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A review development of rhombic drive mechanism used in the Stirling engines

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ABSTRACT

Stirling engines, unlike internal combustion engines, are engines that generate power by using any type of heat energy source. In these engines, air, helium, and hydrogen are generally preferred as the working fluid. In terms of environment, Stirling engines have lower NO_x, HC, and CO emission. The drive mechanisms vary according to the type of the engine. Suitable drive mechanisms need to be designed to obtain high power output from the engine. This study chronologically examines the efforts of development in Stirling engines. Stirling, Ericsson, and Carnot theoretical cycles are compared and their theoretical efficiency is show to be equal. It is shown that the thermodynamic properties of working fluids used in Stirling engines change according to the temperature. The effect of the working fluids on the engine's performance is discussed. The drive mechanisms used in Stirling engine throughout the historical development is studied in details. Theoretical and experimental studies performed on rhombic drive mechanisms that are distinguished among the drive mechanisms used in such engines by their advantages are examined. The rhombic drive mechanism is firstly used in Stirling engines by the Philips Company in 1953. After this date, the applications of the rhombic drive mechanism in various engines with different characteristics were assessed in terms of performance by companies and researchers. The comparison with other drive mechanisms shows that rhombic drive mechanism is the most suited drive mechanism for beta-type Stirling engines.

1. Introduction

Scottish priest Robert Stirling, two hundred years ago designed and manufactured the first Stirling engine that works according to the principle of external heating and that was called the "Economizer". With this engine, registered under the original patent number 4081, in 1816 [1], it was started a new era in the search for a safe "power source" continued for years. Stirling engines that are more efficient and safer than steam engines has been used to power the water pumps used in quarries and coal mines in 1818 [2].

At first, air was used as the working fluid in Stirling engines and they were called "air engine" or "hot air engine" [3]. Up to a certain point, engines named according to the names of their designers such as "Heinrici Air Engine", "Robinson Air Engine", and "Rankine-Napier Air Engine" were developed [4–7]. Other gases like helium, hydrogen, and nitrogen were later used as the working fluid. In the 1950s, these engines entered the literature by the work of Dr. Roelf Jan Meijer that named them "Stirling engines" in honor of Robert Stirling [8].

The invention of internal combustion engines at the end of the 19th century lowered the interest in Stirling engines. But in 1937, the development of Stirling engines resumed in Philips Research Laboratories in order to create small, quiet, economic, and practical electricity generators [9]. In later years, companies like General Motors Company (U.S.A.), DAF (Netherlands), United Stirling (Sweden), MAN-MWM Group (Germany), Ford Motors Company (U.S.A.), Siemens (Germany), Cummins (U.S.A.), and Perkins (U.K.), and NASA (U.S.A.) conducted large scale researches on Stirling engines.

Today, the development process of Stirling engines is continuing in companies and universities in various countries. The aims are the reduction of the dead space, the minimization of manufacturing and maintenance costs, and the augmentation of thermal efficiencies of these engines that share the same working principle.

Stirling engines, except for their manufacturing and maintenance costs, are low cost and environment friendly alternative power sources. Stirling engines that can work with various energy sources are used in many fields such as space technology, irrigation, refrigeration, and electricity generation [10,11].

This paper examines the historical development, the thermody-

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Nomenclature

A_d	displacer piston surface area
A_p	power piston surface area
C_p	heat capacity of working fluid at constant pressure
C_v	heat capacity of working fluid at constant pressure
k	thermal conductivity
L	connecting rod length
L_d	displacer yoke rod length
MAN-MWM	Maschinenfabrik Augsburg-Nürnberg and Motoren Werke Mannheim
m	mass of working fluid
m	mass of piston
NASA	National Aeronautics and Space Administration
N	cylinder number
$P_1, P_2, P_3, P_4,$	pressure of working fluid silent pints on P-V diagram
Q_{in}	heat transfer inlet
Q_{out}	heat transfer outlet
Q_{Rin}	heat transfer regenerator inlet
Q_{Rout}	heat transfer regenerator outlet
R	gas constant
r	radial distance of mass centres of pistons from axis
R_0	radius of swashplate
R_i	radius of swashplate bushing
$T_1, T_2, T_3, T_4,$	temperature of working fluid silent pints on T-S diagram
T_H	maximum temperature
T_L	minimum temperature
$V_1, V_2, V_3, V_4,$	volume of cylinder silent pints on P-V diagram
V_c	volume of compression cylinder
V_e	volume of expansion cylinder

Greek symbols

ρ	density
μ	gas viscosity

namic cycles, the design criteria, and the drive mechanisms of Stirling engines. The working fluids, emission values, noise, friction, and vibration properties of various designs of such engines are studied. Stirling, Carnot, and Ericsson theoretical cycles are shown comparatively, by conducting thermodynamic analyses.

