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Equivalent electrical network model approach applied to a double acting low temperature differential Stirling engine

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ABSTRACT

This work presents a network model to simulate the periodic behavior of a double acting free piston type Stirling engine. Each component of the engine is considered independently and its equivalent electrical circuit derived. When assembled in a global electrical network, a global model of the engine is established. Its steady behavior can be obtained by the analysis of the transfer function for one phase from the piston to the expansion chamber. It is then possible to simulate the dynamic (steady state stroke and operation frequency) as well as the thermodynamic performances (output power and efficiency) for given mean pressure, heat source and heat sink temperatures. The motion amplitude especially can be determined by the spring-mass properties of the moving parts and the main nonlinear effects which are taken into account in the model. The thermodynamic features of the model have then been validated using the classical isothermal Schmidt analysis for a given stroke. A three-phase low temperature differential double acting free membrane architecture has been built and tested. The experimental results are compared with the model and a satisfactory agreement is obtained. The stroke and operating frequency are predicted with less than 2% error whereas the output power discrepancy is of about 30%. Finally, some optimization routes are suggested to improve the design and maximize the performances aiming at waste heat recovery applications.

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1. Introduction

Low temperature differential (LTD) Stirling engines are machines that can operate with hot source temperature of about 150 °C. At this operating temperature and assuming a sink temperature of 25 °C, the Carnot efficiency is 29%. Then, a Stirling generator which would achieve 50% of this efficiency might be of interest for power generation. Solar powered LTD Stirling engine appears to be a promising technology [1] and is also a potential technology for waste heat recovery [2,3]. In both applications, the simplicity and reliability of the Stirling machines are significant advantages toward the development of low cost generators.

Among the various potential Stirling architectures, the double acting engines type also called Rinia or multiphase architecture [4,5] is of particular interest for the aforementioned applications. In such configuration, three, four or more alpha type engines (also called phases) are connected to each other. The piston of the engine *i*-1 acts as the displacer of its neighboring engine *i*. In [6], Abdullah studied such a double acting LTD Stirling. He underlines that the specific material and components required for the crankshaft, the connecting rods and the gaskets are an important issue for LTD applications.

A free piston Stirling engine (FPSE) architecture allows avoiding complex mechanical linkages and the resulting robustness and reliability questions. Though, their optimization has been proven to be difficult especially for the piston-displacer phase angle control [7,8]. The double acting architecture overcomes this difficulty because the phase angle is fixed by the number of phases. It equals 120° in the case of three engines and 90° in the case of four engines. Therefore, the free piston double acting arrangement appears to be a great advantage compared to the usual FPSE. However, a proper sealing of the piston and the displacer can be difficult to ensure.

This last obstacle can be classically solved using membranes. In his work, Minassians proposed a LTD double acting FPSE using membranes instead of pistons [9,10]. The operation has been demonstrated on a $3 \times 350\ cm^3$ total volume engine. A theoretical efficiency of 19.7% which is about 70% of the Carnot efficiency was expected to be reached using helium or pressurized air engine.

In the case of double acting FPSE, the strong coupling between dynamic and thermodynamic has to be addressed properly. The major non-linear effects have to be integrated in the model to predict the performances. These effects are usually associated to the gas friction losses within the components and the mechanical non-linearity [7,8,11–13].

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Nomenclature

A_d	displacer area (m^2)
A_p	piston area (m^2)
A_{ff}	free flow area (m^2)
A_w	wetted area (m^2)
c_d	displacer mechanical dissipation (Nm^{-1} s)
c_p	piston mechanical dissipation (Nm^{-1} s)
C_f	friction factor (–)
D	damping coefficient (Nm^{-1} s)
d_w	wire diameter of the matrix regenerator (m)
d_{hi}	hydraulic diameter of component i (m)
D_d	displacer diameter (m)
D_p	piston diameter (m)
E_b	young modulus (Nm^{-2})
f	frequency (Hz)
f_f	friction factor (–)
f_m	mechanical force (N)
I_b	second moment of the spring beam (m^4)
j	complex number such as $j^2 = -1$
k	gas thermal conductivity (Wm^{-1} K)
K	spring beam stiffness (Nm^{-1})
L_i	length of exchanger (m)
L_b	length of the spring beam (m)
m_{tot}	total mass of gas (kg)
M	mass of a rigid link (kg)
m_i	mass of gas within component i (kg)
n_i	number of channels of component i (–)
P_m	mechanical power (W)
p	pressure (N m^{-2})
r	ideal mass gas constant (J kg^{-1} K^{-1})
S_b	cross-section of the spring beam (m^2)
T_{cold}	cold temperature (K)
T_{hot}	hot temperature (K)
T_i	temperature of gas within component i (K)
T_w	wall temperature (K)
u_i	mean gas velocity in component i (ms^{-1})
V_i	volume of component i (m^3)
V_{sw}	swept volume (m^3)
V_{swe}	expansion space swept volume (m^3)
V_{swc}	compression space swept volume (m^3)

