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REVIEW OF WORKING OF STIRLING ENGINES

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Abstract: For past years the primary goal of clean energy industry has been to analyze ways to harness novel ways of energy conversion. Stirling enignes are are one of such devices. These can be constructed with minimum costs and operated using cheap sources of heat. However a major backlog of these devices is low power ouput as well as low system efficiency. In this work working of this engine has been analzyed with potential future recommendations for use to harvest solar energy.

Keywords: stirling engines, clean energy industry, energy conversion

INTRODUCTION

A thermal engine is a device which converts heat energy into mechanical energy. The operation of a heat engine can be described by a simple thermodynamic cycle as follows:

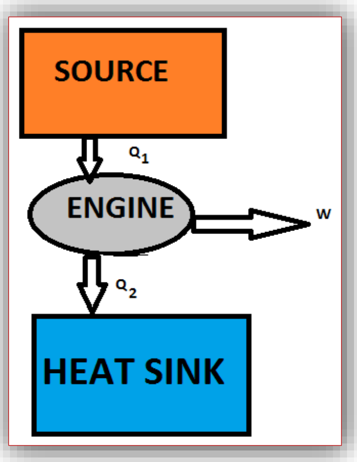


Figure 1: Heat engine [1]

Efficiency of cycle may be expressed as:

$$\frac{W}{Q_h} = \frac{Q_h - Q_c}{Q_h} \qquad [1]$$

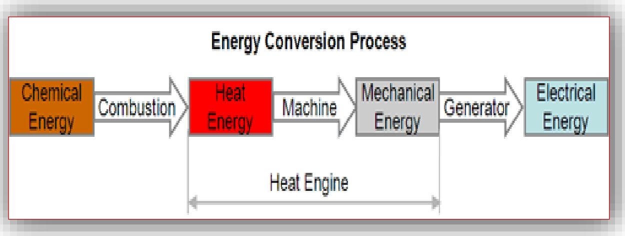


Figure 2: Energy conversion in a Heat Engine [1]

Heat engines can be further classified as external combustion engine or internal combustion engine.

An engine where fuel is burnt outside the engine is an external combustion engine, whereas in the internal combustion engine, the fuel is burnt inside the engine. An engine operating on a Carnot or Stirling cycle is an example of an external combustion engine while one operating on an Otto or Diesel cycle is an internal combustion engine. Comparison of these cycles is presented below.

Table 1: Comparison of various engines [1]

Cycle	Compression	Expansion	Heat addition	Heat Removal
Carnot	Adiabatic	Adiabatic	Isothermal	Isothermal
Stirling	Isothermal	Isothermal	Isometric	Isometric
Otto	Adiabatic	Adiabatic	Isometric	Isometric

BACKGROUND

During the industrial revolution of 18th century, steam engine became a primary source of power. But this device has its own drawbacks. Its maximum efficiency is at the most 2% and there were many accidents involving explosions. This prompted engineers to look for alternative sources of power like Stirling engines.

A Stirling engine is a hot air engine operating on the principle that air expands on being heated and contracts on being cooled. These devices have zero exhaust and are external combustion engines, hence wide variety of fuels can be used to run a Stirling engine which include alcohol, bio -products or waste gases etc. These engines are suitable for operations which have following needs [2].

A) Constant power output.
B) Noise less operation.
C) Long startup period.
D) Low speeds.

Development of Stirling engine is widely attributed to the Scottish scientist Sir Robert Stirling. The first version of this engine developed in 1815 was heated by fire and air cooled. Figures of some of these early versions are presented in coming sections.

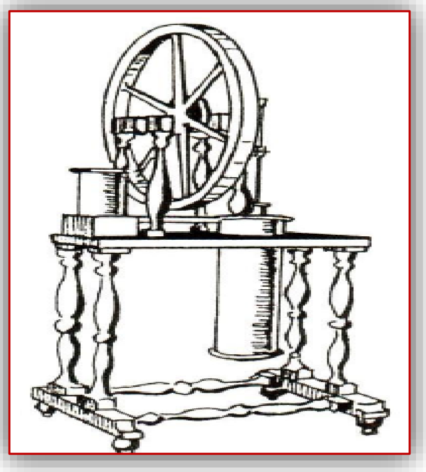


Figure 3: Earliest version of a Stirling engine developed by Stirling brothers [3]

