

LIQUID PISTON ENGINES

Aman Gupta
Shubham Sharma
Sunny Narayan

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Scrivener Publishing
100 Cummings Center, Suite 541J
Beverly, MA 01915-6106

Publishers at Scrivener
Martin Scrivener (martin@scrivenerpublishing.com)
Phillip Carmical (pcarmical@scrivenerpublishing.com)

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Contents

Abstract

Engines and pumps are common engineering devices which have become essential to the smooth running of modern society. Many of these are very sophisticated and require infrastructure and high levels of technological competence to ensure their correct operation. For example, some are computer controlled, others require stable three-phase electrical supplies, or clean hydrocarbon fuels. The first part of the project focuses on the identification, design, construction and testing of a simple, yet elegant, device which has the ability to pump water but which can be manufactured easily without any special tooling or exotic materials and which can be powered from either combustion of organic matter or directly from solar heating.

The device, which has many of the elements of a Stirling engine, is a liquid piston engine in which the fluctuating pressure is harnessed to pump a liquid (water). A simple embodiment of this engine/pump has been designed and constructed. It has been tested and recommendations on how it might be improved are made. The underlying theory of the device is also presented and discussed.

The second portion deals with noise,vibration and harshness performances of internal combustion engines. Features of various sources of noise and vibrations have been discussed and major focus has been on combustion based noise and piston secondary motion.Various equations of piston motion were solved and effects of various parameters on it were analyzed.

List of Symbols

Symbol	Definition	Units
V	Volume	cm^3
P	Pressure	Bar
T	Temperature	Kelvin
R	Gas Constant	J/K-mol
v	Voltage	Volt
I	Current	Ampere
Q, V′	Volume flow Rate	cm^3/s
Q_e	Heat Absorbed	Joules
A	Tube Area	cm^2
q	Charge	coulomb
C_p	Specific Heat	J/Kg-K
η	Kinematic Fluid Viscosity	m^2/S
ω	Frequency	Hz
R_t	Radius Of Tube	cm
X	Fluid Displacement	cm
ρ	Fluid Density	kg/m^3
U	Heat Transfer coefficient	W/m^2-k
L,l	Tube length	cm
g	Acceleration due to gravity	m/s^2

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Introduction

1.1 Background

The Stirling engine system was studied years ago. Such engines have merits the basis of sealings, materials, heat transfer rate, size, and weight issues. During past years the major focus has been on various designs of Stirling engine systems.

This engine is based on a heated reciprocating system. The gas receives heat and expands at constant temperature. Rate of transfer is higher, which is a major drawback of these engines. In contrary the internal combustion (IC) engine is operated by combustion of air-fuel mixture which results in higher heat and pressure rise which is converted to useful work. The temperature varies with the combustion and piston motion. As the heat is supplied externally the following varieties of sources can be used:

- Heat from gaseous, liquid, or solid fuel
- Solar energy
- Recycled Waste heat

Cooling in a Stirling engine cycle can be done in the following ways:

- Convection cooling
- Use of cooling fluids like water, ethylene glycol, or a mixture

Reversible nature of Stirling engine differentiates it from IC engines. Combustion outside results in lower emissions as well as less noise and vibration.

Solar energy may also be harnessed using parabolic dish.

As a smaller number of fuel types or heat sources are available, a Stirling system may be designed as such. This system may use solar heating as the primary heat source, as well as a natural gas burner as an auxiliary unit during nights and cloudy periods.

1.2 Types of Stirling Engines

Using basic concepts of heat engineering many designs of Stirling engines have been proposed over past years. These engines may be classified on the basis of mechanical design features as:

- Kinematic designs: These engines operate on basis of crank-shaft and linkage mechanisms in which the motion of the piston is limited by configuration of linkages.
- Free-piston designs: In these engines the oscillatory motion of the piston in a magnetic field generate electric power. Pressure gradient cause tuned spring-mass-damper motion of displacer. Such machines are simple to operate but more complex on basis of dynamics and thermodynamics. For cooling purposes, the piston may be driven by a motor.

