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Experimentation and Computational Analysis of Micro Stirling Engine to Evaluate System Performance and Feasibility in Residential Context

Abhijit Amares Samanta [1], Dr. Santosh D Dalvi [2]
[1] *Research Scholar, Department of Mechanical Engineering, Lokmanya Tilak College Of Engineering, (Affiliated to Mumbai University), India*
[2] *Associate Professor, Department of Mechanical Engineering, Lokmanya Tilak College Of Engineering, (Affiliated to Mumbai University), India*

Abstract:- This aim of this work is to review working fluids for operation of this engine. Air was found to be a good alternative as a working medium for gamma type engines. The major factors that determine the Stirling engine performance are its thermal efficiency and power output. The higher the swept volume difference, the higher the power output from the pressure to volume (P-V) diagram. Providing heat source (constant heat addition) (Ethanol, Calorific value 29.78 MJ/sec, Density 789kg/m3) Measuring the surface temperature of Hot Cylinder Measuring the temperature of insulated displacer.

***Keywords**:* Stirling engine, Isothermal, Power piston, Displacer piston.

1. Introduction

Stirling engines are considered promising for residential applications primarily because of (i) their high total efficiency, (ii) favorable ratio of thermal to electrical power, similar to a typical heat-to-electricity demand ratio of a domestic load, and (iii) low emissions with respect to alternative technologies, like internal combustion engines, allowed by their external and stationary combustion process. In view of these issues with reference to the use of biomass, agricultural and other waste energy sources it was necessary to identify equipment which can be used in micro tri- and cogeneration plants dedicated for use in agriculture and forestry.

The scope of the anticipated uses and the type of used energy can include such issues to agro-power plants. Considering the scope of anticipated application of the equipment and the local capacity of energy raw materials the desirability of meeting local energy needs has been indicated. Focusing on the local balance of power has forced an indication of small machines, high resistance to harsh operating conditions and resistance to changes in quality of energy resources. The possibility to use energy resources that are not used in the power industry and transport is very important. Additionally, energy facilities can be installed in residential or farm buildings. It turned out that the fulfilment of all of these conditions is possible using Stirling engines.

Stirling engines are heat engines with external combustion. Due to this fact, the type of sources of heat used to drive this type of engines, the source of fuel is of lesser importance than in internal combustion engines. This property is the cause of the growing interest in engines of this type. This is due to the possibility of using a variety of fuels without strictly followed restriction of special quality requirements. First of all, in the heat engines with external combustion there is greater of choice and frequent changes of specific fuels.

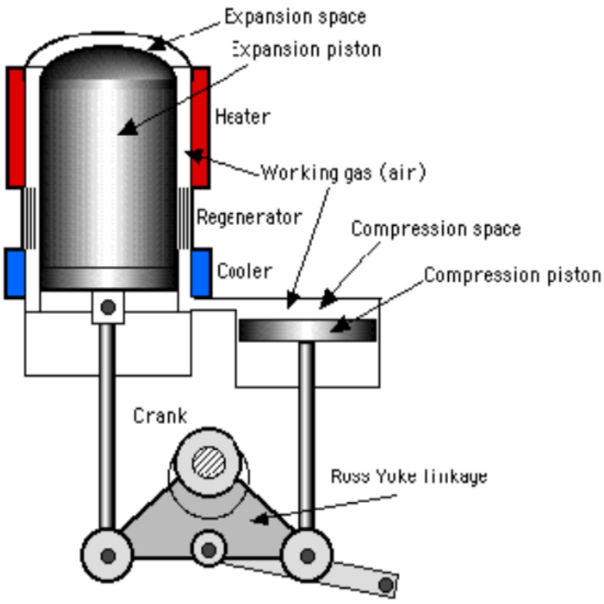

Fig.1 Stirling Engine Constructional Features [2]

