencies are not related to the mean pressure.

Two design points are considered: optimal efficiency (dashed gray bars) and optimal power (white plain bars). Assessments of the performances and losses of the engine for the same parameters are given in Fig. 4a for air. Each bar represents the remaining power when the specified loss is subtracted from heat input. For comparison purpose, the first bar stands for ideal Stirling cycle theoretical power. An electromechanical conversion efficiency of 50% is assumed which gives realistic value for the available electric power.

These results underline that the conduction loss is the most important source of dissipation which amounts to 1.3 W. In Fig. 4b, the thermal impedance associated to static parts of the engine is doubled. Conduction losses are predictably half the previous one reduced to 0.65 W. It is worthy of note that for case (Fig. 4b) since the heat entering the device is lower because of a better thermal isolation, the electric available power remains approximately at the same value. Conduction losses have been pointed out by the previous analysis, though for improved isolation cases, reheat losses associated to the regenerator effectiveness amount to 1.3 and 3.4 times the conduction losses for optimal efficiency and optimal power cases. For Helium, these values are: 0.5 and

Table 1: Main parameters for the design test cases.

Heat source T_H	[°C]	400	Cold source T_C	[°C]	25
Phase angle α	[deg]	120	swept volume ratio K	[-]	1.01
Swept volume V_{sw}	[mm ³]	100	Working fluid		Air / He
Mean pressure p_{mean}	[MPa]	$0.4 < p < 1$	Operating frequency f	[Hz]	$20 < f < 800$
Wire mesh regenerator					
wire diameter d_w	[μm]	58	porosity of the regenerator matrix ϵ_v		0.759 / 0.812
regenerator hydraulic radius r_{hR}	[μm]	45 / 62	regenerator length	[mm]	$10 < L_R < 22$

2.8. Therefore, the effects of the regenerator characteristics on performances have to be studied.

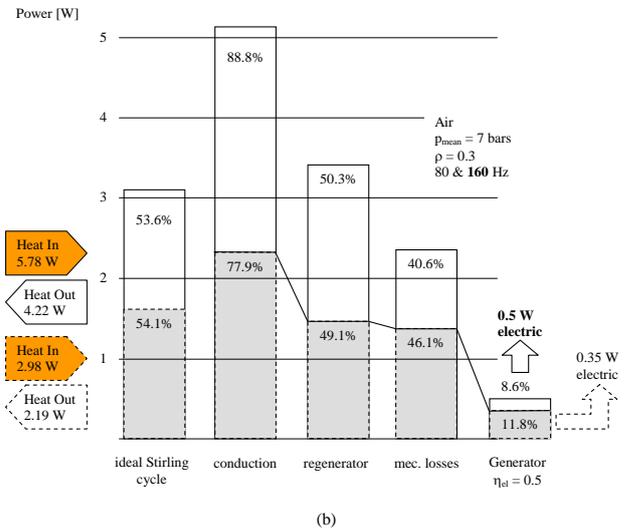
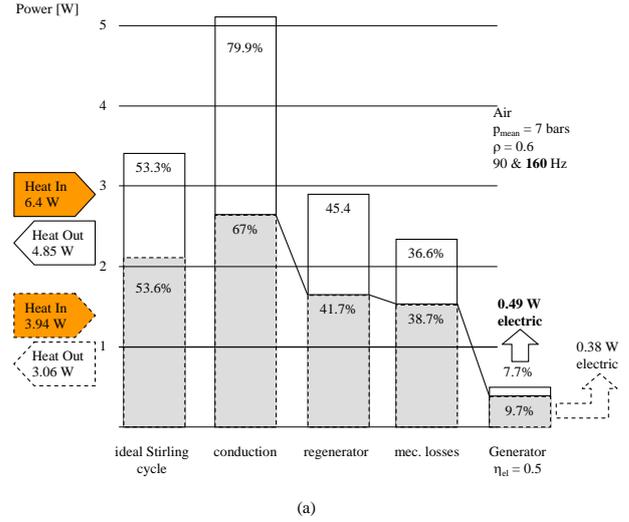


Fig. 4: Power appraisal for air.

The regenerator is a key component of the Stirling cycle. Its global efficiency is mostly determined by the regenerative effect effectiveness [4]. From similitude theory, sets of parameters for wire mesh regenerator has been derived. From these values, the regenerator length would be chosen from 10 to 22 mm which encompasses the similitude values. Two different porosities are tested 0.759 and 0.812.

For a porosity of 0.759, the effect of the length of the regenerator is shown in Fig. 5. As the length increases, heat effectiveness of the regenerator leads to higher efficiency but less output power. Conversely, with smaller length, higher power can be produced. It is worthy of note that only 5% variation for the porosity has much greater effect than 50% variation for the length.

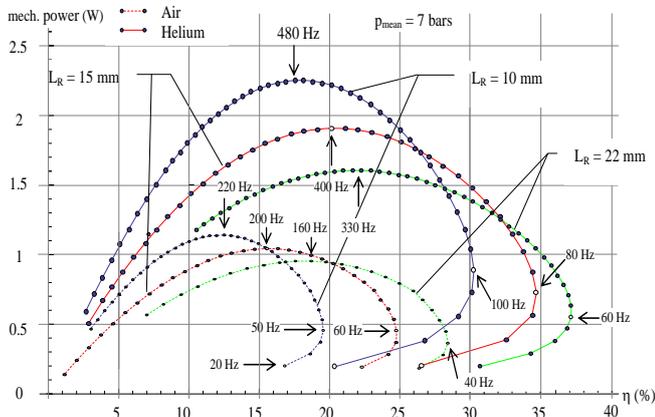


Fig. 5: Effect of regenerator length on performances.

