Design of a Stirling Engine to Generate Green Energy in Rural Areas of Bangladesh

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Abstract— **In Bangladesh the peak demand of power is greater than the amount of power generated. 30% of the villages of Bangladesh are deprived of electrical power. Again a great deal of energy is wasted in the form of heat in the mud stoves used for cooking purpose in rural areas. The temperature difference between the stoves and the environment can be used to produce green power with the help of Stirling engine. Stirling engine is a heat engine that is operated at various temperature levels by cyclic operation of expansion and compression of working gas. It converts heat energy to mechanical energy. It works on Stirling cycle. A DC generator is used to convert the mechanical energy to electrical energy. In this paper a displacer type Stirling engine has been designed and using the design parameters a prototype has been simulated that can be implemented on the mud stoves. Using helium as working fluid this prototype can generate 52 W of mechanical power at 100 rpm engine frequency, 4.216×10^{-4} m^3 displacer swept volume, 90^0 phase angle and about 150 ^{0}K of temperature difference. This research concentrates on the design and implementation of Stirling engine in rural areas to generate green energy and lessen energy crisis of Bangladesh.**

Keywords- energy crisis; mud stove; Stirling engine; green energy; AutoCAD design

I. INTRODUCTION

Energy crisis is a burning issue of Bangladesh. About 62% of the population has excess to electricity [1]. The areas covered by electrical power do not have continuous supply due to scarcity of power. Electricity is produced by gas, diesel or coal, which are non-renewable fuel and will run-out in near future. Again these power plants cause pollution which is drastically harmful to environment. Considering the above circumstances, Stirling engine (SE) can be a better alternative to generate green power and meet the national energy demand.

Stirling engine is a closed cycle regenerative heat engine operating on cyclic compression and expansion of permanently gaseous working fluid at different temperature levels [2][3]. Working on Stirling cycle, it converts heat energy to mechanical energy. In 1816, Robert Stirling and his brother James first invented and patented this engine [4]. In 20th century Philips used the engine as a low power portable generator for his radio [5]. William Beale is another forerunner SE researcher who invented the free piston Stirling engine. This engine had few moving parts and no crank shaft. In 1978 a SE was designed to power a submarine. In 1985 McDonnell Douglas designed a large solar parabolic mirror setup which has a capability to track the sun and focus its energy on a SE that is centrally mounted. Now 850 MW power is generated using this setup [4].

SE running on small temperature difference between the heated and cooled end of the displacer cylinder is called low temperature differential (LTD) SE [6]. In recent years LTD SE has been immensely researched and developed.

In this paper, energy crisis scenario of Bangladesh is presented in section two. Stirling cycle on which SE works is discussed in section three. AutoCAD designs of several components of the displacer type SE is depicted in section four. Design specifications, theoretically calculated results and MATLAB simulation of corresponding changes in pressure and volume of the designed SE are presented in section five. Theoretical calculations show that working on a temperature difference of 150 ^{0}K the SE designed in this paper can produce 52 W mechanical power at 3.0595×10^{-3} m^3 momental volume, 100 rpm engine frequency and 90^0 phase angle. In section six the prototype that can generate 47 W of electrical power implementing it on mud stoves of rural areas, is depicted. Economic and environmental advantages of SE are discussed in section seven.

II. ENERGY CRISIS IN BANGLADESH

Bangladesh has been a gas dependent mono-energy country for the last four decades with gas being used to generate up to about 90% of the electricity. By 2005-2006 the country first came to realize that the dwindling gas reserve could no longer singly support to the increasing energy demands. By 2010, the shortage of energy became so acute that it started to cause negative consequences on the economy of the country [7]. So, to release pressure from gas reserve, from 2010 use of coal in energy sector has increased. In 2010, shares of gas and coal for electricity generation were 80% by gas and 4% by coal. The shares of gas and coal in power generation are projected to gradually change to 54% by gas and 24% by coal in 2020, 36% by gas and 30% by coal in 2025 and 25% by gas and 50% by coal in 2030[8]. But, in spite of using coal based power plants per capita generation of Bangladesh is 321 kWh, which is very low compared to other developing countries [1]. Now in Bangladesh the peak demand of power per day is 9268MW [9]. As per 27 June, 2014 the daily generation of power is 6625 MW [10]. So there is a shortage of 2643 MW on an average every day. Again, among 87,316 villages about 53,281 villages are supplied with electrical power [11]. That is, a big portion of our rural areas are out of electricity. Not only this, another big problem is that coal based power plant is causing severe effects on air, water and soil [11]. So, echo-friendly equipment like SE can be a good source to meet up the demand. In rural areas biomass fuels such as wood chips, leaves, log wood are used as fuel in stoves. In these stoves above 85% of the generated heat is wasted. Stirling engine can be designed to produce electricity from this waste heat.

