

ME 400: Project and Thesis

Design & Fabrication of an Alpha Type Stirling Engine

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Declaration

The contents presented herein are the result of a undergraduate final year project and research performed in the 2005-06 session at Bangladesh University of Engineering and Technology (BUET), Dhaka. It has been done by the undersigned students and has not been submitted anywhere for the award of any degree or diploma.

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The project's aim was to develop a working model of Stirling cycle external combustion engine from available thermodynamic analysis. Though the technology dates back to early 1920's, yet the only successful application has been made only by the department of defense of the United States of America. Seeing the potential of this technology, an effort was made to develop an engine which can give meaningful work output. This type of engine if developed successfully allows tremendous fuel type flexibility for being an external combustion engine and also works with higher efficiency than any other regular I.C engine. Another advantage would be its low noise emission. In this project a working model was fabricated using locally available material and then to troubleshoot the physical model, a mathematical simulation model was also developed. The working model was tested and results were compared to results available from the simulation. This report gives a total description of the entire project.

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Section

1



Background Study

Global environment protection has come to be more and more important recently, and demand for engines with high efficiency and low pollution is increasing. Stirling engines have a potential solution to the above problems, because they have excellent characteristics which are high thermal efficiency, multi-fuel capability and low pollution. Engines operating on the Stirling Cycle are the most efficient practical heat engines ever built. As an engine they can run on any heat source (including solar heating), and if combustion-heated, they produce very low levels of harmful emissions.

Basic Idea:

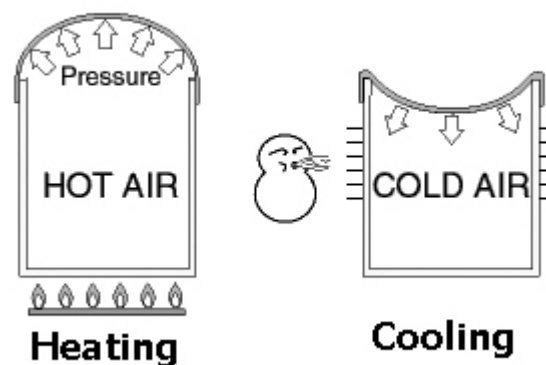


Fig 3.1: Expansion and contraction of gas due to heating and cooling

Any gas expands under heating and it contracts when cooled (Figure 1.1). If we consider a closed quantity of gas in a flexible chamber, the chamber itself would also expand and contract with the gas. When the gas is heated and cooled simultaneously, the expansion and contraction of the gas can be converted to reciprocating or rotary motion depending on the mechanism used. This is the general idea behind any Stirling cycle engine.

Stirling Cycle:

Stirling engines run on a cycle consisting of two constant volume processes and two isothermals. It is known as the Stirling Cycle. In practice, the working gas is heated and cooled in two different regions rather than simultaneously heating and cooling the gas in the same region. These are termed as the hot end and the cold end. To carry out the isothermal processes, the temperatures of the two ends are kept fixed. The cycle also consists of a regenerator. In an ideal Stirling cycle engine the components of the machine interact to produce four separate thermodynamic processes. These processes are shown on pressure-volume and temperature-entropy diagrams in Figure 1.2

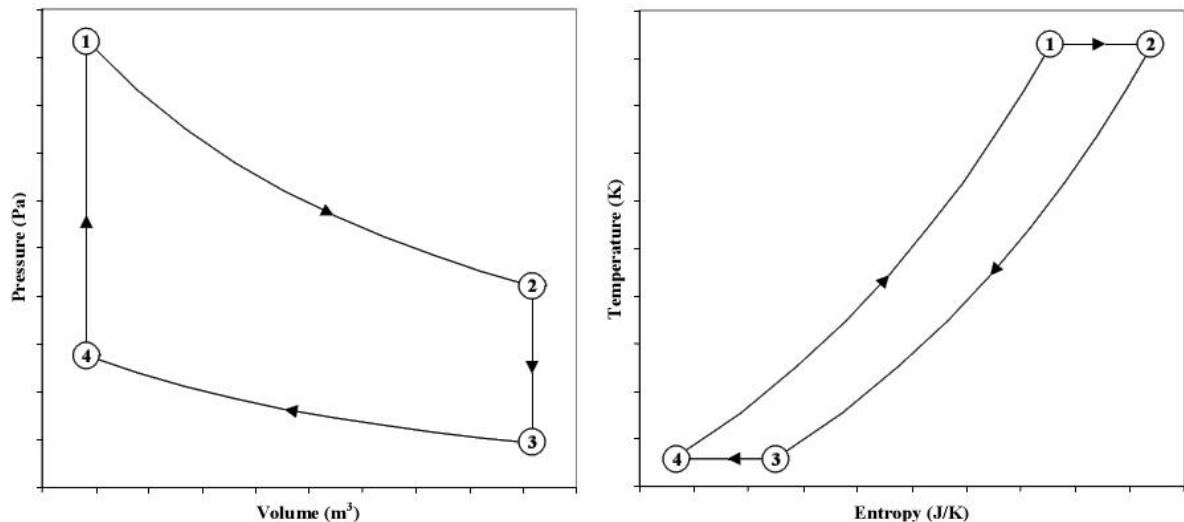


Fig 3.2: P-V and T-S Diagram of Stirling Cycle

1 – 2: Isothermal (constant temperature) Expansion –

The high pressure working gas absorbs heat from the hot space and expands isothermally, thus doing work on the hot end piston.

2 – 3: Isochoric (constant volume) Displacement –

The hot end piston transfers all the working gas isochorically through the regenerator to the cold end of the engine. Heat is absorbed from the gas as it passes through the regenerator, thus lowering the temperature of the gas to that of the cold space. As the temperature reduces, the gas pressure drops significantly.

3 – 4: Isothermal Compression –

The cold end piston does work on the gas and compresses it isothermally at cold end temperature, hence rejecting heat to the cold space. Because the gas is at low pressure, less work is required for compression than was obtained from the gas during expansion. The cycle therefore has a positive work output.

4 – 1: Isochoric Displacement –

The cold end piston transfers all the working gas isochorically through the regenerator to the hot end of the engine. Heat is delivered to the gas as it passes through the regenerator, thus raising the temperature of the gas to that of the hot space. As the temperature rises, the gas pressure increases significantly, and the system returns to its initial conditions.

Engine Components:

All the processes described before are carried out by several engine components in practice. There are five main components in a Stirling cycle engine. These are –

1. **Working Gas** – The Stirling cycle is a closed cycle and the various thermodynamic processes are carried out on a working gas that is trapped within the system. Working gas can be air, hydrogen, helium etc.

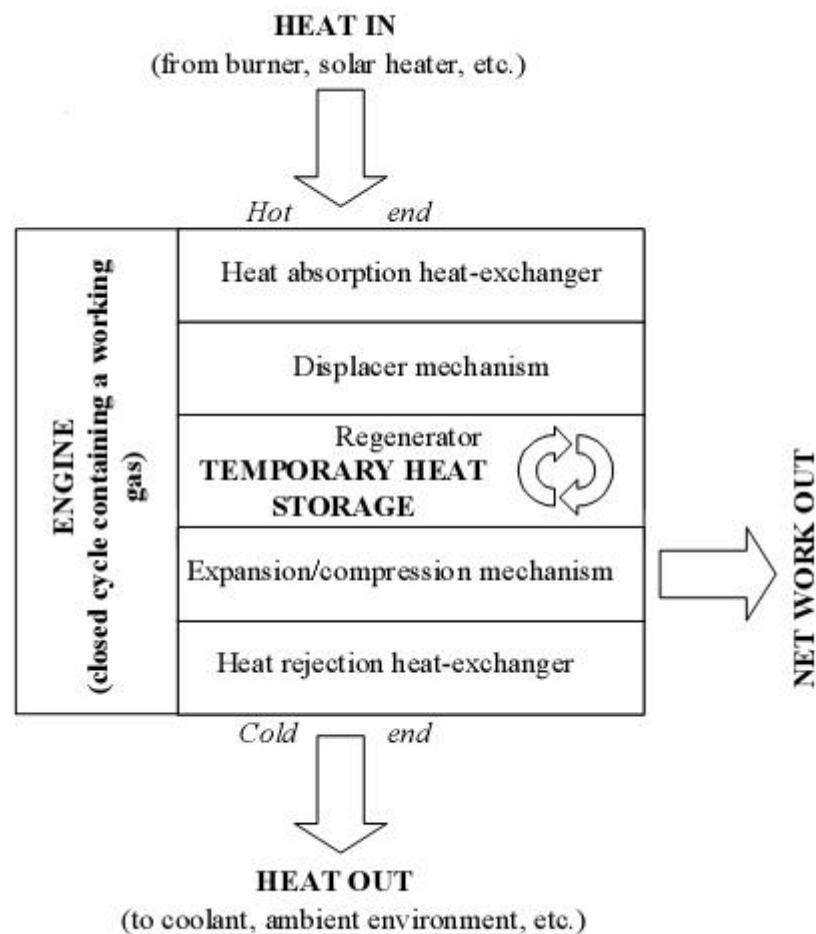


Fig 3.3: Block diagram of Stirling Cycle

2. **Heat Exchangers** – Two heat exchangers are used to transfer heat across the system boundary. A heat absorbing heat exchanger transfers heat from outside the system into the working gas and a heat rejecting heat exchanger transfers heat from the working gas to outside the system. For example, on an engine the heat

absorbing heat exchanger might transfer heat from a burner into the working gas, and the heat rejecting heat exchanger might transfer heat from the working gas to coolant in a water jacket.

3. **Displacer Mechanism** – This moves (or displaces) the working gas between the hot and cold ends of the machine (via the regenerator).

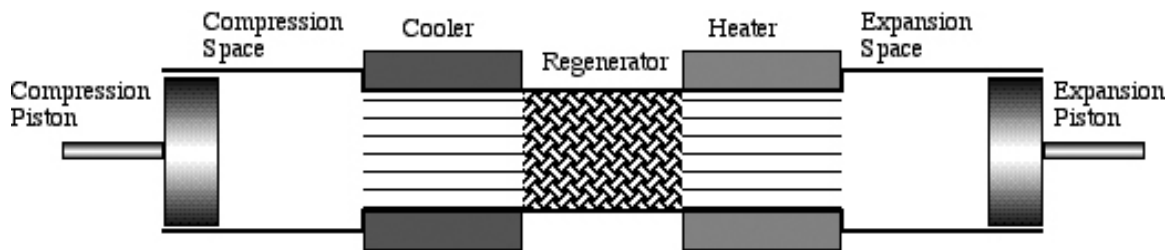


Fig 3.4: Schematic diagram of Stirling Cycle

4. **Regenerator** – It acts both as a thermal barrier between the hot and cold ends of the engine and also as a thermal storage for the cycle. Physically a regenerator usually consists of a mesh material and heat is transferred as the working gas is blown through the regenerator mesh. When the working gas is displaced from the hot end of the engine (via the regenerator) to the cold end of the machine, heat is deposited in the regenerator, and the temperature of the working gas is lowered. When the reverse displacement occurs, heat is withdrawn from the regenerator again, and the temperature of the working gas is raised.
5. **Expansion/Compression Mechanism** – this expands and/or compresses the working gas. In an engine this mechanism produces a net work output. Same components can be used as displacer and expansion/compression mechanism depending on engine type.

Pressurization:

Most high performance Stirling engines are pressurized, that is the mean pressure of the working fluid is above atmospheric pressure. This increases the mass of working fluid processed per cycle, thus, all other things being equal, the engine produces more power. Unfortunately all other things seldom are equal, and to realize the potential of pressurization larger heat exchangers (including the regenerator) are required. This inevitably increases dead space and possibly gas flow resistance, both of which tend to reduce power output. Like most aspects of Stirling engine design, optimization of this aspect is a delicate balancing act between often conflicting requirements.

Advantages & Disadvantages of Stirling engines:

Advantages	Disadvantages
Multi Fuel Capability	Higher Manufacturing Cost
Quiet Operation	
Flat Part Load Characteristics	Lower Seal Reliability
Low Pollutant Emissions	
Low Cycle Torque Variation	Larger Radiator Sizes
Low Lubricant Consumption	
Low Internal Wear Rates	Complex Control System
Variety in Design	

Generally engineers classify Stirling engines into three distinct types. These are α (alpha) type, β (beta) type and γ (gamma) type. The Alpha type engine relies on interconnecting the power pistons of multiple cylinders to move the working gas, with the cylinders held at different temperatures. The Beta and Gamma type Stirling engines use a displacer piston to move the working gas back and forth between hot and cold heat exchangers in the same cylinder. Changes to the configuration of mechanical Stirling engines continue to interest engineers and inventors. Notably, some are in pursuit of the rotary Stirling engine; the goal here is to convert power from the Stirling cycle directly into torque, a similar goal to that which led to the design of the rotary combustion engine. No practical engine has yet been built but a number of concepts, models and patents have been produced. There is also a field of "free piston" Stirling cycles engines, including those with liquid pistons and those with diaphragms as pistons.

α (alpha) type:

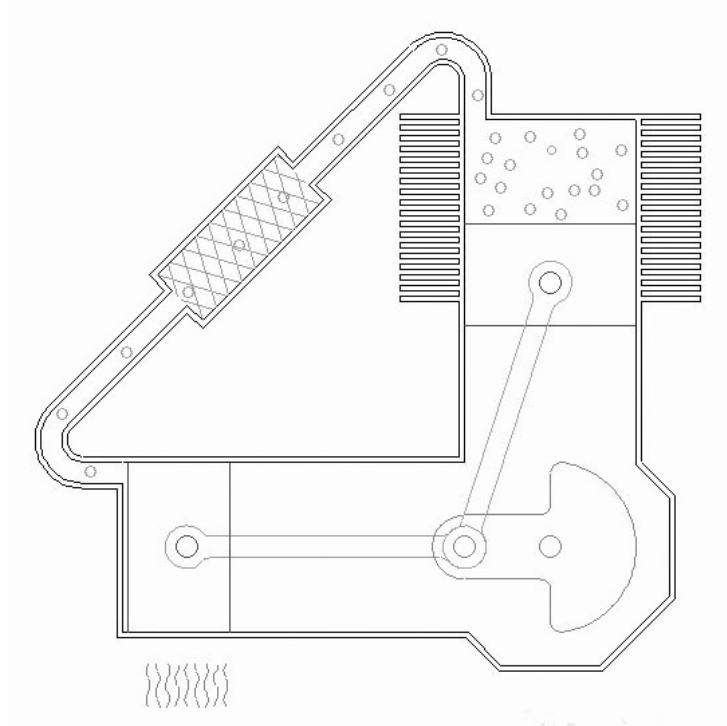


Fig. 4.1: Schematic diagram of an alpha Stirling engine

An alpha Stirling contains two separate power pistons in separate cylinders, one hot piston and one cold piston. The hot piston cylinder is situated inside the higher temperature heat exchanger and the cold piston cylinder is situated inside the low temperature heat exchanger. This type of engine has a very high power-to-volume ratio but has technical problems due to the usually high temperature of the hot piston and the durability of its seals.

(a) **Expansion** – At this point, most of the gas in the system has just been driven into the hot cylinder. The gas heats and expands driving both pistons inward.

(b) **Transfer** – At this point, the gas has expanded. Most of the gas (about 2/3rds) is still located in the hot cylinder. Flywheel momentum carries the crankshaft the next 90 degrees, transferring the bulk of the gas to the cold cylinder.

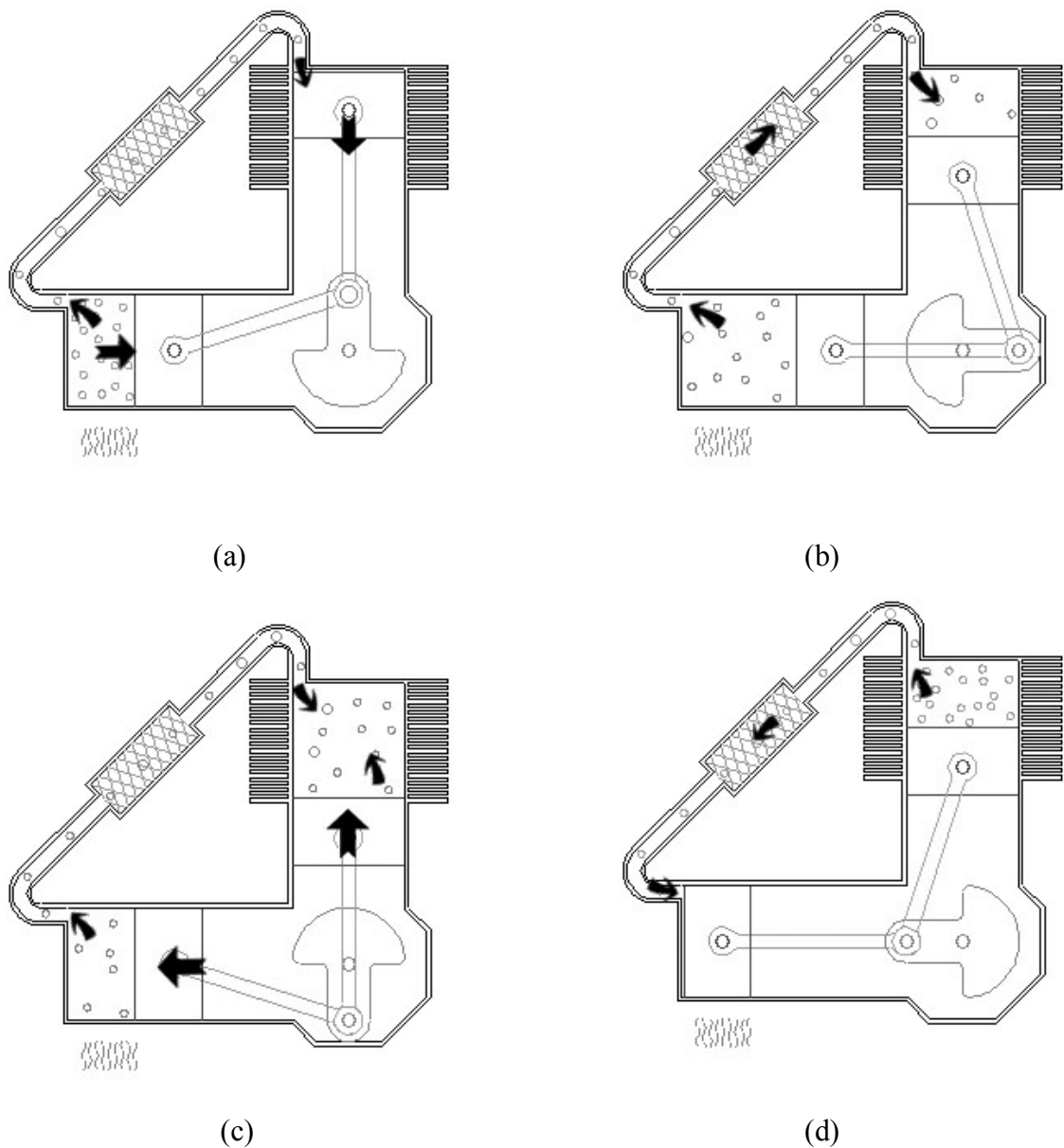


Fig 4.2: (a) Expansion (b) Transfer (c) Contraction and (d) Transfer of gas

(c) **Contraction** – Now the majority of the expanded gas has been shifted to the cool cylinder. It cools and contracts, drawing both pistons outward.

(d) **Transfer** – The now contracted gas is still located in the cold cylinder. Flywheel momentum carries the crank another 90 degrees, transferring the gas to back to the hot cylinder to complete the cycle.

β (beta) type:

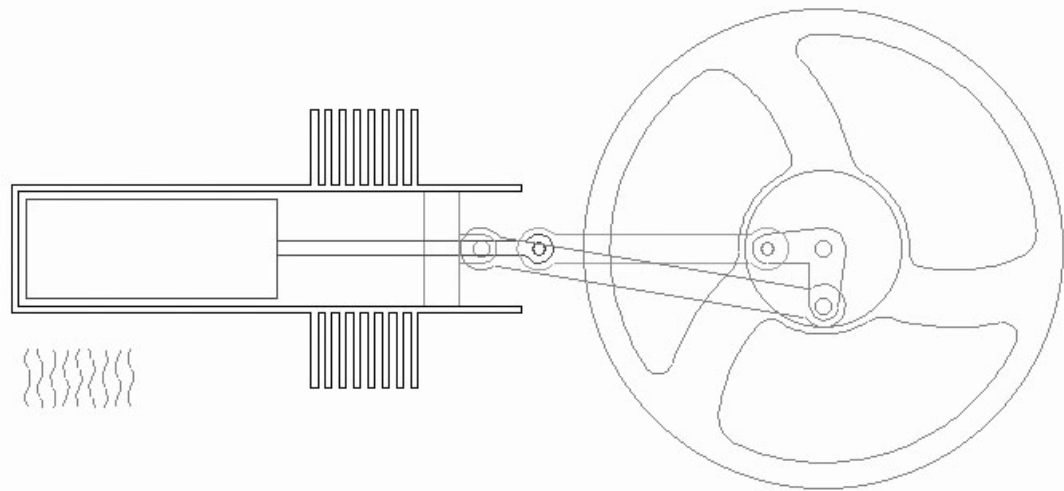


Fig 4.3: Schematic diagram of a beta Stirling engine

A beta Stirling has a single power piston arranged within the same cylinder on the same shaft as a displacer piston. The displacer piston is a loose fit and does not extract any power from the expanding gas but only serves to shuttle the working gas from the hot heat exchanger to the cold heat exchanger. When the working gas is pushed to the hot end of the cylinder it expands and pushes the power piston. When it is pushed to the cold end of the cylinder it contracts and the momentum of the machine, usually enhanced by a flywheel, pushes the power piston the other way to compress the gas. Unlike the alpha type, the beta type avoids the technical problems of hot moving seals.