Stirling engines may also have alpha, beta, or gamma configurations which are discussed as follows:

Alpha engines which are seen in Figure 1.1 have two separate pistons that are linked and oscillate showing some phase lag. The working gas moves to and fro passing through a cooler, regenerator, and a heater between the cylinders. These engines are kinematic engines which need proper sealings.

Beta engines that are seen in Figure 1.2 have a displacer-piston arrangement that are in phase with one another. The displacer pushes the gas to and fro between the hot (expansion area) and cold ends (compression

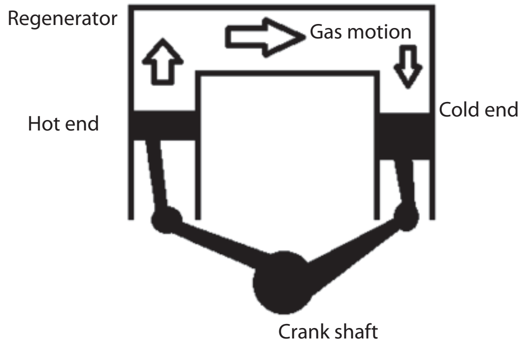

Figure 1.1 Alpha engines.

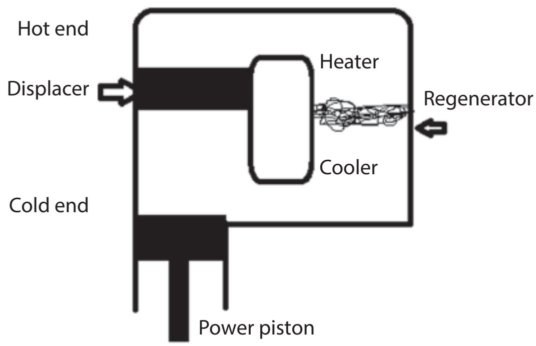

Figure 1.2 Beta engines.

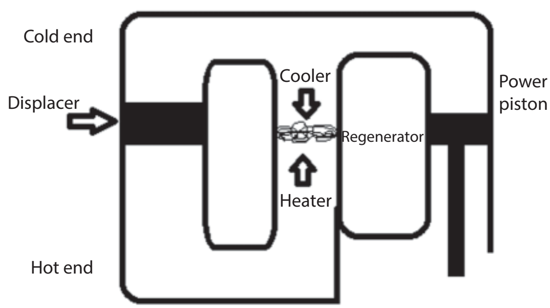

Figure 1.3 Gamma engine.

area). As the working gas moves, it passes through a cooler, regenerator, and heater. Beta engines can be either kinematic or free-piston engines.

Gamma engines which are shown in Figure 1.3 have a system wherein the displacer and power pistons operate in separate cylinders. The displacer moves the working gas to and fro between the hot and cold ends. The cold area has cold side of the displacer and power piston. As the gas moves, it passes through a cooler, a regenerator, and a heater. These engines can be either kinematic or free-piston type.

1.3 Stirling Engine Designs

The power piston in the engine is connected to an output shaft by linkages. Kinematic design of the engine has following merits:

- Coordination of various parts for proper motion during start-up, normal operation, and fluctuations of loads.

Some disadvantages of such a design include:

- Need of lubrication due to rotating parts.
- Need of more maintenance.
- Proper sealing needed.

Some of the novel designs of kinematic engines are discussed next.

Wobble-plate Mechanisms

The wobble-plate that is seen Figure 1.4 has a wobble plate which is in a sliding contact with the crankshaft pivoted by connections to pistons as well as connecting rods. This ensures straight travel inside the cylinder with out rotation. The thrust is transferred to the crank at an offset angle

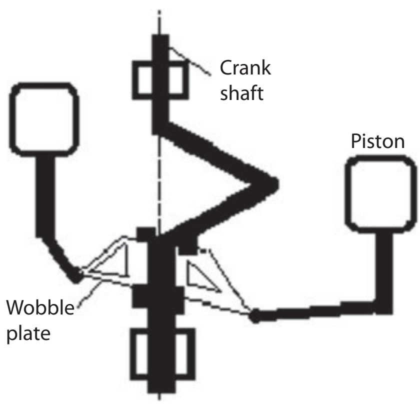

Figure 1.4 Gamma engine.