The second important feature of engine called the Stirling engine is the possibility of direct use of these engines a different heat sources with variable temperatures. In this case, heat sources may include solar thermal, geothermal and waste energy of heating installations, cooling installations and electrical systems. Extremely quiet operation is the third reason for interest in Stirling engines. Low noise allows installation of engines of this type in houses, farm buildings, recreational yachts, quiet submarines, recreational and quiet airplanes. As a result, these motors improve the quality of life in residential areas, improve the working conditions in industrial areas, are of interest for military applications, as well as play a role in recreational facilities and meet the environmental requirements of agricultural and forestry areas. The current state of knowledge makes it possible to build a Stirling engine with properties comparable to the current operating performance of other types of combustion engines. It is estimated that the cost of a Stirling engine of the same power as other commonly used internal combustion engines is two times higher. However, the energy cost of fuel used for propulsion of Stirling engines may be substantially lower. Due to the large volume of low-energy fuel consumed, it is reasonable to use these engines in stationary installations, and not in mobile. On the other hand, there is the possibility of using high-energy fuels to power Stirling engines used for transportation purposes. In this case, the costs of engines are much higher than engines commonly used in transport. It is possible that the current production costs could be lowered by a sufficiently large scale of production. However, silent Stirling engine used for public transport may be a disadvantage declining road safety, rather than an advantage, as in stationary equipment. For these reasons, at present there is no indication of the desirability of widespread use of Stirling engines for transportation. Energy saving usually increases the real cost of power grid capacity, as usually it is associated with increased daily uneven load on the power grid. For this reason, the transmission costs included in total energy costs are separated from the cost of actual consumption of electricity. In general, the cost of energy transmission power grid and services are comparable to the cost of consumed electricity. For these reasons, we can say that electricity charges are two times higher than the cost of electricity. Therefore, the power grid maintenance costs are comparable to the cost of consumed electricity. As a result, while searching for energy savings, it becomes advisable to reduce costs of transmission. The most favorable possibility seems to be a total elimination of transmission costs. However, such an approach undermines the idea of commonly used, large extensive power grids. Implementation of an alternative idea of dispersed, autonomous energy systems requires a change in legal form. Until now, energy law has imposed a monopoly on large grids. Until recently, it could be said that it is a state monopoly. However, at the moment it is unknown who is legitimately the monopoly owner. Most modern countries live from taxes of all economic activity. For this reason, it seems possible that the extensive grid of monopoly power can be removed without harming the system of modern economic. Some energy companies might be interested in this process because it will create a new market for training, services, and energy equipment. The new proposed organizational concept will also enforce the need for a more flexible approach to the quality standards of electricity. In dispersed system of micro agro-power plants, there appear needs to build and exploit periodically working installations, which are excluded from present demands of quality, especially with respect to the continuity of electricity supply. The development of an alternative idea of dispersed, autonomous systems requires a market of appropriate micro power equipment. From the perspective of country's economic development, it is beneficial as it increases all economic indicators. In a paradoxical way, when aiming to increase the consumption of energy equipment, we can achieve energy saving. Even the sense of a variety of local patriotism and a sense of the expectations of the local energy security, can lead to support such distributed autonomous micro agro power plants system.

Ease of Use

A Stirling engine consists of following components as shown in Fig. 1:

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- transmits 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.

Various assumptions which are made in this cycle are:

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

This cycle can be described by following stages as shown in Fig 2:

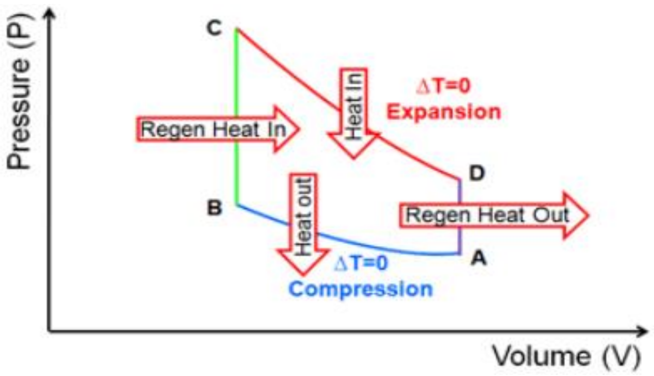

Fig.2 Stirling Engine Cycle PV diagram [2]

Phase C-D: Isothermal expansion-the working fluid undergoes an isothermal 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 equation 1:

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$$We = RTln\left[\frac{V_D}{V_C}\right] = \int pdv = nRTc\ ln\left[\frac{V_D}{V_C}\right] \tag{1}$$

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.