(a) **Expansion** – At this point, most of the gas in the system has just been driven to the hot end of the cylinder. The gas heats and expands driving the piston outward.

(b) **Transfer** – At this point, the gas has expanded. Most of the gas is still located in the hot end of the cylinder. Flywheel momentum carries the crankshaft the next quarter turn. The bulk of the gas is transferred around the displacer to the cool end of the cylinder.

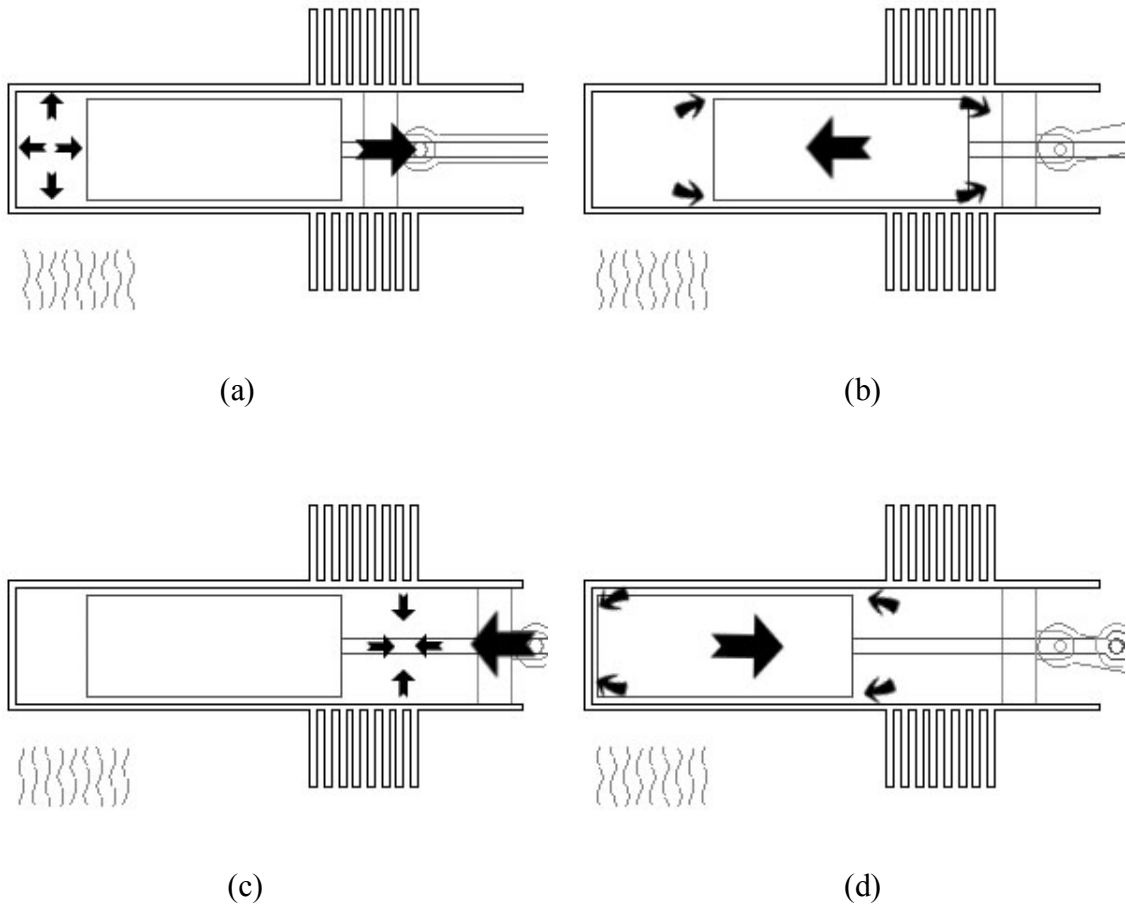


Fig 4.4: (a) Expansion (b) Transfer (c) Contraction and (d) Transfer of gas

(c) **Contraction** – Now the majority of the expanded gas has been shifted to the cool end. It contracts, drawing the piston inward.

(d) **Transfer** – The contracted gas is still located near the cool end of the cylinder. Flywheel momentum carries the crank another quarter turn, moving the displacer and transferring the bulk of the gas back to the hot end of the cylinder.

γ (gamma) type:

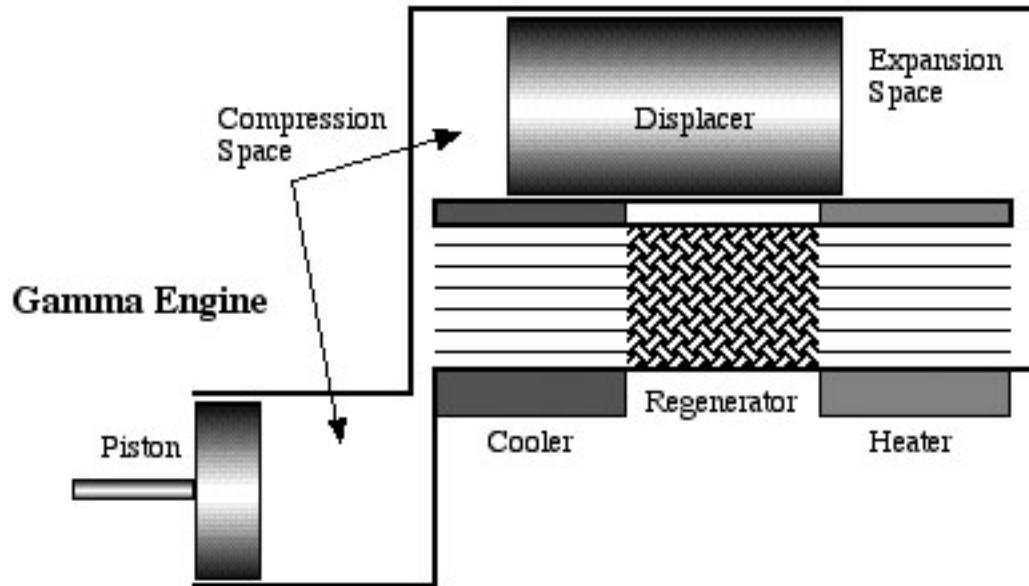


Fig. 4.5: Schematic diagram of a gamma Stirling engine

A gamma Stirling is simply a beta Stirling in which the power piston is mounted in a separate cylinder alongside the displacer piston cylinder, but is still connected to the same flywheel. The gas in the two cylinders can flow freely between them but remains a single body. This configuration produces a lower compression ratio but is mechanically simpler and often used in multi-cylinder Stirling engines.

Combined Heat and Power Applications:



Fig. 5.1: Yacht propelled by onboard WhisperGen CHP System

Combined heat and power (CHP) is an economical source of mechanical or electrical power, which uses a heat source in conjunction with a secondary heating application, usually a pre-existing energy use, such as an industrial process. Usually the primary heat source will enter the Stirling engine heater, since that will usually be at a higher temperature than the heating application, and the "waste" heat from the engine's heater will supply the secondary heating application. The power produced by the engine is often used to run an industrial or agricultural process, which in turn creates biomass waste refuse that can be used as free fuel for the engine, thus reducing waste removal costs. The overall process is very resourceful, thus making it efficient and cost-effective overall.

Solar Power Generation:

Placed at the focus of a parabolic mirror a Stirling engine can convert solar energy to electricity with efficiency better than non-concentrated photovoltaic cells, and comparable to Concentrated Photovoltaic.

Stirling Cryocoolers:



Fig. 5.2: Stirling Cryocooler

Any Stirling engine will also work in reverse as a heat pump: i.e. when a motion is applied to the shaft, a temperature difference appears between the reservoirs. One of their modern uses is in refrigeration and cryogenics.

Nuclear Power:

There is a potential for nuclear-powered Stirling engines in electric power generation plants. Replacing the steam turbines of nuclear power plants with Stirling engines might simplify the plant, yield greater efficiency, and reduce the radioactive by-products. A number of breeder reactor designs use liquid sodium as coolant. If the heat is to be employed in a steam plant, a water/sodium heat exchanger is required, which raises some concern as sodium reacts violently with water. A Stirling engine obviates the need for water anywhere in the cycle.

Automotive engines:

It is often claimed that the Stirling engine has too low a power/weight ratio and too long a starting time for automotive applications. There have been at least two automobiles exclusively powered by Stirling engines that were developed by NASA, as well as earlier projects by Ford and American Motor Companies. The main difficulties involved in using the Stirling engine in an automotive application are start-up time, acceleration response, shut-down time, and weight, not all of which have ready-made solutions. Many people believe that hybrid electric drive systems can bypass all of these setbacks.

Aircraft Engines:

Stirling engines hold theoretical promise as aircraft engines. They are quieter, less polluting, gain efficiency with altitude, are more reliable due to fewer parts and the absence of an ignition system, produce much less vibration (airframes last longer) and safer, less explosive fuels may be used.

Geothermal Energy:

Some believe that the ability of the Stirling engine to convert geothermal energy to electricity and then to hydrogen may well hold the key to replacement of fossil fuels in a future hydrogen economy. This belief was also founded on research conducted at Los Alamos Labs that began as a hot dry rocks research, but later calculated the near limitless energy potential from molten rock on one side of Stirling engine and ocean water on the other. Although currently the most feasible source of commercial electrical generation is solar, very long range predictions show advances in deep drilling and development of methods to work with molten rock could yield exponential levels of clean energy generation for thousands of years.

Low Temperature Difference Engines:



Fig. 5.3: LTD Stirling MM – 7

A low temperature difference (Low Delta T, or LTD) Stirling engine will run on any low temperature differential, for example the difference between the palm of a hand and room-temperature or room temperature and an ice cube. Usually they are designed in a gamma configuration, for simplicity, and without a regenerator. They are typically unpressurized, running at near-atmospheric pressure.

Stirling's air engine (as it is referred to in early text books) was invented by Reverend Dr. Robert Stirling and patented by him in 1816. When the name became simplified to Stirling engine is not known, but may be as recently as the mid twentieth century when the Philips company began to experiment with working fluids other than air. They still refer to it as an 'air engine'. The main subject of that original patent was a heat exchanger which Stirling called the "economizer" for its enhancement of fuel economy in a variety of applications. The patent also described in detail the employment of one form of the economizer in an air engine, in which application it is now commonly known as a regenerator. An engine built by Stirling was put to work pumping water in a quarry in 1818. 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 1845 had sufficiently increased the power output for it to successfully drive all the machinery at a Dundee iron foundry.

As well as conserving fuel, the inventors sought to create a safer alternative to the steam engines of the time whose boilers frequently exploded with dire consequences, often including loss of life. However, the need for the Stirling engine to run at a very high temperature to maximize power and efficiency exposed limitations in the materials of the day and the few engines which were built in those early years had rather short and troublesome lives. In particular, 'hot end' failures occurred more frequently than could be tolerated, albeit with far less disastrous results than a steam boiler explosion.

Though it ultimately failed as a competitor to the steam engine in the field of industrial scale prime movers, during the latter nineteenth and early twentieth centuries smaller engines of the Stirling/hot air type (the boundary between the two is often blurred as in many the regenerator is of dubious efficiency or omitted altogether) were produced in large numbers, finding applications wherever a reliable source of low to medium power

was required, most commonly perhaps for raising water. These generally operated at lower temperatures so as not to tax available materials and thus tended to be rather inefficient, their major selling point being that in contrast to a steam engine, they could be operated safely by anybody capable of managing the fire in a domestic range. As the century wore on, this role was eventually usurped by the electric motor and small internal combustion engines and by the late 1930s the Stirling engine was a largely forgotten scientific curiosity represented only by toys and a few small ventilating fans.

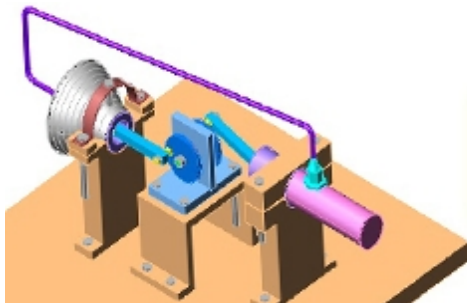
At this time Philips, the large Dutch electrical and electronic manufacturer, was seeking to expand the market for its radio sets into areas where mains electricity was unknown and the supply of short-lived batteries uncertain. Philips' management decided that what was needed was a low-powered portable generator and tasked a group of engineers at the company research lab (the Nat. Lab) in Eindhoven to investigate the practicalities. Reviewing various prime movers old and new, each was rejected for one reason or another until the Stirling engine was considered. Inherently quiet and capable of running from any heat source (common lamp oil "cheap and available everywhere" was favored), it seemed to offer real possibilities. Encouraged by their first experimental engine, which produced 16 watts of shaft power from a bore and stroke of 30x25mm, a development program was set in motion.

Remarkably, this work continued throughout World War II and by the late 1940s they had an engine – the Type 10 – which was sufficiently developed to be handed over to Philips' subsidiary Johan de Witt in Dordrecht to be 'productionised' and incorporated into a generator set as originally planned. The set progressed through three prototypes (102A, B, and C), with the production version, rated at 200 watts electrical output from a bore and stroke of 55x27mm, being designated MP1002CA (affectionately known as the 'Bungalow set'). Production of an initial batch began in 1951, but it became clear that they could not be made at a price that the market would support, besides which the advent of transistor radios with their much lower power requirements meant that the whole *raison d'être* for the set was fast disappearing. Though the MP1002CA may have been a dead end, it represents the start of the modern age of Stirling engine development.

Philips went on to develop the Stirling engine for a wide variety of applications including vehicles, but only ever achieved any commercial success with the 'reversed

Stirling engine' cryocooler. They did however take out a large number of patents and amass a wealth of information relating to Stirling engine technology, which was later licensed to other companies. It was also employed in reverse as a heat pump to produce early refrigeration.

Section 2



Design & Fabrication

The primary objective of the project was to fabricate a completely working model of an α (Alpha) type Stirling engine. Out of all the types, α (Alpha) type Stirling was chosen due to its design simplicity and ease of fabrication.

As any sort of perception about the physical dimension and mechanism of an actual working engine was unavailable, therefore the design and dimensions of the fabricated model are based on common conception about similar small scale IC engines. Yet, in case of fabricating several components the availability of suitable material and machining options played a vital role in designing.

The engine being unconventional, ready made components of locally available IC engines couldn't be used in the prototype. Thus, most of the components had to be fabricated from BUET Machine Shop. In doing so, we only had the opportunity of using machine tools such as lathe, milling and shaper machine. To achieve desirable surface finish of components such as piston and cylinder bore, relatively softer metals like Aluminum was used. Other components were manufactured from easily available and relatively inexpensive metals like mild steel. The hot end, which is more likely to withstand higher temperature, was fabricated from stainless steel tubing.

Considering the engine to be operating between temperatures of 150°C (maximum) and 25°C, the Carnot efficiency ($1 - T_{\min} / T_{\max}$) of the engine becomes 30%. Assuming heat input to be 200 watts, the indicated power of the engine turns out to be 60 watts. The complete design of the prototype is generally based on this assumption.

Hot Cylinder:



Fig. 8.1: Hot End Assembly

The hot cylinder consists of two components:

1. Dead Volume
2. Swept Volume

Dead Volume:

Description – Hollow pipe. One end sealed and the other end open.



Fig. 8.2: Hot End Dead Volume

Raw Material – 150 mm long seamless stainless steel pipe having outer and inner diameters of 39 mm and 36 mm.

Dimension – 150 mm long. Outer diameter 39 mm and inner diameter 36 mm.

Manufacturing Process – Steel pipe was cut from a longer piece and later one end was sealed with a piece of steel sheet by gas welding.

Swept Volume:

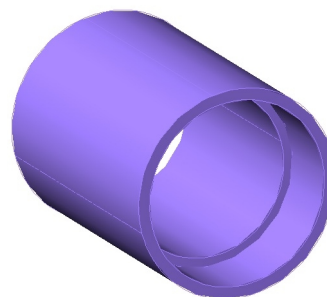


Fig. 8.3: Hot Cylinder

Description – Hollow cylinder. Both ends open.

Raw Material – Hollow Aluminum block. Length approximately 100 mm.

Dimension – 60 mm long. Outer and inner diameters are 45 and 36 mm respectively.

Manufacturing Process – This piece was fabricated by using an Engine Lathe by performing facing, centering, turning, boring, chamfering and parting operations sequentially as stated.

Cold Cylinder:



Fig. 8.4: Cold Cylinder Assembly

The cold cylinder consists of two components:

1. Water Jacket
2. Swept Volume

Water Jacket:

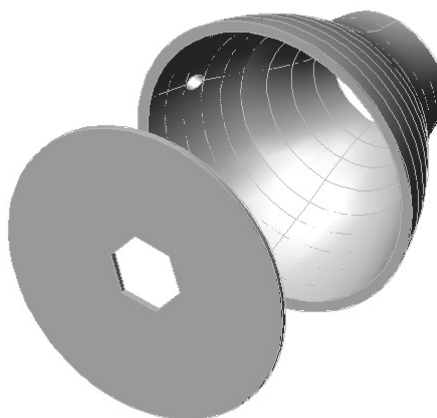


Fig. 8.5: Water Jacket

Description – Confined Heat Exchanger Device with water inlet and outlet ports.

Raw Material – One PVC reducer and two brass nipples.

Dimension – 3" to 1" reducer.

Manufacturing Process – The reducer was cut into suitable size to fit over the swept volume. Two drills were made to fit the nipples as inlet and outlet of water. The larger end of the reducer was sealed by a PVC cap with the aid of PVC glue.

Swept Volume:

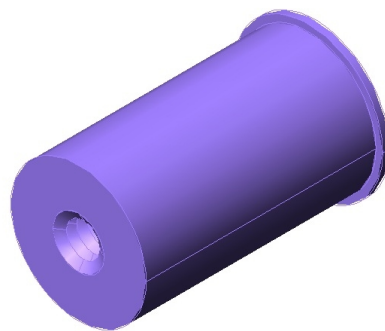


Fig. 8.6: Cold Cylinder

Description – Both end open hollow cylinder. Threaded at one end for fitting brass nipple.

Raw Material – Hollow aluminum bar of length approximately 80 mm.

Dimension – Length is 70 mm. Inner diameter is 27 mm and outer diameter is 40 mm.

Manufacturing Process – Facing, centering, turning, boring, chamfering, threading and parting operations were done sequentially in an engine lathe to fabricate the part.

Pistons:

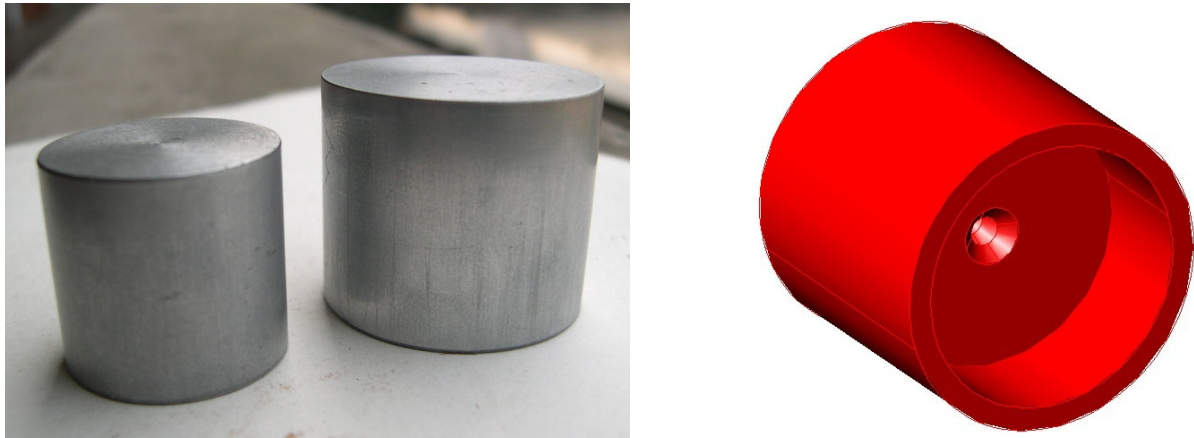


Fig. 8.7: Hot and Cold End Pistons

Description – Two pistons of identical shapes but different sizes were made. One for the hot cylinder and the other one for the cold cylinder. Each piston has a threaded part on the inside for attaching connecting rod to it.