With an optimized regenerator, a maximal power density up to 0.18 W/cc @ 680 Hz and 12% thermal to electrical conversion efficiency (48 % of Carnot efficiency) are predicted performances with Helium.

DESIGN STRATEGY

An iterative global model of the coupled thermodynamic-dynamic behavior of the engine is used to perform design optimization (Fig. 6). Similitude theory is used as a design guideline to define a first set of parameters (o). From swept volumes and mechanical yield stress of the chosen material, diameters of flexural hybrid membranes are defined using Finite Element Models (i). Fluid flow is induced by membranes which lead to unconventional heat exchanger configuration. Since no usual correlation can be used CFD are performed to determine the heat transfer as well as pressure loss coefficients (ii). Then, a thermodynamic Semi

Analytical Model (SAM) allows the operating parameters to be obtained (iii). In a third step, dynamic characteristics are optimized to match previously defined kinematics and operating parameters (iv) [5]. From the required dynamic load an electromagnetic generator can be designed for maximal efficiency and minimal volume (v). Given the convertor size the dissipater can be optimized (vi) and a new iteration is performed. Performances are finally evaluated and compared to initial requirements.

CONCLUSION

A microStirling architecture has been presented as the fruit of a developed global model. Technological constraints associated to process or material can be easily taken into account. As an example, the geometrical as well as dynamic parameters are optimized for a test case. The next step of development will be a dedicated development and experimental validation for a target application.

REFERENCES

- [1] A C. Fernandez-Pello, Micropower generation using combustion: Issues and approaches. *In: Proceedings of the Combustion Institute. USA: Combustion Institute, 2002*, pp.883-898
- [2] F. Formosa, J.J. Chaillout, Free piston Stirling engine design using similitude theory, *Proc. PowerMEMS 2009*, Washington DC, USA, 1-4 December 2009, pp. 562-565
- [3] F. Formosa, J.J. Chaillout, O. Dessornes, Size effect on Stirling cycle microengine, *Proc. PowerMEMS + microEMS 2008*, Sendai, Japan, November 9-12, pp. 105-108.
- [4] Y. Timoumi, I. Tlili, S. Ben Nasrallah, Design and performance optimization of GPU-3 Stirling engines, *Energy*, 2008 33 (7), pp. 1100-1114
- [5] F. Formosa, Nonlinear dynamics analysis of a membrane Stirling engine: Starting and stable operation, *Journal of Sound and Vibration*, 2009, 326 (3-5), pp. 794-808

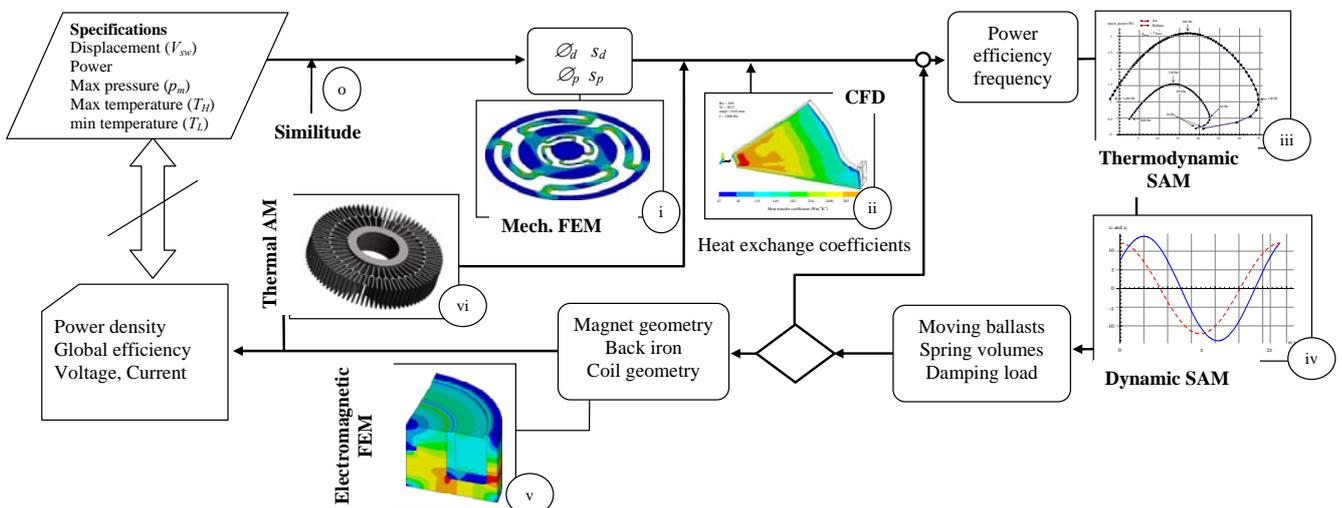


Fig. 6: Iterative design strategy.