Greek symbols

α	swept volume phase angle (rad)
χ	fluid flow resistance coefficient (s^{-1})
Δp	pressure loss (N m^{-2})
ε	scale (–)
κ	swept volume ratio (–)
μ	dynamic viscosity (N m^{-2} s)
ρ	gas density (kg m^{-3})
ρ_b	material density (kg m^{-3})
ω	pulsation (rad s^{-1})
¶	porosity of the regenerator (–)

Subscripts

b	beam
c	compression space
d	displacer
e	expansion space
h	heater
k	cooler
p	piston
r	regenerator

In [9] Minassians proposed an isothermal dynamic model to study the behavior of the multiphase engine. Based on the Schmidt analysis, the instantaneous pressure is expressed as a function of the piston positions. Then the mechanical equilibrium equation of each piston is established including the dissipation forces and the external load. A linearization strategy allows an analytical expression of the start-up condition to be obtained. Above this critical value, a numerical resolution has to be used to obtain the periodic motion of the engine and to evaluate its performance. The flow friction and hysteresis losses have been pointed out because of their effects on the engine performances and have to be taken into account for design of such LTD engines.

Another modeling approach based on the control system theory of a wobble-yoke double acting Stirling engine has been presented in [14,15]. The engine architecture implies some flexibility in the mechanical connections of the pistons so its operation is close to double acting FPSE. The modeling strategy relies on the dynamical equilibrium equations established for each of the piston. The pressure can then be defined as a function of the pistons' position using the Schmidt analysis [4] (perfect gas law, isothermal transformations). A linearization is performed to obtain a state space representation of the system. Such an approach leads to an unstable dynamics so a control concept based modification namely a pre-compensator, is defined to reproduce the pistons' amplitudes. This model has not been compared to experimental results and some important losses such as flow friction are not taken into account.

In this paper, a generic network model is proposed and validated to study the dynamic and thermodynamics behavior of a double acting free membrane Stirling engine.

As a basis for the study, a novel configuration of a LTD double acting FPSE derived from the work of Minassians [10] is introduced. Fig. 1a presents the global engine. It is composed of three alpha type engines using membranes and beam springs which are connected to each other via rigid links. The top side of the system can be connected to the heat source whereas the bottom side is cooled. For each engine, the simplest architecture has been sought here. So, the heater and cooler, the expansion and compression chambers are identical (see Fig. 1b). The heater and cooler consist in 20 holed punched plates fitted together in a total thickness $L_h = L_k$. By doing this, the axial conduction through the solid material is impeded whereas the radial conduction allows aiming at isothermal processes in the heat exchanger volumes. The regenerator consists in a stack of 40 plain weave wire meshes. The wire diameter is 50 μm and apertures are 350 μm squares. The main dimensions and characteristics of the engine are given in Table 1.

In a first part, the equivalent electrical model for each component of the engine is detailed. The classical electrical analogy is chosen: the pressure is seen as the electrical voltage and the volume flow rate as the electrical current. The continuity and momentum equations are established for the compression and expansion chambers, the heat exchangers and the regenerator. Then using linear approximation for the time and space variables, the equivalent electrical circuits are derived. Finally, the electrical circuits are connected to each other to obtain the dynamic equations. A global analysis is then achieved to establish the start-up condition and evaluate the performances. Then, as a first validation step, the thermodynamic results of the proposed model are compared with those obtained using the Schmidt analysis. The effect of the load on the critical start-up temperature and the engine performances is studied. An experimental prototype has been built and is presented in the last part. The experimental measurements are

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