EXPERIMENTAL ANALYSIS AND COMPUTATIONAL VALIDIATION OF MICRO STIRLING ENGINE

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Abstract—This project was set out to with an objective to explore the practicality of power production from a Stirling engine. This would include research, design and fabrication. The engine model would run on different sources of sufficient external heat to generate the desired motion. With this end in sight, a thorough and comprehensive research was carried out on the working and configurations of Stirling engines. Research sources included the internet, engineering books on thermodynamics and engine machines as well consulting the project supervisor. In total, knowledge gathering took about six weeks. After it was decided that the Gamma configuration would best achieve the intended objective, sketches were made. After all the designs were approved by the project supervisor, an acquisition was made for funds and materials. This was then followed by fabrication, assembly and testing that span a period of 8 weeks. Test results revealed that the assembled engine had air leaks that mostly emanated from the piston cylinder. The piston cylinder was the highest precision part and also most expensive. From the theoretical analysis, the Stirling engine designed had and efficiency of about 7.7%. This was pointed out that there were energy losses, which were attributed to friction and the engine having some out-of-balance masses. To rectify this, it was proposed that a kinematic assessment of the engine be carried out to eliminate any out of balance masses.

Index Terms— Displacer swept volume, Power Piston Swept Volume, Regenerator dead volume, Hot space dead volume.

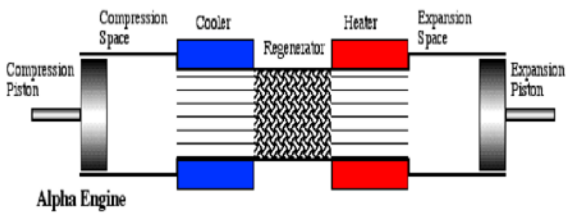
I. INTRODUCTION

A Stirling engine is a heat engine operating by cyclic compression and expansion of air at different temperature levels such that there is a net conversion of heat energy to mechanical work. Like the steam engine, the Stirling engine is traditionally classified as an external combustion engine, as all heat transfers to and from the working fluid take place through the engine wall. This contrasts with an internal combustion engine where heat input is by combustion of a fuel within the body of the working fluid. Unlike a steam engines (or more generally a Rankine cycle engines) usage of a working fluid in both of its liquid and gaseous phases, the Stirling engine encloses a fixed quantity of air. As is the case with other heat engines, the general cycle consists of compressing cool gas, heating the gas, expanding the hot gas, and finally cooling the gas before repeating the cycle. The efficiency of the process is narrowly restricted by the efficiency of the Carnot cycle, which depends on the temperature between the hot and cold reservoir. The Stirling engine is exceptional for of its high efficiency compared to steam engines, quiet in operation and the ease with which it can use almost any heat source. This is especially significant as the prices of conventional fuel prices rise in a more “green cautious” world. Competition from Internal combustion. The invention of the internal combustion engine in the 1900‟s put the nail on the coffin for the Stirling type of engine because it generated more power and proved to be more practical in the automobile industry. Due to the rigorous solar energy exploration taking place in the developed economies, this old technology is being given a newer and fresher approach. Robert Stirling was a Scottish minister who invented the first practical example of a closed cycle air engine in1816, and it was suggested by Fleeming Jenkin as early as 1884 that all such engines was called as Stirling engines. This naming proposal found little favour, and the various types on the market continued to be known by the name of their individual designers or manufacturers, e.g., Rider's, Robinson's, or Heinrici's (hot) air engine. In the 1940s, the Philips company was searching for a suitable name it gave a name for its own version of the 'air engine', which by that time had been tested with working fluids other than air, and decided upon 'Stirling engine' in April 1945. [2]

The Stirling engine is an externally fired engine unlike steam engine, in which heat transfers to and from take place through a solid boundary (heat exchanger) thus isolating the combustion process and any contaminants it may produce from the working parts of the engine. In comparison with an internal combustion engine where heat input is by combustion of a fuel within the body of the working fluid. The main subject of Stirling's original patent was a heat exchanger, which he called an "economiser" for its enhancement of fuel economy in a variety of applications. These economiser [3] in which application it is now generally known as a "regenerator". Subsequent development by Robert Stirling and his brother James, an engineer, resulted in patents for various improved configurations of the original engine including pressurization, which by 1843, had sufficiently increased power output to drive all the machinery at a Dundee iron foundry. [4]

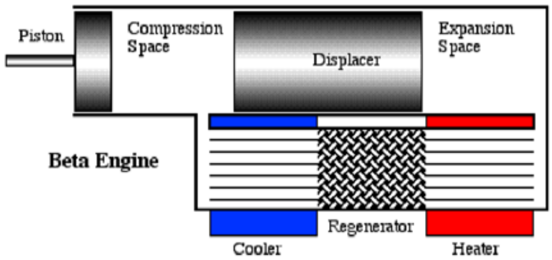
Alpha stirling engine ,Beta stirling engine and Gamma stirling

The simplest Stirling engine is the Alpha engine in which there are two pistons one is hot piston and one is cold piston out of which one is used for compression and expansion. The hot piston used for expansion and is connected in series to a heater, a regenerator, a cooler, and the cold piston used for compression.

