Waste heat is the 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. 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. If some of this waste heat could be recovered, a considerable amount of primary fuel could be saved.

1.1 Waste Heat Recovery

Recent trend in the world concerns about the best ways of using the deployable sources of energy, and using the same also reducing the environmental pollution. This interest has encouraged research and development efforts in the fields of alternative energy sources, cost effective use of the exhaustible sources of energy, and the re-use of the usually wasted forms of energy.

A large number of industrial processes, covering most industrial sectors, use significant amounts of energy in the form of heat, which is rarely utilized efficiently. Thus there is considerable scope for the use of heat exchangers and other forms of heat equipment to enable waste heat to recover.

The energy that is wasted by industry takes the form of unburned but combustible fuel, sensible heat discharge from drain water, and more notably, the sensible and latent heat discharge from the gases.

A survey of the waste heat related industries and concluded that refuse incineration, sewage incineration, cement factories, glass furnaces, foundries, and industrial incinerators provided ample opportunities for waste heat recovery. They suggested that the recovered waste heat be used for water desalination.

Waste energy can be recovered by the installation of combustion equipment to utilize the wasted fuel, and the provision of heat recovery equipment to regain sensible and latent heat. Much effort has been expended during the past two decades to re-use the wasted heat.

1.2 Utilization of Waste Heat

There are many ways through which waste heat energy can be recovered and utilized once again. Depending on the temperature level of the wasted heat and the proposed application, different heat exchanger devices can be employed to facilitate the use of the recovered heat. Energy storage is needed when there is a time span between energy recovery and use. The application of heat recovery should be physically close to the source of waste heat for maximum benefits from recovered energy. The Stirling engine is one of the devices for recover the waste heat now a day.

1.3 Stirling Engine

In the Stirling engine, fuel burn more completely and is able to use all kinds of fuel with any quality. Because of its simple construction and its manufacture being the same as the reciprocating internal combustion engine, and when produced in a large number of units per year, the Stirling engine would obtain the economy of scale and could be built as a cheap power source for developing countries.

1.3.1 Principle of Operation

The Stirling engine could theoretically be a very efficient engine in upgrading from heater to mechanical work with the Carnot efficiency. The thermal limit of the 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 range from 2000 to 4000 rpm.
1.3.2 Stirling Cycle

The ideal Stirling cycle has three theoretical advantages. First, the thermal efficiency of the cycle with ideal regeneration is equal to the Carnot cycle. Therefore, the quantity of heat taken from the external heat source is reduced; this results in improving the thermal efficiency Figure no.1.

The second advantage, over the Carnot cycle, is obtained by substitution of two isentropic processes with two constant-volume processes. This results in increasing the \( p-v \) diagram area. Therefore, a reasonable amount of work from the Stirling cycle is obtained without the necessity to use very high pressures and large swept volumes, as in the Carnot cycle. (refer figure no.1)

![Figure 1 Stirling and Carnot Cycle](image)

The third advantage has recently been discovered. Compared with all reciprocal piston heat engines working at the same temperature limits, the same volume ratios, the same mass of ideal working fluid, the same external pressure, and mechanism of the same overall effectiveness, the ideal Stirling engine has the maximum possible mechanical efficiency. These three advantages reveal that the Stirling engine is a theoretical equivalent of all heat engines.

A Stirling engine is a closed-cycle regenerative heat engine with a gaseous working fluid. Figure no. 2 depicts the Stirling engine in operation. Frame A shows the engine in the starting angular position. In the starting position, we see that the heat cylinder is positioned to maximize the heat in-flow while at the same time the power piston is positioned to maximize output power.

![Figure 2 Stirling engine in operation](image)

In frame B, we see the engine has rotated such that output power is minimized while the heat input area is reducing. In frame C, we see that heat outflow is nearing maximum while mechanical power may actually be flowing back into the engine. Frames D and E, show the transition back to heat in flow and mechanical power outflow. Frame F shows the engine moving back into the maximum thermal power in and mechanical power out position.

