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Review

Technological challenges and optimization efforts of the Stirling machine: A review

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ABSTRACT

The Stirling engines are being carried out worldwide, used for divers' application such as solar generator, micro cogeneration and cryogenic uses. The present paper is an over view of Stirling technologies researches. Several possibilities of resolving technical challenges encountered when manufacturing or using Stirling machines will be discussed. The most appropriate models and optimizations strategies are reported. Stirling engine performances are derived as function of geometric parameters (swept volumes, dead volumes, heat exchange areas, compression ratio…) for several working conditions (speed, mean pressure, temperature difference and working fluid). The effect of each parameter on the Stirling performances when using numerical and/or experimental approaches are presented. It is concluded that multi-objective optimizations methods are useful for predicting geometric and working parameters that corresponding to the optimal performances of the Stirling engine.

1. Introduction

The increasing awareness of the limitation of the world's energy resources has sparked the interest of scientifics to develop new techniques to better use and valorize the existing resources. This situation has encouraged the improvement of energy efficiency, the development of renewable energies, the valorization of thermal discharges, the development of cogeneration or tri-generation systems and the hybridization of different energy sources. In this context, Stirling technology, which could contribute to the future energy mix, benefits from its many advantages over internal combustion engines. The Stirling engine was invented in 1816 by Scottish pastor Robert Stirling [1], before the Diesel engine (1893), the petrol engine (1860) and the electric motor (1869). The study of Stirling technologies has started from 1816 and continued to be improved until today.

The N. V. Philips society of The Netherlands was the first great society interested by Stirling engine since 1936 [2] thanks to its undeniable advantages in stationary operation. It is characterized by a silent mode of operation. It produces little vibration compared to the internal combustion engine. Thanks to the absence of the explosion, the absence of the valves that open and close, the absence of gas escaping, the Stirling engine requires easy maintenance. These engines are robust and deteriorate less rapidly than internal combustion engines. Unlike the internal combustion engine, Stirling engines fits with any heat source, not only conventional solid fuels, liquid or gaseous, by simple adaptation of the burner, but also heat recovered on other systems, the heat of nuclear or solar origin, etc … In this area, great progress can be made when coupling high heat loss systems with a system that can value these losses. Many Stirling engines are manufactured and used for various applications. Table 1 describes working conditions and performances of different types of old high power Stirling engines.

The original goal is to use the Stirling machine as an engine. However, the first real industrial application of this engine uses the reverse cycle to produce cold [8]. Most of the industrial applications of the Stirling cycle concern the refrigeration applications, in particular in cryogenics, where the Stirling cycle presents enormous advantages [8]. It is possible to reach low temperatures quickly, which increases its competitiveness compared to other refrigerating machines. In 1834, John Herschel designed a cooling machine using closed-cycle air for ice manufacture. Philips society developed also refrigeration machines and heat pumps based on the reverse Stirling cycle. In 1941, Philips built a cooler reaching −40 °C. Later, in 1945, Philips made a cooler reaching −200 °C using hydrogen as a working fluid. Between1960 and 1970, Philips sold an industrial Stirling chiller with a cooling capacity of 25 kW to 77 kW. Such machines require an input of mechanical work to accomplish their operation [1]. The Stirling cycle is fundamentally different from the Rankine cycle used in conventional refrigerators [9]. Unlike the Rankine cycle, the working fluid within the Stirling cycle

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Table 1
Working conditions and performances of old high power Stirling Engines.