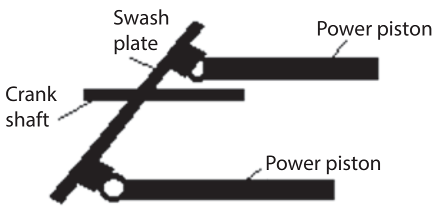

Figure 1.5 Swash plate engines.

to wobble plate which acts as a double-acting engine using the power stroke of one cylinder to compress the cold gas for the adjacent cylinder. The power piston for one cylinder is the displacer piston for another cylinder.

The Z-crank shape that the same to the wobble plate design has pistons connected directly to the crankshaft. Pivot points are made in order to ensure axial motion of the piston in the cylinder. Such design is more compact as compared to a single-piston Stirling engine. However these engines have certain demerits:

- Cyclic load and wear of pivots is quick as they are under compression and bendings.
- Piston-lubrication is a major issue. Oil flow may cause fouling and lesser external heat transfer so reducing the efficiency.

Swash Plate Drive mechanisms – This drive has may same features as wobble plate. Bearings are used to connect the swash plate to the crankshaft and rotates with the crankshaft, but the wobble plate which remains fixed is attached to the shaft. This design has many merits:

- Quiet operation, better sealings with lesser lubrication problems.
- Design of swash plate may be changed for better stiffness and power transfer.
- The balancing of swash plate can be done built by adding additional sets of pistons. This in turn increases the power output and reduces the power-to-weight ratio.

Rhombic Drive – In this mechanism, yokes connect the power piston and the displacer piston. These are linked to twin crankshafts by means of connecting rods, as seen in Figure 1.6. In this drive mechanism power

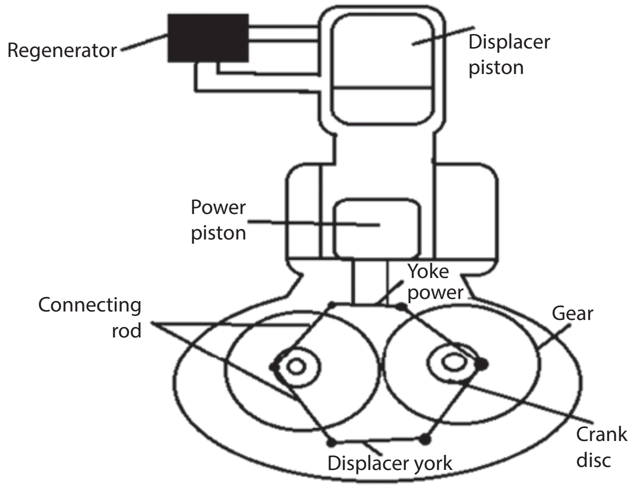

Figure 1.6 Rhombic drive engine.

piston and the displacer piston move with constant lag. The rhombic drive has many benefits:

- The engine has less vibrations due to complete balance of various lateral forces.
- These engines operate at higher power outputs due to higher pressures.
- Many units can move at same time in order to provide power to a multi-cylinder engine.

1.4 Free-Piston Stirling Engines

These engines have two oscillating pistons that are not connected as seen in Figure 1.7. The displacer piston has a smaller mass compared to the power piston. The heavier piston moves undamped. Motion of the displacer is simulated by springs or by the compressible working gas. The springs placed between the displacer and the power piston provide harmonic oscillations of the displacer. These oscillations are maintained by temperature difference, and so the system operates at the natural frequency.

The power in a free-piston system is generated by a linear alternator. Recently some of the designs have been using a hydraulic drive to run the crankshaft. Use of these hydraulics is good in engines having more torque which reduces the lateral forces in such systems.

