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STUDY ON THE PHASE ANGLE EFFECT FOR ALPHA TYPE STIRLING ENGINE THERMODYNAMICS BEHAVIOR

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ABSTRACT

The depletion and high level of pollution caused by fuel are the main reason for today's search and pursuit for an alternative energy source and an efficient engine cycle. Stirling engine (SE) cycle is deemed to meet the demand required. SE. SE has design and mechanical simplicity yet complex thermodynamics operation. This paper studies on the thermodynamics behavior of the Alpha type Stirling engine (ASE). A Computational Aided Engineering (CAE) analysis was performed to predict the thermodynamics behavior of the ASE. The CAE analysis was conducted with the phase angle, □ of 90° between the two pistons of ASE. The results of the analysis in terms pressure, volume, temperature and trapped mass over the crank angle were presented. It was concluded that the thermodynamics performance and behaviour of an ASE are highly dependent on its geometrical design.

Keywords: stirling engine, stirling cycle, phase angle.

INTRODUCTION

SE is one of the examples of external combustion engines. It operates theoretically on the Stirling cycle by using compressible working fluids such as air, hydrogen, helium, nitrogen or vapours. Stirling engines operate on a closed regenerative thermodynamic cycle, with cyclic compression and expansion of the working fluid at different temperature levels [1]. The SE offer possibilities of high efficiency engines with less exhaust emissions compared to the internal combustion engines.

There are three general configurations, namely alpha-, beta- and gamma-configurations commonly used. Each configuration runs on the same thermodynamic cycle but has different mechanical design characteristics [2]. The alpha-type Stirling engine (ASE) was chosen and studied. For alpha-configuration, it has two pistons positioned in separate cylinders, which are connected in series by a heater, regenerator and cooler. The alpha-configuration (Figure-1) is conceptually the simplest among other configurations.

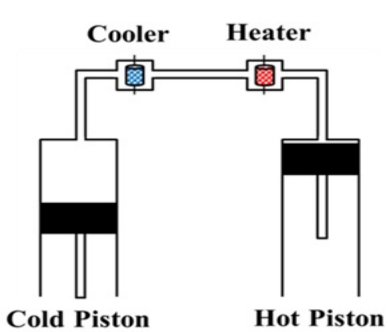

Figure-1. Alpha configuration stirling engine.

SCHMIDT'S THEORY

The Schmidt theory is an isothermal calculation method that has been widely used in the design phase of SE. This theory provides for harmonic motion of reciprocating elements but retains the major assumptions of isothermal expansion and compression and perfect regeneration. The assumption of simple harmonic volume variation permits cycle pressure to be expressed as a function of crank angle, and leads to closed form solutions for work per cycle [3]. In comparison with ideal cycle, this analysis is certainly more realistic and remains highly idealized. The principle assumptions of Schmidt's analysis of Stirling cycle engine are as follows [1].

i. All processes are reversible.
ii. The regeneration process is perfect.
iii. The working fluid obeys ideal gas law,

$$PV = mRT$$

where,

P	Pressure (kPa)
V	Volume (m^3)
m	Working gas mass (kg)
R	Gas constant (J/kg K)
T	Temperature (K)

iv. The mass of working fluid in the system remains constant (no leaks in the system).
v. The volume changes in the working space are sinusoidal.
vi. There is no temperature gradient in the heat exchanger.
vii. The cylinder wall and piston temperature are constant.
viii. The speed of the machine is constant.
ix. Steady state conditions are established.
x. There are no flow and pressure losses.
xi. The temperature in the heater and expansion space is isothermal at T_E.

where,

T_E Expansion temperature (K)

xii. The temperature in the cooler and compression space is isothermal at T_C.

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where,

T_C Cold temperature (K)

xiii. The temperature in the dead volume and regenerator space is isothermal at T_D.

where,

T_D Dead volume temperature (K)

METHODOLOGY

Conceptual of Expansion and Compression Spaces

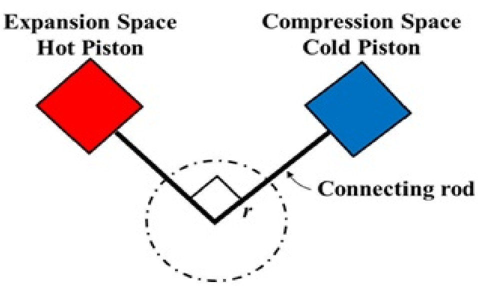

Figure-2. Slider-crank mechanism.

In alpha configuration SE will use slider-crank mechanism (Figure-2) for the piston movements. In order to calculate the piston displacement, s will be based on the following concept as shown in Figure-3.