Raw Material – Aluminum cylinder of 100 mm length and 50 mm diameter

Dimension – Hot piston has a diameter of 36 mm and that of the cold piston is 27 mm.

Manufacturing Process – The sequential lathe machine operations that were carried out to fabricate the pistons are– facing, centering, turning, drilling, boring, parting and finally hand tapping.

Connecting Rod:

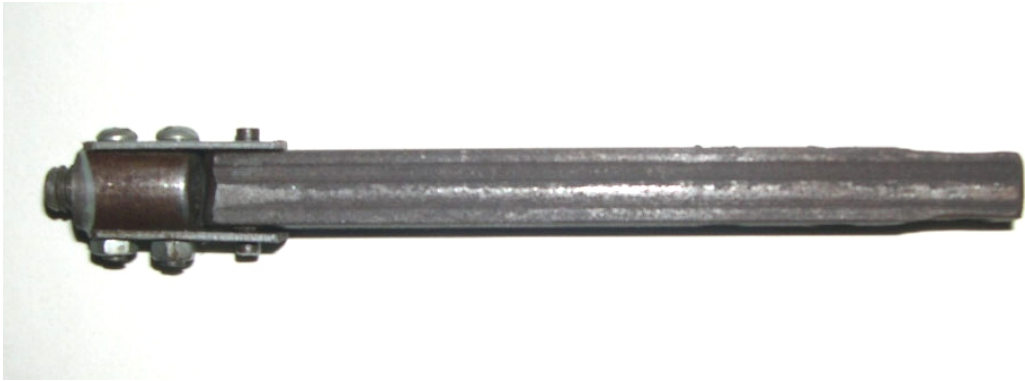


Fig. 8.8: Connecting Rod Assembly

Each of the two connecting rods has two parts –

1. Short Linkage
2. Long Linkage

Short Linkage:

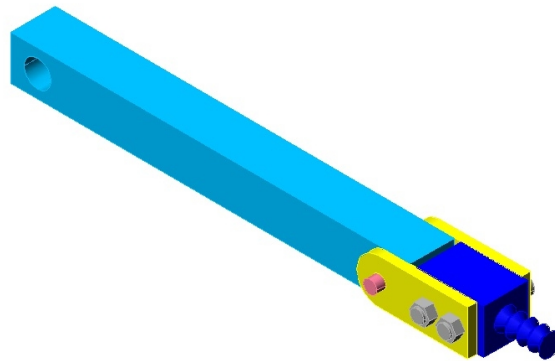


Fig. 8.9: Connecting Rod (3D Model)

Description – One end threaded metallic bar. One piece for each piston.

Raw Material – Mild Steel bar of dimension 40 mm × 10 mm × 10 mm.

Dimension – Total length is 25 mm. Threaded portion has a length of 10 mm. It has a 1/4" BSW thread.

Manufacturing Process – The piece was shaped to the dimension required using a shaper machine first. Then thread was cut at one end using a die. Two drills of 3 mm were done to make provision for fixing long linkage to it using thin metal strips and nut-bolts.

Long Linkage:

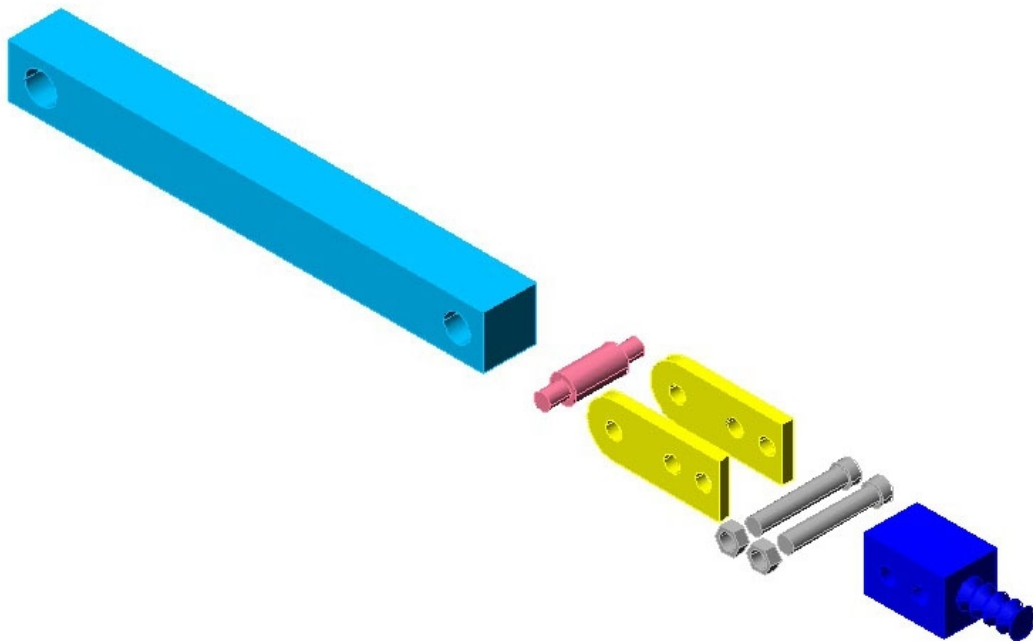


Fig. 8.10: Connecting Rod (exploded view)

Description – Metallic square bar with transverse hole at both ends.

Raw Material – Mild Steel bars of dimension 100 mm × 15 mm × 15 mm.

Dimension – 90 mm × 10 mm × 10 mm. 6 mm diameter hole at big end and 5 mm hole at small end.

Manufacturing Process – The bar elements were shaped using a shaper machine. Then the drills were done using a radial drill machine.

Crank:



Fig. 8.11: Crank and Flywheel Assembly

The crank has the following components:

1. Base
2. Bearing Housing
3. Spindle
4. Flywheel Disk
5. Offset Spindle

Base:

Description – Thick metal plate with a center channel and four corner holes. There are two holes in the groove area for attaching the bearing housing with the base with screws.

Raw Material – Mild steel plate.

Dimension – 100 mm × 60 mm × 10 mm.

Manufacturing Process – The metal plate was shaped using a shaper. Then holes were drilled using a drill machine.

Bearing Housing:

Description – Thick metal plate with a center bore and two threaded side holes.

Raw Material – Mild Steel plates.

Dimension – 10 mm × 60 mm × 70 mm. Bore diameter is 25 mm.

Manufacturing Process – The metal plate was shaped first using a shaper. The center bore was then done in lathe machine. Finally, the two side holes were drilled.

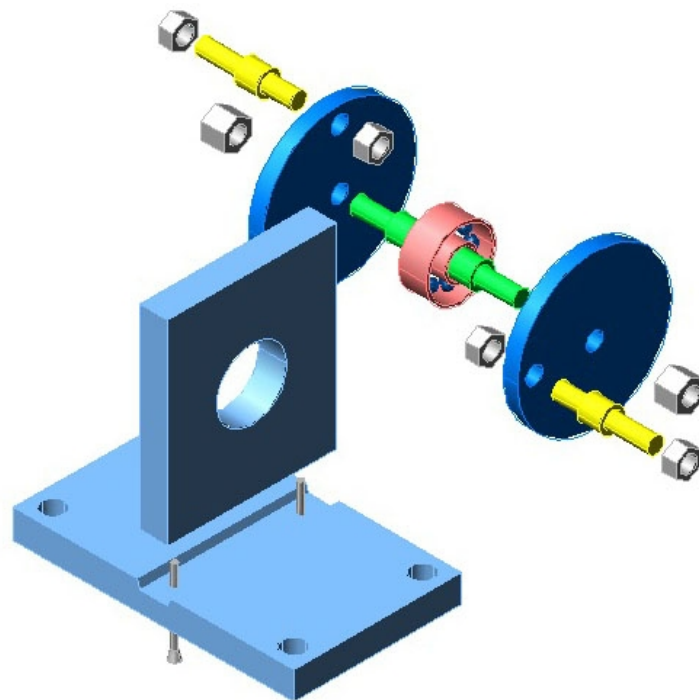


Fig. 8.12: Crank and Flywheel Assembly (exploded view)

Spindle:

Description – Cylindrical bar for attaching flywheels to the bearing.

Raw Material – Mild Steel cylindrical bar.

Dimension – 58 mm long. Diameter varying in different places as per need.

Manufacturing Process – Basically turning operations were done in a lathe.

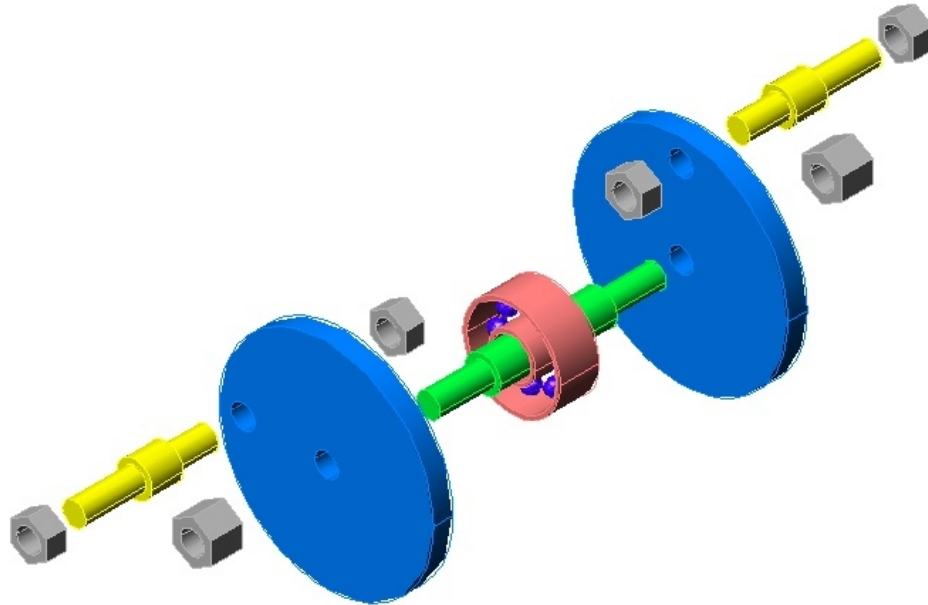


Fig. 8.13: Flywheel, Bearing and Offset Spindles (exploded view)

Flywheel Disks:

Description – Thick cylindrical metal disks for use as flywheels. Drills of 6 mm diameter is done near the periphery for attaching the offset Spindle to it.

Raw Material – Mild Steel plate.

Dimension – 70 mm in diameter, 5 mm in thickness.

Manufacturing Process – The disks were cut from the metal plate using oxy-acetylene flame. Then finishing was done in a lathe machine. 6 mm drills were done after that in drill machine.

Offset Spindles:

Description – Both ends threaded cylindrical elements for connecting flywheels to their respective connecting rods.

Raw Material – Mild Steel rods.

Dimension – 34 mm long with diameter different at places according to necessity.

Manufacturing Process – Both the spindles were fabricated and finished using a lathe machine.

Engine Casing/Holder:

Three separate holders were built –

1. Hot Cylinder Holder
2. Cold Cylinder Holder
3. Crank Base

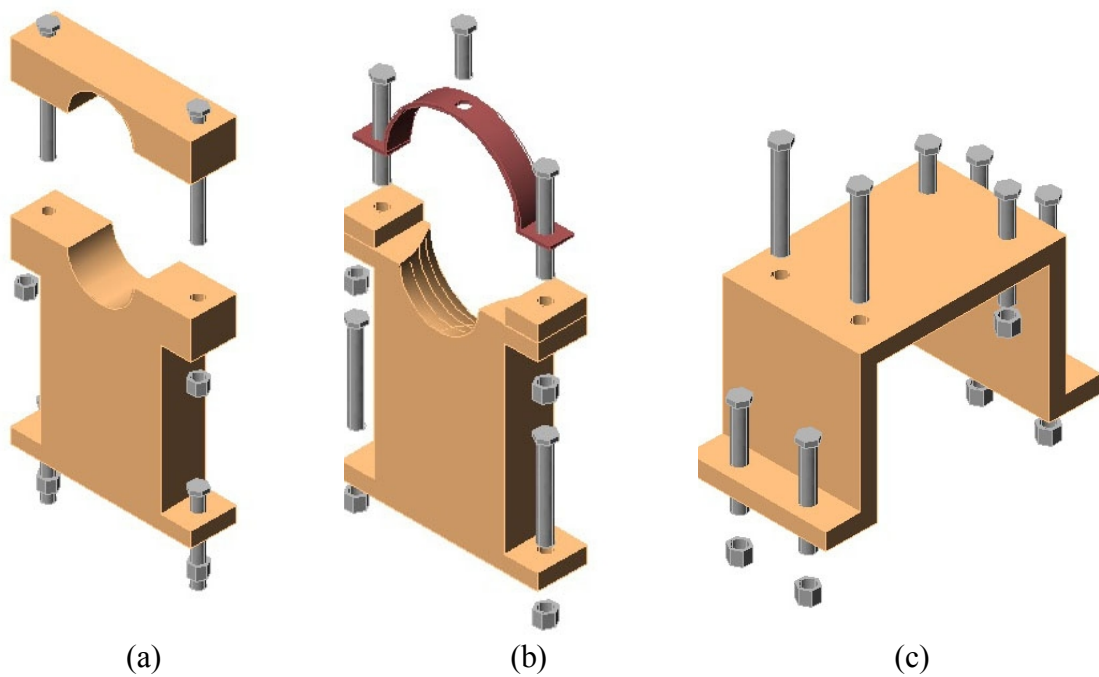


Fig. 8.14: (a) Hot Cylinder Holder (b) Cold Cylinder Holder (c) Crank Base

Description – These holders were built to hold the Hot and Cold Cylinders as well as to keep them perfectly aligned to ensure smooth operation of engine.

Raw Material – Wood plies.

Dimension – As shown in figure above.

Manufacturing Process – Each of the three parts were completely hand crafted and carefully finished by hand tools. Drills were made in different places to accommodate bolts used for rigidity.

Transfer Pipe:

Description – Flexible pipe for gas transfer purpose between hot and cold end.

Material – Plastic

Dimension – 1.5 mm inner diameter. Length is approximately 115 cm. Dead volume inside the cylinder is around 2 cm³.

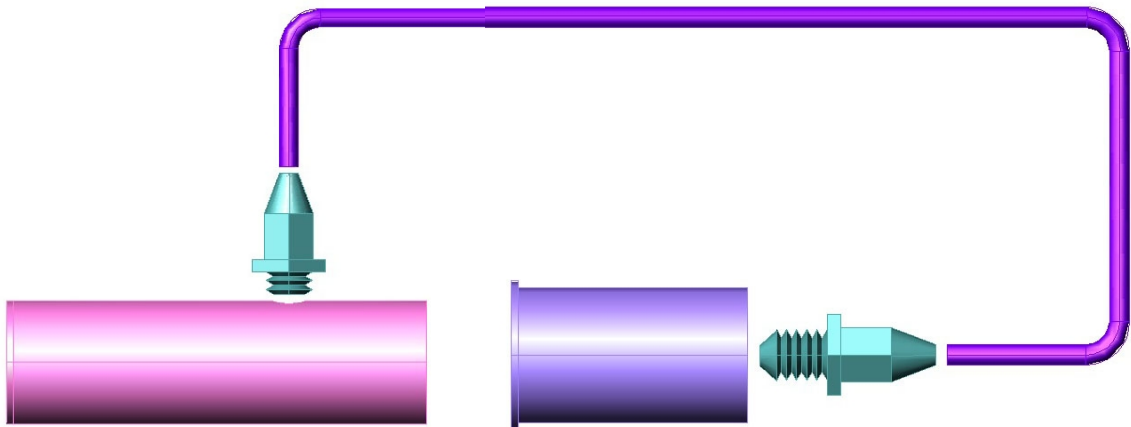


Fig. 8.15: Hot and Cold End Connections with Transfer Piping

Connection Joints:

Description – Connects the transfer Pipe to the cylinders.



Fig. 8.16: Nipple Joint and Flaring Nuts

Raw Material – Brass Nipples, Brass Flaring Nut and Copper Tubes.

Dimension – $\frac{3}{8}$ " Nipples, Nuts and Tubes. Small pieces of $\frac{1}{8}$ " copper tubes.

Installation Process – In the cold cylinder, one end of the nipple was fixed to the thread of the cold cylinder. At the other end, a $\frac{3}{8}$ " copper tube was fixed by flaring it and attaching

with a flaring nut. The end of the copper tube was squeezed and another piece of $\frac{1}{8}$ " copper tube was fixed to it. The other end of the $\frac{1}{8}$ " was fixed with the Transfer Pipe and sealed by epoxy glue. In the hot cylinder, one end of nipple was attached to the dead volume of the hot cylinder by brazing and the other end was flared and joined to the transfer pipe in the same manner as in cold cylinder.

Regenerator:

Description – For increasing the thermal efficiency of the engine.

Raw Material – Metal Wire Mesh.

Installation Process – The net was rolled like a coil and was inserted inside the dead volume of the hot cylinder.

Pressure Indicator:

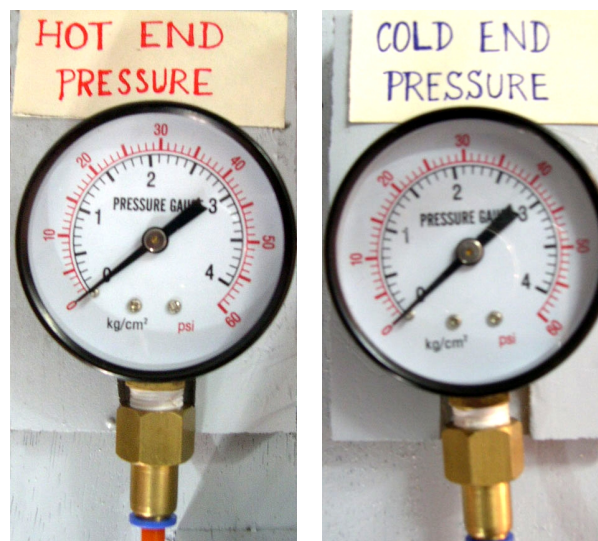


Fig. 8.17: Hot and Cold End Pressure Gauges

Description – Bourdon-Tube Pressure Gauges used for measuring working pressure inside the Hot and the Cold Cylinder.

Scale – 0 to 4 kgf/cm² (gauge) pressure. One for each of the two cylinders.

Installation Process – Pressure Tappings were made in suitable places by drilling first and then inserting copper tubes and fixing then by epoxy glue. Then plastic pipes were used to connect them to the pressure gauges.

Temperature Indicator:

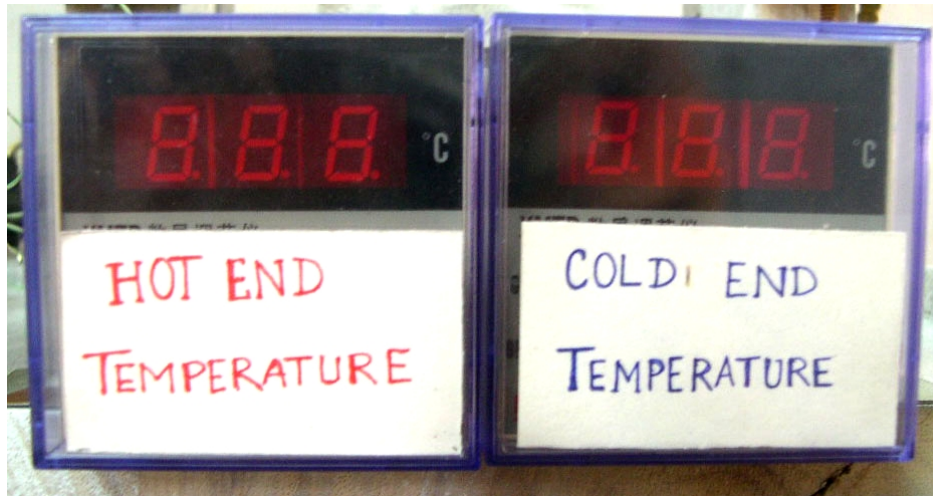


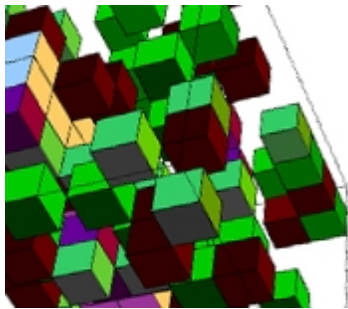
Fig. 8.18: Hot and Cold End Temperature Indicators

Description – Thermocouples and Digital Temperature Indicators used to measure temperatures of Gas inside the Cylinders.

