EXPERIMENTAL ANALYSIS OF LOW TEMPERATURE DIFFERENCE STIRLING ENGINE

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Abstract - *Large amount of heat is wasted in the environment. Heat is generated by way of fuel combustion or chemical reaction, and then waste heat is dumped into the environment even though it could still be reused for some useful and economic purpose. All lot research and techniques are done to find the best ways of using the deployable sources of energy, and of developing techniques to reduce pollution. This interest has encouraged research and development for re-use of the usually wasted forms of energy. There are many methods through which waste heat energy can be recovered and utilized. Stirling engines are mechanical devices working theoretically on the Stirling cycle. It uses air, hydrogen, helium, nitrogen or even vapors as working fluids. The Stirling engine offers possibility for having high efficiency engine with less exhaust emissions in comparison with the internal combustion engine. We had manufactured a gamma type Stirling engine which operates at high temperature difference. In this research paper modification in existing design of Low Temperature Difference (LTD) Stirling engine is done.*

Key Words: **Stirling cycle, Alpha configuration, Beta configuration, Gamma configuration, Rankine Cycle.**

1.INTRODUCTION

Development of Stirling engines is preceding world-wide in spite of their admittedly higher cost because of their high efficiency, particularly at part load, their ability to use any source of heat, their quiet operation, their long life and their non-polluting character. Due to this they were generally called air engines and were characterized by high reliability and safety, but low specific power. A great variety of experimental Stirling engines have been built from the same general principles to directly pump blood, generate electricity, or directly generate hydraulic power. Many are used as heat pumps and some can be used as both heat pumps and heat engines depending upon the adjustment.

1.1 METHODS TO UTILIZES THE REJECTED ENERGY

Thermal Power Plant: It follows Rankine cycle and uses fossil fuels as heat source. Because of large amount of heat is rejected in condenser, it is having efficiency around 25 to 35 %.

Diesel Power Plant: It follows Diesel cycle and uses diesel fuel as heat source. Because of large amount of heat is rejected in condenser, it is having efficiency around 20 %.

Gas Turbine Power Plant: It works on Brayton cycle. Generally they are of open type and uses fossil fuels in gaseous form as heat source. It efficiency is around 40 %.

1.2 WASTE HEAT RECOVERY SYSTEMS

Depending upon the type of process, waste heat can be rejected at virtually any temperature from that of chilled cooling water to high temperature waste gases from an industrial furnace or kiln. Usually higher the temperature, higher the quality and more cost effective is the heat recovery. In any study of waste heat Recovery, it is absolutely necessary that there should be Some use for the recovered heat. Typical examples of use would be preheating of combustion air, space heating, or pre-heating boiler feed water or process water. With high temperature heat recovery, a cascade system of waste heat recovery may be practiced to ensure that the maximum amount of heat is recovered at the highest potential. An example of this technique of waste heat recovery would be where the high temperature stage was used for air pre-heating and the low temperature stage used for process feed water heating or steam raising

2. BASICS OF WASTE HEAT RECOVERY

- The essential quality of heat is not the amount but rather its “value”.

- The strategy of how to recover this heat depends in part on the temperature of the waste heat gases and the economics involved.
- Large quantity of hot flue gases is generated from Boilers, Kilns, Ovens and Furnaces.
- Waste heat is heat, which is generated in a process by way of fuel combustion or chemical reaction, and then "dumped" into the environment even though it could still be reused for some useful and economic purpose.

Table -1: Typical waste heat temperatures at high temperature range from various sources

Types of Device	Temp. °C
Nickel refining furnace	1370 –1650
Aluminum refining furnace	650-760
Zinc refining furnace	760-1100
Open hearth furnace	650-700
Cement kiln (Dry process)	620- 730
Glass melting furnace	1000-1550
Solid waste incinerators	650-1000
Fume incinerators	650-1450

2.1 MEDIUM TEMPERATURE HEAT RECOVERY

Table 2 gives the temperature ranges of waste gases from process equipment in the medium temperature range. Most of the waste heat in this temperature range comes from the exhaust of directly fired process units

Table -2: Typical waste heat temperatures at high temperature range from various sources

Type of Device	Temp. °C
Steam boiler exhausts	230-480
Gas turbine exhausts	370-540
Reciprocating engine exhausts	315-600
Reciprocating engine exhausts (turbo charged)	230- 370
Heat treating furnaces	425 - 650
Drying and baking ovens	230 - 600
Catalytic crackers	425 - 650
Annealing furnace cooling systems	425 - 650

2.2 DIRECT BENEFITS

Recovery of waste heat has a direct effect on the efficiency of the process. This is reflected by reduction in the utility consumption & costs, and process cost.