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 equation 2:

$$Wc = RTln\left[\frac{V_B}{V_A}\right] = \int pdv = nRTh\ ln\left[\frac{V_B}{V_A}\right] \tag{2}$$

Phase B-C: 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 (equation 3-4).

$$Wnet = We - Wc$$
$$= nR[Th - Tc]\left[\frac{Vmax}{Vmin}\right] \tag{3}$$

But

$$V_B = V_C \ \& \ V_A = V_D$$

$$efficiency\ of\ engine = \eta = \frac{Wnet}{Qe} = \frac{nR(Th - Tc)\ln\left[\frac{Vmax}{Vmin}\right]}{nR\ Th\ \ln\left[\frac{Vmax}{Vmin}\right]}$$

$$\eta = \frac{Th - Tc}{Th} \tag{4}$$

In Stirling cycle, two Isochoric processes replace the two Iso-entropic processes s in an ideal Carnot cycle as shown in Fig 2. 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 in Fig 3.

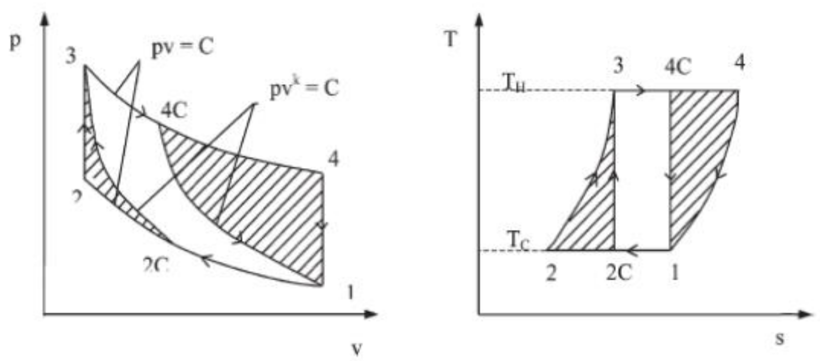


Fig.3 Stirling Engine P-V and T-S Cycle [3]

2. Review of Literature

Mahendru [8], make case study on solar powered water pumping project in Samastipur, Bihar, India. In this technology solar panel operating voltage-220V×8 panels, maximum power per panel-230 W, maximum power of solar array1840 W, submersible pump-2HP, water discharge12000 lit/hour on sunny day, size of each pond-1 Acre, total ponds-44. Khandker et. al. [9], suggested that the provision of high quality energy services to rural areas has lagged behind urban areas. It is both financially and physically more difficult to service remote and poor populations compared to those living in urban areas. There are still significant challenges in improving the reliability of power supply in rural area in the country. The challenges are basically two-fold: How to improve the access of rural households to electricity beyond the current rate of 56 percent and how to ensure reliable and adequate supply of electricity. Although rural energy activities receive significant support from the Government of India, our findings would tend to confirm that there is still a long way to go to ensure that the rural poor can take advantage of the many benefits of modern energy and the services that they provide to consumers.