Equipments – K-type thermocouple and Digital Two-Position ON/OFF Controllers of model XMTD-2001M using 220V power supply.

Range/Resolution – Thermocouple range is 0 to 400°C. Indicator Resolution is 1°C

Section 3



Modeling & Simulation

A mathematical model is an abstract model that uses mathematical language to describe a system. A mathematical model usually describes a system by a set of variables and a set of equations that establish relationships between the variables. Stirling engine models can be classified as follows –

First Order Model – It is characterized by harmonic sinusoidal motion of piston, different swept volumes for hot and cold end, hot end phase angle lead by a wide range and the existence of dead volumes. Only conservation of mass is followed in the first order model.

Second Order Model – It is a first order model consisting of several losses. Generally the losses are frictional and thermal losses both static and dynamic. Second order model follows the conservation of mass as well as the conservation of energy.

Third Order Model – In this model all three laws of conservation are followed namely the conservation of mass, energy and momentum. The model gives complete understanding of thermo fluid processes occurring in the engine.

In terms of thermodynamics, all the Stirling engine models stated above can be generally classified into isothermal model and adiabatic model.

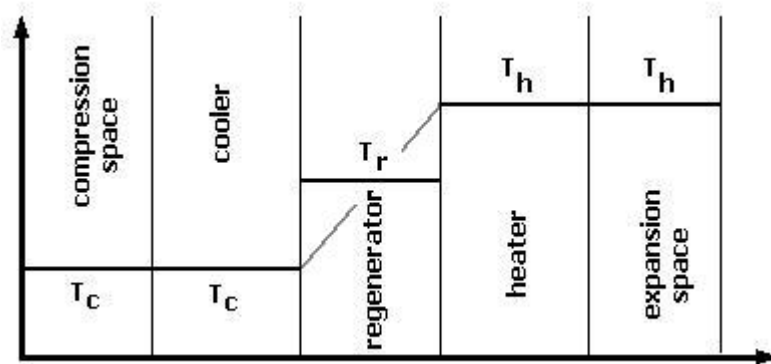


Fig. 9.1: Temperature Distribution in Isothermal Model

Isothermal Model – In this category, the temperature of displacement space (expansion / compression) and the heat exchanger (heater / cooler) at any end is same and are kept fixed. The gas in the expansion space and the heater is at the constant upper source temperature and the gas in the compression space and the cooler is at the constant lower sink temperature.

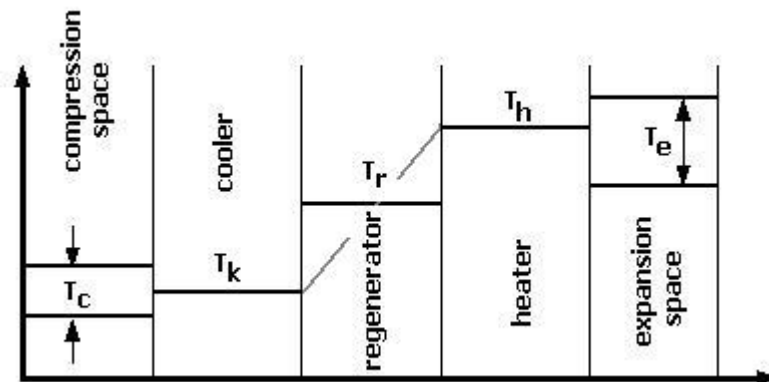


Fig. 8.2: Temperature Distribution in Adiabatic Model

Adiabatic Model – In this category, the temperature of displacement space (expansion / compression) and the heat exchanger (heater / cooler) at any end is not same rather the displacement space temperature varies with the motion of the piston while the heat exchanger temperatures are kept fixed. Both the compression and expansion spaces are adiabatic, in which no heat is transferred to the surroundings. The temperature in the compression and expansion spaces (T_c and T_e) vary over the cycle in accordance with the adiabatic compression and expansion occurring in the working spaces.

1st Order Isothermal Model of an α (alpha) Stirling Engine

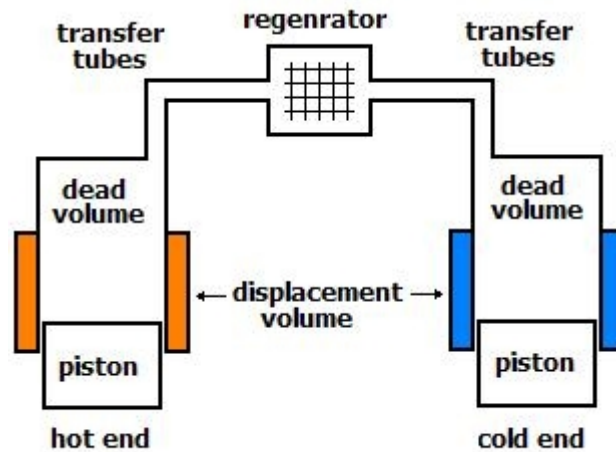


Fig. 10.1: Schematic Diagram of an α (alpha) – Stirling Engine

Assumptions:

- The working gas in the system is air.
- The gas in the expansion space and the heater is at the constant upper source temperature.
- The gas in the compression space and the cooler is at the constant lower sink temperature.
- Volumes of the working spaces (displacement volumes) vary sinusoidally.
- The analysis is initialized as the total mass of gas in the engine is constant and the mass is evaluated taking the source and sink temperature into consideration, not at initial room temperature.
- All the external heat transfer occurs across the boundaries of the compression and expansion spaces.
- The system is a single pressure system i.e. ideally only one pressure exists in the system at any given instance.
- System is not pressurized initially.

Notations:

T_h	– Source temperature (temperature of expansion space and the heater)
T_c	– Sink temperature (temperature of compression space and the cooler)
V_{hd}	– Dead volume at hot end
V_{cd}	– Dead volume at cold end
V_{hw}	– Displacement volume of hot end
V_{cw}	– Displacement volume of cold end
V_h	– Total volume of hot end (sum of dead and displacement volume)
V_c	– Total volume of cold end (sum of dead and displacement volume)
V_r	– Regenerator volume
V_t	– Transfer tube volume
m_h	– Mass of gas in hot end
m_c	– Mass of gas in cold end
m_r	– Mass of gas in regenerator
m_t	– Mass of gas in transfer tube
M	– Total system mass
P	– System pressure
θ	– Cycle angle
α	– Phase angle
R	– Gas constant

Element Volumes:

The volumes of the hot and cold end vary sinusoidally while other volumes remain constant over the cycle. Figure 7.2 shows the volume variations of the hot and cold end (V_h and V_c) over a single cycle. The hot end volume variation leads that of the cold end by a wide angle α .

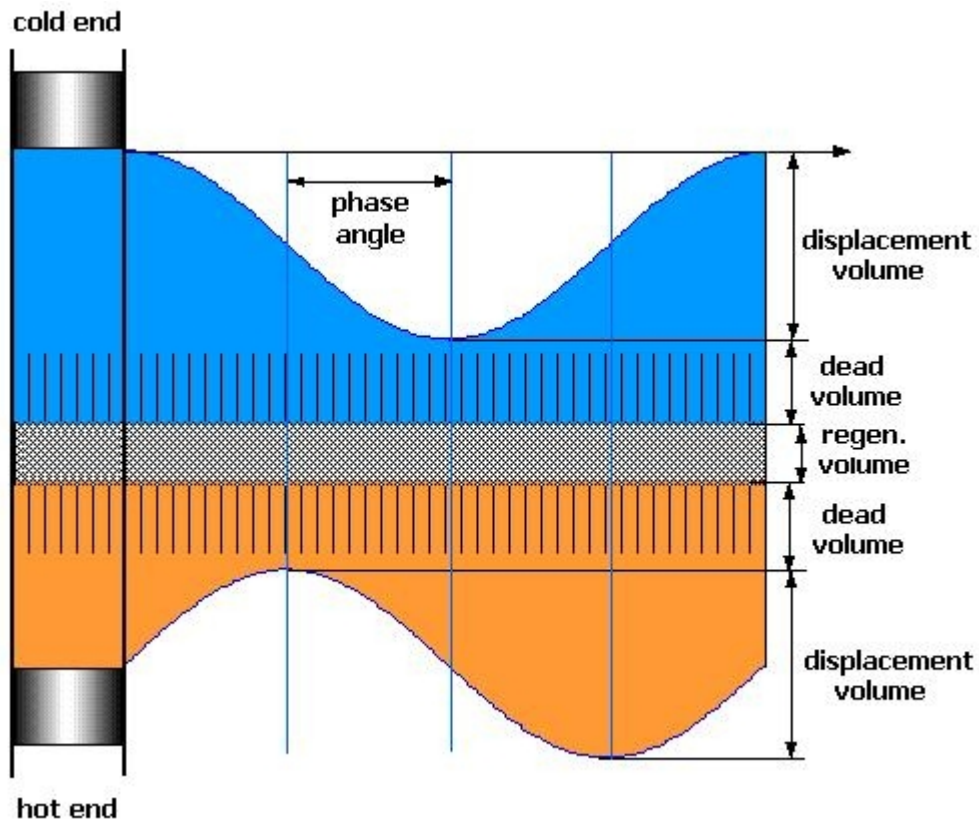


Fig. 10.2: Hot End and Cold End Volume Variations

For cold end –

$$V_c = V_{cd} + (1/2) * V_{cw} [1 + \sin \theta]$$

----- (1)

For hot end –

$$V_h = V_{hd} + (1/2) * V_{hw} [1 + \sin (\theta - \alpha)]$$

----- (2)

System Parameters:

From the conservation of mass –

$$M = m_h + m_t + m_r + m_c \quad \text{----- (3)}$$

Substituting the ideal gas law given by –

$$m = PV / R T \quad \text{----- (4)}$$

We obtain,

$M = P (V_h / T_h + V_t / T_r + V_r / T_r + V_c / T_c) / R \quad \text{----- (5)}$
--

Here, M is the initial mass of gas in the system which remains constant through out the analysis for fixed hot and cold end temperatures. M is evaluated putting $\theta = 0^\circ$ in equations (1) and (2).

Thus given the volume variations V_h and V_c we can solve the above equation for system pressure P as a function of V_h and V_c .

$P = MR / (V_h / T_h + V_t / T_r + V_r / T_r + V_c / T_c) \quad \text{----- (6)}$

For simplicity, temperature of the gas at the transfer tube and that at the regenerator are assumed equal. As the transfer tube gas volume is much smaller relative to other volumes, its effect on the overall system is negligible.

Choosing the effective regenerator temperature is critical. It depends on the regenerator geometry and its placement relative to the hot and cold end. Depending on the mentioned factors, T_r may be equal to T_h , LMTD of T_h and T_c or asymptotically distributed over the regenerator volume. In our system we use,

$T_r = T_h$

Using SIMULINK:

SIMULINK is an extension of MATLAB that allows engineers to rapidly and accurately build computer models of dynamic systems using block diagram notation. A SIMULINK model can include both continuous and discrete time components. Additionally, a SIMULINK model can produce graphical animations that show the progress of a simulation visually, significantly enhancing understanding of the system's behavior.

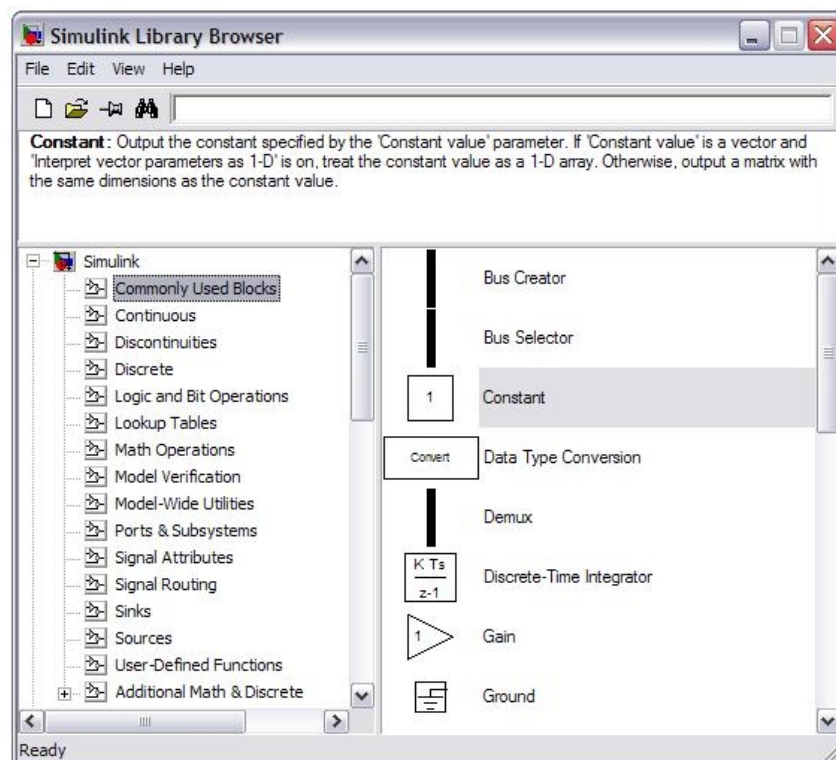


Fig. 11.1: SIMULINK Library Browser window

SIMULINK Model of α (alpha) Stirling Engine:

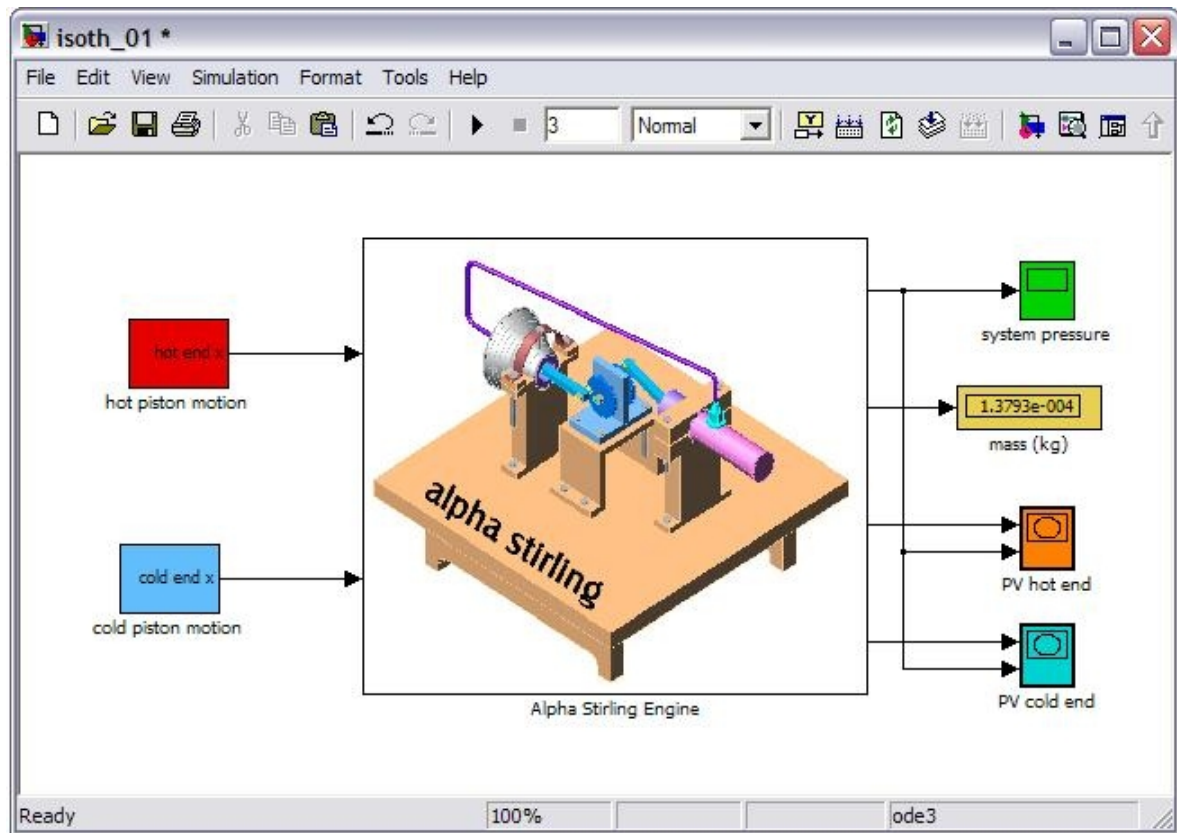


Fig. 11.2: SIMULINK Model of α (alpha) Stirling Engine

The system consists of hot and cold piston motion subsystems, main engine subsystem and several output blocks such as, *Scope* (system pressure), *Display* (system mass) and *XY Graph* (PV diagram for hot and cold end).

The Alpha Stirling Engine subsystem is masked using the Mask Editor. A mask is a custom user interface for a subsystem that hides the subsystem's contents, making it appear to the user as an atomic block with its own icon and parameter dialog box. As a result of masking, the complete set of input can be fed to the system in a single window.

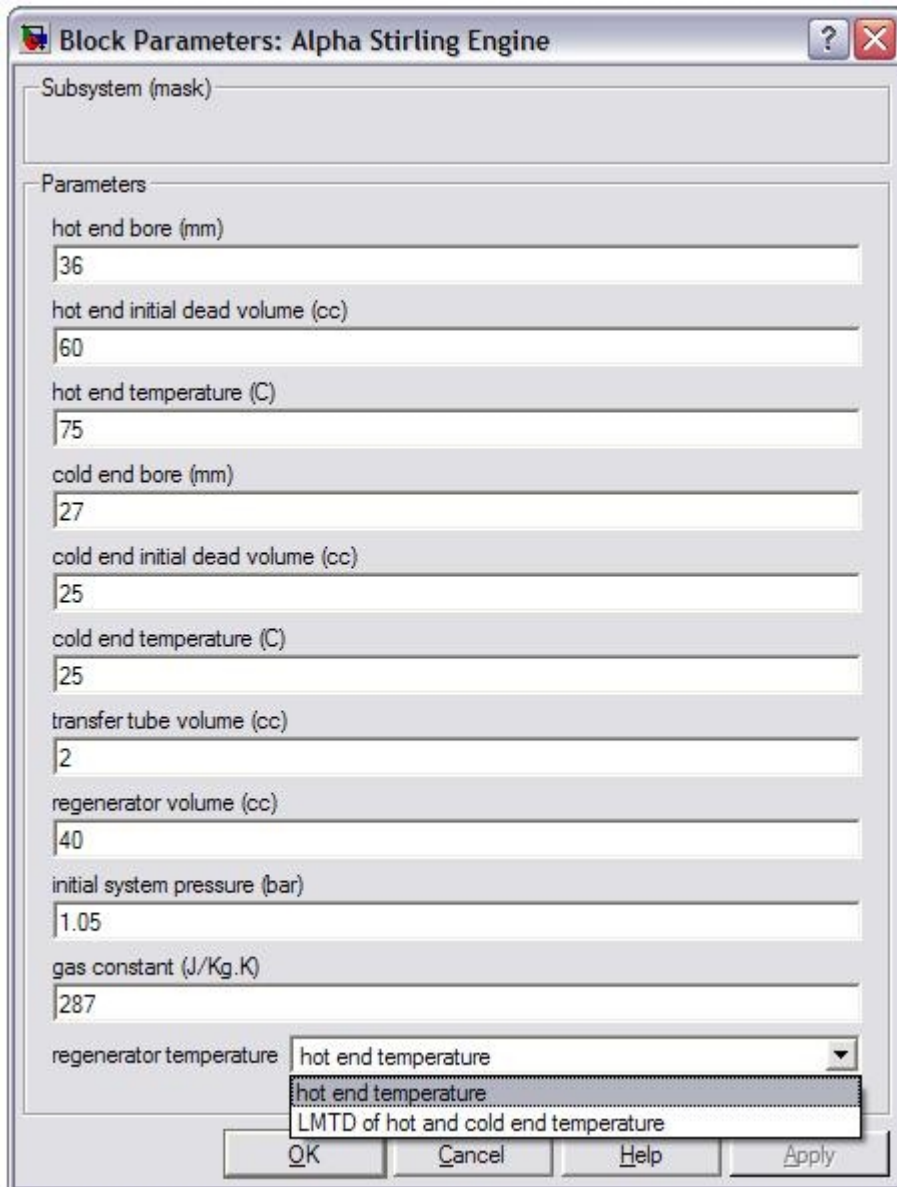


Fig. 11.3: Block Parameter window for the Alpha Stirling Engine subsystem (masked)

Masking the Alpha Stirling Engine subsystem also allows the user to select the criterion for the regenerator temperature without looking inside the subsystem. In case of our analysis, hot end temperature is used as the regenerator temperature.