2.3 DEVELOPMENT OF WASTE HEAT RECOVERY SYSTEM

Understanding the process is essential for development of Waste Heat Recovery system. This can be accomplished by reviewing the process flow sheets, layout diagrams, piping isometrics, electrical and instrumentation cable ducting etc. Detail review of these documents will help in identifying;

1) Sources and uses of waste heat
2) Upset conditions occurring in the plant due to heat recovery
3) Availability of space,
4) Any other constraint, such as dew point occurring in an equipments etc.

After identifying source of waste heat and the possible use of it, the next step is to select suitable heat recovery system and equipments to recover and utilize the same.

It is necessary to evaluate the selected waste heat recovery system on the basis of financial analysis such as investment, depreciation, payback period, rate of return etc. In addition the advice of experienced consultants and suppliers must be obtained for rational decision .Types of waste heat recovery systems are;

1) Recuperates,
2) Regenerator,
3) Heat wheels,
4) Heat pipe

Above mentioned waste heat recovery systems can utilize high and medium temperature waste heat only. They cannot recover low temperature waste heat effectively. So if we want to recover low and very low temperature waste heat we can go for STIRLING ENGINE, which can recover any kind of low grade waste heat because it is external combustion engine and also its efficiency is very good

3. INTRODUCTION TO STIRLING ENGINE

The Stirling engine (or Stirling's air engine as it was known at the time) was invented and patented by Robert Stirling in 1816. It followed earlier attempts at making an air engine but was probably the first to be put to practical use when in 1818 an engine built by Stirling was employed pumping water in a quarry.

3.1 STIRLING ENGINE PRINCIPLE

It converts thermal energy into mechanical energy by following Stirling cycle.

1) Isothermal expansion,
2) Isochoric (constant volume) heat removal
3) Isothermal compression,
4) Isochoric heat addition.

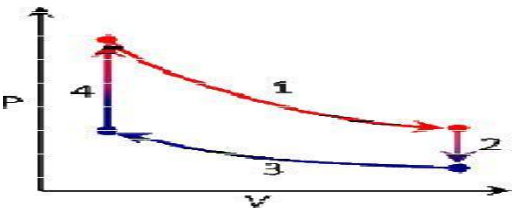

Fig -1: Stirling Cycle P-V Diagram

3.3 STIRLING ENGINE OPERATION

Since the Stirling engine is a closed cycle, it contains a fixed mass of gas called the "working fluid", most commonly air, hydrogen or helium. In normal operation, the engine is sealed and no gas enters or leaves the engine. No valves are required, unlike other types of piston engines. The Stirling engine, like most heat engines, cycles through four main processes: cooling, compression, heating and expansion. The gas follows the behavior described by the gas laws which describe how a gas 'pressure, temperature and volume are related. Power piston has compressed the gas, the displacer piston has moved so that most of the gas is adjacent to the hot heat exchanger. The heated gas increases in pressure and pushes the power piston to the farthest limit of the power stroke. The displacer piston now moves, shunting the gas to the cold end of the Cylinder. The cooled gas is now compressed by the flywheel momentum. This takes less energy, since when it is cooled its pressure dropped

3.4 STIRLING ENGINE TYPES

There are two major types of Stirling engines that are distinguished by the way they move the air between the hot and cold sides of the cylinder:

Alpha Type

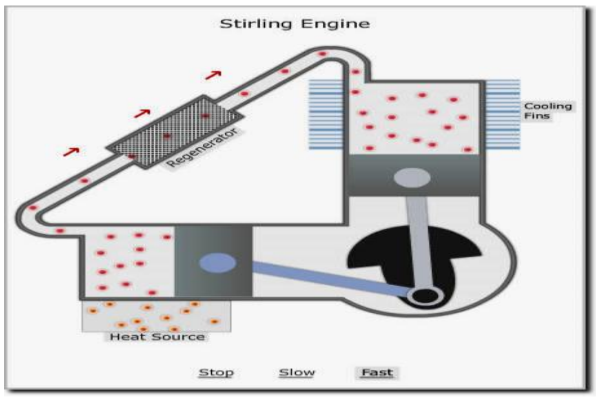

Fig -2: Alpha Configuration

An Alpha Stirling contains two power pistons in separate cylinders, one hot and one cold. The hot cylinder is situated inside the high temperature heat exchanger and the cold cylinder is situated inside the low temperature heat exchanger. This type of engine has a 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. In practice, this piston usually carries a large insulating head to move the seals away from the hot zone at the expense of some additional dead space.