Christoph et. al. [10], analyze the Stirling engine from economic point. They pointed that (i) Only a very small power operation can carry out a Stirling engine, which contributes a lot to energy conservation. (ii) If solar is used to produce energy for the Stirling engine, the cost would be cut down for quite a lot, it costs much to manufacturing. (iii) Stirling engine exhausts cleanly and avoid lot of pollution, which reduce so much cost for pollution control and government. (iv) At the end of 18th century and the early 19th century the heat engine efficiency is very low, only 3% to 5% but now the efficiency of Stirling engine can come up to 80% or even more. So another part of cost is saved. Risberg [11], built a Stirling engine with specification as follow: Crankshaft – 7 inches long with a ½ inch depth, Crankshaft supports – 4.5 inches high, 1.25 inches wide, Pressure Vessel and displacer – 3 9/16 inch diameter, Displacer Bottom - 1.3 inches high, Displacer Top pin - 2.2 inches high, Stand - 3.5 inches high. Efficiency, Torque, Power, Angular speed, and acceleration are all unknown since the engine did not successfully run.

Kwankaomeng and Burapattanon [12], develop a gamma type Stirling engine with double power piston working temperature range of 512-54°C at the hot head engine and air cooler section respectively. The prototype has displacer diameter and stroke of 218.5 mm and 80 mm respectively. And power piston diameter and stroke of 98.5 mm and 110 mm respectively. The engine was improved and tested over wide range of operating conditions for comparison. The results indicate that power of the improved prototype is better than unpressurized engine and using air as working gas. The maximum engine power was 5.05 W at 68.7 rpm and maximum torque was 0.978 N-m at 45 rpm. Maximum engine speed was 130 rpm at temperature of 560° C. The test results showed that the engine started operation in 5 minute at temperature about 490° C on the hot engine head and temperature of 47°C at air cooler section. Hirata et. al.[13], evaluate performance for a 100 W Stirling engine on the basis of pressure, pressure loss, leakage of working gas, buffer space loss, indicated work and power, mechanical loss etc. analytical and compare with model.

From this they conclude that

1. The pressure loss at the regenerator, the gas leakage and the heat transfer in the buffer space was presented. It can simulate the engine performance adequately.
2. The buffer space loss of the prototype engine is estimated adequately, when it is considered the heat transfer with the number of heat transfer unit, NTU=0.1.3. Working gas flowed without an enough extending in the regenerator in the prototype engine. Koichi [14], develop compact and low cost a gamma type Stirling with simple moving-tu4be-type heat exchangers and a rhombic mechani4sm. Its target shaft power is 50 W at speed of 4000 rpm and mean pressure of 0.8 MPa. The test was done in without load, using air in atmospheric condition. Also, a mechanical loss measurement was done in highly pressurized condition in which the engine was driven by motor. Thombare and Verma [15], published review paper on isothermal analysis, heat transfer in isothermal and adiabatic model, maximum obtainable efficiency, Schmidt's theory, heat transfer phenomenon in different parts of sterling engine such as heater , cooler, regenerator analysis, engine configuration and classification, working fluid, power and speed control, performance governing factor and different characteristics of Stirling engine. Stirling Energy Systems (SES) [16] Company in partnership with

Sandia National Lab managed to break the world record for solar-to-grid conversion efficiency at an amazing 31.25 % on January 31, 2008. SES Serial 3 was erected in May 2005 as part of the Solar Thermal Test Facility which produced up to150kW of grid ready electrical power during the hours of sunlight. Each dish consisted of 82 mirrors that can focus the light into an intense beam (Systems, 2008). SES solar Stirling engine, named Sun Catcher, was awarded the 2008 Breakthrough Award winner by Popular Mechanics for its role as one of the top 10 world-changing innovations. The Sun Catcher is a 25 kWe solar dish Stirling system which uses a solar concentrator structure which supports an array of curved glass mirror which are designed to follow the sun and collect the focused solar energy onto a power conversion unit.

The diagram below illustrates the workings of SES's Sun Catcher. Minassians and Sanders [17], make feasibility study of a low-cost solar-thermal electricity generation technology, suitable for distributed deployment, based on nominating solar concentrators, integrated with free-piston Stirling engine devices incorporating integrated electric generation. Concentrator collector operates at moderate temperatures, in the range of 120°C to 150°C.