1.3.3 Heat Sources for Stirling Engines

Theoretically at any temperature difference the Stirling engine produces power. The heat source may be derived from fuel combustion, hence the term "external combustion engine", although the heat source may also be solar, geothermal, waste heat, nuclear or even biological. Likewise a "cold sink" can be used in lieu of a heat source, if it is below the ambient temperature. A cold source may be the result of a cryogenic fluid or ice, water. In the case where a small temperature differential is used to generate a significant amount of power, large mass flows of heating and cooling fluids must be pumped through the external heat exchangers, thus causing parasitic losses that tend to reduce the efficiency of the cycle.

In all external heat engines, a heat exchanger separates the working gas from the heat source, so a wide range of heat sources can be used, including any fuel or waste heat from some other process. Since the combustion products do not contact the internal moving parts of the engine, a Stirling engine can run on landfill gas without the accumulation of silica that damages internal combustion engines running on this fuel.

1.3.4 Stirling Engine Optimization

Usually the design point of a Stirling engine will be somewhere between the two limits of: (1) maximum efficiency point; and (2) maximum power point. Markman et al.\(^8\) conducted an experiment using the beta-configuration of the Stirling engine to determine the parameters of a 200 W Stirling engine by measuring the thermal-flux and mechanical-power losses. The aim of the project was to optimize and increase the engine efficiency.

Orunov et al.\(^9\) presented a method to calculate the optimum parameters of a single-cylinder Stirling engine. They concluded that mass and size characteristics of the engine could be improved by using the correct choice of the optimal parameters which would result in larger efficiency.

Abdalla and Yacoub\(^10\) studied the feasibility of using waste heat from a refuse incinerator with a Stirling engine. Heat from incineration was used to power the desalination plant and the Stirling engine. Using saline feed raw water as the cooling water and by assuming 50% heat recovery efficiency, they claimed that the engine efficiency could be improved and a thermal efficiency of 27% was obtained.

1.3.5 Applications of Stirling Engines

The most common applications of said engine are combined heat and power applications, solar power generation, Stirling cryo coolers, heat pump, marine engines, nuclear power, aircraft engines, low temperature difference engines, etc.

1.3.6 Low Temperature Differential Engine Configurations

A low temperature differential (LTD) Stirling engine can be run with small temperature difference between
the hot and cold ends of the displacer cylinder.\cite{18} It is different from other types of Stirling-cycle engines, which have a greater temperature difference between the two ends, and therefore the power developed from the engine can be greater.

LTD engines may be of two designs. The first uses single-crank operation where only the power piston is connected to the flywheel, called the Ringbom engine. This type of engine, that has been appearing more frequently, is based on the Ringbom principle. A short, large-diameter displacer rod in a precise-machined fitted guide has been used to replace the displacer connecting rod.\cite{18} The other design is called a kinematic engine, where both the displacer and the power piston are connected to the flywheel. The kinematic engine with a normal 90° phase angle is a gamma configuration engine.\cite{18}

Some characteristics of the LTD Stirling engine\cite{18} 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.

LTD Stirling engines provide value as demonstration units, but they immediately become of interest when considering the possibility of power generation from many low temperature waste heat sources in which the temperature is less than 100°C.\cite{7} A calculation using the Carnot cycle formula shows that an engine operating with a source temperature of 100°C and a sink temperature of 35°C gives a maximum thermal efficiency of about 17.42%. If an engine could be built for achieving 50% of the maximum thermal efficiency, it would have about 8.71% overall Carnot efficiency. Even the calculated thermal efficiency seems rather low, but LTD Stirling engines could be used with free or cheap low temperature sources. This engine should be selected when the low cost engines are put into consideration. Although the specific power developed by LTD Stirling engines is low, lightweight and cheap materials such as plastics can be used as engine parts.

