Design and microfabrication of a Microscale-Stirling Engine (M-SE) for low temperature heat recovery

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***Abstract*—This study concerns the design and microfabrication of a Microscale-Stirling Engine (M-SE) for the recovery of low temperature thermal energy ranging from 50 to 200°C. This M-SE consists of a stack of silicon, glass and hybrid membranes (HMs) based on a silicone elastomer embedded in a planar silicon spring. Design of hybrid membrane is briefly presented in this paper, followed by M-SE design and their microfabrication process. In addition, numerical simulations (finite element model) were performed in order to check mechanical and dynamic behavior of hybrid membrane salong with the expected power budget of the assembled M-SE using Schmidt analysis.**

I. Introduction

A reliable source of energy is essential for the industrial progress that underpins the economic development of any country. The world is going through an energy crisis that affects the stability of countries and consequently people's lives [1]. One of the important ways to reduce the energy crisis could be the recovery of heat at low and medium temperatures (from 50 to 200°C), such as from industrial waste heat, heating energy, solar heat, biomass, friction, Joule effect, exhaust pipes of vehicles and so on. In this paper, we mainly concern about MEMS based energy devices. Many MEMS devices need a high energy density to achieve a long operating time. Therefore, there is a need for high energy density micro power generation systems to replace the existing electrochemical batteries, which are not sufficient (~ 1 kJ / g) to sustain the power requirements of long periods [2]. Dynamic heat engines are more efficient than electrochemical conversion systems and achieve higher conversion efficiencies than static heat engines [2]. Therefore, several designs for micro-scale dynamic heat engines have been fabricated. For example, a microscale rotary engine (Otto cycle) [3], a microscale heat engine with reciprocating liquid piston (Otto/Diesel cycle) [4] and a microscale gas turbine engine (Brayton cycle) [5, 6] were fabricated. A micro heat engine (called P^3) for MEMS power system based on expansion and compression of a two-phase working fluid was developed [2]. Among the dynamic engines, the Stirling engine has many advantages, including no internal combustion and a very high efficiency in terms of energy conversion. This engine is based on a reversible cycle of compression and dilatation of a gas (e.g. air). In this paper, we propose a membranes-based microfabricated Stirling engine to harvest waste heat for temperature ranging from 50°C to 200°C.

II. Design and fabrication

A. Hybrid Membrane design

While miniaturizing classical engine, sliding piston must be replaced in order to avoid friction losses and fluid leakage through the cylinder–piston gap, designated as one of the main limitations [7,8]. For this reason, membrane are preferred in order to replace pistons in MEMS engine. The hybrid membranes (HMs) presented in this paper are based on the work of Chutani et al. [9] and were designed to be used for miniaturized Stirling engine. These HMs consisted of thin RTV silicone polymer based membrane embedded in silicon spiral spring with central disk (Figure 1). These membranes have been numerically simulated [10]. Moreover, they were dynamically characterized, and their aging and temperature stability were previously studied [10].

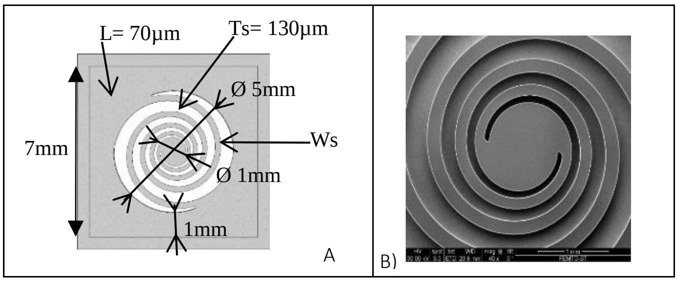

FIGURE 1. A) SILICON SPIRAL SPRING ARCHITECTURE AND GEOMETRICAL PARAMETERS; L IS THE LOCATION AND THICKNESS OF THE RTV-SILICONE LAYER THERE, WS IS THE WIDTH OF THE TURNS OF THE SPIRAL AND TS IS THE THICKNESS OF THE SPIRAL. B) A SEM IMAGE OF A SPIRAL

The role of each part of the HM is summarized in TABLE 1.

TABLE 1. THE ROLE OF EACH PART OF THE PLANAR SPRING AND THE POLYMER OF THE HM.

Components	Control/Role
Spiral spring	Stiffness, Flexural shape, Uniform stress distribution (width vs angle), Spring restoring force
Central disc	Inertia and Swept volume
RTV-silicone	Sealing, Spiral Robustness reduction, elasticity

B. M-SE design and microfabrication

M-SE (Figure 2A) consists of five different parts: four silicon plates (two, top and bottom on which compression and relaxation chambers are etched, the other two carrying the

HMs) and in between a thick glass plate with through holes to encapsulate incompressible liquid (Vaseline in this case).
The assembly of the M-SE consisted of four major microfabrication steps (cf. FIGURE 2.b)): two thermocompression bonding steps to assemble the silicon plates followed by two anodic bonding steps to assemble the latter with the thick glass plate.