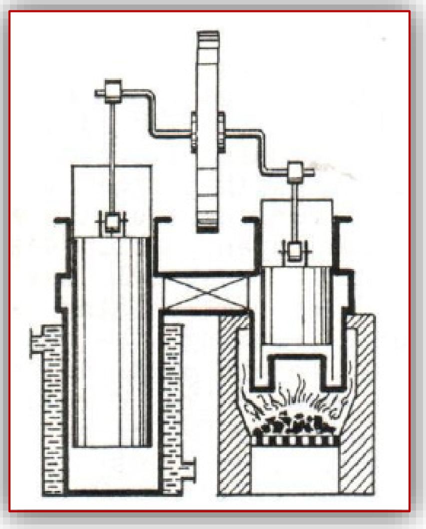


Figure 4: Alpha type Stirling engine developed in 1875[4]

Later Erickson in the year 1864 invented the solar powered engine to heat the displacer tube at hot side. The heat was obtained by use of solar reflectors. First alpha type engine was built in the year 1875 by Rider. Reader and Hooper proposed the first solar powered heat engine for irrigation purposes in the year 1908. Following this Jordan and Ibele designed a 100W solar powered engine for pumping of water. In year 1983 a low temperature difference Stirling engine was patented by the White having an efficiency of about 30%.Colin later presented a design with a low temperature difference of 15°C & Senft published specifications of an engine with very low temperature difference of 5°C between hot and cold ends[5].

Some of following events can be considered as important milestones in the design and development of a Stirling engine for use as a pump:

- 1688: Thomas Savery develops a drainage pump which was a liquid piston machine.
- 1909: Development of Humphrey pump.
- 1931: Malone designed and developed an engine with regenerative cycle similar to a Stirling engine.
- 1965: Philips Company patented a Stirling engine.
- 1977: The metal box company develops Stirling engine for irrigation purposes in Harwell lab.
- 1985: McDonnell designed an engine with parabolic reflectors to focus solar energy thus achieving a high temperature of 1400°C.

STIRLING ENGINES

In a Stirling engine the fluid is contained in a confined space, hence there are no problems of contamination. In order to reduce the heat losses, the mass flow rate must be low which can be maintained by low viscosity fluid or high working pressures. These engines are 30 to 40% efficient in a temperature range of 923–1073 K [6].

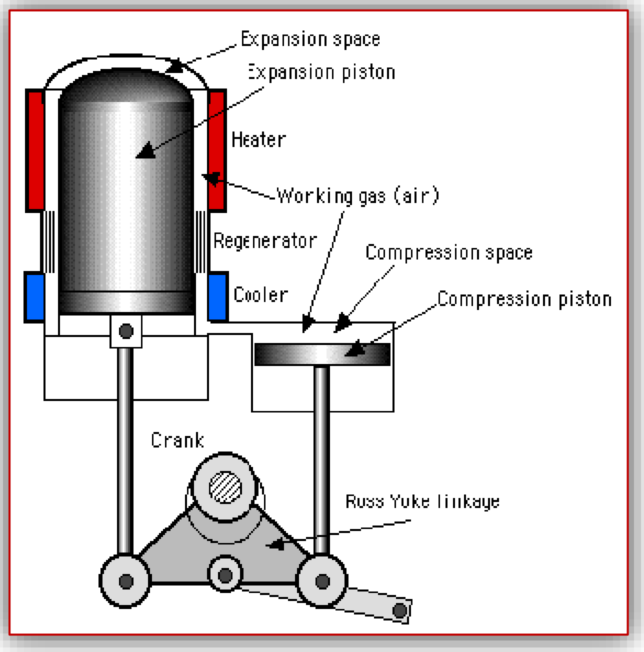


Figure 4: Stirling engine [7]

A Stirling engine consists of following components:

1. Heat source - as fuel does not come in direct contact with the working fluid, Stirling engines can work on fluids which may damage parts of a conventional engine.

2. Regenerator - the function of regenerator is to use the waste heat from being lost to environment by storing it temporarily, thus helping to achieve high efficiencies close to an ideal Carnot cycle. A simple configuration consists of fine mesh of metallic wires.

In an ideal Stirling cycle, the connecting space between hot and cold ends acts as regenerator.

3. Heat sink - typically the ambient environment acts as an ideal heat sink, otherwise the cold side can be maintained by iced water or cold fluids like liquid nitrogen.

4. Displacer piston - it causes the displacement of working gas between hot and cold regions so that expansion and contraction occurs alternatively for operation of engine.

5. Power piston - transmit's the pressure to crankshaft.

In a Stirling engine, hot air expands when heated and contracts when cooled. This principle of operation was most properly understood by Irish scientist Robert Boyle from his results on experiments on air trapped in a J shaped glass tube.

