DESIGN AND PERFORMANCE STUDY OF AN ALPHA V-TYPE STIRLING ENGINE CONVERTED FROM DIESEL ENGINE

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To my beloved family,
The lover in you who brings my dreams comes true.

To my beloved wife, Nurhayati Sharifuddin and kids, Farah Ameera
Adam Airil and Danish Hakim who have brought a new level of love, patience
and understanding into our lives.

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ABSTRACT

The design of an alpha V-type Stirling engine converted from Yamaha four-stroke diesel engine was realized with few major modifications on the engine housing, heater head, swirl burner, regenerator, oil lubrication system, auxiliary cooler and flywheel. The methodology of developing a 25 W alpha V-type Stirling engine that is simple in design, low cost and multi-fuel potential due to its easy integration with external heat sources had been successfully established and it is proven practicable. The engine can be marked as a closed regenerative cycle engine that pioneers the research of high temperature differential (HTD) alpha V-type Stirling engine operating in self-pressurized mode using air as a working gas. The engine is featured with 90^{o} phase angle, bore and stroke of 53 mm and 44 mm respectively, total swept volume of 194 cc., total dead volume of 115 cc., volume compression ratio of 2.2, 4 mm spherical bed regenerator and Liquefied Petroleum Gas (LPG) as fuel. At heat input of 1100 J/s, the engine performance was successfully tested. For mechanical shaft power assessment, torque, output-power and thermal efficiency variations were obtained at different engine speeds, hot and cold cylinder temperatures. The engine approximately produced a maximum brake power of 7 Watt, brake thermal efficiency of 0.6% at 717 rpm speed, 811^{o}C hot cylinder temperature and 96^{o}C cold cylinder temperature. For electrical power assessment, the engine is capable of generating a maximum electrical output power of 1.7 Watt, system thermal efficiency of 0.15% at 657 rpm, 855^{o}C hot cylinder temperature and 98^{o}C cold cylinder temperature. The investigation of engine seal, oil lubricant, flywheel size and configuration, regenerator tube diameter, total dead volume and auxiliary cooler have significantly contributed to a successful performance of the engine in self-pressurized mode.

ABSTRAK

Rekabentuk bagi enjin Stirling jenis-V alpha diubahsuai dari enjin Yamaha disel empat-lejang direalisasikan dengan pengubahsuaian utama pada rumah enjin, kepala pemanas, pembakar pusar, penukar haba, sistem minyak pelincir, pendingin tambahan dan roda tenaga. Metodologi pembangunan bagi enjin Stirling jenis-V alpha 25 W yang berciri ringkas dalam rekabentuk, murah dan berupaya dalam penggunaan pelbagai bahan api disebabkan penyambungannya yang mudah dengan sumber haba luaran telah berjaya dibentuk dan ianya terbukti berkesan.. Enjin ini ditanda-aras sebagai enjin kitaran penukaran haba tertutup sebenar sebagai pelopor terhadap kajian enjin Stirling jenis-V alpha bersuhu bezaan tinggi yang beroperasi dalam mod bertekanan-diri menggunakan udara sebagai gas bekerja. Enjin ini diperincikan dengan sudut fasa 90^o, 53 mm x 44 mm lubang dan lejang, 194 cc. jumlah isipadu sapuan, 115 cc. jumlah isipadu mati, 2.2 nisbah mampatan isipadu, 4 mm penukar haba lapisan sfera dan Gas Petroleum Cecair sebagai bahan bakar. Pada haba masukan 1100 J/s, prestasi enjin berjaya diuji. Untuk penilaian kuasa aci mekanik, variasi tork, kuasa terhasil dan kecekapan terma diperolehi pada kelajuan enjin, suhu silinder panas dan suhu silinder sejuk yang berbeza. Enjin menghasilkan 7 Watt kuasa brek maksimum, 0.6% kecekapan terma brek pada kelajuan 717 ppm, suhu silinder panas 811^{o}C dan suhu silinder sejuk 96^{o}C. Untuk penilaian kuasa elektrik, enjin mampu menghasilkan 1.7 Watt kuasa terhasil elektrik maksimum dan 0.15% kecekapan terma sistem pada kelajuan 657 ppm, suhu silinder panas 855^{o}C dan suhu silinder sejuk 98^{o}C. Penyelidikan terhadap penutup enjin, minyak pelincir, saiz dan bentuk roda tenaga, diameter tiub penukar haba, jumlah isipadu mati dan pendingin tambahan secara ketara telah menyumbang pada kejayaan operasi enjin ini dalam mod bertekanan-diri.