Beta Type

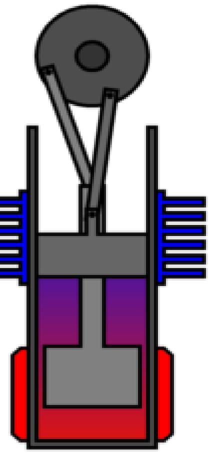

Fig -3: Beta Configuration

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.

Gamma Type

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 and remains a single body. This configuration produces a lower compression ratio, but is mechanically simpler and often used in multi-cylinder Stirling engines

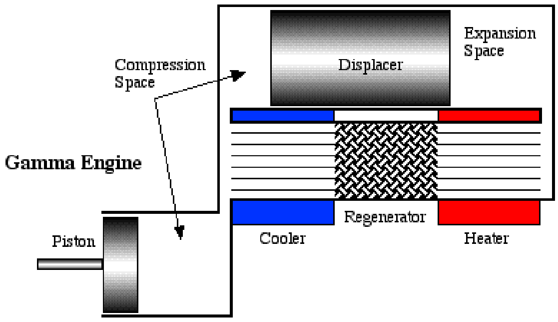

Fig -4: Gamma Configuration

4. MATERIAL SELECTION AND DIMENSIONS OF LTD STIRLING ENGINE AND CALCULATION OF EFFICIENCY

Generally most of power producing devices is designed based on output power requirement. But case is very much different for low temperature difference Stirling engine. Ltd Stirling engine are designed based on heat input available from the heat source and temperature difference available across the engine.
LTD Stirling engines are generally having configuration of gamma type, because in gamma configuration large area is made exposed to heat source and sink. So it is effective for recovering low temperature waste heat. Some characteristics of the LTD Stirling engine are as follows;
1. Displacer to power piston swept volumes ratio is large, 2. Diameter of displacer cylinder and displacer is large , 3. Displacer is short, 4. Effective heat transfer surfaces on both end plates of the displacer cylinder are large, 5. Displacer stroke is small, 6. Dwell period at the end of the displacer stroke is rather longer than the normal Stirling engine, 7. Operating speed is low.

4.1 MATERIAL SELECTION & DIMENSIONS

Heat exchanging surfaces have to be of higher thermal conductivity so that better heat transfer can take place from source to system and from system
1.Copper, 2. Aluminum, 3. Mild steel, 4. G.I. (galvanized iron).

We have used aluminum sheet (2mm thick). Size:
Aluminum: 250 * 250 * 2 mm

Displacer cylinder should have good resistance to heat transfer (lower thermal conductivity) so that heat cannot flow from hot surface to cold surface through cylinder body. Kinds of the displacer cylinder materials that satisfy above requirement and can be used are as follows:
1) Wood, 2) Concrete, 3) Plastic, 4) Glass.

We want to design LTD Stirling engine model for recovering waste heat from exhaust gases of I.C. engine or wood fired water heater. So we made heat exchanging surfaces of 250mm*250mm area and thickness of 2mm. Material that we selected was aluminum. And displacer cylinder of diameter 125mm, height of 50mm and thickness of 2mm. Material that we selected was plastic. It is the cylinder in which displacer performs its stroke. Displacer cylinder must have low thermal conductivity, because heat should not flow from hot surface to cold surface. Size: Plastic: 125 mm diameter, 1 mm thickness
There is empirical relation available for dia. of displacer that the diameter of displacer should be somewhat smaller than diameter of piston so that it gives small radial clearance around 2mm to 3mm between displacer and its cylinder for displacing of air across cylinder.
Thickness of displacer should be slightly greater than half the height of displacer cylinder.
Diameter of displacer ≈ diameter of displacer cylinder – 2* radial clearance
Displacer has to be light in weight and good resistant to heat transfer. So material of displacer should be of lower density and lower thermal conductivity. Kinds of displacer materials that satisfy above requirement and can be used are as follows:

1) Wood ,2) Thermocol , 3) RPF (reinforced plastic).