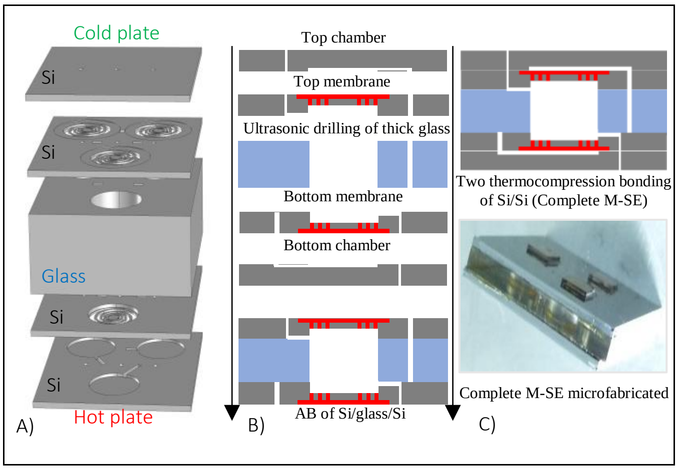

FIGURE 2. A) SCHEMATIC VIEW OF COMPONENTS OF THE M-SE, B) MICROFABRICATION PROCESS FLOWCHART AND C) PICTURE OF THE FULLY ASSEMBLED M-SE

All these microfabrication and assembling steps have been successfully completed, which led to the realization of the first M-SE entirely realized in a clean room at wafer level.

III. RESULTS

A FEM model, using COMSOL Multiphysics, was carried out to study the influence of the HM geometric parameters on the resonance frequency and the mechanical constraints resulting from a displacement. For the specific HMs used for the present M-SE, a resonance frequency of 2.9 kHz was found.

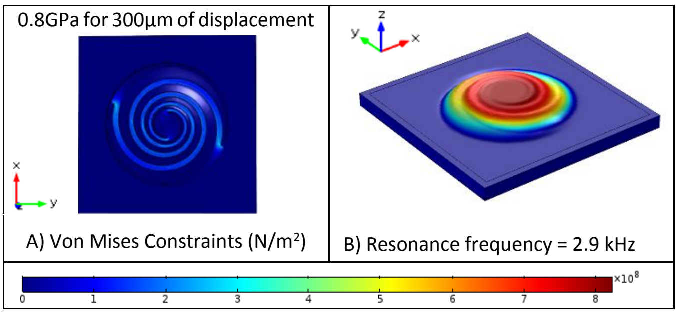

FIGURE 3. A) VON MISES CONSTRAINTS OF HMS FOR 300µM PRESCRIBED DISPLACEMENT, B) HMS RESONANCE FREQUENCY.

Static displacement of HMs versus air pressure was also experimentally determined: for a single membrane, a displacement of about 0.4 mm at 0.2 bar was found while for the same pressure, a displacement of about 0.15 mm was achieved for a hybrid fluidic membrane (ie. two HMs linked with the Vaseline in between [9]). Further, an isothermal simulation of the machine was done to determine the engine performance prediction, based on Schmidt analysis. Set parameters are given on TABLE 1. A mechanical Power output of 177 mW was found for the engine, and its yield was estimated to reach 37% of Carnot efficiency.

TABLE 2. PARAMETERS USED IN THE SCHMIDT MODEL. WITH V_{SWC} THE SWEPT VOLUME; P THE PRESSURE, TH THE HOT PLATE TEMPERATURE, TC THE COLD PLATE TEMPERATURE, F THE OPERATING FREQUENCY AND α THE PHASE ANGLE

gas	V_{swc} (m^3)	P	Th(°k)	Tc(°k)	F(kHz)	α(rad)
Air	$0.3.10^{-6}$	Amb.	473	298	1	2.09

IV. CONCLUSION

We have designed and microfabricated a microStirling engine. The numerical simulation based on FEM model made it possible to determine the resonance frequency of the HM used in the micro-engine. Moreover, calculation based on the Schmidt analysis enable to predict the engine efficiency. The achieved machine will be characterized.

ACKNOWLEDGMENT

This work has been supported by the Labex ACTION project (contract "ANR-11-LABX-0001-01"), the Region Bourgogne Franche-Comté STIP'MEMS project and the French National Research Agency (ANR) under grant no. ANR-12-SEED-0005-01 (MISTIC Project). It has been partly supported by the French RENATECH network and its FEMTO-ST technological facility.

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