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LIST OF SYMBOLS AND ACRONYMS

a - Inner radius of solid disk flywheel, m

a_e - Coefficient of linear expansion, m/^{o}C

A - Area, m^2

A_b - Surface area of spherical ball, m^2

A_{wg} - Wetted area, m^2

b - Outer radius of solid disk flywheel, m

b_1 - Outer radius of webbed solid disk flywheel, m

b_2 - Radius of web, m

B - Constant

BDC - Bottom dead center

c - Central bore of flywheel, m

$\mathrm{C_v}$ - Specific volume

$\mathrm{C_p}$ - Specific heat, kJkg^{-1}K^{-1}

d - Diameter of spherical ball, m

d_g - Grain diameter, m

$\mathrm{d_{RT}}$ - Diameter of regenerator tube, m

$\mathrm{d_{vessel}}$ - Diameter of regenerator vessel, m

D - Diameter, m

$\mathrm{D_e}$ - Exit diameter, equivalent diameter, m

$\mathrm{D_i}$ - Inner diameter, m

$\mathrm{D_o}$ - Outer diameter, m

$\mathrm{DV_C}$ - Dead volume of cold cylinder, m^3

$\mathrm{DV_H}$ - Dead volume of hot cylinder, m^3

$\mathrm{DV_{RT}}$ - Dead volume of regenerator tube, m^3

DV_R - Void volume inside regenerator, m^3

DV_{total} - Total dead volume, m^3

E_k - Kinetic energy storage, J

F_r - Friction force, N

f - Cycle frequency, Hz

g - Gravitational acceleration

G - Working gas mass flow, kg/m^2s

G_ϕ - Flux of angular momentum, kgm^2/s^2

G_x - Flux of linear momentum, kgm/s^2

HTD - High temperature differential

I - Moment of inertia, Nms^2

K - Equilibrium constant

l - Length, m

l_1 - Thickness of flywheel, m

l_2 - Thickness of web, m

l_{RT} - Length of regenerator tube, m

l_{vessel} - Length of regenerator vessel, m

L - Length of stroke, m

L_0 - Original length of material, m

L_f - Final length of material, m

LTD - Low temperature differential

LPG - Liquefied Petroleum Gas

m - Mass, kg

$\dot{m}$ - Mass flow rate, kg/s

M - Mass of flywheel, kg

N - Engine speed, rpm

N_B - Beale number

n - Number of heat input channel

p - Pressure, bar or Mpa

p_m - Mean pressure, bar or Mpa

P - Power, W

P_{el} - Electrical output power, W

P_{atm} - Atmospheric pressure, bar or Mpa

P_{min} - Minimum pressure, bar or Mpa

P_{max} - Maximum pressure, bar or Mpa

PTFE - Polytetrafluoroethylene (Teflon)