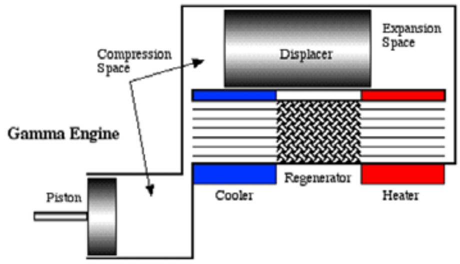


Beta Stirling engine

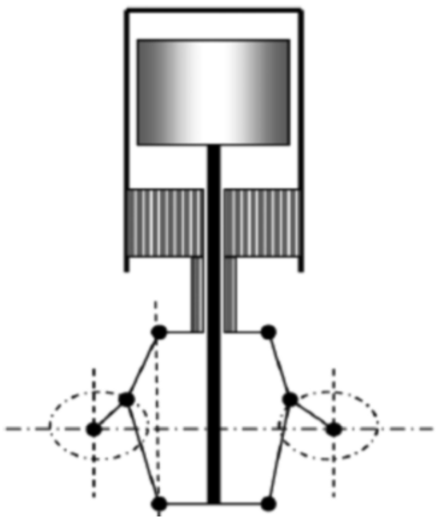
The displacer-piston arrangement in Beta engine configuration has separate cylinders are used to house each piece. An interconnecting transfer port joins the two cylinders, which share the compression space.



Gamma Stirling Engine



The slider crank drive is used in twin cylinder versions of the Stirling engine due to which it is to manufacture this type of engine. In the 1950s, the rhombic drive which is dynamically balanced even in an arrangement with a single cylinder making it the most well known and most developed of single cylinder Stirling engines. Each assembly requires numerous moving parts, and bearing surfaces causing the complexity of the unit to be its main disadvantage in this type of mechanism. (Philip, 1987).



Rhombic drive

II. LITERATURE SURVEY

A. Review Stage

In this segment various types of fault recognition procedures in various surfaces are reviewed and described briefly as follow In 2006 Bancha Kongtragool, Somchai Wongwises [5] invested on the thermodynamic analysis of Stirling engine. An isothermal model is developed for an imperfect regeneration Stirling engine with dead volumes. In this the engine net work is affected by only the dead volumes and due to regenerator effectiveness . The engine net work decreases with increasing dead volume. The heat input increases with increasing dead volume and decreasing regenerator effectiveness . The engine efficiency decreases with increasing dead volume and decreasing regenerator effectiveness. The dead volume will decrease both the engine network and the thermal efficiency and increase both the external heat input and output. However, a real engine must have some unavoidable dead volume. To attain high efficiency, a good regenerator is needed. However, the Stirling engine is able to attain a low efficiency without a regenerator. Here the engine operates between two temperatures of 923 and 338 K, respectively and the Engine efficiency ranges from about 30 to 40% r, and normal operating speed range from 2000 to 4000 rpm. In 2008 D.G. Thombare , S.K. Verma [6] discussed about the Technological development in the Stirling cycle engines .The objective of this paper is to provide fundamental information and development of the Stirling cycle engine and techniques used for engine analysis. This paper discuss about the Isothermal analysis, heat transfer in an isothermal model Heat transfer in adiabatic engine model ,Maximum theoretical obtainable efficiency of Stirling cycle engine, Schmidt’s theory for classical analysis. Schmidt developed a theory, which provided sinusoidal volume variation in the Stirling engines. In this theory some the major assumptions were made of isothermal compression and expansion and of perfect regeneration. In 2011 Chin-Hsiang Cheng, Hang-Suin Yang [8] developed an analytical model for Stirling engine to analyze the effect of operating speed on shaft power output. he developed a numerical relationship between operating speed and shaft power output . It was observed that the shaft power output corresponds to any changes or not with the variations in the Temperature of expansion and compression spaces as well as corresponding variation in to operating speeds were investigated by using a lumped-mass transient model. In 15 November 2012 Zhigang Li a, Yoshihiko Haramura b, Yohei Kato b, Dawei Tang [9] , Optimization of both the porous sheets regenerator and the conventional wire mesh regenerator shows that under given operating conditions, the porous-sheets regenerator has 38% to 51% lower total entropy generation rate while maintaining the same or higher thermal effectiveness, thus leading to less available work loss, contributing to higher power output and thermal efficiency. In January 2015 Mohammad Hossein Ahmadi ,Mohammad Ali Ahmadi [13] , makes attempts to perform multi-objective optimization on the solar-powered Stirling engine with high temperature differential , A new model was proposed based on the finite-time thermodynamic. Furthermore, the thermal efficiency of the solar Stirling system with a rate of finite heat transfer, regenerative heat loss, the output power, finite regeneration process time and conductive thermal bridging loss is specified.