1.3.7 Advantages of Stirling Engines
1. They can run directly on any available heat source, 2. A continuous combustion process can be used to supply heat, 3. Most types of Stirling engines have the bearing and seals on the cool side of the engine, and they require less lubricant and last longer than other reciprocating engine types. 4. The engine mechanisms are in some ways simpler than other reciprocating engine types, 5. A Stirling engine uses a single-phase working fluid which maintains an internal pressure close to the design pressure, and thus for a properly designed system the risk of explosion is low, 6. In some cases, low operating pressure allows the use of lightweight cylinders, 7. They can be built to run quietly and without an air supply, for air-independent propulsion use in submarines, 8. They start easily (albeit slowly, after warm-up) and run more efficiently in cold weather, in contrast to the internal combustion which starts quickly in warm weather, but not in cold weather, 9. A Stirling engine used for pumping water can be configured so that the water cools the compression space, 10. They are extremely flexible. They can be used as CHP (combined heat and power) in the winter and as coolers in summers, 11. Waste heat is relatively easily harvested (compared to waste heat from an internal combustion engine) making Stirling engines useful for dual-output heat and power systems.

1.3.8 Disadvantages of Stirling Engines
1. Stirling engine designs require heat exchangers for heat input and for heat output, and these must contain the pressure of the working fluid, where the pressure is proportional to the engine power output. In addition, the expansion-side heat exchanger is often at very high temperature, so the materials must resist the corrosive effects of the heat source, and have low creep (deformation). 2. All thermodynamic cycles require large temperature differentials for efficient operation. In an external combustion engine, the heater temperature always equals or exceeds the expansion temperature. This means that the metallurgical requirements for the heater material are very demanding. 3. Dissipation of waste heat is especially complicated because the coolant temperature is kept as low as possible to maximize thermal efficiency. This increases the size of the radiators, which can make packaging difficult. 4. A Stirling engine cannot start instantly, 5. Power output of a Stirling tends to be constant and to adjust it can sometimes require careful design and additional mechanisms.

1.4 Gamma Type Stirling Engine
A gamma Stirling engine is simply a beta Stirling engine in which the power piston 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. Gamma type engines (figure no.3) have a displacer and power piston, similar to Beta machines, but in different cylinders. This allows a convenient complete separation between exchangers associated with the displacer cylinder and the compression and expansion work space associated with the piston.

Furthermore during the expansion process some of the expansion must take place in the compression space leading to a reduction of specific power. Gamma engines are therefore used when the
advantages of having separate cylinders outweigh the specific power disadvantage.

The advantage of this design is that it is mechanically simpler because of the convenience of two cylinders in which only the piston has to be sealed. The disadvantage is the lower compression ratio but the gamma configuration is the favorite for modelers and hobbyists.

2. LITERATURE REVIEW

2.1 Literature Review Related Gamma Type Stirling Engine.

In year 2010 a gamma-configuration Stirling engine have designed and constructed. The single and twin power cylinder engines are tested with air at atmospheric pressure by using an electric heater as a heat source. The engine is tested with heater input of 156.3W, 187.6W, and 223.2W. Variations of engine torque, shaft power and brake thermal efficiency with engine speed and engine performance at various heat inputs are presented. The results indicate that at the maximum heater input of 223.2 W, the heater temperature for single power cylinder and twin power cylinder are 612°C and 574°C. The two engines produce a maximum torque of 0.13 Nm at 405 rpm and 0.15Nm at 412 rpm; a maximum shaft power of 5.73 W at 456 rpm and 6.47 W at 412 rpm; a maximum brake thermal efficiency of 2.57 % at 456 rpm and 2.9 % at 412 rpm, respectively. The following design parameters were used:-

<table>
<thead>
<tr>
<th>Table 1 Engine Design Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power piston</td>
</tr>
<tr>
<td>Bore</td>
</tr>
<tr>
<td>Stroke</td>
</tr>
<tr>
<td>Swept volume</td>
</tr>
<tr>
<td>Displacer piston</td>
</tr>
<tr>
<td>Bore</td>
</tr>
<tr>
<td>Stroke</td>
</tr>
<tr>
<td>Swept volume</td>
</tr>
<tr>
<td>Swept volume ratio</td>
</tr>
<tr>
<td>Compression ratio</td>
</tr>
<tr>
<td>Phase</td>
</tr>
</tbody>
</table>