Generating Piston Motion:

The model is characterized by harmonic sinusoidal motion of piston. To obtain this, *Sine Wave* block from the *Source* block set is used for both the hot and cold end piston motion.

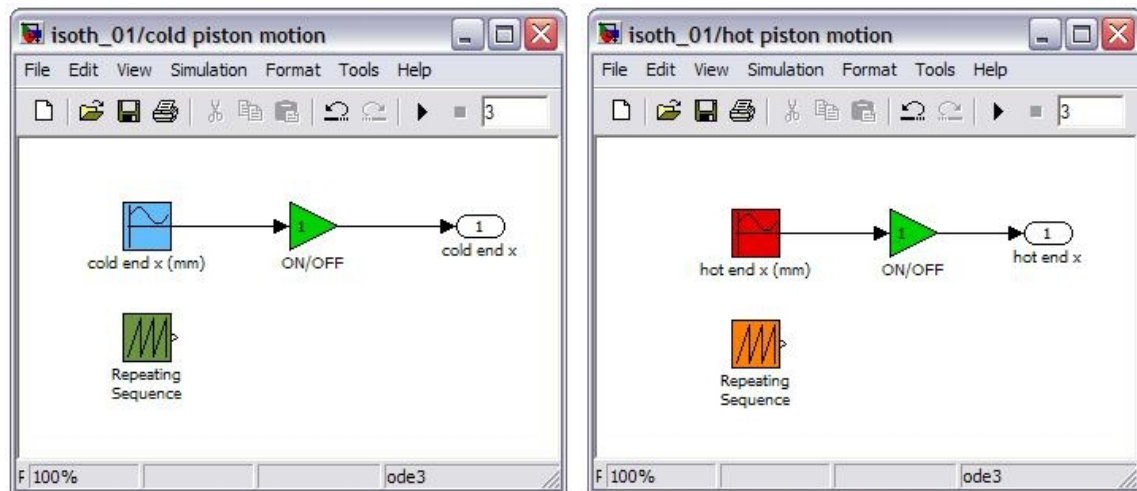


Fig. 11.4: Hot Piston Motion and Cold Piston Motion Subsystems

Output a Sine Wave – $O(t) = \text{Amp} * \sin(2*\pi*\text{Freq}*t + \text{Phase}) + \text{Bias}$

Here, frequency of 2π rad / sec is used in both the cases. Bias and Amp is also same in both cases and is equal to half the stroke length of the piston. Phase angle is $-\pi/2$ rad in case of hot end motion and 0 rad in case of cold end motion.

Provision for motions other than sinusoidal is given by using the *Repeating Sequence* block. The ON/OFF switch is a simple *Gain* block (unit gain) to manipulate the piston motions.

Alpha Stirling Engine subsystem:

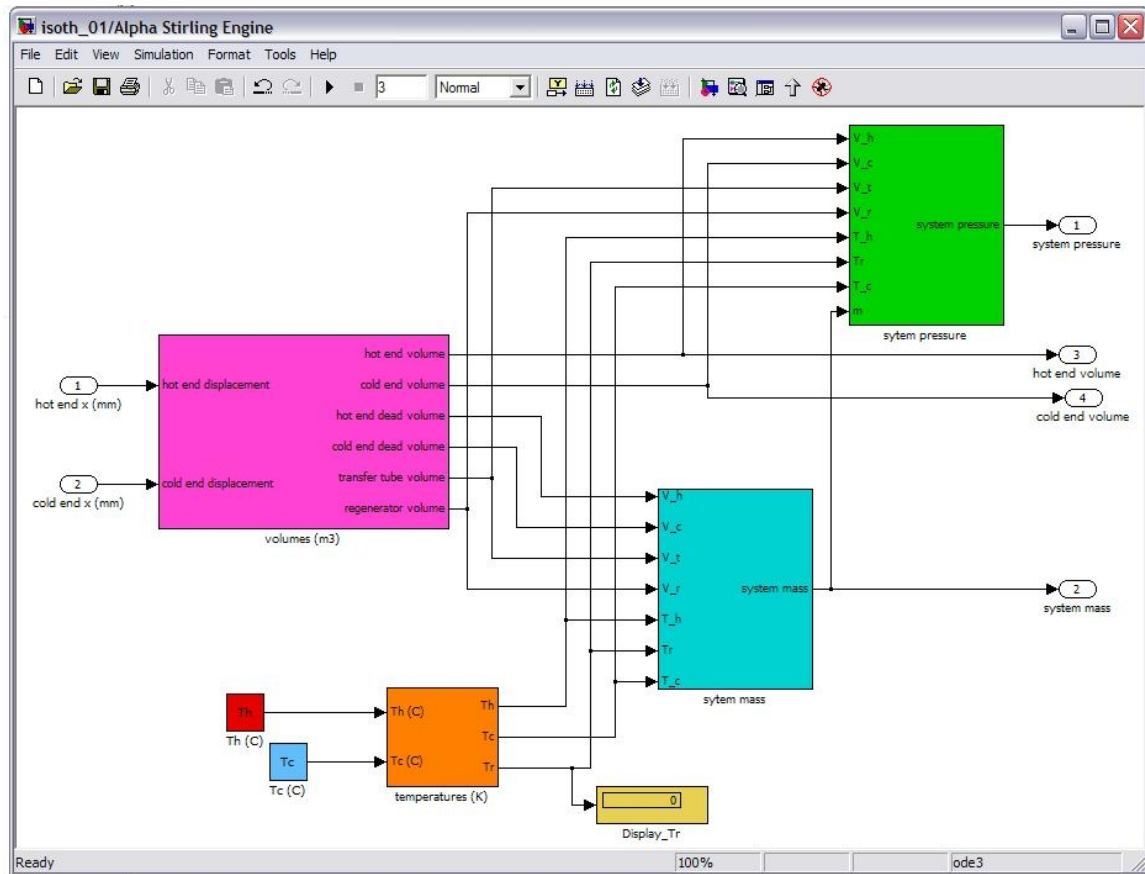


Fig. 11.5: Inside the Alpha Stirling Engine subsystem

This subsystem consists of several subsystems namely, volume, temperature, system mass and system pressure subsystem. It takes the piston motions as input and delivers several system parameters (system pressure, volume variations etc.) as output.

Volumes Subsystem:

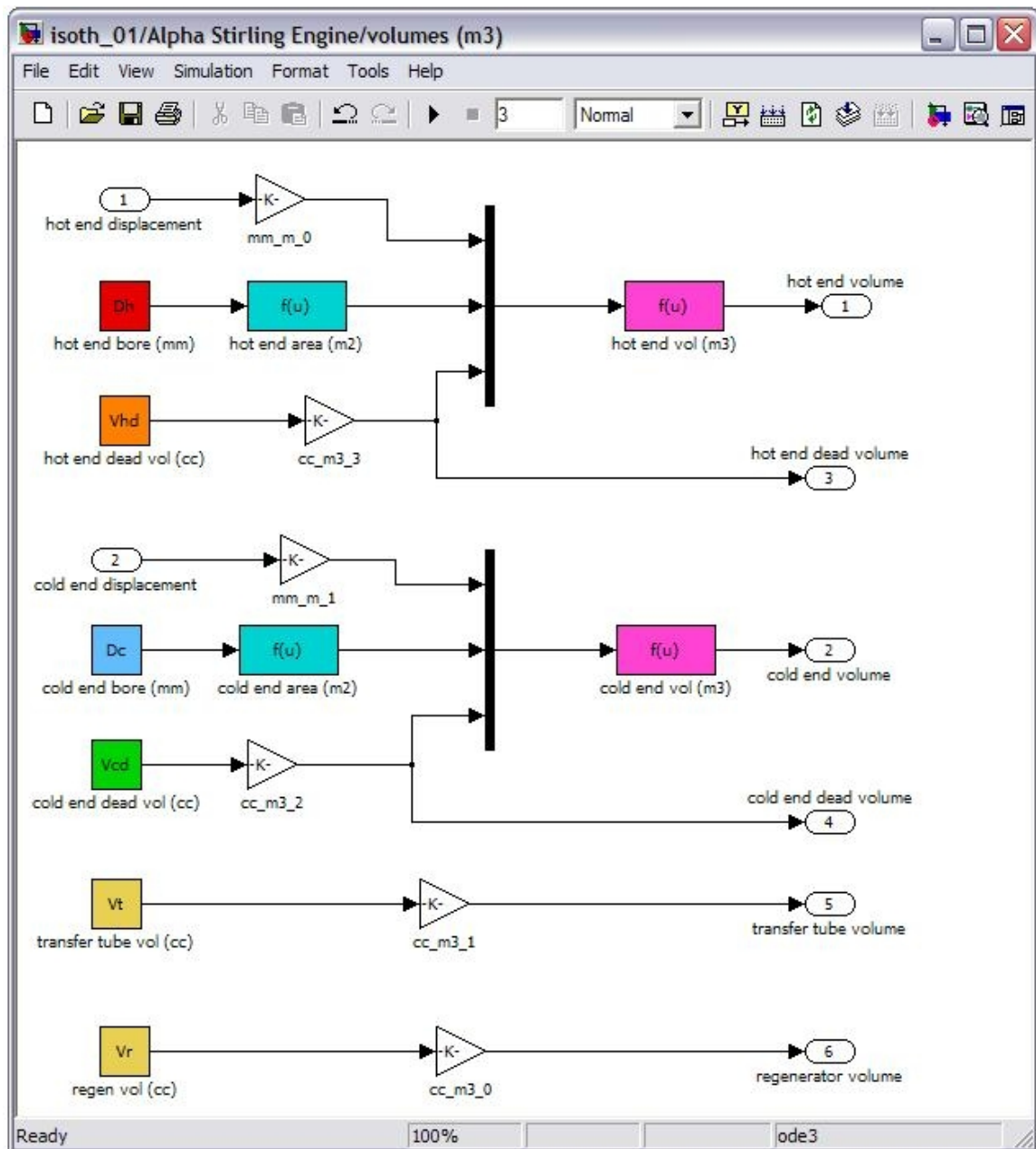


Fig. 11.6: Inside the Volumes subsystem

Function blocks are used to calculate the area and volumes of the hot and cold end. The unit conversions are done by using *Gain* blocks. System dead volumes are introduced as constants. The subsystem takes the hot and cold end displacements as input and delivers several volumes as output.

Temperature Subsystem:

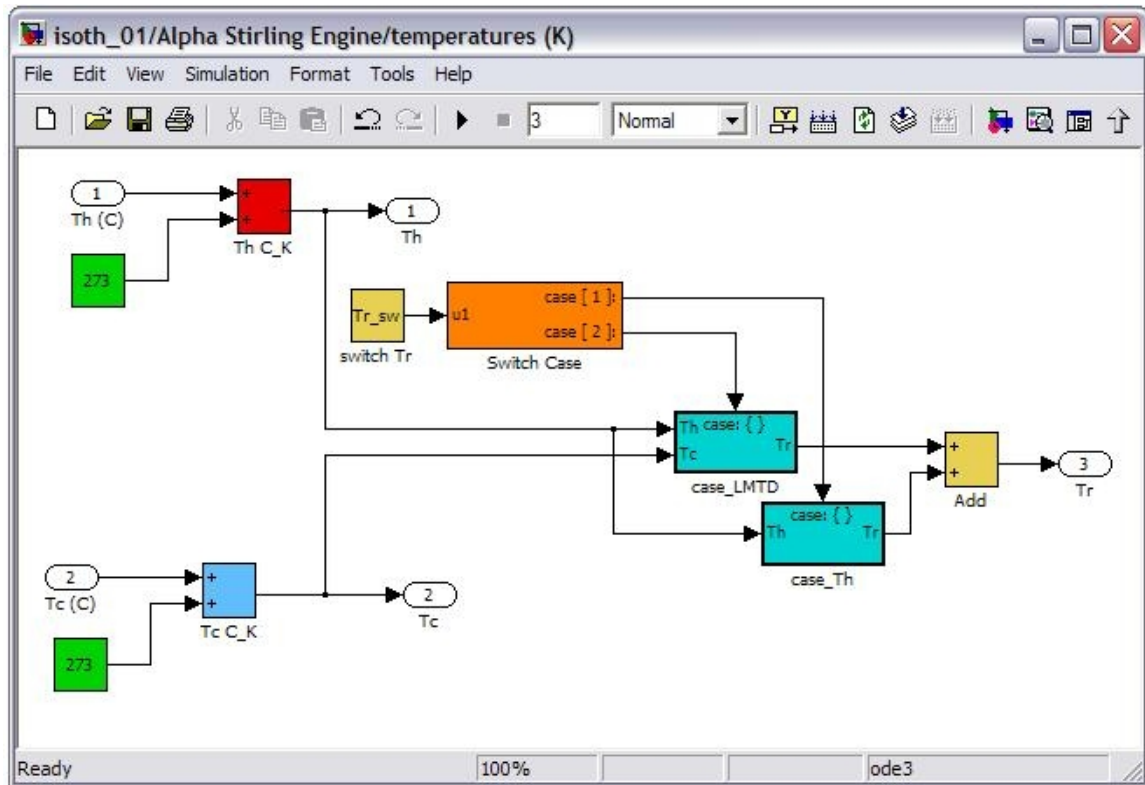


Fig. 11.7: Inside the Temperature subsystem

Celsius temperatures are converted to Kelvin by simply adding 273 (*Constant* block). The conditional regenerator temperature, which is set by the user at the start of simulation, is formed by using *Switch Case* block. Case 1 is characterized by hot end temperature while Case 2 is by LMTD of hot and cold end. The subsystem takes the hot and cold end temperature ($^{\circ}\text{C}$) as input and delivers system temperatures (K) as output.

System Mass Subsystem:

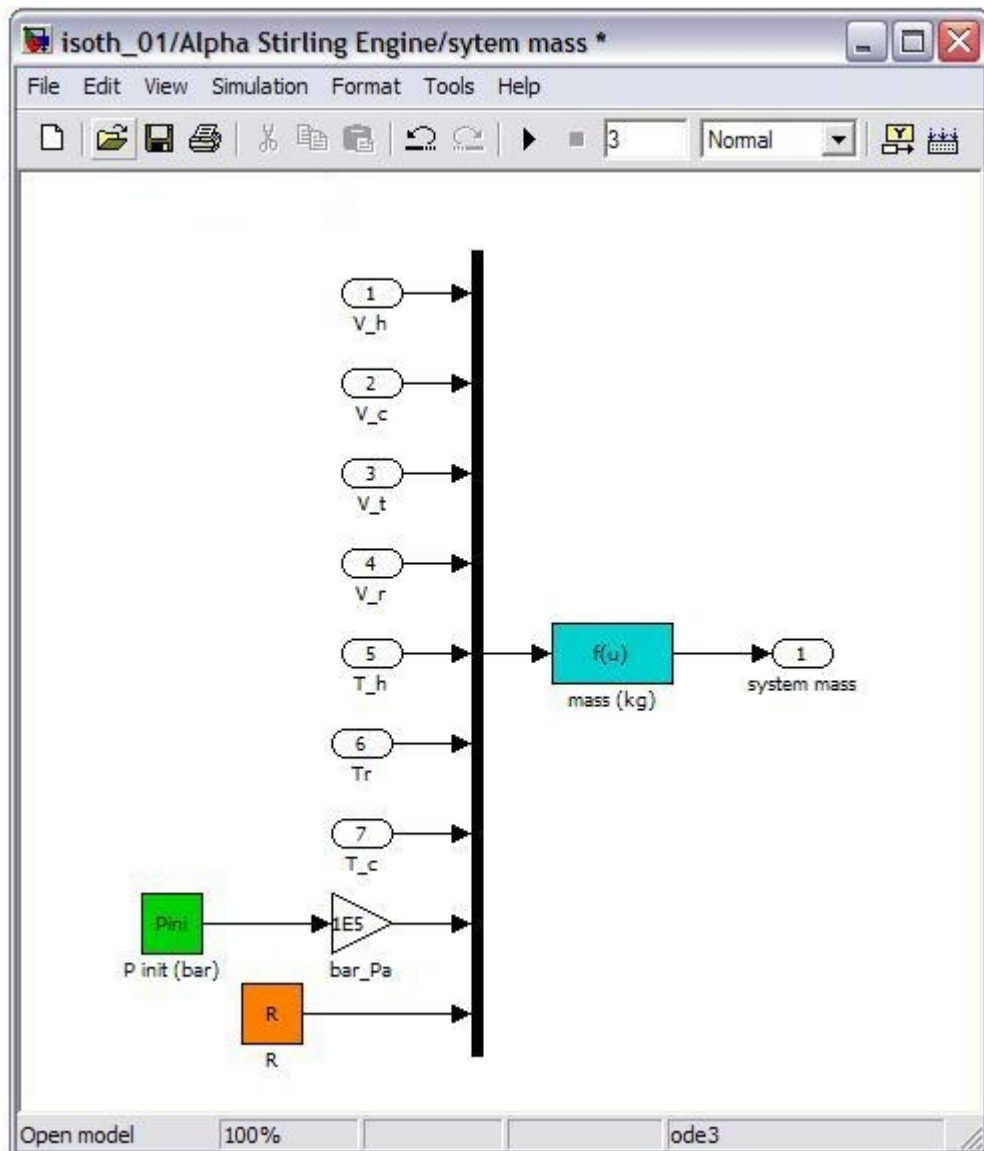


Fig. 11.8: Inside the System Mass subsystem

The system mass is calculated by the *Function* block. The initial system pressure is introduced to the system as constant and is converted by using the *Gain* block.