Q - Amount of heat, J/s or W

Q_{SOURCE} - Amount of heat source, J/s or W

Q_{HEAD} - Amount of heat input to engine head, J/s or W

R - Universal gas constant

R_e - Reynolds number

r - Radius, m

S - Swirl number, Constant, Spring load, N

S_g - Geometric swirl number

S_{gT} - Non-isothermal geometric swirl number

T - Temperature, ^oC or Kelvin

TDV - Total dead volume, m^3

TDC - Top dead center

U - Average exit velocity, m/s

U_{max} - Maximum torque, Nm

u - Rubbing velocity, m/s

V - Volume, m^3

V_0 - Displacement volume, m^3

V_b - Volume of spherical ball, m^3

V_e - Volume of the expansion space, m^3

V_c - Volume of the compression space, m^3

V_D - Dead volume, m^3

V_m - Matrix metal volume, m^3

V_{swept} - Swept volume, cm^3

V_{vessel} - Volume of regenerator vessel, m^3

V_{CR} - Volume compression ratio

V_{max} - Maximum volume, m^3

V_{min} - Minimum volume, m^3

$\dot{V}$ - Volume flow rate, m^3/s

W - Amount of work, J; Weight, kg

w - Angular speed, rad/s

X - Dead-volume ratio

x - Piston displacement, m

$\dot{x}$ - Piston velocity, m/s

$\ddot{x}$ - Piston acceleration, m/s^2

τ - Temperature ratio

λ - Engine stroke, mm

v - Kinematics viscosity

k - Swept-volume ratio

ψ - Regenerator matrix porosity

ε - Regenerator effectiveness

ρ - Density, kg/m^3

γ - Material density, N/m^3

μ - Coefficient of friction

η - Efficiency of heat engine, %

η_{bt} - Brake thermal efficiency, %

η_{st} - System thermal efficiency, %

η_{hs} - Combustion system efficiency, %

η_C - Carnot efficiency, %

η_S - Stirling engine efficiency, %

δ - Constant

δL - Thermal expansion rate

θ - Crank angle

ΔT - Temperature difference

ΔR - Uncertainty limit, %

σ_y - Yield strength

σ_0 - Material constant

k_y - Material constant

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CHAPTER 1

INTRODUCTION

1.1 Overview

Since its conception in the early 1800s, the Stirling engine has periodically enchanted engineers and physicists since theoretically, Stirling engines have the same efficiency as the Carnot engines. Today, interest in the Stirling engine is again on the rise. Among the reasons for this are great advances in materials technology, inherent environmental advantages of Stirling engine and the fact that, as an externally heated engine, it can be powered by a number of energy sources [Blank and Wu, 1995].

1.2 Background of the problem

Stirling engines are eminent for their prospect of high efficiency, safe operation, long life, fuel flexibility, low emissions, low pollution, low vibration and low noise level (Scott et al., 2003) compared to internal combustion engine.

However, a wide spread utilization of Stirling engines has not yet become a reality due to commercial and economical factors (Raggi et al., 1997). Issues such as low specific power and high manufacturing cost of Stirling engines are main challenges that make mass production of Stirling engines not feasible at present. Up-to-date, the cost of 1 kW free piston Stirling engine as reported by Sun Power Inc. is about USD120,000 or equivalent to RM480,000 (Crawford, 2007). The cheapest and nearest available Stirling engine within Asia is 3HP ST5 beta-type Stirling engine from Stirling Technology, Japan at the cost of USD45,000 or equivalent to RM180,000. (Tezuka, 2007). Apparently, the unit cost of both beta-type and free piston Stirling engine is 4 to 10 times higher than the cost of four-stroke diesel or gasoline engines in the market.

Modifying an internal combustion engine into the Stirling engine has been the preferred alternative especially for academic and experimental purposes (Raggi et al., 1997). Apparently, the manufacturing cost of the modified engine can be very much reduced since the ready engine components have the quality in terms of material strength and parts precision. The engineering time (design and fabrication) can be shortened and the spare parts can be easily sourced if the engine is subjected to wear and tear. The numerous investigations made by scientists and engineers since the invention of the engine have made good base line information for designing engine system, but more insight is essential to design systems together for thermo-fluid-mechanical approach. It is seen that for successful operation of such system a careful selection of drive mechanism and engine configuration is essential. An additional development is needed to produce a practical engine by selection of suitable configuration; adoption of good working fluid and development of better seal may make Stirling engine a real practical alternative for power generation (Thombare and Verma, 2006). Due to the cost factor and simplicity in design, alpha-type Stirling engine is typically selected because many parts from the industrial mass production can be used. The necessary maintenance and repair work of this engine can also be done by a standard car workshop (Podesser, 1999).

In developing practical Stirling engines, the design consideration of efficient fuel burning system is very important. Efficiency of the fuel burning system will be determined by the capability of the external heat source system to provide sufficient heat input and the capability of the engine heater head to store the heat supply for the working cylinder and to minimize heat loss. Many researchers had incorporated electrical heater as part of the engine pre-heating or heating head section, particularly for the alpha V-type Stirling engine, since it is easier to assemble the electrical heater to the engine body as compared to other means of heating systems due to its sloped position. The electrical heater acts as heat interface between fuel burner and the engine hot working cylinder. Undeniably, it is good for continuous, stable and easy to regulate heating purposes but there are a few other alternatives that can also potentially be utilized especially in the development of a low cost and multi-fueled Stirling engine for power production.