In year 2003 a gamma type Stirling engine with 276 cc swept volume designed and manufactured. The engine was tested with air and helium by using an electrical furnace as heat source. Working characteristics of the engine were obtained within the range of heat source temperature 700–1000°C and range of charge pressure 1–4.5 bar. Maximum power output was obtained with helium at 1000°C heat source temperature and 4 bar charge pressure as 128.3 W. The maximum torque was obtained as 2 Nm at 1000°C heat source temperature and 4 bar helium charge pressure. Results were found to be encouraging to initiate a Stirling engine project for 1 kW power output.

The schematic illustration of the engine is shown in figure no.4.

![Schematic Illustration of The Engine](image)

The crankshaft was manufactured from different steels having appropriate properties. The body of the pistons was made of spheroid-graphite cast. The pistons were connected to the crankshaft by light rods made of aluminium. The cylinder liners were made of hardened AISI 4080 steel. The heads of cylinders were made of ASTM duct. The displacer and its cylinder, which works as heater head, were also made of ASTM steel duct. The rod of displacer was made of hardened AISI 4080 steel, which works in a cast iron bed.

The following technical specifications were used:-

<table>
<thead>
<tr>
<th>Table 2 Technical Specifications of the Engine</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine type</td>
</tr>
<tr>
<td>Swept volume</td>
</tr>
<tr>
<td>Phase angle</td>
</tr>
<tr>
<td>Working fluid</td>
</tr>
<tr>
<td>Cooling system</td>
</tr>
<tr>
<td>Compression ratio</td>
</tr>
<tr>
<td>Maximum engine power</td>
</tr>
<tr>
<td>Engine speed</td>
</tr>
<tr>
<td>Dead volume</td>
</tr>
</tbody>
</table>

The stroke volume of displacer and pistons was equal to each other, 138 cc. The total dead volume of the engine was 169 cc. The compression ratio was measured as 1.82. The surface area of the displacer and inner surface area of the displacer cylinder were 425 and 505 cm², respectively. The inner surface of expansion cylinders was 170 cm². The inner surface area of the connecting pipe was about 100 cm². The total heat transfer area of the engine was approximately 1200 cm².

In year 2003, a power output determination of a gamma-configuration low temperature differential Stirling engine have study. The former works on the calculation of Stirling engine power output are discussed. Results from this study indicate that the mean pressure power formula is most appropriate for the calculation of a gamma-configuration, low temperature differential Stirling engine power output. In the preliminary design phase, some design parameters are unknown. The Schmidt formula and West formula are more difficult to use when compared with the Beale formula and the mean pressure formula. In principle, the Beale formula is simpler, however, an accurate value of the Beale number is critical and the existing data on the Beale
number are not available for LTD Stirling engines. The mean pressure power formula gives the same simplicity as the Beale formula and could be used for every temperature ratio and should then be used for this purpose.

For design purposes, the mean pressure power formula can be used to calculate the engine rated output, or inversely, to evaluate the approximate operating parameters of the Stirling engine for a required or given power output. The mean pressure power formula allows us to initiate an initial design process rapidly.

For LTD Stirling engines operated by a low temperature source, results from this study indicate that the rated power output of a LTD Stirling engine can be directly calculated from the mean pressure power formula by using an appropriate factor F.

In year 2006 a two single-acting, twin power piston and four power pistons, gamma-configuration, low temperature Differential Stirling engine have been designed and constructed. The engine performance is tested with air at atmospheric pressure by using a gas burner as a heat source. The engine is tested with various heat inputs. Variations of engine torque, shaft power and brake thermal efficiency at various heat inputs with engine speed and engine performance are presented. The Beale number obtained from testing of the engines is also investigated. The results indicate that, for twin power piston engine, at a maximum actual heat input of 2355 J/s with a heater temperature of 589 K, the engine produces a maximum torque of 1.222 Nm at 67.7 rpm, a maximum shaft power of 11.8 W at 133 rpm, and a maximum brake thermal efficiency of 0.494% at 133 rpm, approximately. For the four power pistons engine, the results indicate that at the maximum actual heat input of 4041 J/s with the heater temperature of 771 K, the engine produces a maximum torque of 10.55 Nm at 28.5 rpm, a maximum shaft power of 32.7 W at 42.1 rpm, and a maximum brake thermal efficiency of 0.809% at 42.1 rpm, approximately.