System Pressure Subsystem:

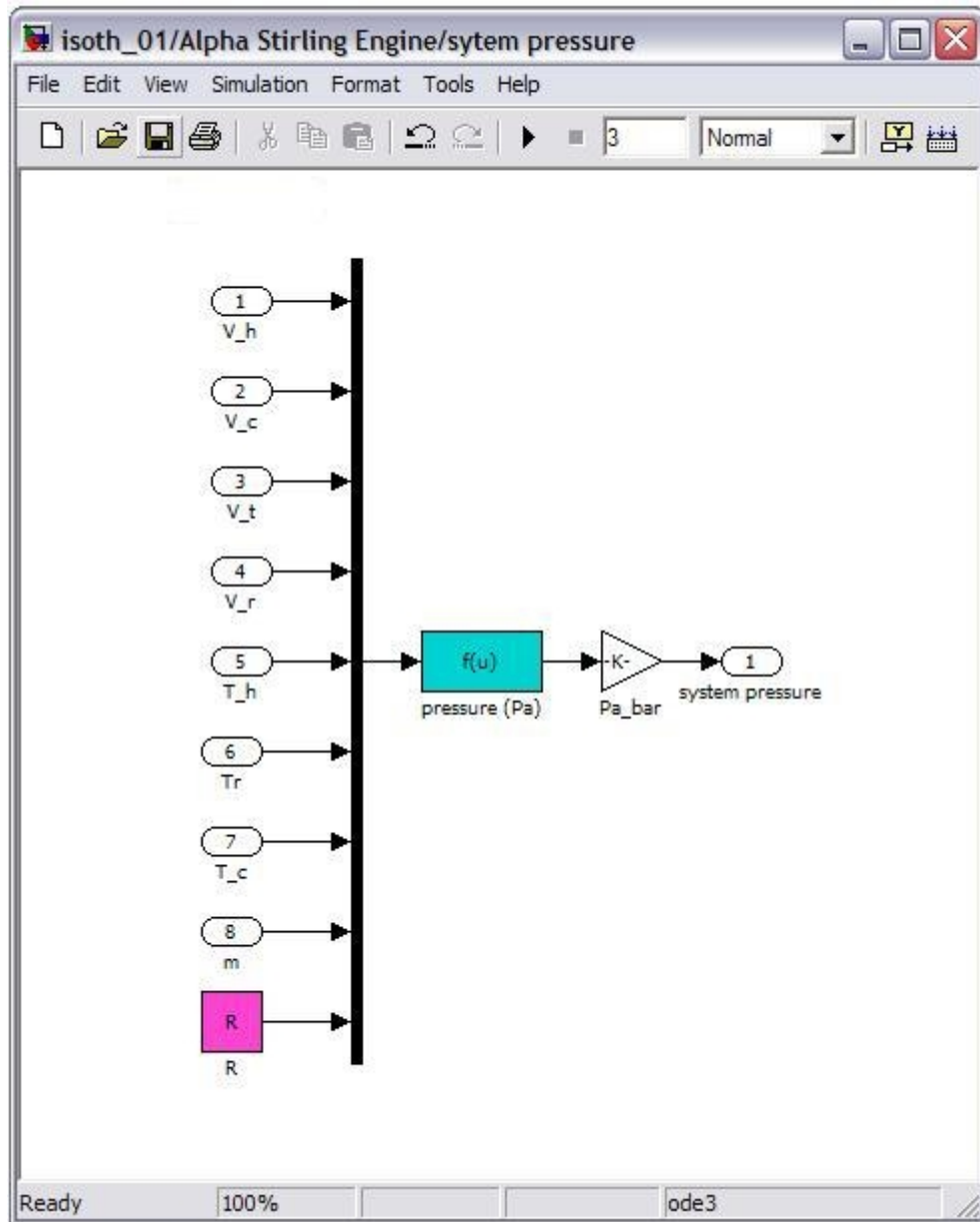


Fig. 11.9: Inside the System Pressure subsystem

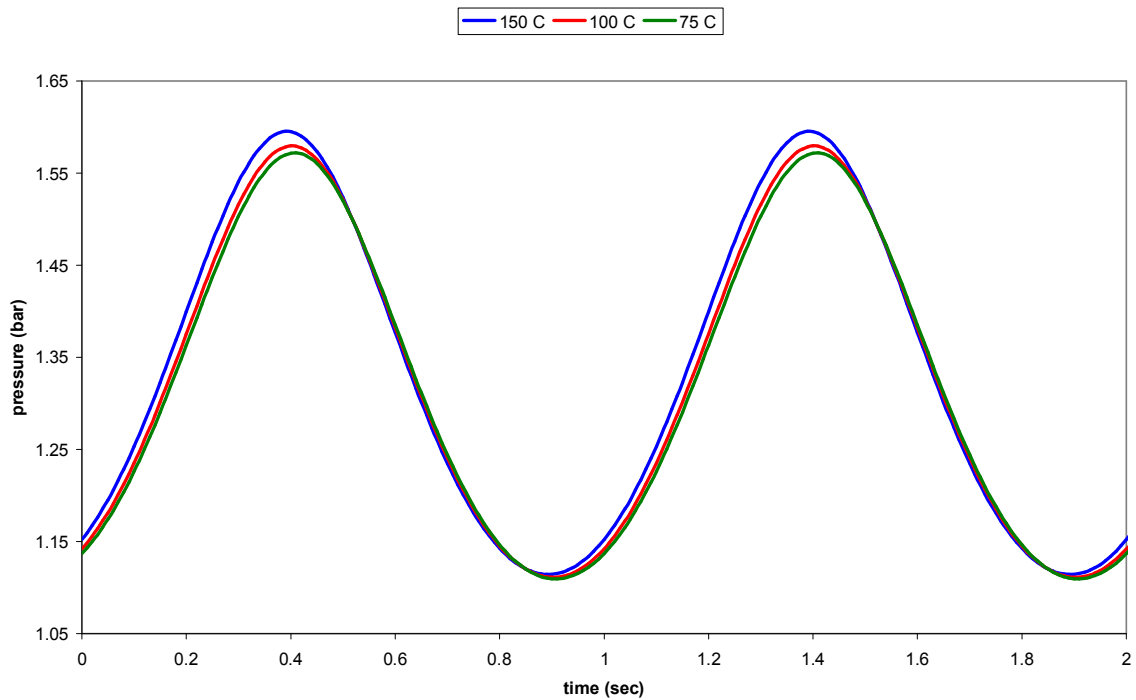
The system pressure is calculated by the *Function* block. The pressure is later converted to bar from Pa using *Gain* block.

Experimentation & Result Analysis

Input Data:

Hot end bore	= 36 mm
Hot end cylinder length	= 100 mm
Cold end bore	= 27 mm
Cold end cylinder length	= 65 mm
Hot end maximum dead (initial) volume	= 60 cm ³
Cold end maximum dead (initial volume	= 25 cm ³
Transfer tube bore	= 1.5 mm
Transfer tube length	= 80 cm
Transfer tube volume	= 2 cm ³
Regenerator length	= 100 mm
Regenerator diameter	= 35 mm
Regenerator volume	= 40 cm ³
Gas constant (for air)	= 287 J/Kg.K
Initial system pressure	= 1.05 bar
Hot end piston length	= 30 mm
Cold end piston length	= 25 mm
Piston stroke (hot & cold end)	= 30 mm

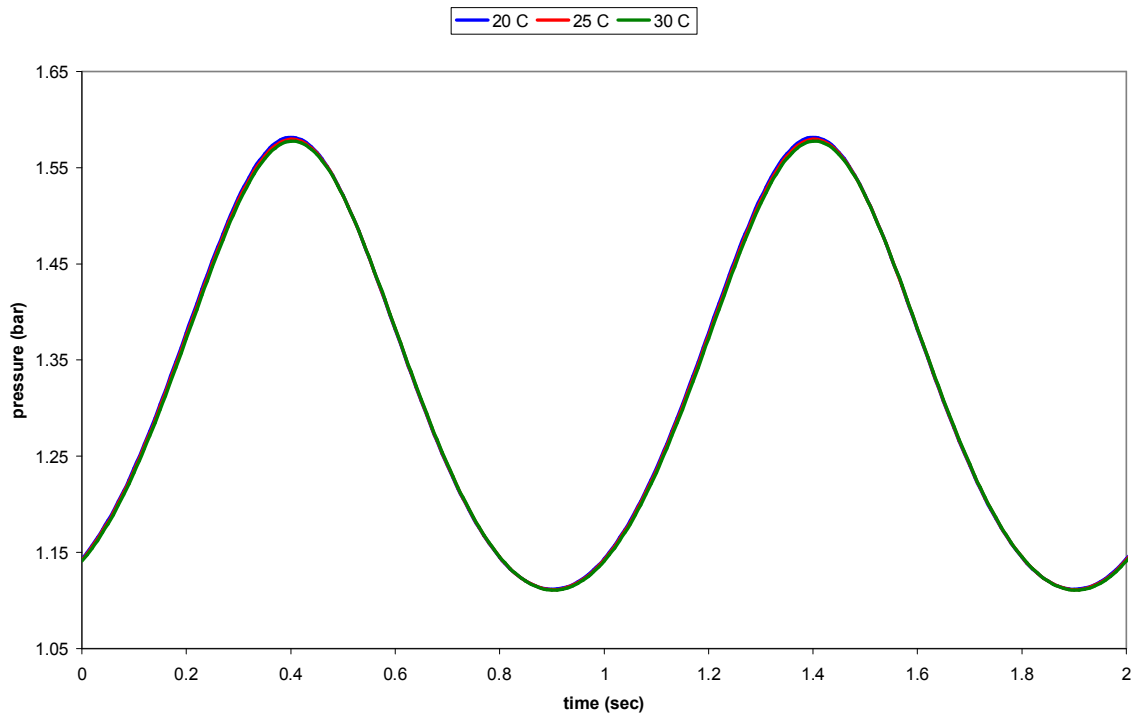
Effect of Hot End Temperature on System Pressure:



Plot 12.1: variation of system pressure with time (crank angle) and hot end temperature

Surely, the system pressure increases with increasing the hot end temperature. But at the same time, the system mass also decreases. It should be noticed that, the system mass is not the same for all the three curves shown above. Reduction in system mass lowers the system response. Thus, much higher temperature shouldn't be used. Increasing the hot end temperature is also limited by the material's capability to withstand high temperature. Cold end temperature is kept fixed to 25°C in this case.

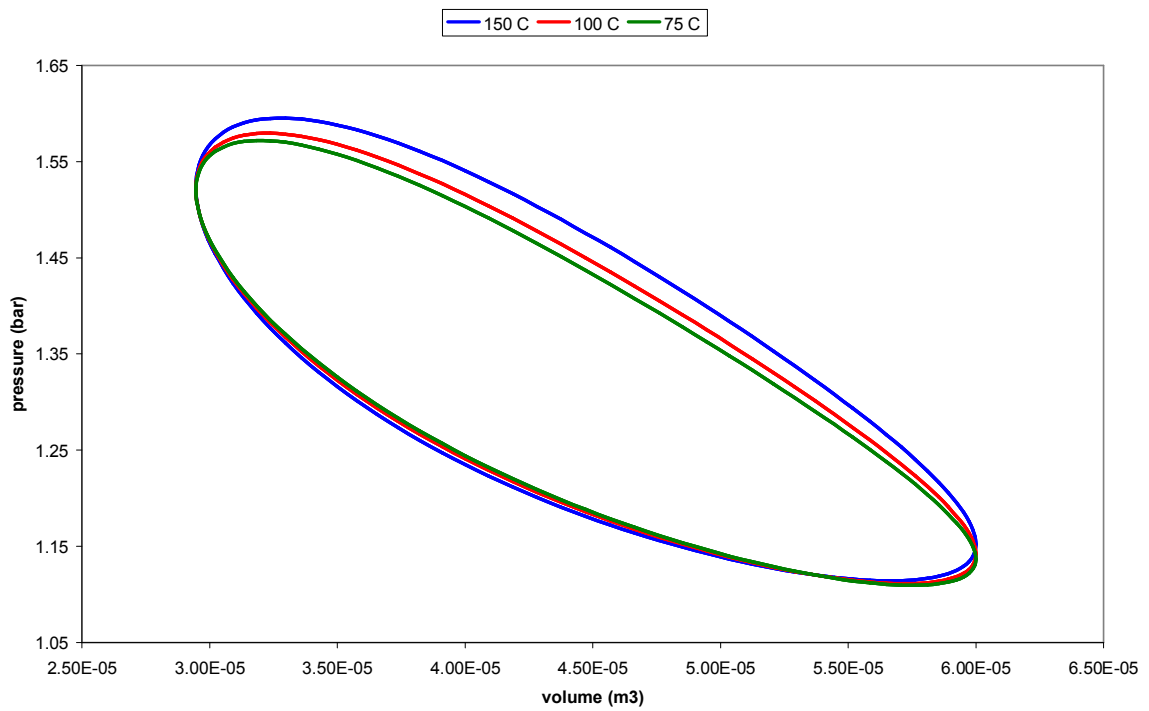
Effect of Cold End Temperature on System Pressure:



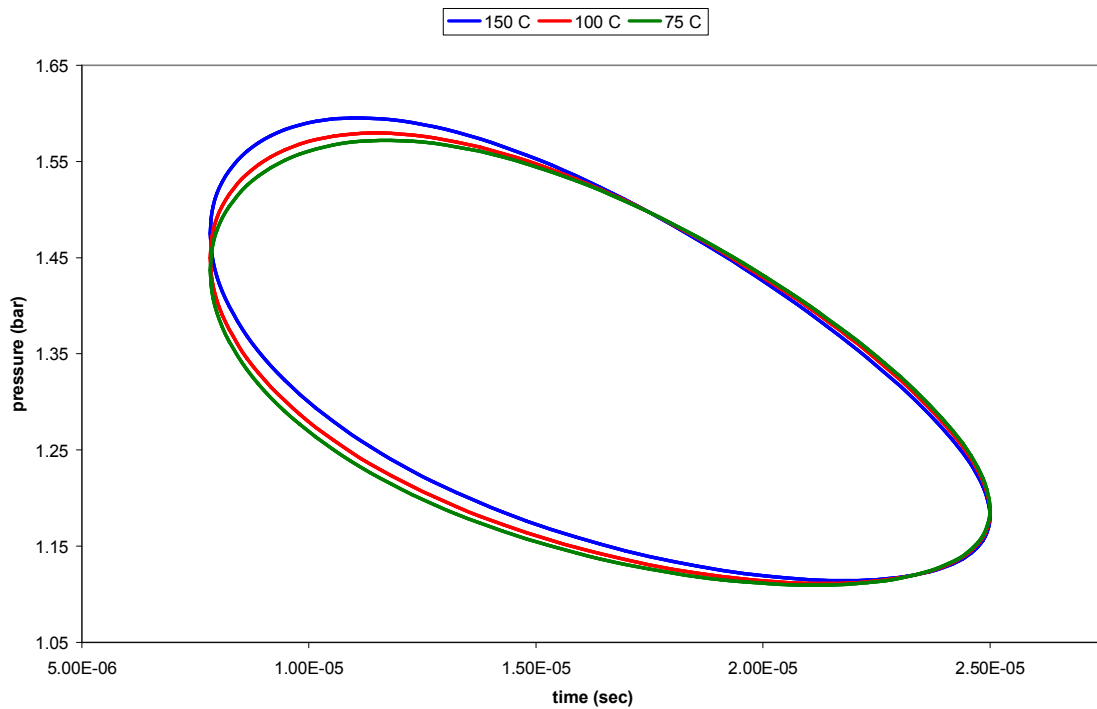
Plot 12.2: variation of system pressure with time (crank angle) and cold end temperature

There is not much change in system pressure with the change in cold end temperature and in real case; cold end temperature is dependent on ambient conditions. Thus, it can be deduced that, system pressure is almost independent of cold end temperature. Hot end temperature is kept fixed to 100°C in this case.

P – V Diagrams at Different Hot End Temperatures:

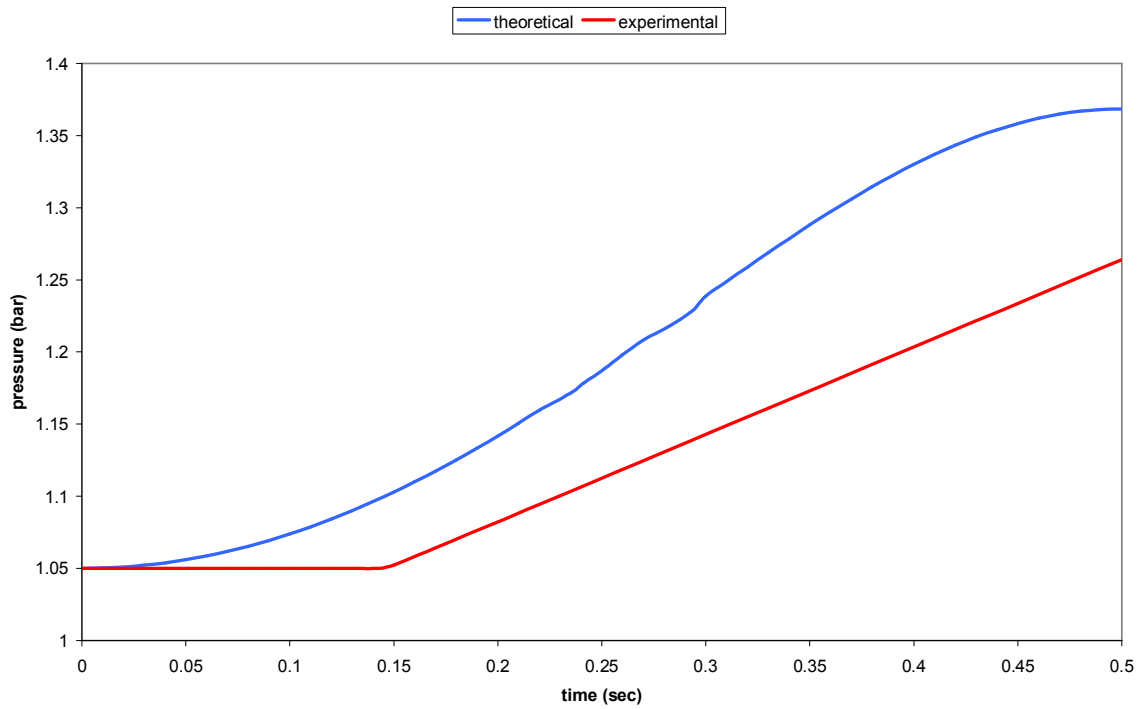


Plot 12.3: hot end PV diagram @ different hot end temperatures

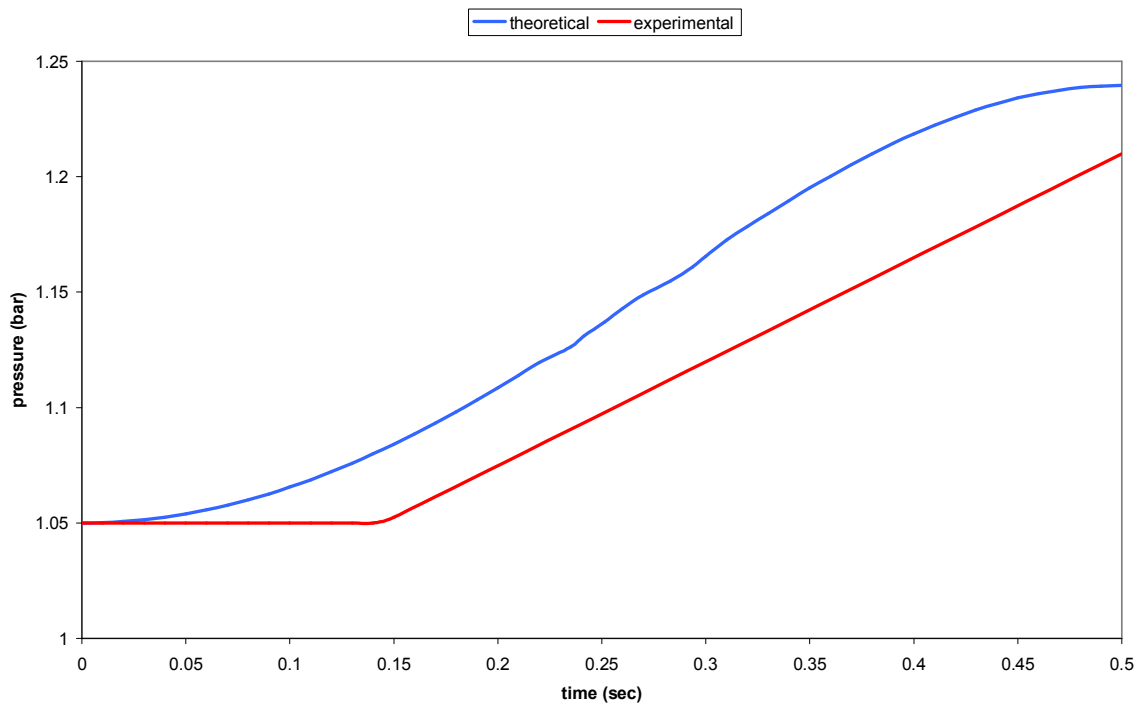


Plot 12.4: cold end PV diagram @ different hot end temperatures

Study of Basic Thermodynamic Laws:



Plot 12.5: variation of system pressure with time (crank angle) without cold end motion



Plot 12.6: variation of system pressure with time (crank angle) without hot end motion

The experiment is done in two stages –

Case – 1: the hot piston is moved manually keeping the cold piston fixed (plot 8.5)

Case – 2: the cold piston is moved manually keeping the hot piston fixed (plot 8.6)

At higher hot end temperatures the system becomes less responsive due to reduced system mass and higher side leakage. The whole experiment was done at several hot end temperatures with cold end at 25°C. But as all the curves show similar trend, plots corresponding to Th – 75°C and Tc – 25°C are shown here.

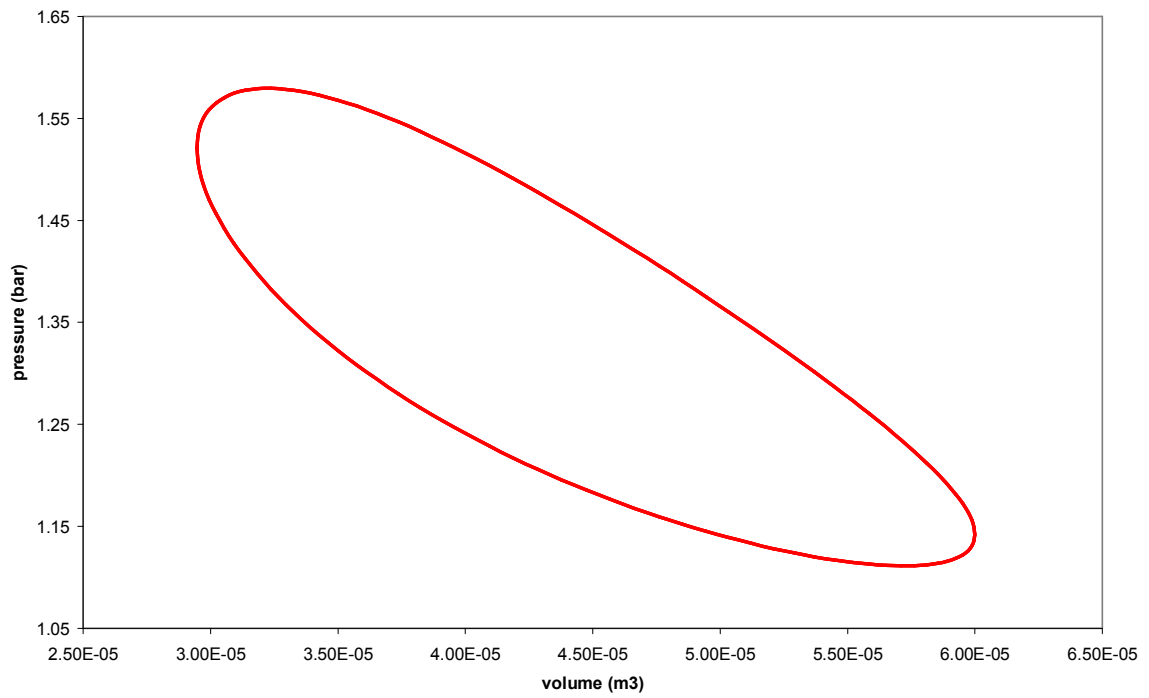
In both the cases, the experimental pressure lags the theoretical one, which is due to side leakage and pressure loss in indicator piping, connections and bends. It is also observed that the pressure loss in both the cases is not identical. Case – 1 shows much higher pressure drop than Case – 2. This may be due to difference in shape and geometry of the two ends.