III. Striling Cycle

Stirling engine works on Stirling cycle which comprises of four processes. These are shown in Fig. 1.

A. *Isothermal Compression*

When the power piston travels inwards this stage occurs. In this stage gas is compressed and volume is reduced which in turns raises the pressure. In isothermal compression process heat is removed to the environment by the cooled cylinder.

B. *Isochoric Heating*

At this stage, the piston remains at its most inwards point and the volume is kept constant. Heat is added to the gas and its temperature is raised from cooling temperature to heated temperature. Gas pressure reaches maximum point. Maximum amount of energy is available in this stage to do work.

C. *Isothermal Expansion*

The expanding heated gas pushes the power piston outwards. This increases the overall volume and lowers the pressure.

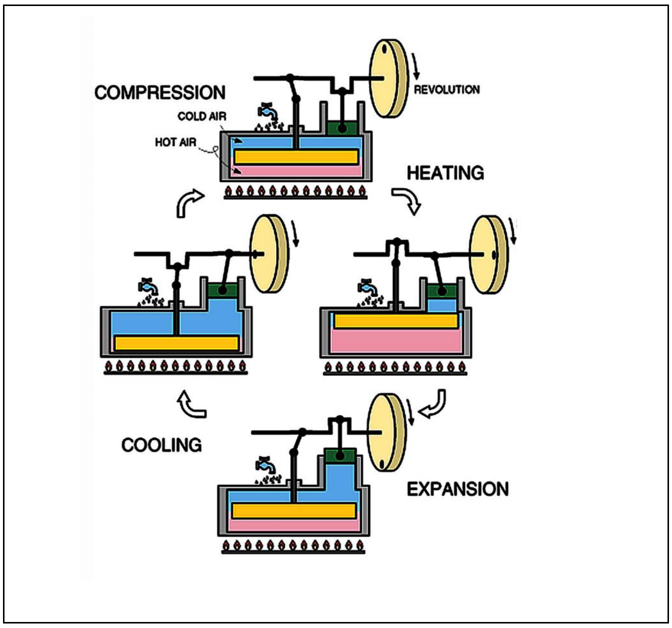

Figure 1. Stirling cycle [12]

D. *Isochoric Cooling*

At this stage, the piston remains at its outer most point and the volume is kept constant. Heat is absorbed from the gas and its temperature is lessened from hot to cool. Gas pressure gets down to the minimum point.

IV. Design

Three types of Stirling engines (SE) are available. These are alpha type, beta type and gamma or displacer type. In this research purpose, displacer type SE is used as it has large heat transfer area, works on low and medium temperature difference and it is easy to be constructed. Specific designs of all components of displacer type SE are drawn via AutoCAD. These components are discussed below:

A. *Displacer Cylinder*

The displacer piston moves to and fro the displacer cylinder. It is covered by top plate and bottom plate which are placed above and below of the cylinder respectively. The displacer cylinder is shown in Fig. 2.

B. *Power Cylinder*

Power piston moves through this cylinder. It is placed above displacer cylinder. Power cylinder is shown in Fig. 3.

C. *Power Piston*

It is like the piston used in internal combustion engine. The working fluid works on the piston face, generates power which is transmitted to the crankshaft through the piston. It is shown in Fig. 4.

D. *Crank Shaft*

It resembles the crankshaft in an internal combustion engine. It translates the linear piston motion into rotation. The power piston is attached through connecting rods to the rotating shaft and its stroke is determined by the length of the crank.