This temperature range is consistent with the use of optical concentrators with low-concentration ratios, wide angles of radiation acceptance which are compatible with no diurnal tracking and no or only a few seasonal adjustments. Therefore, costs and reliability hazards associated with tracking hardware systems are avoided. They further outline the design, fabrication, and test results of a single-phase freepiston Stirling engine prototype.

A very low loss resonant displacer piston is designed for the system using a very linear magnetic spring. The power piston, which is not mechanically linked to the displacer piston, forms a mass-spring resonating subsystem with the gas spring, and has a resonant frequency matched to that of the displacer. The design of heat exchangers is discussed, with an emphasis on their low fluid friction loss; an appropriately dimensioned Stirling engine candidate is discussed. Wood et. al. [18], preliminary design a linear motion free-piston Stirling engine / blower coupled to a rotary turbine / generator. The design combines several features of prototype free-piston machines that are nearing commercial production.

The Stirling driver is comprised of two conventional, displacer types, free-piston engines configured as a dynamically balanced opposed pair. Using the outer face of its power piston, each engine drives a single acting blower. The single turbine / generator use commercial units and are separate from the engines and connected by ductwork. The engines and turbines utilize the same helium working fluid. Moon and Miller [19], complete a rigorous computational model of the engine using Fluent fluid dynamics software.

After that attempt they made to model the engine in Solidworks' Floworks application, that software proved inadequate for analyzing the transient states present in Stirling engine operation. Then they conduct another experiment in order to determine the actual heat flux concentrator capable of producing, in order to closely match the performance of engine with that of our dish. Finally, they finalize all design elements and. They also wrote all CNC code using Solidworks and Mastercam, in order to do the required machining using SDSU's facilities. Kangtrageal and Wongwises [6], published a review of solar power Stirling engine. They give some idea about low temperature differential Stirling engine, its characteristics. Also state that engine operation of the Stirling engine depends on the material used for construction. Engine efficiency ranges from about 30% to 40% resulting from a typical temperature range of 923-1073 K and a normal operating speed from 2000 to 4000 RPM, motion diagram , engine indicated work, Stirling engine feasibilities for rural and remote areas, engine optimization techniques, utilization of solar energy using concentrating collector, solar disc technology.

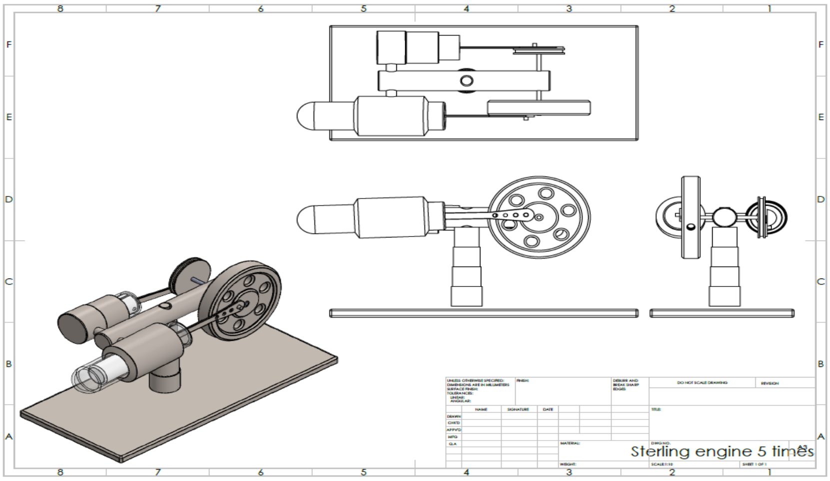
	Bare Cylinder temp °C	Bare Displacer temp °C
1	105	51.5
2	97	44.4
3	93.3	39.5
4	81.9	37.7
5	56.2	36.1

3. Objectives

Temperature Measurement with Heat Source Continuous Heat Addition.The equations in the operating system were integrated through complete cycles to determine the pressure, displacement and velocity of the piston and displacer, the pressure drop and heat losses, and the volume of the expansion and compression spaces until the steady state operation of the engine.