Boyle stated that pressure of a gas is inversely proportional to its volume and product of pressure and volume occupied is a constant depending on temperature of gas.

$$\text{Hence } PV=NRT \qquad [2]$$

Various assumptions are made in this cycle are: [8]

1) Working fluid is an ideal gas.
2) Conduction and flow resistance is negligible.
3) Frictional losses are neglected.
4) Iso-thermal expansion and contraction.

This cycle can be described by following stages: [9]

1) Phase C-D: -the working fluid undergoes an iso-thermal expansion absorbing the heat from source. The power piston moves out, hence increasing the volume and reducing the pressure. The work done in expansion of gas is given by:

$$We= RTlog(\frac{V_D}{V_C})= \int PdV \qquad [3]$$

$$= NRT_c log(\frac{V_D}{V_C}) \qquad [4]$$

2) Phase D-A: Power piston now reaches the outermost position and stays there so that volume is constant. The working fluid is passed through the regenerator where it gives up heat for use in next cycle. Hence its temperature and pressure falls. No work is done during this phase.

3) Phase A-B: The power piston stats moving inwards, reducing its volume and increasing its pressure the working fluid gives up heat to cold sink. The work done in compressing the gas is given by:

$$Wc= RTlog(\frac{V_B}{V_A})= \int PdV \qquad [5]$$

$$= NRT_H log(\frac{V_B}{V_A}) \qquad [6]$$

4) Phase 2-3: The power piston is at its most inwards point and stays there to keep volume constant. Working fluid passes again through the regenerator, recovering the heat lost in 2nd phase, hence its pressure and temperature goes up.

$$W_{net} = We - Wc \qquad [7]$$

$$= NR[T_h - T_c]log(\frac{V_{max}}{V_{min}}) \qquad [8]$$

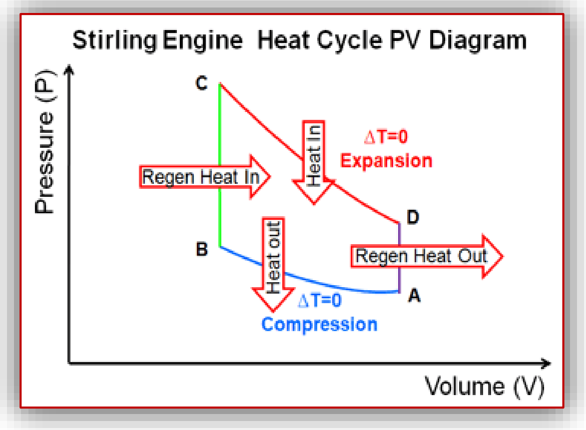
But

$$V_B=V_C, V_A = V_D \qquad [9]$$

Hence efficiency of system may be expressed as –

$$\frac{W}{Q_h} = \frac{NR\,[T_h - T_c]log\left[\frac{V_{max}}{V_{min}}\right]}{NR\,[T_h]log\left[\frac{V_{max}}{V_{min}}\right]} \qquad [10]$$

$$\frac{W}{Q_h} = \frac{[T_h - T_c]}{[T_h]} \qquad [11]$$



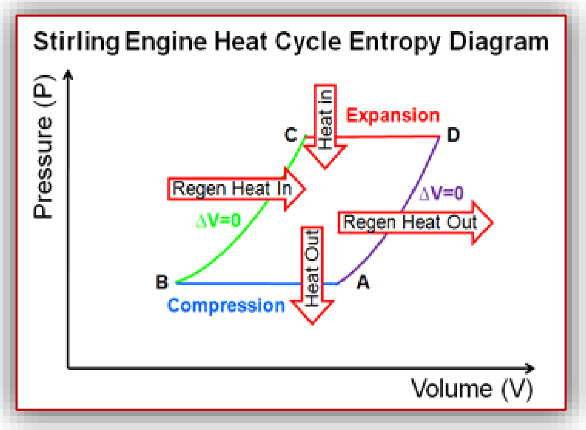


Figure 5: P-V & T-S plot of a Stirling cycle [9]

In Stirling cycle, two Isochoric processes replace the two Iso-entropic processes s in an ideal Carnot cycle. Hence more work is available than a Carnot cycle as net area under P-V curve is more. Thus there is no need for high pressures or swept volumes. This can be seen in the figures presented below.

CONCLUSION

Most common application of the Stirling engines is as a liquid piston system for use in irrigation pumping. Other important applications include use as drainage pumping, fail safe cooling of nuclear reactors, cooling of combustion engine with waste heat, circulation of water in remote areas without use of electricity. These devices are simple to construct and can be used easily for demonstrations and teaching purposes.

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