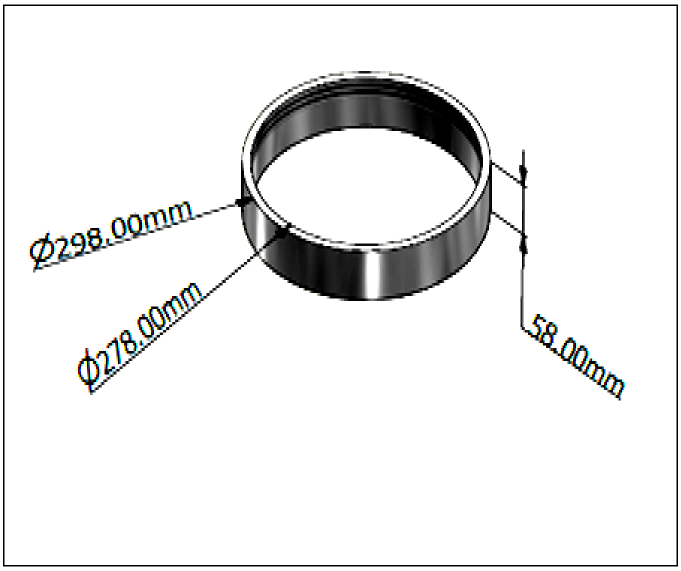

Figure 2. Displacer cylinder

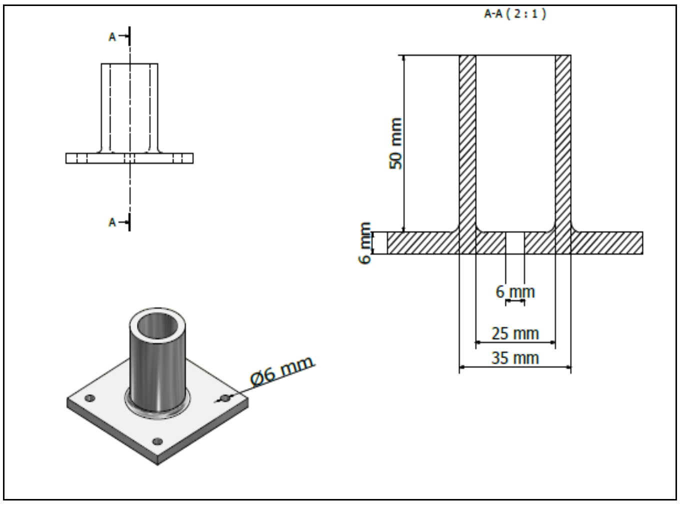

Figure 3. Power cylinder

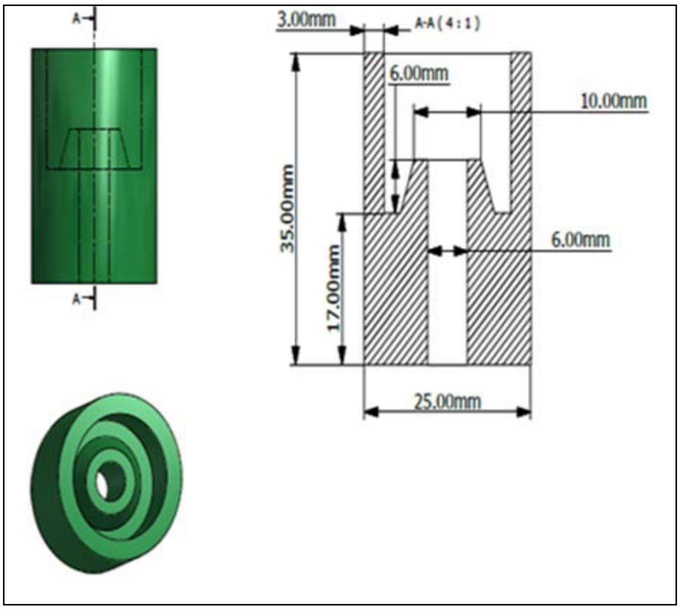

Figure 4. Power piston

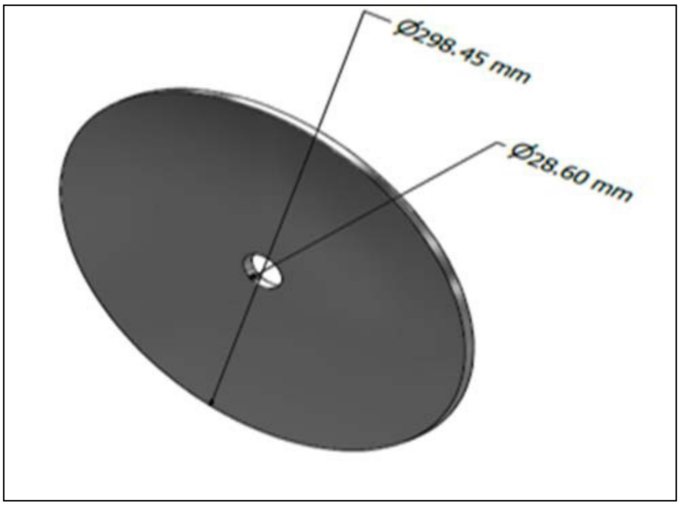

Figure 5. Flywheel

E. *Flywheel*

In a Stirling cycle there is only one power producing phase. So, a flywheel is used to keep the engine motion smooth. The amount of energy stored is proportional to the square of its rotational speed. The stored energy of a flywheel is released to a mechanical load [12].The flywheel is shown in Fig. 5.

F. *Connecting Rod*

In displacer type SE, displacer connecting rod connects the displacer piston to the crankshaft and power piston connecting rod joins the power piston to the crankshaft. These connecting rods work on the mechanism of converting reciprocating motion into rotating motion together with the crank. Displacer connecting rod and power piston connecting rod are shown in Fig. 6 and Fig. 7 respectively.