Stirling engine type designation	Working conditions					Performances		Cylinder dimensions			Ref(s)
	Speed (rpm)	Mean pressure (bar)	Working gas	Mean hot space temperature (°C)	Mean cold space temperature (°C)	Mechanical output power (KW)	Thermal efficiency (%)	Bore (mm)	Stroke (mm)	Number of cylinders	
Double acting SE developed by MAN	1000	150	He	760		225		–	–	6	[3]
Double acting SE	1010	50	He	747		35		142	76	4	[4]
The NASA 25 kWe FPSE		100	He	800		25				1	[5]
Sunpower RE-1000 FPSE	1800	70	He	541	49	1		57.22	40	1	[6]
Sunpower M100 FPSE		22		593	49			–	–	1	
Ford 4-215	4500	200	H_2	750	64	200		73	52	4	[7]
GPU3 General motors	2500	69	H_2	704	15	7.5		69.9	70.1	1	[7]
SE Prototype developed by United Stirling	2000	145	H_2	691	71	35	30	–	–	4	[2]
4-235 SE Prototype developed by Philips	1800	221	He	683	43	175	31	–	–	4	[2]
40 HP SE Prototype developed by Philips	725	142	H_2	649	16	23	38	–	–	4	[2]
Anal. Ph. 1 SE developed by United Stirling	1200	145	H_2	719	71	76	35	–	–	8	[2]
4-400 SE developed by Man-MWH	1000	108	He	633	41	88	32	–	–	4	[2]

undergoes no phase change. The Stirling cycle cryocoolers is widely used because of its advantages: high efficiency, fast cool-down, small size, light weight, low power consumption, high reliability, no pollutant generation like carbon monoxide and so on [10]. Nowadays, the Stirling cycle cryocooler is applied to domestic and commercial refrigerators. Table 2 describes performances and working conditions of old Stirling cryocoolers.

In this article, we present over view of Stirling technologies researches. Section 2 presents an overview of Stirling technology. Section 3 describes the Stirling engine applications. Section 4 presents technological challenges uncounted during manufacture and use of Stirling engines. Section 5 presents models and different optimizations methods made to enhance the performances of these machines. Optimization criterion, methods and parameters used will be investigated. Finally, conclusions are summarized in Section 6.

2. Over view of the Stirling technology

2.1. Cycle and main operation

The Stirling engine (SE) uses a working fluid (air, helium, hydrogen …) contained in a closed domain. Heated by an external hot source at one end and cooled by an external cold source at the other end. The pressure of the working gas will increase on heating and decrease on cooling. Repeated heating and cooling will cause a reciprocating movement of the piston which can be converted to rotary motion using a mechanical drive system. The gas inside the SE is moving from the hot side to the cold side and it is alternately expanding and contracting. The piston movement is converted into useful mechanical work.

The Stirling cycle is a reversible one. It means that inassimilable phenomena can arrive from an engine designed according to this cycle [8]. Providing a temperature difference to this engine leads to get a mechanical power output. In this case the Stirling machine is called heat engine (Fig. 1(a)). But, conversely, bring mechanical energy to the same engine, leads to produce cold or hot heat quantities. In this case the Stirling machine is called a heat pump or cooler depending on the direction of rotation (Fig. 1(b)) [12].

The Stirling's ideal thermodynamic cycle is composed of two isochoric and two isotherms. It is similar to the Carnot cycle; the only difference between them is that the two isothermal processes in the Carnot cycle are replaced by two isochoric processes in the Stirling cycle. As shown in Fig. 2, the working gas trapped in the engine undergoes the following transformation: During the first transformation ($3 \rightarrow 4$), the volume of the gas decreases and the pressure increases as it gives up heat Q_k to the cold source. During the second transformation ($4 \rightarrow 1$), the volume of the gas remains constant as it passes back through the regenerator and regains some of its previous heat. During the third transformation (12)→, the gas absorbs energy Q_h from the hot source, its volume increases and its pressure decreases, while the temperature remains constant. Finally, during the fourth and last transformation ($2 \rightarrow 3$), the volume of the gas remains constant as it transfers through the regenerator and cools. Compared to Ericsson engine, at nearly the same working conditions, the Stirling engine presents higher specific indicated work and efficiency due to the presence of the regenerator [11].

The actual efficiency of Stirling engines is obviously lower than the theoretical efficiency. The first reason is that heat transfer requires keeping a temperature difference between the sources and the working fluid. Thus, in particular, the internal transfer only partially supports heating 4-1 and cooling 2-3. We denote by α the fraction of heat exchanged:

$$q_{4a} = \alpha q_{41} = -q_{2b} = -\alpha q_{23} \quad (1)$$

The rest heat exchanged quantities q_{a1} and q_{b3}, must be performed with sources and significant thermal differences, which consumes extra energy at the hot source (q_{a1}), increases irreversibilities, and therefore