1.3 Statement of the problem

Alpha engines have two pistons in separate cylinders, which are connected in series by a heater, regenerator and cooler. Alpha engine is conceptually the simplest Stirling engine configuration; however, it suffers from the disadvantage that both pistons need to have seals to contain the working gas (Thombare and Verma, 2006). Development of alpha-configuration Stirling engine is rarely seen in the most recent publications particularly due to its sealing problem that affects the engine performance. Technical problems arise when the working gas inside the cylinders is not sealed properly. Firstly, pressure inside the hot working cylinder will reduce as gas leaks out from the engine. Secondly, engine power will drop with decrease of internal pressure and eventually, stop the engine. Numerous efforts had been done by many researchers to overcome sealing problem on alpha-configuration Stirling engine. Among them are; the use of moving sealer in the gap clearance between piston and cylinder wall and the manufacture of a highly precise piston to cylinder wall materials with a gap clearance less than 0.1 mm. Typically, these types of sealing requirements substantially increase manufacturing cost of the engine and the use of piston and cylinder with the nearest gap clearance is still insufficient to overcome pressure drop inside the engine (Walker, 1980). And the use of moving sealer or sliding seal in high pressure, high temperature engine working cylinder is rather difficult to maintain. Many companies and individual researchers have declared their successful Stirling engines operations by operating their engines at some degree of pressurization of the working fluid where the flow is controlled by valves. In fact, only a few experimental investigations of Stirling engines deal with working fluid charging into the engine (pressurization of working fluid) for both assessment and improvement of the engine performance. Conceptually, these engines are no longer closed regenerative cycle engines and referring them as ‘Stirling engine’ is rather misleading. Walker (1980) stated that distinction between a closed regenerative cycle engine and an open regenerative cycle engine is not widely established in practice and the name ‘Stirling engine’ is frequently indiscriminately applied to all types of regenerative machines. He emphasized that clear distinction should always be made between Stirling engines that apply constant volume system and Ericsson engines that apply constant pressure system, because they have radically different characteristics.

Stirling engine designs including alpha-configuration require a regenerator for heat storage (input) and heat release (output), and these must contain the pressure of the working gas, where the pressure is proportional to the engine power output. In addition, the engine heater head section and hot end regenerator are continuously at very high temperature. Thus, the part materials must require resistance to corrosive effects of the heat source and must have low thermal creep effect due to successive heating and cooling processes. Again, requirements of such materials considerably escalate manufacturing cost. As an evidence, sintered wire screens made of material typically stainless steel make a good regenerator for high performance engines, with a typical effectiveness of 95%-98%, but the unit is expensive to build (West, 1986). There are other alternatives and less costly regenerators have been sought including knitted wires (Spatz, 1981), ceramic sponge (Vincent et al., 1982) and quartz tubes or plates (Schneider et al., 1984), but they are hardly available in the local market and must be custom made. Therefore, an exploration of a low cost, readily and easily available regenerator material is desired.

1.4 Objectives

The objectives of this research are:

1. To develop an external combustion system for the Stirling engine operation.
2. To design 53 mm bore x 44 mm stroke with 97 cc., develop and operate an alpha V-type Stirling engine converted from diesel engine for 25 Watt power.
3. To determine the power and torque of high temperature differential (HTD) Stirling engine operation in self-pressurization mode and to profile critical operating parameters such as temperatures of hot cylinder, cold cylinder, regenerator and fuel burner.
4. To analyze the optimum operating parameters and correlation for design engine for an optimal power production.

1.5 Scopes of the study

The purpose of this study is to develop a simple, portable, low-cost, multi-fueled characteristic and high temperature differential (HTD) alpha V-shaped Stirling engine by using custom-made components of YAMAHA four-stroke diesel engine and industrial mass production materials. An in-depth understanding of Stirling cycle and its working principle is demanded in developing converted diesel to Stirling engine since internal combustion engine applies a totally different cycle from Stirling engine. Pure experimental investigations are critical to study both characteristics and performance of the engine in self-pressurization mode. Finally, the engine performance will be characterized and optimized in order to fulfill the expectation of delivering a small-scale power production.

Scope 1: The research will commence with the selection process of the most suitable type or configuration of the Stirling engine to be developed. At this stage, understanding of thermodynamics principle of the Stirling cycle is demanded. The main criteria for the selection process include the engine cylinder layout/arrangement, drive mechanism, type of heater or burner, cylinder and piston forms of coupling, type and size of regenerator and crankcase construction. Design considerations of the Stirling engine to be developed must also notice major output characteristics such as net power output, thermal and mechanical efficiency, cost-effectiveness and simplicity in design.