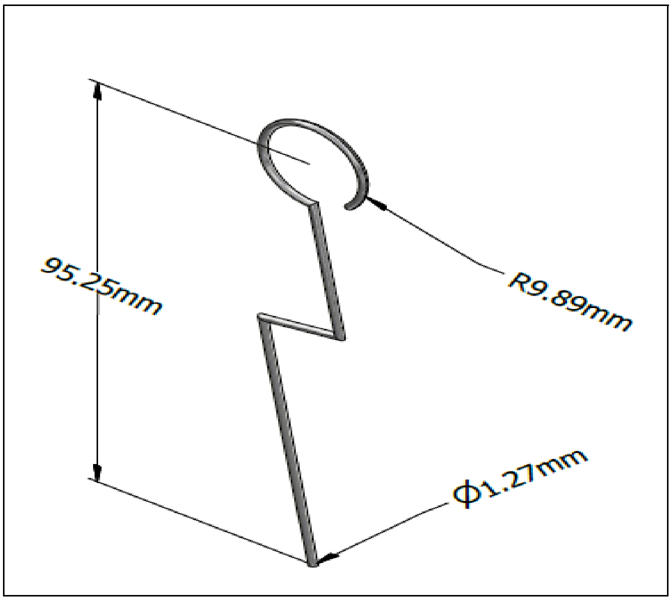

Figure 6. Displacer connecting rod

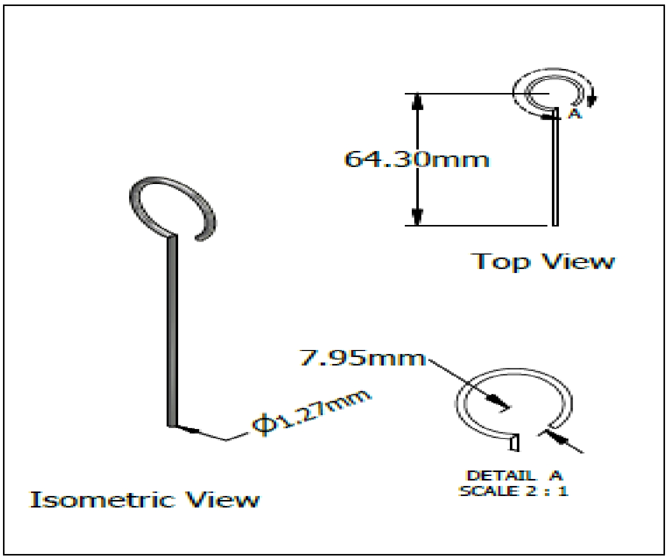

Figure 7. Power piston connecting rod

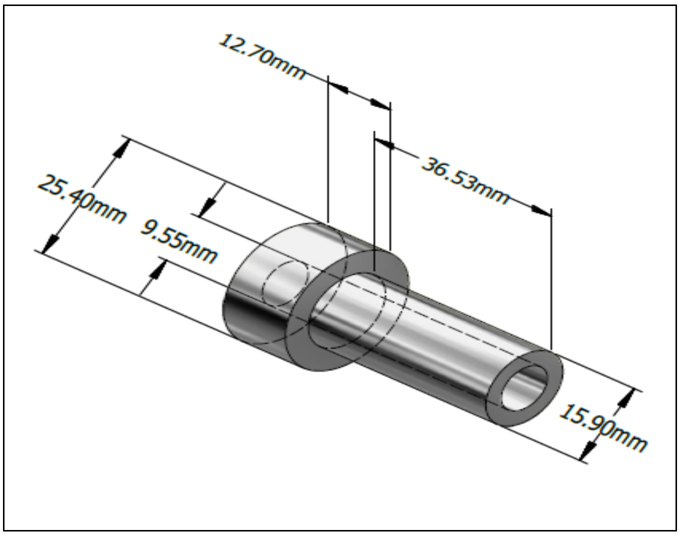

Figure 8. Flywheel housing

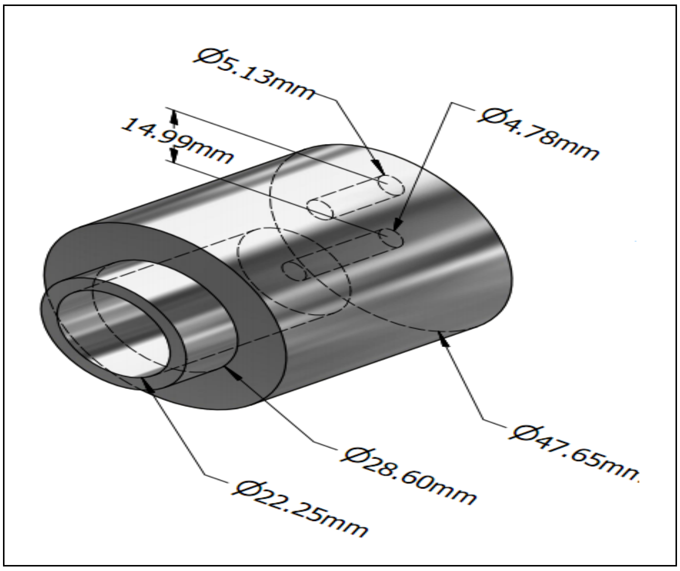

Figure 9. Flywheel hub

G. *Other Components*

The displacer type Stirling engine designed in this paper also comprises of displacer guide, flywheel housing, flywheel stand, flywheel hub, cylinder base and O' ring. The designed flywheel housing and flywheel hub is shown in Fig. 8 and Fig. 9 respectively.

V. CALCULATION AND SIMULATION

The design parameters of Stirling engine designed in this research are shown in Table I.

TABLE I. DESIGN PARAMETERS OF STIRLING ENGINE

Design Parameters	Specifications
Engine Type	Displacer
Working Gas	Helium
Displacer: bore× stroke	0.278 m× 0.046 m
Displacer: Swept volume, V_{SE}	4.216×10^{-4} m3
Displacer: Dead volume, V_{DE}	2.3758×10^{-4} m3
Power piston: bore× stroke	0.025 m × 0.033 m
Power piston: Swept volume, V_{SC}	1.619×10^{-3} m3
Power piston: Dead volume, V_{DC}	8.3448×10^{-4} m3
Expansion volume, V_E	60.699×10^{-3} m^3
Compression volume, V_C	4.909×10^{-4} m^3
Heated temperature , T_E	463 ^{0}K
Cooled temperature , T_C	313 ^{0}K
Phase angle , dx	90□
Mole Number of Helium , n	0.8
Gas constant, R	8.314 J $mol^{-1}K^{-1}$
Cooling method	Water cooling

Using above parameters, from Schmidt formula [13] mechanical power output of the displacer type Stirling engine is calculated.