Various drive mechanisms are used in Stirling engines for the transfer of the generated power. In this study, various aspects of the rhombic drive mechanism, preferred in recent years for reducing the size, the number of mechanical connections, and friction losses are assessed. The aim of this study is to guide designers and researchers working in the field of Stirling engines.

2. Thermodynamic cycles

The complexity of the real phenomena occurring inside the engines, makes researchers to focus on theoretical cycles. Theoretical cycles are instructive in the understanding of real cycles. The efficiency obtained in theoretical cycles is evaluated as a success criterion for the design.

2.1. Stirling cycle

Stirling engines work according to a closed cycle. The heat required for working fluid is provided continuously by a special external heat source. For this reason, Stirling engines are part of the external combustion engines class. The transfer of the heat to the outer environment is realized through a special cooling system [12].

P-V and T-S diagrams for the ideal Stirling cycles are shown in Fig. 1. In these diagrams, the field under the P-V diagram shows the net work obtained, and the field under the T-S diagram shows the heat transfer. In the Stirling cycle with regenerator, every change of state involves heat transfer. As can be seen on the P-V and T-S diagrams, the cycle comprises:

1–2 compression in constant heat and expulsion of the heat from the system, to the external source
2–3 heat transfer from the regenerator into the system in constant volume,
3–4 expansion in constant heat and introduction of heat into the system from the external source
4–1 transfer of heat from the system to the regenerator in constant volume.

Stirling engines go through state changes as shown in Fig. 2. The examination of Fig. 2a reveals:

1. When the power piston is at the bottom dead center, most of the working fluid is in the compression zone and the displacer piston is at the top dead center. During this state change (T_L), the working fluid is at a low temperature.
2. When the displacer piston is stationary at the top dead center, the power piston creates compression by moving from the bottom dead center to the top dead center. To ensure constant temperature during the increase of pressure due to compression, the heat is transferred from the working fluid to the outer environment via the cooling system.

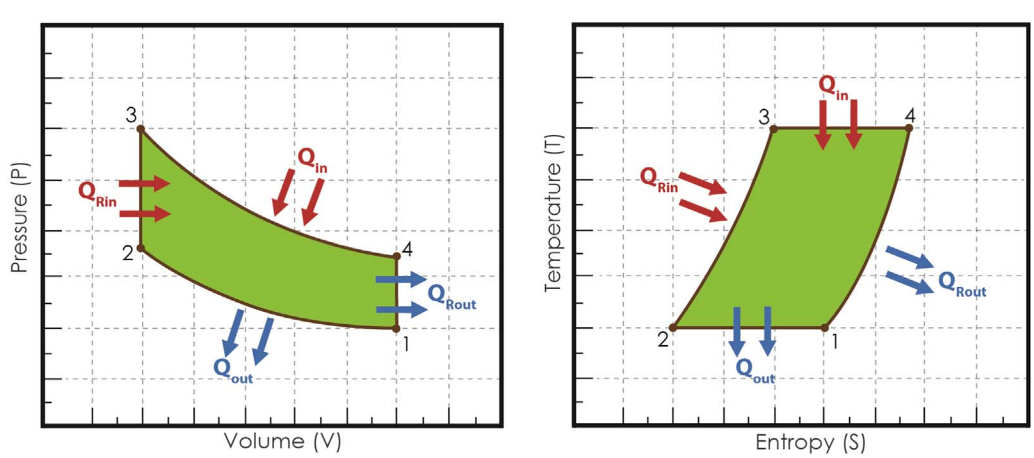

Fig. 1. P-V and T-S diagrams of the Stirling cycle with regenerator.