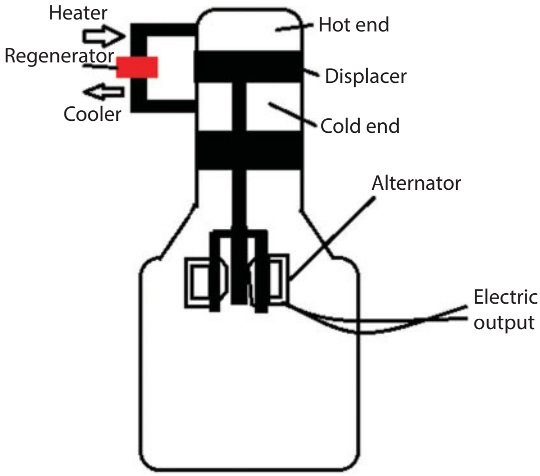

Figure 1.7 Free piston engine.

Free-piston systems have major advantages:

- Less lateral forces and lubrication needs due to absence of rotating parts.
- Less maintenance.
- Properly sealed units prevent loss of the working gas.

These systems have following disadvantages:

- Need of complex calculations to ensure proper working.
- Lower response time as compared to kinematic and IC engines.
- Piston position is an important parameter to control system as oscillations may become unbalanced.

The Alpha configuration of engine is the simplest form having two pistons and two cylinders connected by a regenerator. Both these cylinders are normal to one another connected by a flywheel. The hot piston is in contact with located high-temperature source while the cold piston is with the low-temperature reservoir. The pistons are arranged in a manner that the linear motion is converted to rotatory motion and a constant phase difference is maintained. The pistons are joined at a common point on flywheel.

As compared to the other basic designs the alpha type engine has greater volume due to higher compression ratios.

Figure 1.8 An Alpha Stirling engine.

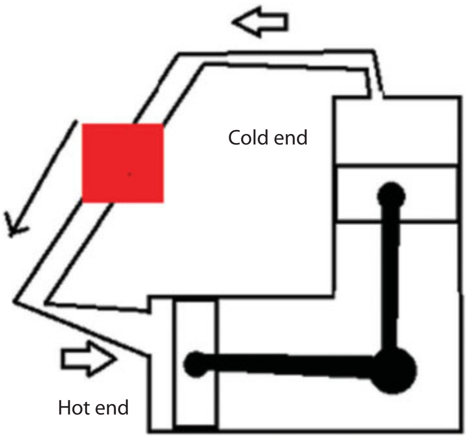

Figure 1.9 Alpha engine - Transfer phase.

WORKING OF ENGINES: working of a Stirling engine can be divided into four operations steps that are similar to I.C. engine. Heat is added and removed at constant temperatures. The working of I.C. Engines occurs on the basis of Otto and Diesel cycles, respectively. Mechanisms of these engines is complex as motion is based on movements of multiple pistons.

Working of an Alpha Stirling can be analyzed as follows:

1. Transfer of working gas from cold side to hotter side:

Flywheel moves clockwise, the hot piston moves towards right hand side towards Dead Centre and the cold piston moves up towards Top Dead Centre (TDC) as seen in Figure 1.9.

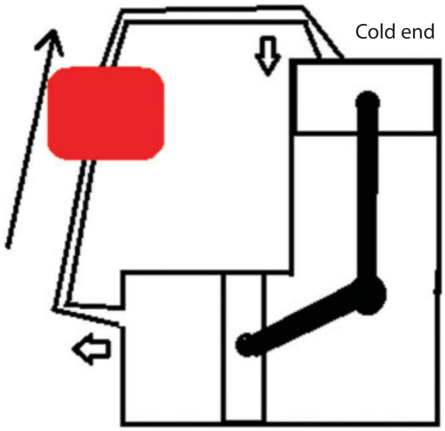

Figure 1.10 Alpha engine - Power stroke.

The regenerator connects both pistons and operates at hotter temperatures.

