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Optimization of rhombic drive mechanism used in beta-type Stirling engine based on dimensionless analysis

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In the present study, optimization of rhombic drive mechanism used in a beta-type Stirling engine is performed based on a dimensionless theoretical model toward maximization of shaft work output. Displacements of the piston and the displacer with the rhombic drive mechanism and variations of volumes and pressure in the chambers of the engine are firstly expressed in dimensionless form. Secondly, Schmidt analysis is incorporated with Senft's shaft work theory to build a dimensionless thermodynamic model, which is employed to yield the dimensionless shaft work. The dimensionless model is verified with experimental data. It is found that the relative error between the experimental and the theoretical data in dimensionless shaft work is lower than 5.2%. This model is also employed to investigate the effects of the influential geometric parameters on the shaft work, and the optimization of these parameters is attempted. Eventually, design charts that help design the optimal geometry of the rhombic drive mechanism are presented in this report.

1. Introduction

Stirling engines are potentially competitive when applied in a number of emerging engineering technologies since the engines are referred to as the external-combustion engines which are suitable for a variety of external heat sources. For example, the engines using nuclear energy could power deep-space exploration probes [1], using fossil or hydrogen fuel could drive a vehicle like an automobile [2], or a submarine [3], and using a solar dish collector could produce electricity [4]. A typical solar dish apparatus consists of a large dish aimed at the sun to reflect the rays into the focus point, which is located at a thermal receiver of the Stirling engine. The engine operates by converting the heat received from the solar dish into mechanical work. The work output of the Stirling cycle is then used to drive a generator and create electricity. Furthermore, the electrical power generated by the Stirling engine can be further used to electrolyze water for producing hydrogen. The hydrogen gas could be stored properly and then fed into a fuel cell for electrical power generation when needed [5].

As reviewed by Senft [6], the Stirling engine was named after its inventor Robert Stirling who invented his first engine in 1816. The first successful theoretical analysis was presented by Schmidt [7] in 1871. Schmidt's analysis led to a simple closed-form solution for indicated work of the engine. Lately, a large numbers of Stirling engine prototypes with various configurations, which have been categorized in to α-, β-, and γ-type Stirling engines, have been created [8]. In addition, some single-piston designs, such as thermal-lag Stirling engine [9] and pulse tube engine [10], are also presented. On the other hand, development in thermodynamic models [11–14], optimization methods [15–18], and measurement methods for engine performance [19–21] is also advanced by the progress in prototype building. Based on Schmidt's model, a group of researchers, such as Finkelstein [15], Kirkley [16] and Walker [17] investigated the optimal phase angle and swept volume ratio for various types of Stirling machines. Senft [13] introduced a concept of effectiveness of mechanism and proposed a relation between the forced work and the shaft work of the engine. Later, the same author [18] combined the Schmidt theory and the shaft work theory to carry out the optimal combination of the phase angle and the swept volume ratio for the γ-type Stirling engine. Recently, theoretical analysis was extended to the irreversible cycle analysis. Cheng and Yu [12] proposed a thermodynamic model for the β-type Stirling engine with rhombic-drive mechanism by taking into account the effectiveness of the regenerative channel as well as the thermal resistances of the heating and cooling heads. The thermodynamic model was then incorporated with a dynamic model to perform a dynamic simulation model for the β-type Stirling engines with cam-drive mechanisms by the same group of authors [22].

According to studies of and Kirkley [16] and Cheng and Yang [23], it is recognized that among α-, β-, and γ-type Stirling engines,

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Nomenclature

A	cross section area (m^2)
e	l/r
E	effectiveness of mechanism
l	length of linkage (m)
m	mole number of working fluid (mol)
p, p_b	pressure and buffer pressure (Pa)
r	offset distance from the crank to the center of shaft (m)
R	gas constant R = 8.314 (J/K mol)
R	radius of gear (m)
S	stroke (m)
T	temperature (K)
V	volume (m^3)
W_i, W_f, W_s	dimensionless indicated work, forced work, and shaft work
y_0, y_1	lengths of displacer and piston rods (m)
y_d, y_p	locations of top and bottom links of rhomboid (m)