Experimental Data Table:

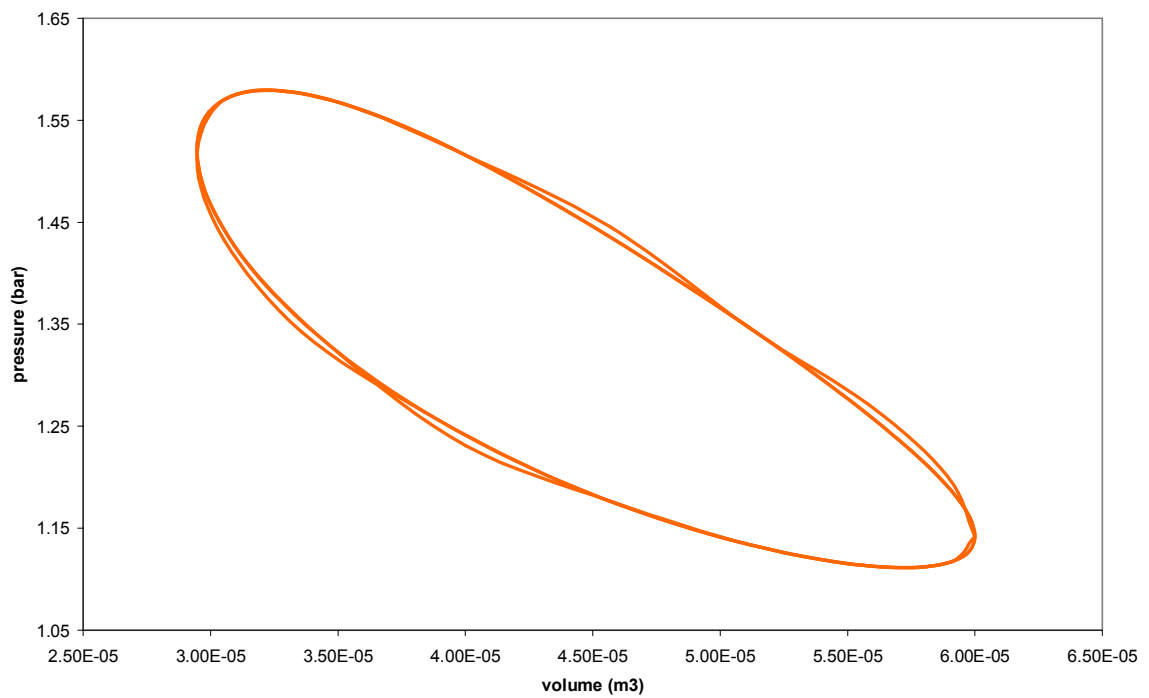
Piston Motion	Hot End Temp (°C)	Cold End Temp (°C)	Indicated Pressure (psi)		Pressure Rise (psi)	ΔT °C (hot end)	ΔT °C (cold end)
			Initial	Final			
Case – 1	40	25	1	3	2	0	0
	50		2	4	2	-2	1
	60		3	6	3	-3	1
	75		3	7	4	-4	1
Case – 2	40	25	1	2	1	0	1
	50		2	3	1	0	1
	60		2	4	2	-1	3
	75		3	6	3	-1	3

Effect of SIMULINK Solver on Analysis:

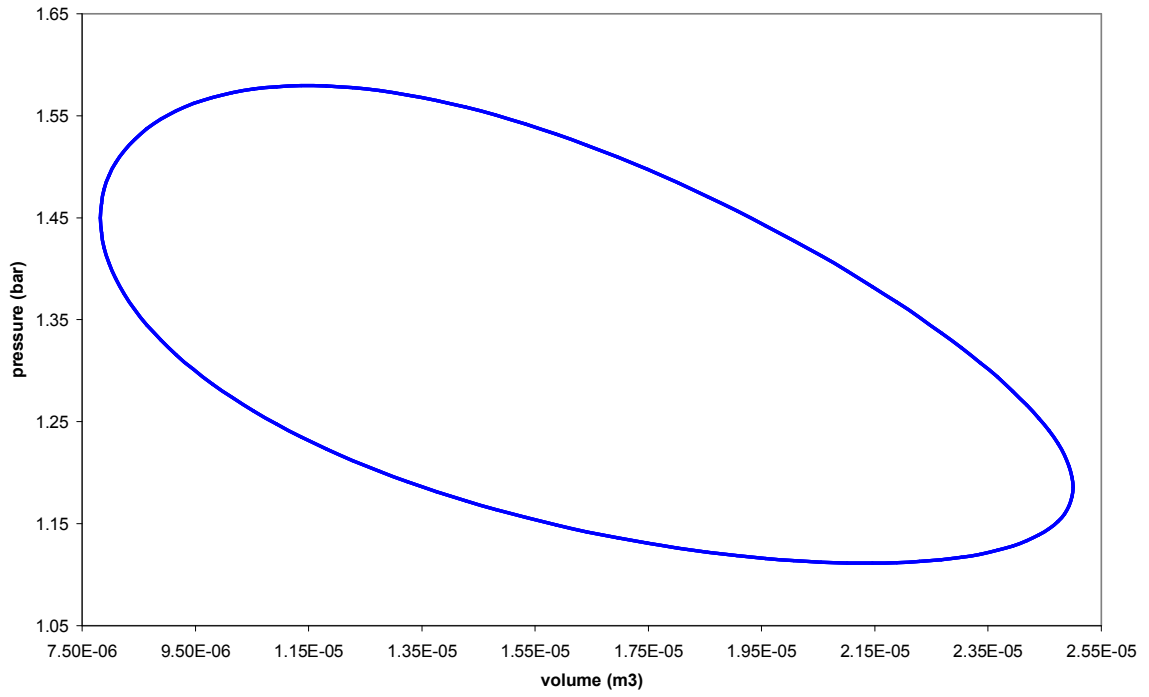
Plot 12.7: hot end PV diagram using fixed step solver



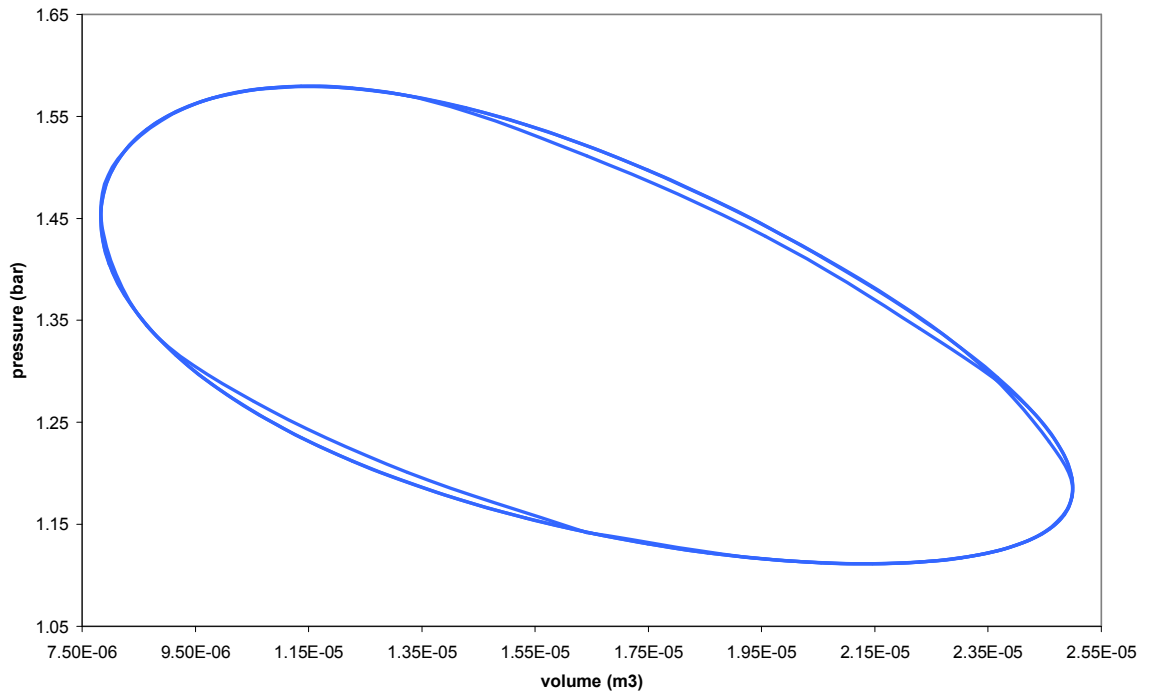
Plot 12.8: hot end PV diagram using variable step solver



Plot 12.9: cold end PV diagram using fixed step solver



Plot 12.10: cold end PV diagram using variable step solver



The complete analysis is done using ODE3 (Bogacki – Shanpine) fixed step solver. The fixed step size (fundamental sample time) is 0.01. The total sampling time was kept fixed to 3 sec throughout the analysis. This gives a total of 301 data points.

Solving the same model with variable step solver (relative tolerance 1E-3) gives the result similar to a real cycle as the P-V diagram is different from cycle to cycle. This is due to the fact that, the same points in the model were solved for different step sizes from time to time and the result is naturally different.

Section 4



Concluding Remarks

The prototype and the simulation has the following limitations –

Cold End Response – Though the hot end of the prototype develops considerable thrust producing about 180° rotation of the crank shaft, the cold end response of the system is not strong enough to complete the cycle.

Slow Heating and Cooling of Working Gas – Effective running of the engine requires quick heating and cooling of the working gas inside the hot and cold end respectively. This is quite difficult to achieve due to lower thermal conductivity of working gas used i.e. air and also due to the concentrated heat addition by gas burners used.

Side Leakage – At temperatures above 80°C, the hot end response reduces drastically. This is mainly due to the fact that, at higher temperatures the increased pressure and thermal expansion of the components increases the side leakage of the piston cylinder assembly.

Larger Dead Volume – As indicated by the simulation, smaller dead volumes result in higher system pressure. It is more likely to achieve considerable power output at higher system pressure. The larger dead volumes in the prototype are more responsible for lower system pressure and slow response.

Weaker Flywheel – At the initial stage, the uncertainty about the hot end thrust and the constraints in machining options tempted us to fabricate a much lighter and smaller flywheel. In reality, the weaker flywheel couldn't properly harness the hot end thrust to recover lag in cold end response.

Smaller Swept Volume – Due to limitations in machining, the cylinder bore length is limited up to only 65 mm. As a result, the stroke length as well as the displacement volume is much smaller than usual.

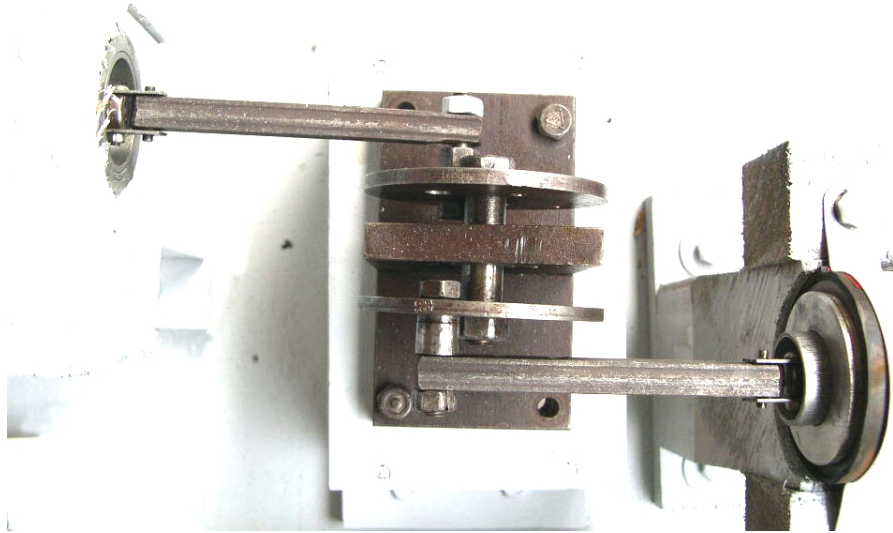


Fig. 13.1: Opposed Piston Arrangement of Prototype

Positioning of Hot and Cold End – The usual schematic arrangements described before uses a 90° physical arrangement between the hot and cold ends keeping the connecting rods joined at the same point in a flywheel. Due to difficulties in placement and holding arrangements, the prototype has an opposed piston arrangement with connecting rods joined to the flywheel at 90° phase angle.

Simulation Model – According to the mathematics, all the required external heat transfer occurs across the boundaries of the working spaces. This apparent paradox is a direct result of the isothermal model in which the compression and expansion spaces are maintained at the respective cooler and heater temperatures. Obviously this cannot be correct, since the cylinder walls are not designed for heat transfer. In real machines the working spaces will tend to be adiabatic rather than isothermal, which implies that the net heat transferred over the cycle must be provided by the heat exchangers. Thus, for a better approximation, an alternative ideal adiabatic model can be established.

Miscellaneous – Opposed piston arrangement caused the distance between the hot and cold gas transfer ports to increase. So the longer transfer pipe resulted in relatively larger pressure drop reducing the system response even further.

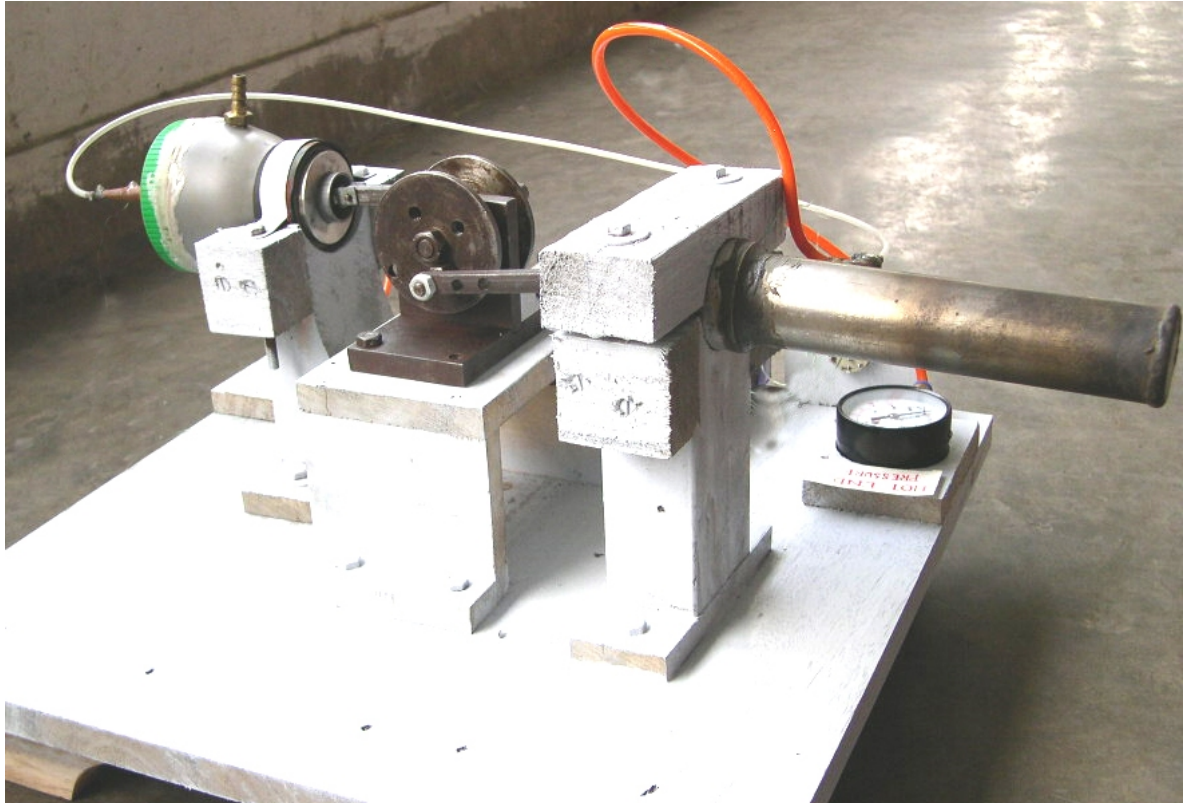


Fig. 14. 1: Alpha Stirling Prototype

Starting from theoretical thermodynamic analysis, a prototype of Stirling engine was developed. But lack of desired response in the cold cylinder prompted us to develop a computer simulation in order to identify the problems occurring inside the engine. Comparing the results from the simulation with those from the experiment conducted, some area of improvement was identified. We are very much hopeful that with the proposed refinements, our successors will be able to run this prototype.

Incorporation of Quick Heating Arrangement:

Using a mesh type electric heater covering a larger surface area would reduce the heating period and therefore increase the system response.

Redesigning the Flywheel:

A larger flywheel would surely assist in harnessing the hot end thrust to recover the lag in cold end response.

Reduction in Dead Volume:

Dead volumes created in hot end should be reduced to increase system pressure.

Identical Hot and Cold End Dimensions:

From the SIMULINK Model, it is observed that identical hot and cold end dimensions enable easier manipulation of system parameters which is not done in the prototype.

Incorporation of a Regenerator:

In the prototype, a wire mesh is placed inside the hot end dead volume to work as a regenerator. In further models, a regenerator with a better design and proper placement can be used. Redesigning the regenerator would also require a minute change in the simulation model.

Initial Pressurization:

To increase the power density, initially pressurized systems as stated in chapter five can be used.

Working Gas:

Modern Stirling engines use working fluids like helium, hydrogen etc. to utilize their higher thermal conductivity rather than using air. In further working models, this concept can also be used.

Insulation of Gas Transfer Arrangement:

The transfer arrangement can be insulated to reduce heat loss during gas transfer.