The pistons move in such a manner that the change in the engine volume is minimum and heat addition occurs at constant volume.

Towards end of the process, the working gas will be hotter and the major portion of remains in the hot cylinder. This is similar to suction stroke.

2. Power stroke

As flywheel roates by 90°, the majority of the working gas is now in the hotter cylinder and volume of the engine is minimum.

The fluid receives heat from a hot source. It expands moving the flywheel further. This is similar to power stroke of the engine and all energy is derived from this stroke.

As the hot piston moves towards right side due to gas pressure, the gas expands, with a portion passing through the regenerator.

As the heat added to the system at constant temperature it is converted to work, with a little rise in temperature. A perfect isothermal processes will cause a phase change.

This may be compared to the power stroke.

The working fluid expands to about three times its original volume. The flywheel turns by another quarter rotation and the hot piston starts to move to Dead Centre. The cold piston moves downwards. The regenerator gets heated up as the hot fluid passes by.

Heat rejection occurs at constant volume and can be seen as the exhaust stroke of the engine.

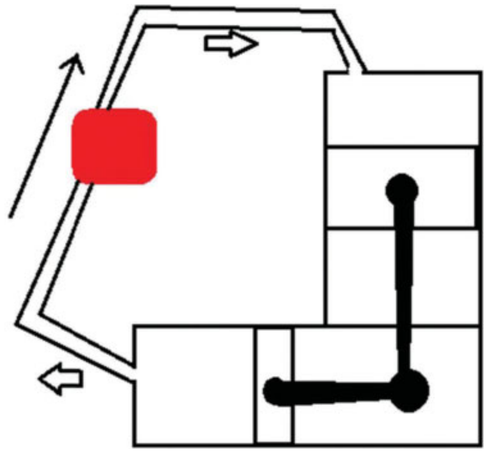

Figure 1.11 Alpha engine - Transfer stroke.

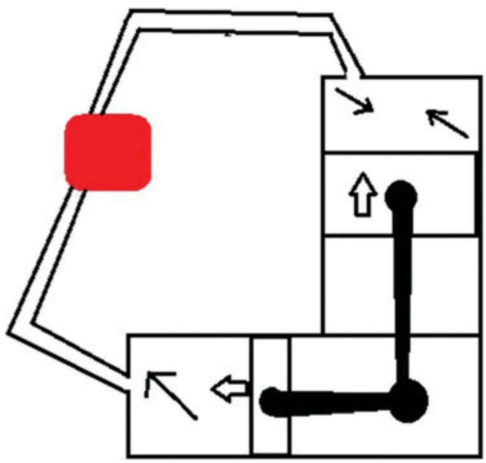

Figure 1.12 Alpha engine - compression stroke.

3. Compression stroke
The crank moves by quarter of rotation. The cold piston is at the bottom dead center location and the hot piston moves towards inner dead center.

The working gas has major portion in the cold cylinder which cools down rejecting heat to cold reservoir. As the cold piston moves to the top dead center, volume is reduced and the working gas is compressed.

During Isothermal Compression the working gas rejects heat and gets compressed. There is minimum change in the internal energy and work needed is also minimum. Towards the end of the process, almost all the gas

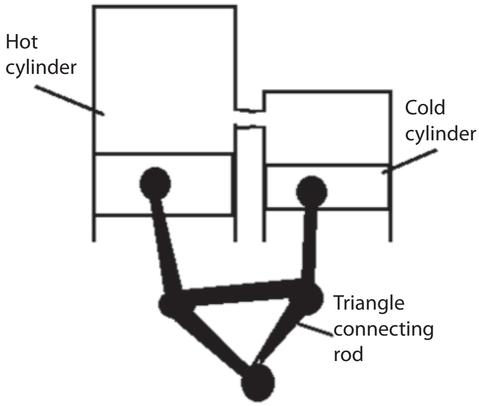

Figure 1.13 Ross engine.