Total momental volume,

$$V=V_E+V_C=3.0535\times10^{-3}m^3 \tag{1}$$

Maximum pressure, p_{max} is calculated using the equation,

$$p\times V=n\times R\times T \tag{2}$$

$$p_{max}=n\times R\times\frac{T}{V}=1.006\times10^6 Pa$$

The temperature ratio t, swept volume ratio v, expansion and compression dead volume ratios, X_{DE} and X_{DC} respectively and other constants are found using the following equations.

$$t=\frac{T_C}{T_E}=0.67602 \tag{3}$$

$$v=\frac{V_{SC}}{V_{SE}}=3.84 \tag{4}$$

$$X_{DE}=\frac{V_{DE}}{V_{SE}}=0.56 \tag{5}$$

$$X_{DC}=\frac{V_{DC}}{V_{SE}}=1.9793 \tag{6}$$

$$a=\frac{\tan^{-1}(v\times \sin dx)}{(t+\cos dx+1)}=66.4204 \tag{7}$$

$$S=t+2t\times X_{DE}+4t\times\frac{V_R}{(1+t)}+v+2\times X_{DC}+1=10.23 \tag{8}$$

$$B=(t^2+2(t\text{-}1)\,v\times\cos dx+v^2-2\times t+1)^{0.5}=3.85 \tag{9}$$

$$c=\frac{B}{S}=0.3767 \tag{10}$$

Indicated power,

$$W=\left\{ p_{max}\times V_{SE}\times 3.1416\times c\times(1-t)\times \sin a\times \frac{\left\{\frac{(1-c)}{(1+c)}\right\}^{0.5}}{\{1+(1-0.16077^2)^{0.5}\}} \right\}$$

$$=52.05\text{W} \tag{11}$$

The frequency of the rotor is calculated from Beale formula [16].

$$W= B\times n\times p_{mean}\times f\times V \tag{12}$$

Here, mean pressure,

$$p_{mean}=\frac{p_{max}}{\left\{\frac{(1+c)}{(1-c)}\right\}^{0.5}} = 676.9037\times10^3\text{Pa} \tag{13}$$

Rotor frequency,

$$f=\frac{W}{(B\times n\times p_{mean}\times V)}=100\text{rpm} \tag{14}$$

Using the design parameters corresponding changes in volume and pressure of the designed Stirling engine is simulated in MATLAB. The simulated p-V diagram is shown in Fig 10.

VI. IMPLEMENTATION

The mechanical power generated in Stirling engine (SE) can be converted into electrical power using a DC generator. Flywheel of the SE is coupled with the rotor of the DC generator using conveyor belt.

In this research, using the previously mentioned AutoCAD designs, a prototype has been simulated that can be implemented on the mud stoves of rural areas of Bangladesh. The prototype is shown in Fig.11. The temperature inside the mud stove is about 463 ^{0}K. Using water cooling system, the temperature of the top plate is maintained at 313 ^{0}K.