Books & Review Papers –

1. Engineering Thermodynamics: Rogers, G., Matthew Y. (Pearson Education)
2. Fundamentals of Stirling Technology: Walker, Fauvel, R.
3. An Introduction to LTD Stirling Engines: Senft, James R. (Moriya Press)
4. Build a Two Cylinder Stirling Cycle Engine: Gingery, David J. (Library of Congress)
5. Stirling and Hot Air Engines: Press, C.
6. The Evolution of the Heat Engine: Kolin, I.
7. Thermodynamics and Gas Dynamics of the Stirling Cycle Machine: Organ, Allan J.
8. Thermodynamic Analysis of the Stirling cycle machine – a review of the literature: Organ, Allan J. (IMEchE 1987)
9. A user friendly graphics oriented Stirling engine simulation program: Weiss, M., Fauvel, R. (ISEC 1986)

Internet Resources –

1. <http://www.stirlingengine.com/>
2. <http://www.keveney.com/Engines.html>
3. <http://www.ent.ohiou.edu/~urieli/stirling/me422.html>
4. <http://www.cse.iitk.ac.in/~amit/courses/371/abhishe/main.html>
5. <http://engine.stirling.cz/tedom-stirling-engine-history.html>
6. http://en.wikipedia.org/wiki/Stirling_engine

Detailed Drawings of the Prototype

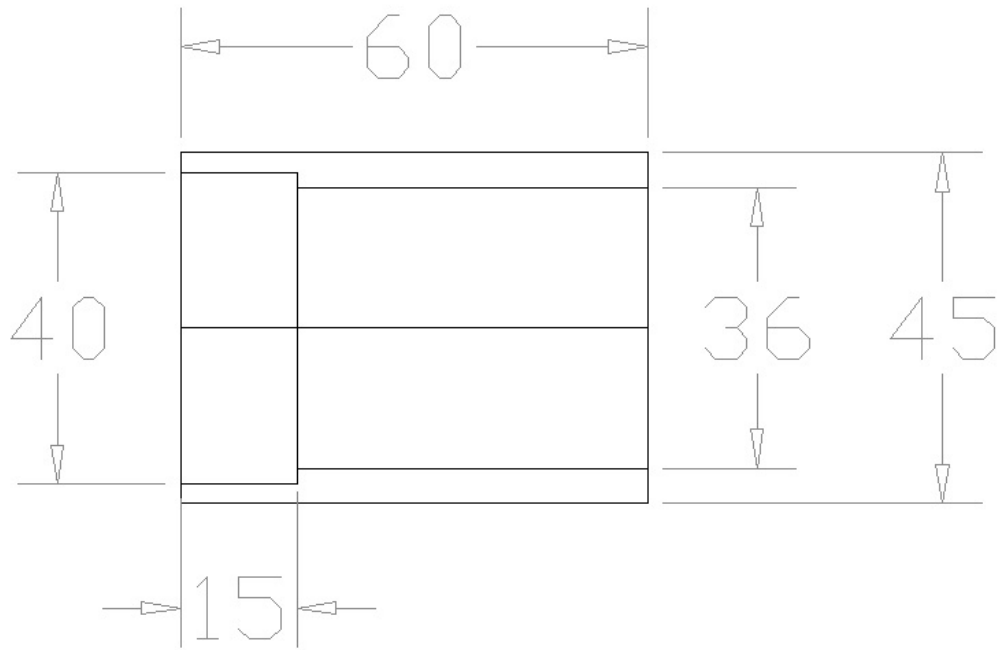


Fig. 17.1: Hot End Cylinder

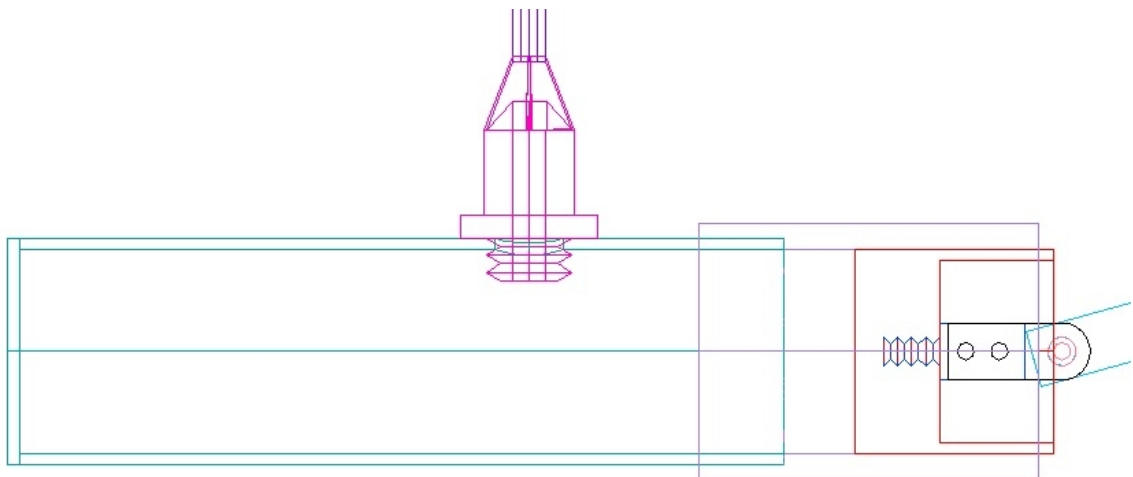


Fig. 17.2: Hot End Assembly

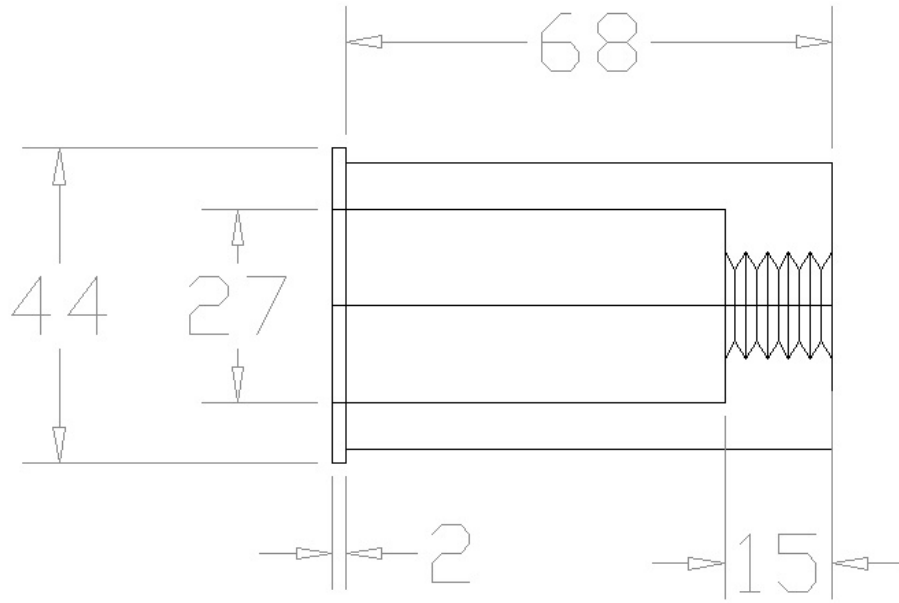


Fig. 17.3: Cold End Cylinder

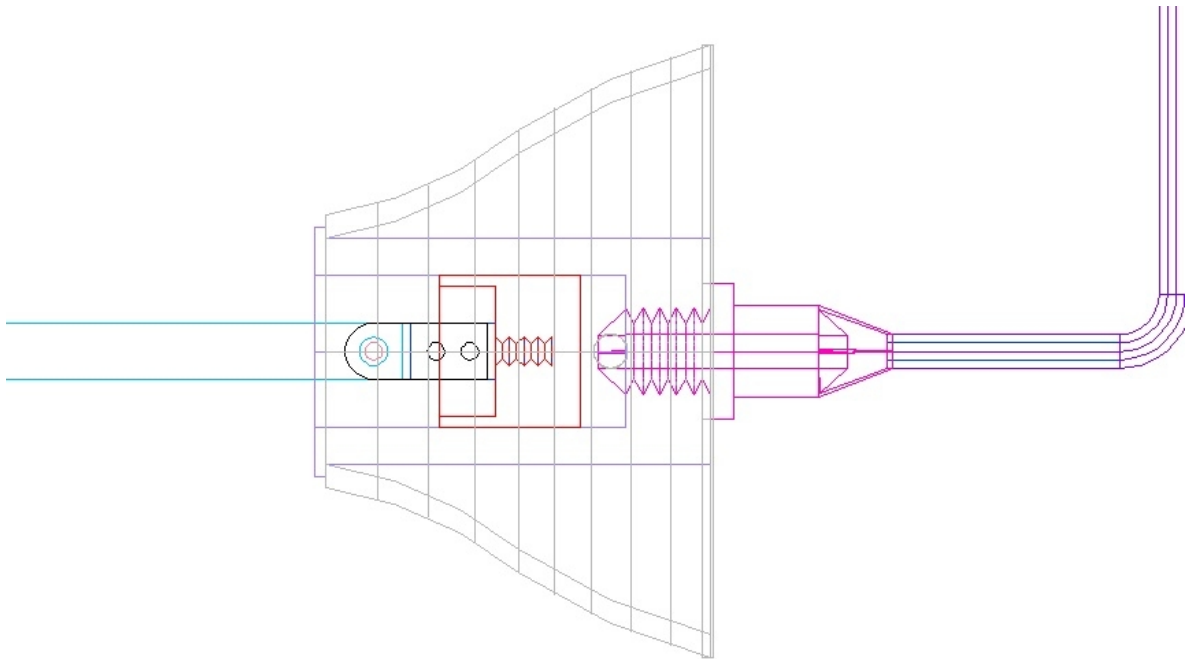


Fig. 17.4: Cold End Assembly

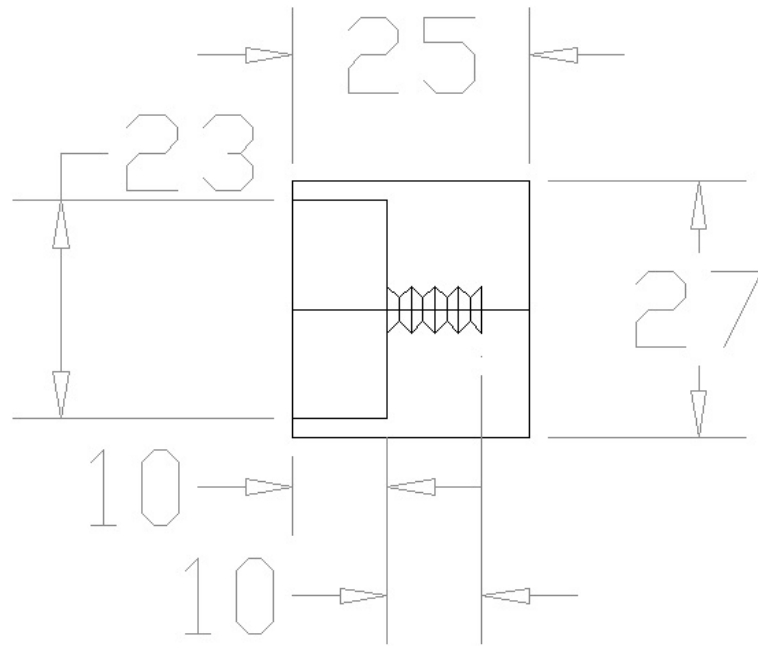


Fig. 17.5: Cold End Piston

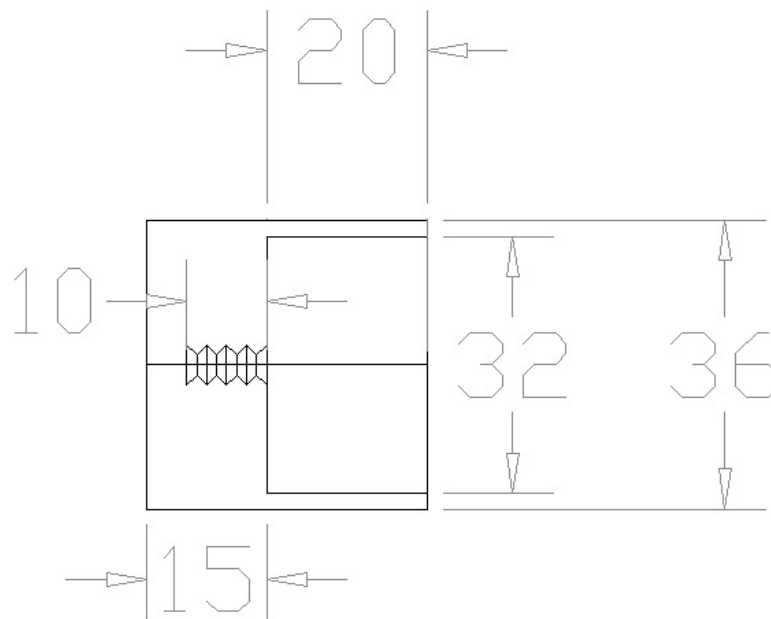


Fig. 17.6: Hot End Piston

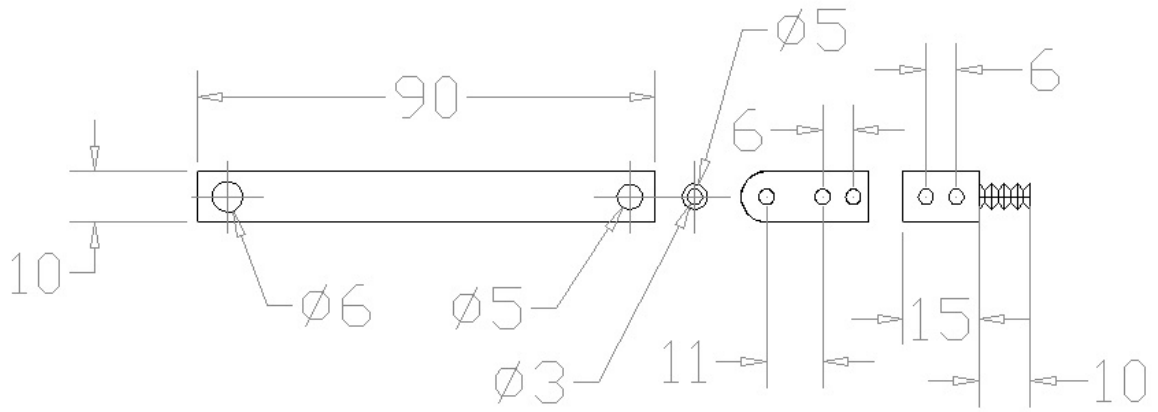


Fig. 17.7: Connecting Rod Assembly

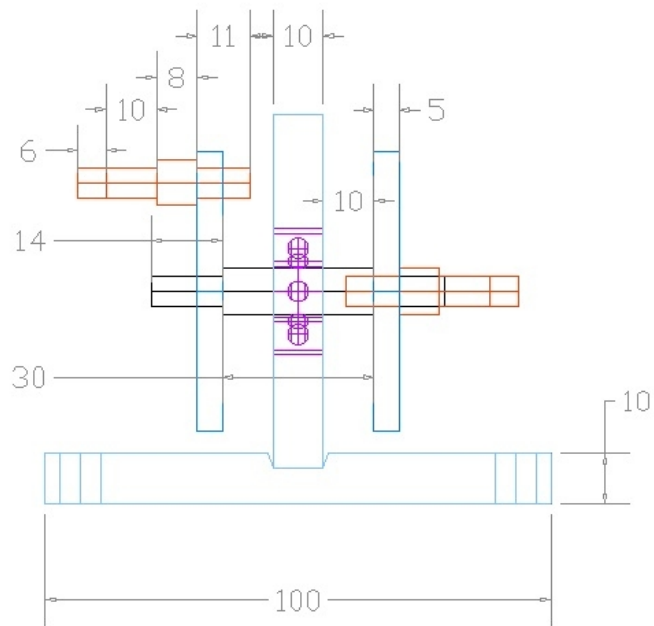


Fig. 17.8: Crank & Flywheel Assembly (Front View)

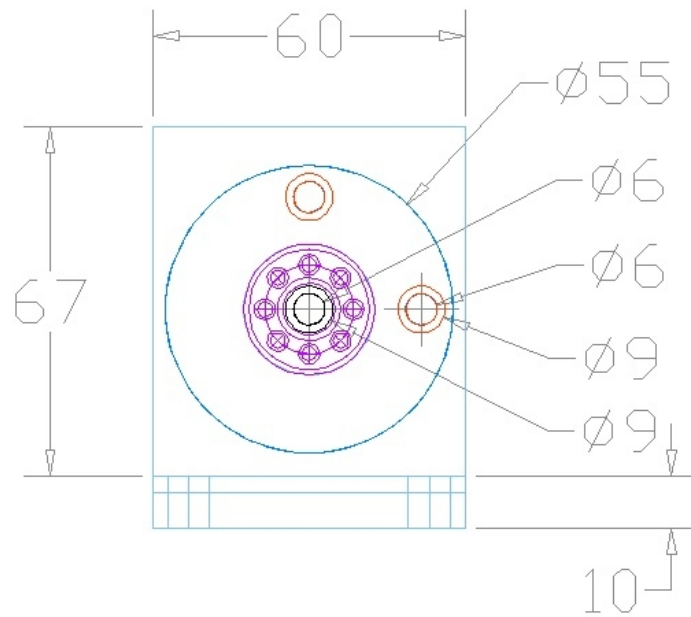


Fig. 17.9: Crank & Flywheel Assembly (Side View)

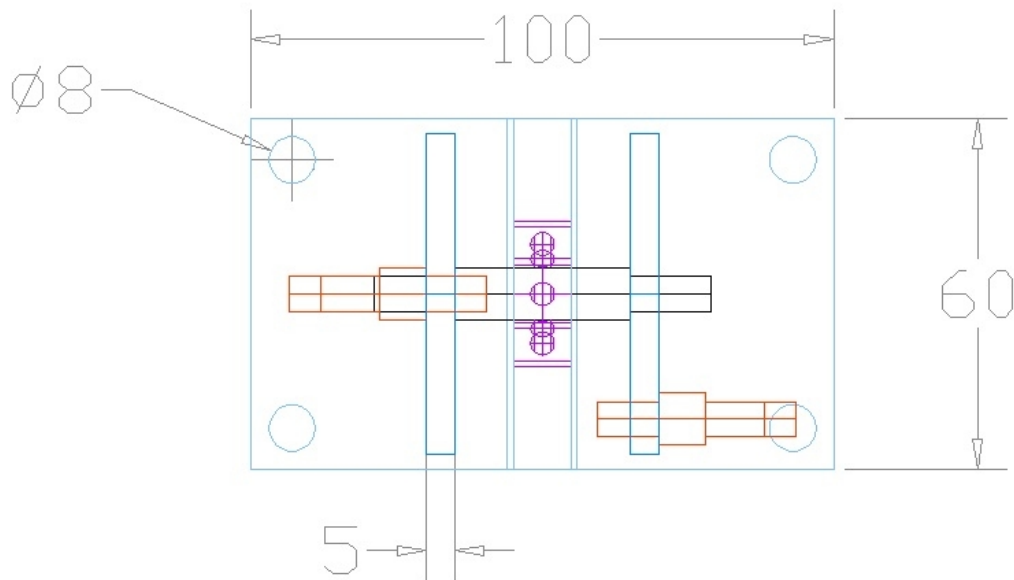


Fig. 17.10: Crank & Flywheel Assembly (Top View)

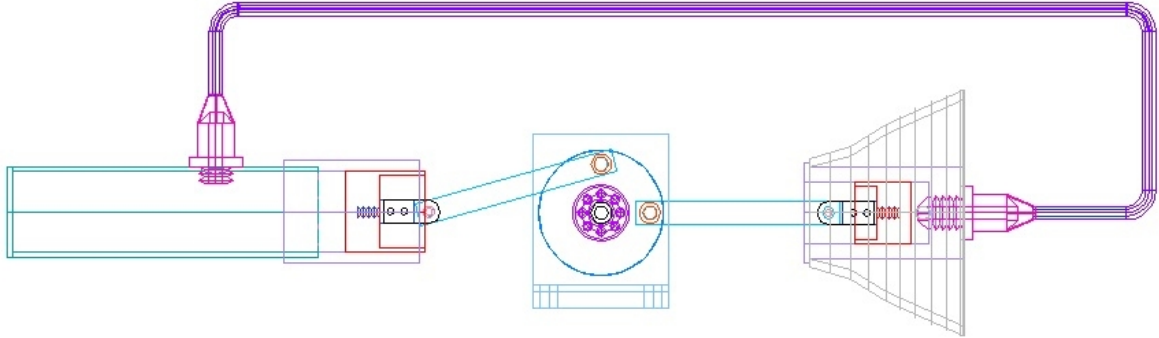


Fig. 17.11: Engine Assembly

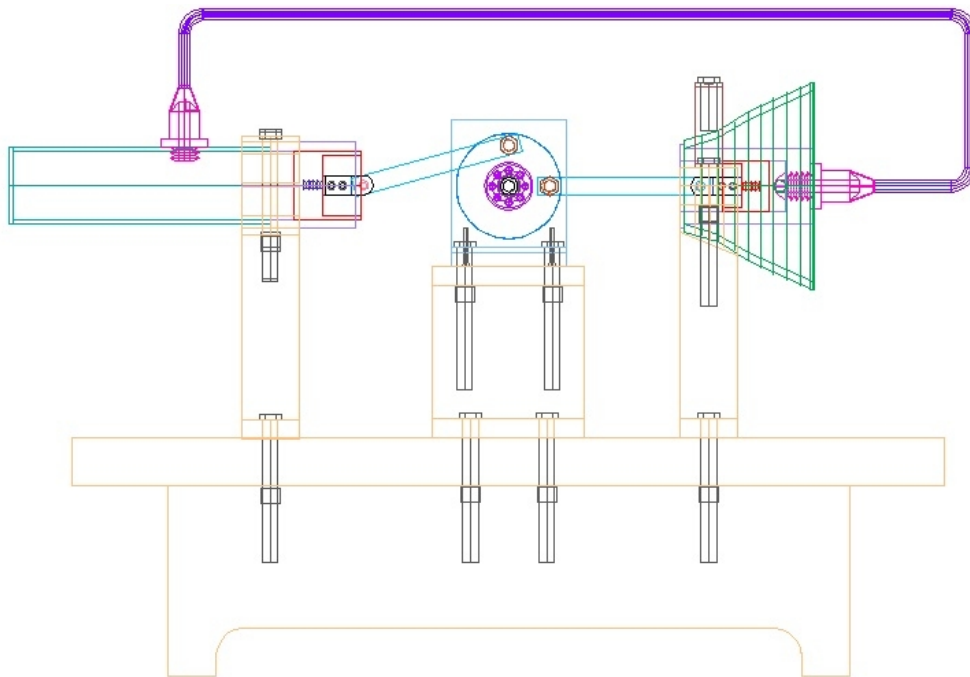


Fig. 17.12: Engine Assembly with Base and Holder