4. Methodology For Pilot Run Project

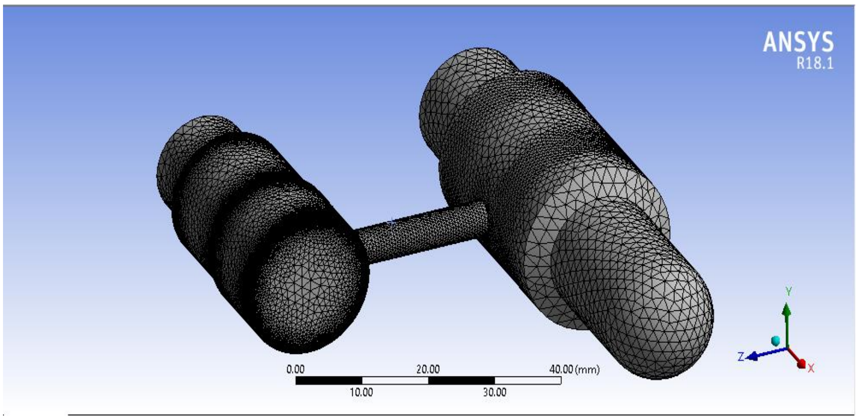
Stirling Engine Assembly Drawing



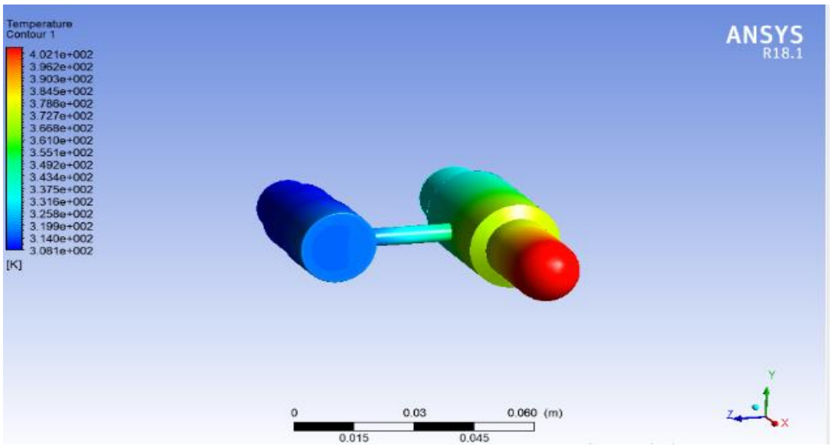
Input parameters of the gamma Stirling engine for model validation (data collected from Gheith et al. [25]).

Engine Data	Value
Mean Pressure (bar)	2.068
Heater Temperature (°C)	105
Cooler Temperature (°C)	51.5
Phase angle (degree)	90^0
Working gas	Air

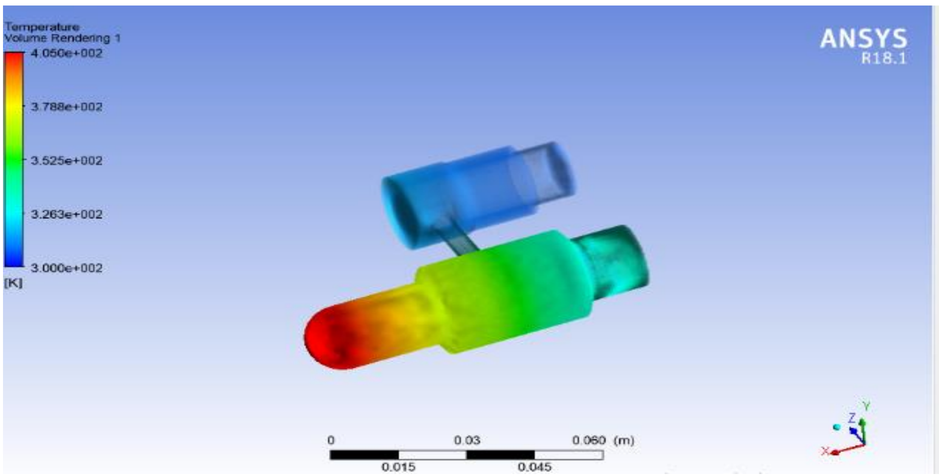
Ansys meshing was used to mesh the model