It displaces working fluid (air in our case) between hot and cold surface. It has to be low in weight and low thermal conductivity. Size:: Thermocol: 120 mm diameter, 30 mm thick

Power piston expansion volume =
$$\frac{122.72 * 10^2}{25}$$

$= \quad 4908.8mm^3$

Power piston expansion volume = π × (dia.ofcylinder)^2 × stroke
Diameter of power piston cylinder =4

$$POWER= \sqrt{\frac{4908.8 \times 4}{\pi \times 10}}$$

= 25mm.

As mention above diameter of displacer is 125mm and we have taken radial clearance of 2mm. Putting these values in above equation.
Diameter of displacer ≈ diameter of displacer cylinder – 2* radial clearance
Diameter of displacer ≈ 125-2* 2 =121mm ≈ 120mm (taken data)
We have taken thickness of 30mm which is higher than half of the height of cylinder (25mm).
There is equation available for stroke of displacer.

Stroke= (height of cylinder- thickness of displacer)- 2* clearance
We have to provide some clearance between cold surface and upper surface of displacer and between hot surface and lower surface of displacer. We provided clearance of 5mm.
So, stroke=(50−30)−2×5=10mm
Kinds of materials that satisfy above requirement and can be used are as follows:
1. Steel piston and steel cylinder, 2. Graphite piston and glass cylinder, 3.Epoxy resin piston and glass or steel cylinder, 4. Brass piston and brass cylinder, etc.

Stroke of power piston = stroke of displacer = Stroke of power piston = 10 mm

Crank Radius=$\frac{Stroke}{2}$ =5 mm

Crankshaft: It converts reciprocating motion into rotary motion and also supports flywheel. Size: SS, 2 diameter, 160 mm length.90° phase angle difference. Flywheel: it is made up of plastic with 120 mm diameter, 1 mm thickness. Supports for Crank Shaft: It supports crank shaft between two point bearings Size: ms, 10 mm diameter, and 120 mm height
Power piston expansion volume =$\frac{Swept\ volume\ of\ Displacer\ cyclinder}{25}$

Swept volume of displacer cylinder = $\frac{\pi}{4} \times 125^2 \times 10$

= $122.72\times10^3 mm^3$

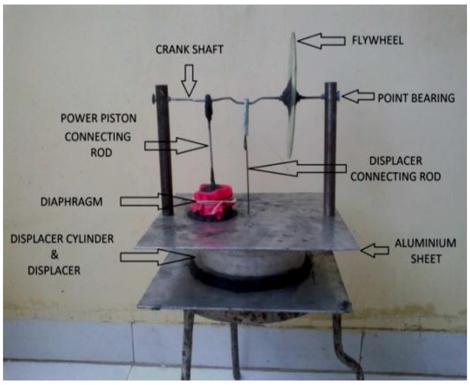

Fig -5: Final Configuration

4.6 CALCULATION STEPS TO FIND OUT THERMAL EFFICIENCY OUTPUT POWER

According to BEALE FORMULA,

$P_{out} = 0.015\times p_m \times f \times V_p$

Where,
P_{out} - the engine power output in Watts, 0.015 is BEALE CONSTANT,
p_{m}- the mean cycle pressure in bar,
f -the cycle frequency in Hz, and
V_{P}- is displacement of power piston in cm^3.

$P_{in} = m_f \times C.V. = m_e \times Cp_e \times (T_{in} - T_{out})$

Where,
P_{in} - heat input in Watts,
m_f - mass flow rate of fuel in kg/sec, C.V. is calorific value of fuel in J/kg,
m_e - mass flow rate of exhaust gases, Cp_e is specific heat of exhaust gases,
T_{in}- inlet temperature of exhaust gases, T_o outlet Temperature of exhaust gases.

Thermal efficiency= $\frac{P\ out}{P\ in}$

5. CONCLUSIONS

Here we have selected materials and dimensions of our Model, according to materials and dimensions specified by American Stirling Engine Company for their model Which is having efficiency of 20 %.After making model heat is supplied from the heat source of candle and kerosene burner. The engine was working but didn't give output as the amount of supplied heat is less to conduct the experiment on our model. CFD Analysis can be done to get better performance, as it give the accurate and precise values and pressure-temperature images to visualize the effect and better heat recovery from Stirling Engine. So our main objective to find out optimum temperature difference at which model would give maximum thermal efficiency is in process

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