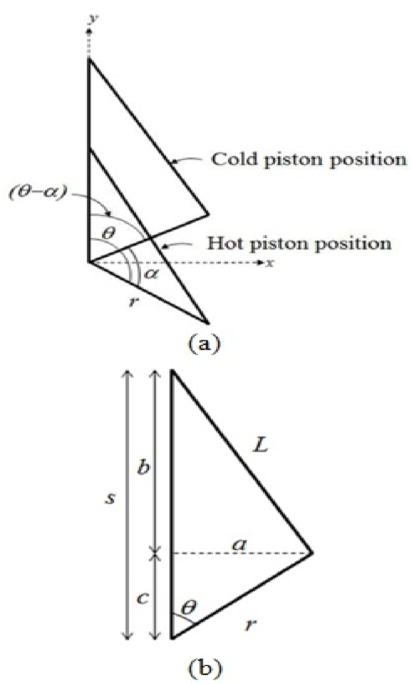

Figure-3. Schematic diagram of (a) overall and (b) displacement stroke.

Using the theorem phytagoras theory defined,

$$a^2 + b^2 = L^2 \quad (1)$$

When $a = r\sin\theta$ and $c = r\cos\theta$, equation (1) is defined as,

$$b^2 + (r\sin\theta)^2 = L^2 \quad (2)$$

$$b = \sqrt{L^2 - (r\sin\theta)^2} \quad (3)$$

Therefore the piston displacement is expressed as,

$$s = b + c \quad (4)$$

$$s = b + r\cos\theta \quad (5)$$

$$s = \sqrt{L^2 - (r\sin\theta)^2} + r\cos\theta \quad (6)$$

Based on the piston displacement gained, the expansion space volume, V_E for hot piston can be expressed by the following equations.

$$V_E = A_p \times s \quad (7)$$

$$V_E = \frac{\pi d_{piston}}{4} \times s \quad (8)$$

$$V_E = \frac{\pi d_{piston}}{4} \times \left(\sqrt{L^2 - (r\sin\theta)^2} + r\cos\theta\right) \quad (9)$$

For the compression space volume, V_C for cold piston is governed by the equations,

$$V_C = \frac{\pi d_{piston}}{4} \times \left(\sqrt{L^2 - (r\sin\theta - \alpha)^2} + r\cos(\theta - \alpha)\right) \quad (10)$$

ASE Configuration

In this study, Computer Aided Engineering (CAE) analysis using GT-POWER software is conducted based on the ASE concept. This computational analysis is performed to predict the effect of piston phase angle towards thermodynamics performance of the ASE at engine speed of 800 rpm.

The baseline parameters used in the CAE analysis performed is based on the Table-1.

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Table-1. Baseline parameters for alpha configuration stirling engine.

COMPONENTS	PARAMETERS		PART	
			Hot	Cold
Cylinder	Pressure		100 kPa	100 kPa
	Temperature		400 °C	30 °C
Engine	***Cylinder geometry***			
	Cylinder dimension	Bore	80 mm	80 mm
		Stroke	72 mm	72mm
	Connecting rod length		80.5 mm	80.5 mm

RESULTS AND DISCUSSION

In this study, the phase angle is the main operating parameters in resulting the variation of thermodynamics performance of ASE. The CAE analysis results of ASE at α = 90° are presented in Figures 4a-4f:

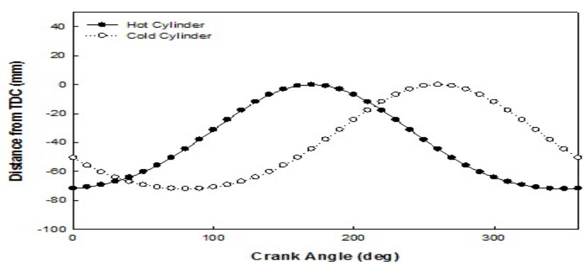

Figure-4a. Effect of piston movement at different crank angle.

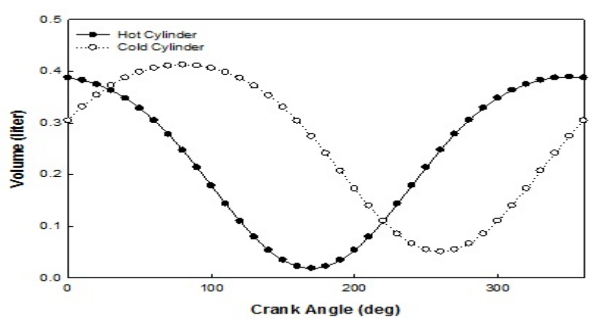

Figure-4b. Effect of volume in cylinder at different crank angle.

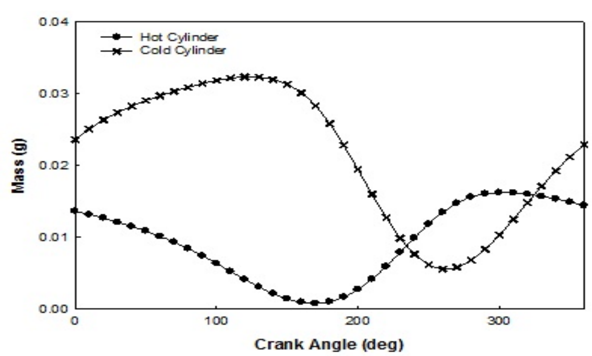

Figure-4c. Effect of mass of working fluid in cylinder at different crank angle.