In August 2015 M. Hooshang a, R. Askari Moghadam a, S. AlizadehNia b [14] presented a dynamic model of a gamma-type Stirling engine and examines variations of the crank rotational speed against time (Dynamic response). Kinematic relations of the engine linkages were determined and Lagrange formulations were formed for rigid body dynamics. Working gas pressures on each surface of the rigid bodies were calculated over time using a third order thermodynamic analysis code. In November 2015 Ana C. Ferreira , Manuel L. Nunes ,Jose C.F. Teixeira [15] Thermodynamic and economic optimization of a solar-powered Stirling engine for micro-cogeneration purposes In this model, the pressure losses have a great influence in the work and efficiency mainly at high speeds. Thus, the pressure drop is converted into work loss, which is accounted to determine the total engine work per cycle. The model also accounts for there generator heat-transfer reduction. In December 2015 Jian Moua, Wei Li b, Jinze Li, Guotong Hong [16] analyzed Gas action effect of free piston Stirling engine (FPSE) is very important to solve the key problem of startup and find the way to increase its efficiency. In Jan2016 Ruijie Li, Lavinia

Grosu [17]discussed about, irreversible processes in solar powered Gamma type Stirling engine have been investigated in order to highlight the impact of losses on provided mechanical power and its performance. In March 2016 Zhongyang Luo, Umair Sultan , Mingjiang Ni [18], suggested that Stirling engine has become preferable for high attention towards the use of alternate renewable energy resources like biomass and solar energy. Stirling engine is the main component of dish Stirling system in thermal power generation sector. S. H. Babaelahi has discussed Polytropic analysis of Stirling engine with Various Loss mechanisms (PSVL) approach shows The numerical thermal study [19] of polytropic compression/expansion processes. It is used for estimating performance of Stirling engines . To achieve this goal, differential governing equations were developed to include polytropic heat transfers. In 2018 Ahmed Abuelyamen made a Energy efficiency comparison by CFD simulation [20] of three types of Stirling engine (α, β, and γ) , in which the performance of each type was estimated. S.A. El-Ghafour☐, M. El-GhandourA, in 2019 [21]developed a three-dimensional Computational Fluid Dynamics (CFD) simulation for the GPU-3 Stirling engine is performed. In this Firstly, the performance of six different eddy-viscosity models are assessed. In this study, [22] the nodal thermodynamic and dynamic analysis of an alpha type Stirling engine driven by Scotch yoke mechanism is presented. The nodal thermodynamic section of the analysis is performed via 15 nodal volumes. The temperature variations in nodal volumes are calculated by means of the first law of the thermodynamics given for the open systems. Lukasz Kuban1, Jakub Stempka, Artur Tyliszczak [23] has performed detailed 3D CFD analysis of heat transfer and flow dynamics inside a commercial gamma-type Stirling engine, including its structural details and variability of the working spaces. The study deals with the impact of different initial engine parameters, like rotational speeds, filling pressure and heater temperatures, on the engine's characteristics. In this paper[24], we presented for the first time in literature an analysis of the regenerative processes of the Stirling engine using finite-time thermodynamics. Based on an even-distribution temperature assumption, we derived equations for the regenerative effectiveness and regenerative duration. We found that the regenerative effectiveness cannot be greater than 0.5. In practice, the duration time of the Stirling engine cycle is very short, so that the temperature of the regenerator follows an uneven distribution. Based on an uneven distribution temperature assumption, a regenerator was modeled by dividing it into n sub-regenerators.