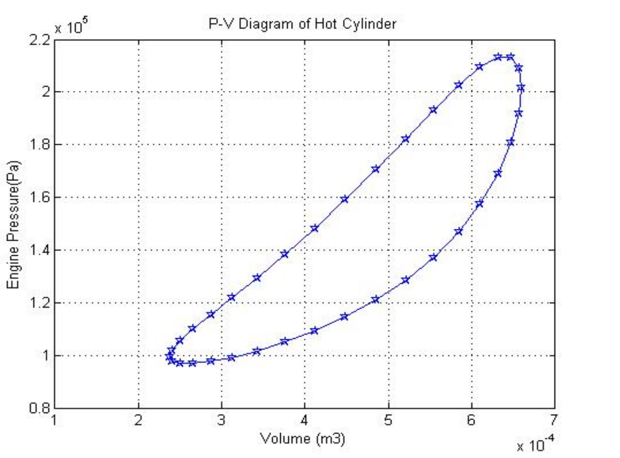

Figure 10. p-V diagram

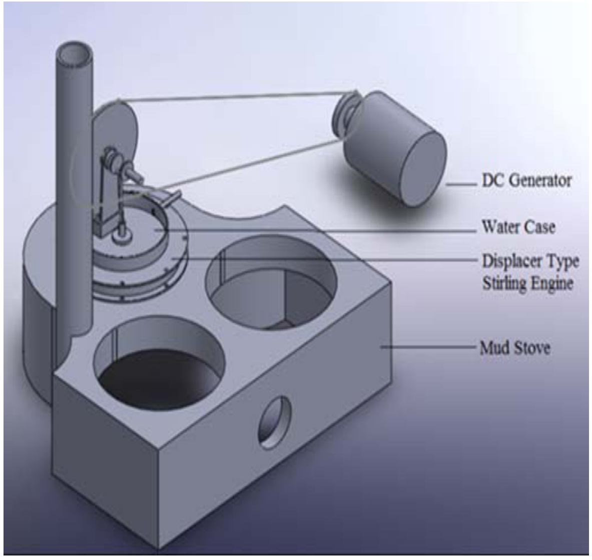

Figure 11. Prototype to implement on mud stove

As mentioned previously, by using this 150 0K temperature difference with a DC generator having 90% efficiency, 52×0.9= 47 W of electrical power can be generated in each mud stove. So it can work as a mini power plant for each of the houses where it is planted.

VII. ADVANTAGES

The Stirling engine (SE) works on temperature difference between the mud stove and outside environment, so the people of rural areas don't need any other gasoline fuel for power generation. The heat wasted earlier is now generating power. Again there is no internal combustion in this engine. So, SE produces no harmful gas that can pollute environment.

The working fluid used in SE is an inert gas. So, there is minimal risk of explosion. Cylinders designed in this research are of low volume and weight of helium is also very less. Hence, the entire setup is of less weight which makes it portable.

SE designed in this paper is implemented in the house. So, there is minimal distance between generating and the load end which tremendously lessens the transmission loss [15][16].

For advantages discussed above, implementing SE in rural areas of Bangladesh can be a greener solution to lessen energy crisis to a certain level.

VIII. CONCLUSION

In this research a low temperature differential displacer type Stirling engine has been designed that can be implemented on the mud stoves of rural areas. Using the design parameters Pressure vs. Volume diagram of the Stirling engine has been generated by MATLAB simulation. The SE designed in this paper can generate 52 W of mechanical power at 100 rpm and 150 K of temperature difference. 47 W of electrical power can be produced using a DC generator and this electricity can be used for household purposes in rural areas. Further research of this work includes manufacturing a low cost SE using the design presented in this paper. Increasing the output electrical power is also under consideration. The results of this research show that rural families can generate power for household use implementing SE, which produces power from the waste heat of mud stoves. As SE uses no additional fuel and it is non-polluting, it can be a good alternative to conventional power plants running on gasoline fuel. Efficient implementation of SE can ensure green energy production and fulfill the ambition of delivering power to all.

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REFERENCES

[1] Ministry of Power, Energy and Mineral Resources (http://www.powerdivision.gov.bd/user/brec1/30/1) (28 June, 2014)
[2] G. Walker, Striling Engines, Clarenden Press, Oxford, page1,1980.
[3] W.R Martini, Stirling Engine Design Manual, Richland: Martini Engineering, 1983.
[4] Kolin. Ivo, Stirling Motor- History, Theory and practice, Dubrovnik: Zagrab University Publications, LTD., 1991.
[5] Hargreaves, C.M, The Philips Stirling Engine, Amsterdam: Elsevier Science Publishers, 1991.
[6] http://diystirlingengine.com/ltd-stirling-engine/
[7] “Solar powered Stirling Engine for Self-Generating Electricity” by R.Aishwarya, K.DhivyaBharathi.
[8] Imam, B.,2013,Enegry Resources of Bangladesh, University Grant Commission of Bangladesh, Dhaka, 7-8 p.
[9] Bangladesh Power Development Board (http://www.bpdb.gov.bd/bpdb/index.php?option=com_content&view=article&id=12&Itemid=126) (June 27, 2014)
[10] http://www.kabirhat.com/village/ (June 23, 2014)
[11] Chowdhury A. H. , Environmental Impact of Coal based Power Plant of Rampal on the Sundarbans and Surrounding areas ,2013
[12] http://www.stirlingengine.com/displacer-still/ (June 29, 2014)
[13] G. Walker., Stirling Engines, (1980),17, Oxford Univ. Press
[14] Beale Formula- Reader GT, Hooper C. Stirling engines. London: Cambridge University Press; 1983.
[15] http://peswiki.com/index.php/Stirling_engine#Advantages(June24,2014)
[16] http://www.robertstirlingengine.com/advandisadvan.php(June 25, 2014).