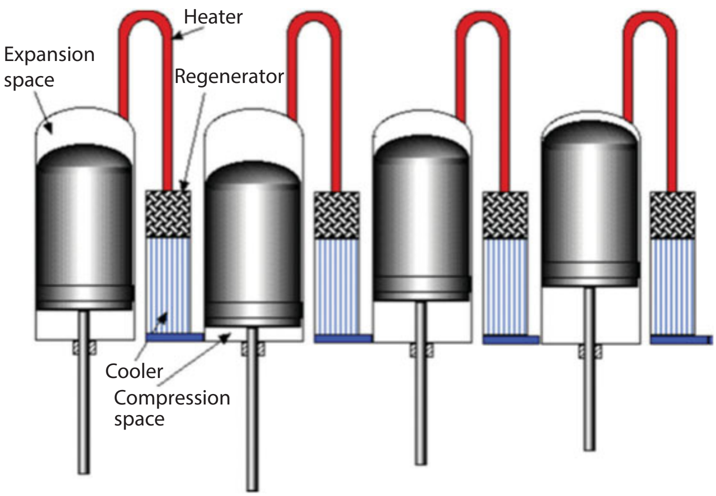

Figure 1.14 Double-acting engine.

is in the cold piston, so volume reduces to about one-third of its original and the cycle goes on.

This final stroke may be compared to action of a supercharger or turbocharger. There is no need of compression inside the power piston.

This mechanism was first proposed by Andy Ross. This linkage makes design more compact as connecting rods move in a straight line. This in turn reduces the force on the pistons and thus improves performance of the engine. Wear is less due to less friction and life is also increased.

The double-acting-engine has four cylinders. The pistons act as the expansion space of one engine and at the same time as compression space

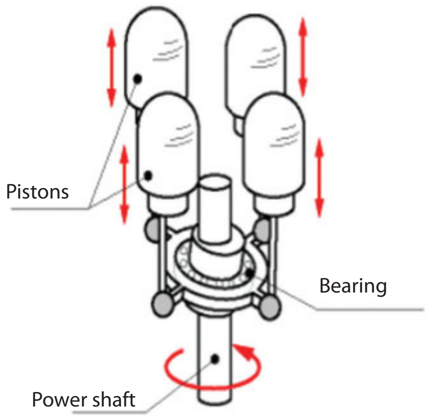

Figure 1.15 Rocking yoke.

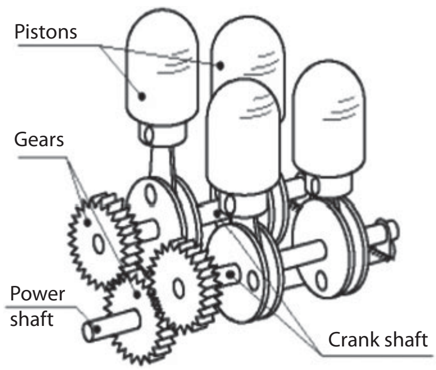

Figure 1.16 Gear mechanism.

of a neighbouring one. Thus this is the same as four Alpha engines. Sir William Siemens has done major work to develop these engines.

The cylinders are connected in a circular manner with cold and hot regions of neighbouring cylinders connected by a reservoir. Hence the outlet of the last cylinder is connected to the first one. So this system is more compact and with high specific power output. All the pistons move at a phase difference of 90°.

Maintaining the phase difference between the pistons and harnessing power is complicated.

All the above mentioned mechanisms face problems due to excessive side thrust and excessive wear and they have lower life and reliability.

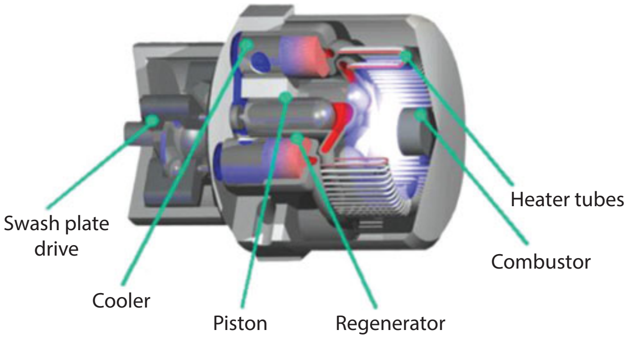

Figure 1.17 Swash plate mechanism.