III. PROBLEM STATEMENT

The objective of the research is fundamental experimental and computational investigation on gamma type Micro Stirling engine. The scope of the investigation includes, Design and Development of a lab scale gamma type Stirling engine with maximum thermal efficiency by enclosing it with a glass envelop reducing the heat loss and improving the Regenerator Performance. Performance Measurement Using Computational studies Experimental Validation of Results

Assuming $T_{max} = 1000\ K$ and Assuming $T_{min} = 338\ K$

For $\epsilon = 1$ $\eta_E = 1 - \frac{T_{min}}{T_{max}} = 1 - \frac{338}{1000} = 0.662$

Temperature ratio $\tau = \left(\frac{T_{min}}{T_{max}}\right) = \frac{338}{1000} = 0.338$

Using Beale concept L/D ratio is 1:2 and length of Power Piston to length of cylinder is 1:1

Let LD = Length of Displacer (hot cylinder) =10 cm

DD= Diameter of displacer = 8.5 cm

Lrg= Length of Regenerator = 4 cm

DD= Diameter of Regenerator = 8.5 cm

and length of Power Piston to length of cylinder is 1:1

Let LD = Length of Power Piston (cold cylinder) = 100 mm

Calculation for power

P = engine Power (watts)

p =mean cycle pressure

f =cycle frequency or engine speed in hertz

Vo = displacement of power piston cm3

$$V_o = \frac{\pi}{4} \times D^2 \times \frac{D}{2}$$

$$V_o = \frac{\pi}{4} \times 4^2 \times \frac{10}{2}$$

V_o = 62.83 cm3

$$P = 0.015p \times f \times V_D$$

$$1000 = 0.015p \times 5 \times 62.83 \times 10^3$$

p = 0.2122 Mpa

$$D = \sqrt[3]{\left(\frac{8P}{0.03\pi pf}\right)}$$

$$D = \sqrt[3]{\left(\frac{8 \times 1000}{0.03\pi \times 0.212 \times 5}\right)}$$

D = 43.1 mm

Calculation of Flywheel

Energy stored in Flywheel

$$= \frac{1}{2} I\omega^2$$

I= mr2 =50 x 10-3 x 352 = 61.25

IV. 1 SOLID WORKS STIRLING MODEL

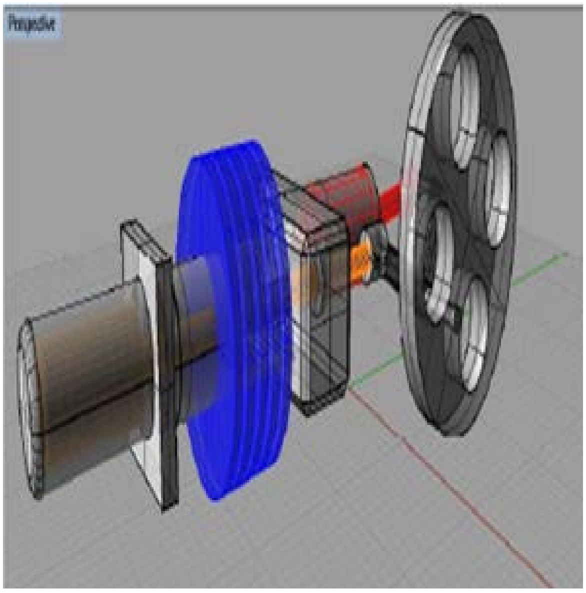


Figure Solid work Model

Actual working Model

V. CONCLUSION

After the first test was conducted, by heating using oxyacetylene flame and cooling by ambient air, massive air leakages were discovered from the power cylinder assembly. This was because piston rings had not been fitted on the piston during assembly. It is however noted that the piston rings omission was intentional to make the engine smooth running with as little friction as possible in the power cylinder. Before the second test, the piston rings were fitted on the piston and adequate lubrication put in the power cylinder and other moving parts to reduce friction. It was noted that after fitting the piston rings the engine became too stiff and therefore need to make it as free running as possible. To achieve this, the assembled engine was run on a lathe by clamping the flywheel to the lathe jaw and running at varying speeds. In the second test, it was discovered that there was reduced air leak in the power cylinder. Further, due to increased pressure in the power cylinder, air leaks were discovered from the gaskets. Before the third test, the engine was disassembled and new gaskets used between the flanges and fresh sealant (silicone) used to curb the new found leaks. On the overall, the project was successful on several accounts. First, a successful research led to a design that was simulated on Autodesk Inventor, and showed kinematic synchronization. In addition, the prototype was fabricated and pointed the project exploration in the right direction. The setbacks encountered were used to give recommendations and pointed out some ways of project improvement. A theoretical energy assessment showed that with an open flame of sufficient temperature, (about 600 ^{0}C) the designed Stirling engine would generate 45watts of power.

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