Scope 2: The research will proceed with design, fabrication and development of Stirling engine based on the most suitable configuration to be developed. The expectation of low manufacturing cost Stirling engine will be realized by utilizing common materials from the local foundries and by adopting common spare parts of internal combustion engines. Technical specifications of the manufactured Stirling engine that complies with the thermodynamics principle of Stirling engine cycle will be originated at the end of this stage via preliminary investigations.

Scope 3: The research will then continue with the performance testing of the Stirling engine workability and operation. At this stage, critical design features of the Stirling engine such as crank mechanism, heater or burner, cylinder-piston coupling and sealing, regenerator, flywheel, working gas etc. will be examined for their operability. Measurement of critical operating parameters such as heater temperature, hot temperature of the expansion working cylinder, cold temperature of the compression working cylinder, regenerator temperature, cooling temperature of the cooling system and so forth will be measured and profiled. Thermal heat input into the engine heater head section will be controlled via a fuel flow rate measurement.

The engine power output (both mechanical shaft power and electrical power) will be determined experimentally via various tests.

Scope 4: The final stage of this research will cope with the performance characterization of the Stirling engine operation. Specifically, size and/or type of material for the engine critical parts such as flywheel, piston, piston ring or sealer, regenerator, lubrication oil etc. will be characterized for determining any significant effect on the engine output characteristics. Variation study of the engine critical operating parameters such as fuel flow rate, heater and cooling temperature will be performed as well to determine any potential improvement on the engine power production. Ultimately, Stirling engine performance curves will be established.

1.6 Significance of the study

A successful development of a small-scale, portable, low cost, self-pressurized and fuel flexible Stirling engine will help to contribute another alternative for power generation system particularly in rural or remote areas. The Stirling engine with multi-fueled capability will create options in utilizing lower cost and highly available source of fuel. Consequently, it will help to reduce operational cost of the Stirling engine. Using common materials from local foundries and common spare parts from internal combustion engines will help to minimize manufacturing cost and to realize commercialization of Stirling engines.

1.7 Expected findings and summary

The possible outcomes of the research project are as per following:-

- Capability of Stirling engine to produce a small-scale power output can be demonstrated.
- Understanding of the effect or relationship of each process parameters in contributing a successful operation of the Stirling engine to produce power can be accomplished.
- Performance characterization of the overall Stirling engine system including the external combustion process can be established.
- Potential application of the overall Stirling engine system for a small-scale power generation can be analyzed and corroborated.

1.8 Organization of the thesis

The thesis is organized in such a way that it provides a continuous and smooth flow of information to the reader in regards to development and performance characterization of alpha V-Stirling engine converted diesel engine for a small scale power production.

Chapter 1 presents a brief background of Stirling engine development, its major problems that hinder mass production of the engine for active commercialization and challenges for solving the problems.

Chapter 2 deals with literature review pertaining to both historical and technological development of Stirling engine in various configurations, the pros and cons of different types of Stirling engine configuration with respect to both specific power and thermal efficiency, selection process of Stirling engine critical parts and components and decision making of the suitable Stirling engine to be developed.

Chapter 3 describes the methodology for design, development and operation of the Stirling engine. Key considerations in designing the Stirling engine are elaborated and that includes material selection for the engine critical components, dimensioning of the engine size and volume, dimensioning of the engine critical parts, setting-up of the external combustion system, cooling system and heat regeneration system, selection of flywheel for the energy storage system, selection of the working medium, selection of the engine lubricant and so forth. All the relevant mathematical formulations for designing and operating the Stirling engine are presented and discussed in this chapter.

Chapter 4 presents the Stirling engine performance curves at both no load and load conditions. The engine performance at load condition consists of two main sections. The first section presents and discusses the experimental results of the engine mechanical shaft power assessment. In this section, variation of engine characteristics as a function of the critical operating parameters comprises of engine speed, hot cylinder temperature, cold cylinder temperature and operation time are presented and discussed. The second section deals with experimental results of the engine electrical power assessment where variation of engine characteristics primarily current load, voltage output and electrical power at different engine speeds, hot cylinder temperatures and cold cylinder temperatures are elaborated. Characterization of critical parameters of the engine for its optimal performance is also discussed in this chapter that affects the engine performance significantly.

Chapter 5 accentuates key achievements of the study with reference to the set of objectives outlined in Chapter 1. Both theoretical and experimental results as discussed in the previous chapters are justified in this chapter. One of the objectives of this study is to identify areas where more research work is needed in order to improve methodology and techniques for overall performance and power production capability of the developed engine. These potential areas are pointed up under work recommendations.

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