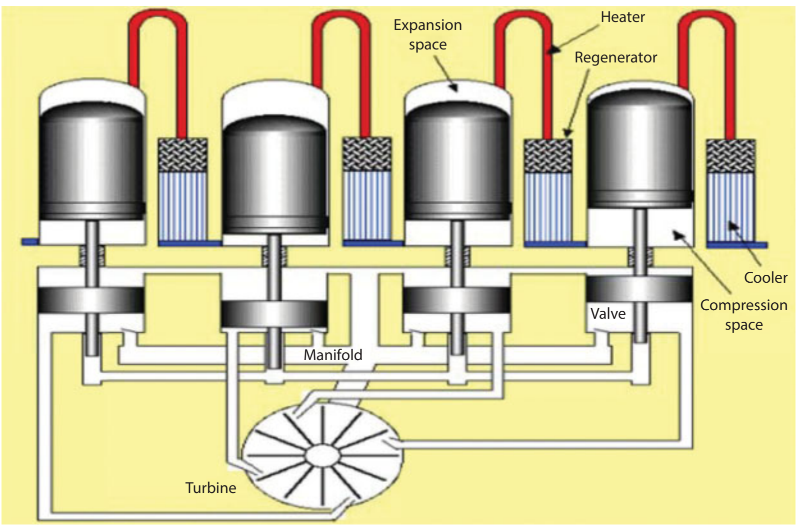

Figure 1.18 Beal engine.

William Beale later designed an engine in which a turbine was used to harness power out.

Such mechanism that is seen in Figure 1.18 uses gas compressors to run turbines. Double-acting compressors may be used for more pulses of air per cycle but at lesser specific power of the engine. Uniform loading and lesser thrust force also increases life of the engine.

WORKING: Working of the double acting Stirling engine can be understood from the design of Alpha Stirling engine. Various engines in alpha design can have the same stroke. For that the phase lag between any two adjacent pistons must be 90°.

As shown in Figure 1.18, first see the first piston moving downwards. The engine between the last and the first cylinder may be considered as a fourth engine. The first and second piston move downwards at the same time, this transfers the working gas to the hotter side with negligible change in volume.

Hence the first engine is working on Isochoric heat transfer in working fluid. The second one is vicinity of the BDC and third piston moves upwards. The second one is in power stroke, and the volume of fluid is maximum. Similarly, other engines are in transfer stroke which moves fluid from hot to cold end. A Beta configuration of engine has a displacer and piston in same cylinder with a 90° phase difference. Robert Stirling was first to invent a Beta Stirling engine that was an inverted beam engine. It was similar steam engine having a beam linkage.

These are more suited for space limited applications, but output is lower than other engines. Use of a regenerator is complex in absence of insulation between the hot and cold ends. There is loss of RPM of the engine and hence its output.

WORKING: The basic working of a Beta Stirling engine is similar to that of Alpha Stirling engine. The difference lies in the way the working gas

Figure 1.19 Beta engine.

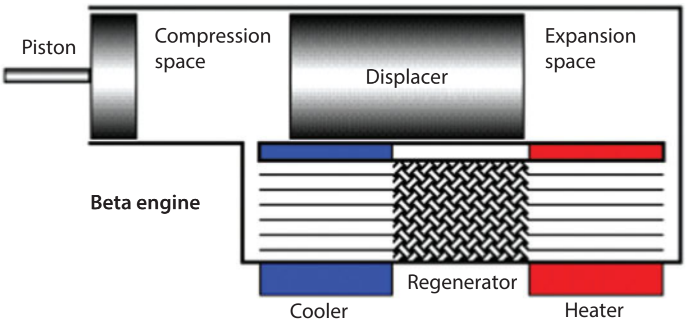

Figure 1.20 Beta engine in working.