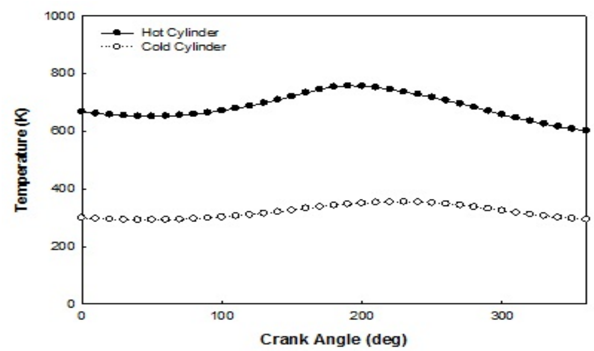

Figure-4d. Effect of temperature at different crank angle.

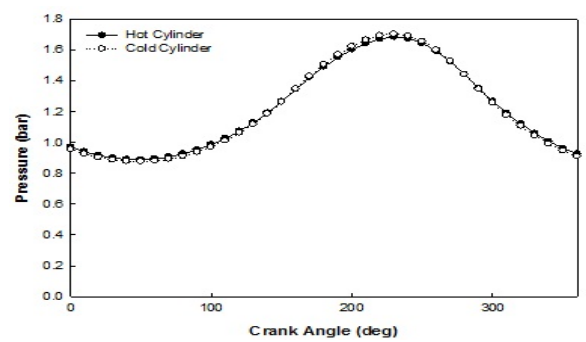

Figure-4e. Effect of pressure in cylinder at different crank angle.

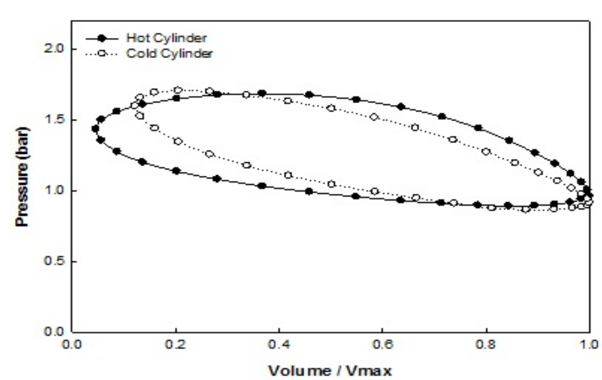

Figure-4f. Effect of pressure at volume/volumemax ratio.

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Figure-4a shows the hot and cold pistons motion in their respective cylinders of the ASE, with a phase angle of 90° relative to one another. The hot cylinder moves ahead of the cold cylinder by 90° phase angle. The volume variation at different crank angle of the expansion and compression space is showed in Figure-4b. The fixed volume of the working fluid is shuttled back and forth in the cylinders as the pistons moves to and fro between TDC and BDC.

Figure-4c shows the mass variation in both the cylinders at different crank angle for the ASE. This results indicates the mass of working fluid is shuttled back and forth in the cylinder by the motion of the pistons and the volume variation. Figure-4d shows the temperature variation at different crank angle. Both the temperature and volume variation at different crank angle graphs indicate the distribution of the fixed mass of working fluid at each phase of the engine's operation. The pressure variation at different crank angle is showed in Figure-4(e). The pressure depends on the volumes of working fluid in the cold and hot cylinders.

Figure-4(f) shows the pressure as a function of volume for both the hot and cold cylinders at $\alpha = 90°$. It signifies the expansion and compression work done by the hot and cold cylinder respectively. As observed, the expansion volume is bigger than the compression volume, hence producing positive work output for the ASE. Figure-5 shows the effect of phase angle on the total volume enveloped between the expansion space and compression space. This shows the work output and hence the performance of the SE is optimum and therefore maximum at $\alpha = 90°$.

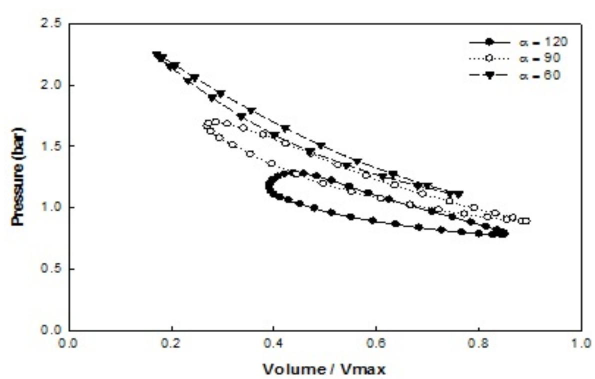

Figure-5. Effect of pressure for variation of volume at different phase angle.

CONCLUSIONS

Based on the analysis performed, it was reviewed that SE thermodynamics behavior was complicated. Through CAE analysis, the results of pressure, volume, temperature and trapped mass of ASE was presented over the variation of crank angle. It was concluded that, phase angle is a significant geometrical parameter in affecting the performance of SE. Hence, phase angle need to be at an optimum value, which is theoretically at 90^{O}. For future development, the CAE analysis can be carried out by varying other geometrical and operating parameters of the ASE for further improvement.

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