Ansys fluent is used for simulation temperature distribution



On the surface the temperature observed was minimum temperature of 308K or 35 ^{0}C & maximum temperatures of 402K or 129 ^{0}C.



Regenerator material	Heater Temperature	Charge Pressure	Brake Power (W) (Experiment)	Brake power (W) (Simulation)	RMS Error (%)
Stainless Steel	105	3	150	146	0.028
		5	275	269	0.042

5. Conclusion

The Stirling engine performance thermal efficiency and power output are compared by experimental and simulation model higher the swept volume difference, the higher the power output from the pressure to volume (P-V) diagram.

References

[1] M. Kordab, Priority option of photovoltaic systems for pumping in rural areas in ESCWA member countries, Science Direct, desalination, 209, 2007, 73-77.
[2] G. Walker, Stirling engine (Oxford Clarendon Press, Calgary).
[3] W. B. Stine, Stirling Engines, (CRC Press, Boca Raton, 1998).
[4] M. J. Dadi, I. M. Molvi, A. V. Mehta, The most efficient waste heat recovery device: a gamma type Stirling engine, International journal of advanced engineering technology, January – March, 2012, 189 – 195.
[5] G. Cronenberg, the Stirling Engine, Uppasala University, 2005.
[6] B. Kongtragool, S. Wongwises, A review of solar powered Stirling engines and low temperature differential Stirling engine, Science Direct renewable and sustainable energy, 7 ,2003, 131 – 154.
[7] D. Aranda, K. LaMott, S. Wood, Solar Stirling Engine for Remote power and Disaster Relief, Florida International University, 2010.
[8] V. Mahendru, Case study on solar powered water pumping project in Samastipur, Bihar, India, Claro energy private limited, 2012.
[9] S. R. Khandker, D. F. Barnes, H. A. Samad, Energy poverty in rural and urban india, Policy research working paper, The world bank development research group, agriculture and rural development, 2011, 5463.
[10] M. Christoph, G. Arnaud, A. Rafael, S. Li, Y. Xue, Stirling engine, university of Gavle, 2007.
[11] R. Brandon, Stirling engine, Applied Science research, 12th Grade, 2007.
[12] S. Kwankaomeng, K. Burapathananon, Development of a Gamma Type Stirling Engine with Double Power Piston, The international conference of the thai society of agricultural engineering, Chiangmai, Thailand, 2012.
[13] K. Hiratai, S. Iwanmoto, F. Toda, H. Kazuhiro, Performance evaluation for 100 W Stirling engine, 8 th International Stirling engine conference, 1997, 19 – 28.
[14] K. Hirata, Development of a small 50 W class striling engine, Ship research institute, Shinkawa, Mitaka, Tokyo, Japan, 6-38-1.
[15] D. G. Thombare, S. K. Verma, Technological Development in the Stirling Cycle Engines, Science Direct, Renewable and Sustainable Energy Reviews, 12, 2008), 1 – 38.
[16] S. Sets, World Record for Solar – to – Grid Conversion Efficiency, S. E. Systems, 2008.
[17] A. D. Minassians, S. R. Sanders, Stirling engines for distributed low cost solar thermal electric power generation, Journal of solar energy engineering, 133, 2011.
[18] J. Wood, N. Lanel, W. Beale, Preliminary design of a 7 kWe free piston Stirling engine with rotary generator output, proc. 10th ISEC, Osnabruck, Germany, 2001.
[19] K. S. Moon, F. J. Miller, Stirling solar engine design, San diego state university, 2009.