The following design parameters were used:-

**Table 3 Design Parameters of Twin Power Piston Engine**

<table>
<thead>
<tr>
<th>Mechanical configuration</th>
<th>Gamma</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Power piston:</strong></td>
<td></td>
</tr>
<tr>
<td>Bore × stroke (cm)</td>
<td>8.3 × 8.26</td>
</tr>
<tr>
<td>Swept volume (cc)</td>
<td>893.8</td>
</tr>
<tr>
<td><strong>Displacer:</strong></td>
<td></td>
</tr>
<tr>
<td>Bore × stroke (cm)</td>
<td>32 × 7.95</td>
</tr>
<tr>
<td>Swept volume (cc)</td>
<td>6393.8</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>7.15</td>
</tr>
<tr>
<td>Phase angle</td>
<td>90°</td>
</tr>
</tbody>
</table>

**Table 4 Design Parameters of Four Power Piston Engine**

<table>
<thead>
<tr>
<th>Mechanical configuration</th>
<th>Gamma</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Power piston:</strong></td>
<td></td>
</tr>
<tr>
<td>Bore × stroke (cm)</td>
<td>13.3 × 13.3</td>
</tr>
<tr>
<td>Swept volume (cc)</td>
<td>7391</td>
</tr>
<tr>
<td><strong>Displacer:</strong></td>
<td></td>
</tr>
<tr>
<td>Bore × stroke (cm)</td>
<td>60 × 14.48</td>
</tr>
<tr>
<td>Swept volume (cc)</td>
<td>40941</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>5.54</td>
</tr>
<tr>
<td>Phase angle</td>
<td>90°</td>
</tr>
</tbody>
</table>

In year 2010 a 500 W prototype Stirling engine system have designed to determining the potential viability of using low enthalpy heat sources, where temperature differentials may be as low as 300 C, for practical power generation. The design methodology has utilized the modified Beale Number, preliminary numerical modelling, and fin-tube heat exchanger approximations. The result is a novel gamma-type engine configuration capable of being pressurized to 1 MPa. Being a research prototype, important engine parameters such as displacer piston velocity profile, piston phasing, and those associated with the regenerator matrix, are able to be varied in order to optimize engine performance.

The modified Beale number, \(B_M\) is,

\[ P_{O} = \left( \frac{P_{av}}{S_{av}} \right) \left( \frac{f}{(T_{H} - T_{C})} \right) / (T_{H} + T_{C}) \]  

Where, \(P_{O}\) is the output power (W), \(S_{av}\) is the swept volume of the power piston (cm\(^3\)), \(P_{av}\) is the average engine pressure (bar), and \(f\) is the engine rotational frequency (Hz).

This equation was used to determine a power piston size requirement, given our intended power output and pressure specifications.

**Bancha Kongtragool, Somchai Wongwises**

In year 2005 an experimental investigation on the performance of a low-temperature differential Stirling engine has done. In this study, a twin power piston, gamma-configuration, low-temperature differential Stirling engine is tested with non-pressurized air by using a solar simulator as a heat source. The engine testing is performed with four different simulated solar intensities. Variations of engine torque, shaft power and brake thermal efficiency with engine speed and engine performance at various heat inputs are presented. The Beale number, obtained from the testing of the engine, is also investigated. The results indicate that at the maximum simulated solar intensity of 7145 W/m\(^2\), or heat input of 261.9 J/s, with a heater temperature of 436 K, the engine produces a maximum torque of 0.352 N m at 23.8 rpm, a maximum shaft power of 1.69 W at 52.1 rpm, and a maximum brake thermal efficiency of 0.645% at 52.1 rpm, approximately. The schematic illustration of the engine is shown in figure:

![Fig.no. 5 Schematic Diagram of the Stirling Engine](image-url)
The following design parameters were used:

<table>
<thead>
<tr>
<th>Mechanical configuration</th>
<th>Gamma</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power piston: Bore × stroke (cm)</td>
<td>8.9 × 8.26</td>
</tr>
<tr>
<td>Swept volume (cc)</td>
<td>893.8</td>
</tr>
<tr>
<td>Displacer: Bore × stroke (cm)</td>
<td>32 × 7.95</td>
</tr>
<tr>
<td>Swept volume (cc)</td>
<td>6393.8</td>
</tr>
<tr>
<td>Swept volume ratio</td>
<td>7.15</td>
</tr>
<tr>
<td>Phase angle</td>
<td>90°</td>
</tr>
</tbody>
</table>

In year 2002 a review on the development of Stirling engines, solar-powered Stirling engines, and low temperature differential Stirling engines was done and found a feasible solution which lead to a preliminary conceptual design of a workable solar-powered low temperature differential Stirling engine. The research indicate that Stirling engines working with relatively low temperature air are potentially attractive engines of the future, especially solar-powered low temperature differential Stirling engines with vertical, double-acting, gamma-configuration. The indicated work per cycle of a gamma configuration Stirling engine can be determined by Schmidt formula.

\[ W_{\text{schmidt}} = \pi (1 - \tau) p_{\text{mmax}} V_p \frac{k_p \sin \alpha}{Y + \sqrt{Y^2 - X^2}} \sqrt{y - x} \]

(2.10)

Where,

\[ k_p = \frac{V_p}{V_D} \]

\[ V_D = A_D L_D \]

\[ V_p = A_p L_p \]

\[ X = \sqrt{(1 - \tau)^2 - 2(1 - \tau)k_p \cos \alpha + k_p^2} \]

\[ Y = 1 + \tau + \frac{4k_p \tau}{1 + \tau} + k_p \]

\[ \tau = \frac{T_C}{T_H} \]

\[ k_s = \frac{V_S}{V_D} \]

Where, \( W_{\text{schmidt}} \) is the indicated work per cycle in N m, \( p_{\text{mmax}} \) the maximum pressure attained during cycle in N/m², \( k_p \) the swept volume ratio, \( k_s \) the dead space volume ratio, \( V_D \) the displacer swept volume in m³, \( V_p \) the power piston swept volume in m³, \( V_S \) the dead space volume in m³, \( A_D \) the displacer cylinder cross-section area in m², \( A_p \) the power cylinder cross-section area in m², \( L_D \) the displacer stroke in m, \( L_p \) the power piston stroke in m, \( \alpha \) the phase angle lead of the displacer over the power piston in degrees, and \( \tau \) is the temperature ratio.

\[ p_{\text{mmax}} = p_n \frac{\sqrt{Y + X}}{\sqrt{Y - X}} \]

(2.11)

From Eqs. 2.10 and 2.11 the indicated work for gamma engine determine by,

\[ W_{\text{schmidt}} = \pi (1 - \tau) p_{\text{mmax}} V_D \frac{k_p \sin \alpha}{Y + \sqrt{Y^2 - X^2}} \]

(2.12)

The power output of several Stirling engines could be determine approximately from Beale formula,

\[ P = 0.015 p_n f V_p \]

(2.13)

Where, 
\( P \) is the engine power output in Watts, \( p_n \) the mean cycle pressure in bar, \( f \) the cycle frequency in Hz, and \( V_p \) is displacement of power piston in cm³.

Eqn. (2.13) may be written in a general form as follows:

\[ P/(p_n f V_p) = \text{constant} \]

(2.14)

The resulting dimensionless parameter \( P/(p_n f V_p) \) are called the Beale number. It is clear that the Beale number is a function of both source and sinks temperatures.

REFERENCES