Greek symbols

α_d	displacement phase angle (deg)
α_v	volume phase angle (deg)
γ	compression ratio
ε	$(R - l)/r$
θ	crank angle (deg)
κ	swept volume ratio (V_{sc}/V_{se})
τ	temperature ratio (T_c/T_e)
χ	total dead volume ratio

Superscripts

–	dimensionless quantity

Subscripts

c	compression chamber
d	displacer
e	expansion chamber
h	heater
k	cooler
l	lower yoke
max, min	maximum and minimum
p	piston
r	regenerator
s	swept volume
t	total
u	upper yoke

the β type possesses higher power density than the other two types. Therefore, the attention of this study is focused on the beta-type Stirling engine. Furthermore, a mechanism is typically installed with the beta-type Stirling engine to drive a displacer and a piston in order to fulfill the required phase angle between the two moving parts as well as the designed strokes of the displacer and the piston. The drive mechanism with the beta-type Stirling engine could be a mechanism of crank drive, bell-crank drive, twin inclined Scotch yoke drive, spring drive, or rhombic drive [6,24–26]. As was described in Ref. [26], the rhombic drive uses a jointed rhomboid to convert linear motion of the reciprocating piston and displacer to a rotation of the flywheel. In the rhombic drive mechanism, one rigid rod is installed connecting the piston to the top link of the jointed rhomboid, and another rigid rod connecting the displacer to the bottom link of the rhomboid. Two symmetric gears of equal diameter are connected to the right and the left links of the rhomboid fixed on the gears at an offset distance from respective gear centers. The two gears are in contact and rotate in opposite

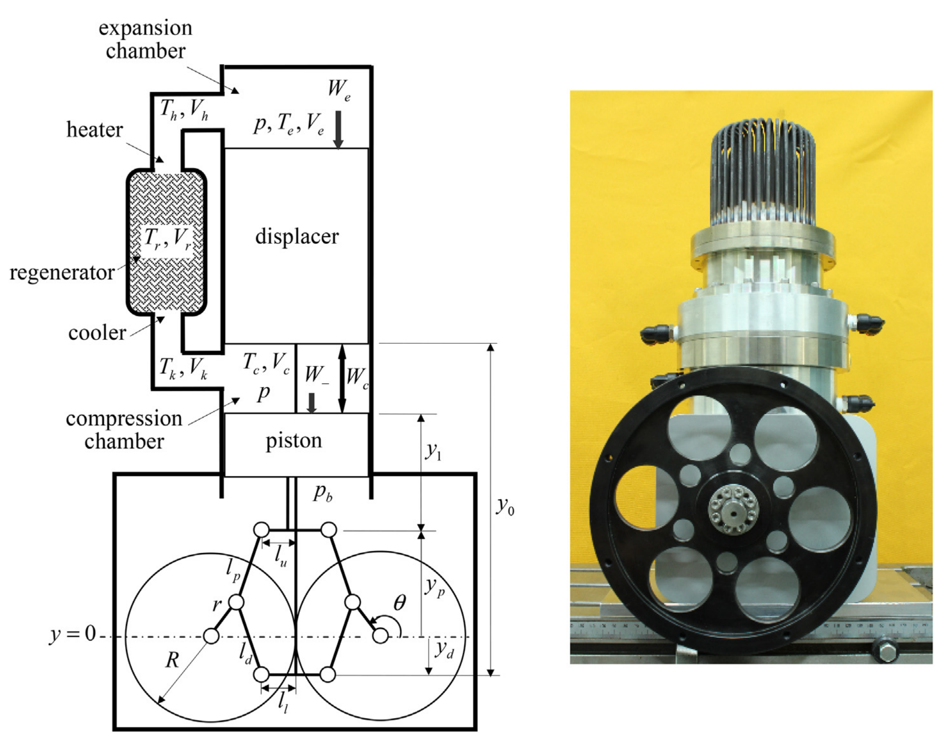

Fig. 1. Schematic and photo of 300-W beta-type Stirling engine with rhombic-drive mechanism [Model NCKU300-2, developed by Power Engines and Clean Energy Laboratory (PEACE Lab.), National Cheng Kung University].