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Transformation of Heat Energy into Mechanical Work at Low Environmental Pollution

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The most frequently used heat engines for transformation of heat into useful mechanical work are internal and external combustion engines. These engines work with high combustion temperatures and large temperature differences are necessary to achieve high efficiency. Harmful byproducts result from the combustion processes. In order to solve the environmental problem during the transformation of heat into mechanical work, new alternative fuels, alternative drives and new technologies are being investigated. This paper hypothesizes that it is possible to transform heat into work at low temperatures and at low temperature differences with less environmental pollution. First, the Stirling and internal combustion engines are compared in view of efficiency, mechanical and heat load, engine start and its adaptability to various working regimes, used fuel, material of engine components, and economy and ecology characteristics. To verify the advantages of the Stirling engine, a small unique model of a working Stirling engine was developed and a thermodynamic analysis of this model performed. The thermal efficiency of this engine, running at maximal temperature of the working fluid of 52 ℃ and maximal temperature difference of 24 ℃, is 7.4 %. Such an engine can be driven by the heat of the sun, exhaust gasses, and similar sources. In this manner a Stirling engine can use the energy, which would otherwise be lost.

INTRODUCTION

Recent years have witnessed remarkable advances regarding energy sources and energy transformation development. The most useful natural sources for energy are: oil, coal, natural gas, wood, vegetable oil, biomass, nuclear fuels, tidal power, wind, geysers and the sun (Lundmark 2010; Kegl 2008; Panwar et al. 2011; Lin et al. 2011). Of all these, the primary energy forms are obtained as follows: chemical energy from fossil fuels and biomass, nuclear energy from radioactive materials, geothermal energy from geysers, potential energy of water, kinetic energy of wind and solar energy from the sun. Hydropower is used for power generation; solar energy is used for solar home systems, solar dryers and solar cookers; but also for photovoltaic, thermal power generation and water heaters; wind energy is used for power generation, wind generators, windmills and water pumps; wave and tidal energy have many uses as well (Panwar 2011). However, the renewable energy sources provide about 15 % of the total world energy demand; the rest is covered by fossil fuels, such as oil, coal and natural gas. The main problem with combustion of fossil fuels, where chemical fuel energy is transformed by way of heat energy into mechanical work, is the harmful emissions. It is known that, besides the thermal power plants, the heat engines are very frequently used to transform the primary energy of fuels into heat, mechanical and electrical energy. Recently, related to heat engines, there are two kind of important issues, the environmental and energy crisis issue. The environmental is due to global warming, induced by the increase of greenhouse gases concentration in the atmosphere, acid rain and the ozone hole. Another aspect is the energy crisis, where increasing petroleum prices have impacts on domestic energy situation and local society life. Therefore, the interest in promoting renewable alternatives to meet the developing world's growing energy demand is general (Edmonds and Smith 2001).

Until present days, heat engines have been improved in many aspects. Many investigations are related to alternative fuels for external combustion engines (Gupta et al. 2010; Onovwiona 2006), to the control of the injection and combustion processes, exhaust gas after-treatment, on the usage of alternative fuels in internal combustion engines (Demirbas 2009; Kegl et al. 2008; Pehan et al. 2009), and also to various improvements of Stirling engines (Kongtragool and Wongwises 2003; Sripakagorn and Srikam 2011; Walker 1980).

Few research works related to the processes in the moderate temperature range exist. Kongtragool and Wongwises (2003) demonstrated the performance of gamma-type Stirling engines with single-acting, twin power piston and four power pistons. The maximum power output reached 32.7 W for the four power piston version at 500 °C heater temperature under atmospheric pressure. Cinar et al. (2005) manufactured a beta-type Stirling engine to run at atmospheric pressure. The hot-source temperature is a fundamental parameter of the experimental study. Experiments were performed with an electrical heater at 800, 900 and 1000 °C. Torque and output-power variations were obtained for different engine speeds. The test engine reached a maximum of 5.98 W at 208 rpm, at the hot-source temperature of 1000 °C.

Sripakagorn and Srikam (2011) describe the design and construction of a Stirling engine developed for the moderate temperature range (350-500 °C). The engine prototype was experimentally evaluated such that the potential of the moderate temperature Stirling engine could be demonstrated. Under the atmospheric pressure, the engine produces a maximum power of 3.8 W at 205 rpm and 350 °C. At 500 °C and 7 bar charged

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pressure, the maximum power reached 95.4 W at 360 rpm. At these conditions, the thermal efficiency is 9.35 %.

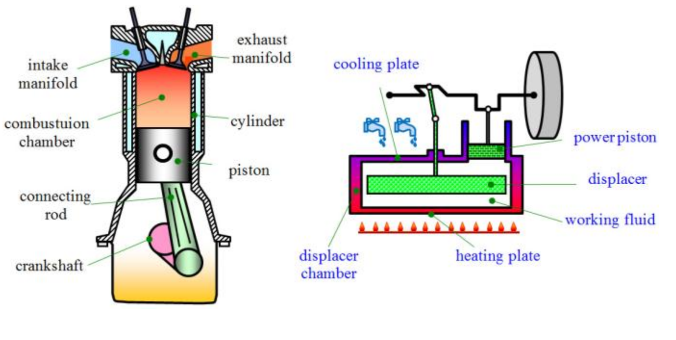

Figure 1 A scheme of Diesel and Stirling engine

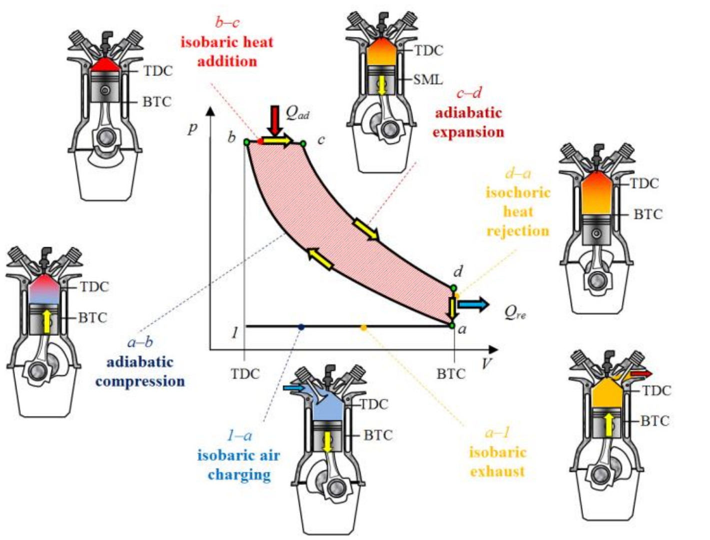

Figure 2 Ideal Diesel cycle

Sources such as the sun or exhaust gases offer heat energy at low temperatures. In many cases this energy is regarded as a problem and often the objective is to dissipate it as cheap as possible. However, various types of heat engines are available for its transformation into mechanical work. We hypothesized that it is possible to transform heat energy at a temperature difference reaching 30 °C and a maximum temperature of 55 °C into mechanical work with low environmental negative effects.

To verify this hypothesis, the heat transformation characteristics at high and low maximal temperatures and temperature differences, respectively are compared. For the comparison, the working cycle of Diesel internal combustion engines, being representative for high maximal temperature and large temperature differences, and Stirling engine, representative for low maximal temperature and small temperature differences, are chosen (Figure 1). To confirm the hypothesis and for practical illustration of the thermodynamic analysis of the working cycle, a Stirling engine model was developed. Finally, some critical elements are exposed and some practical applications of Stirling engines are proposed.

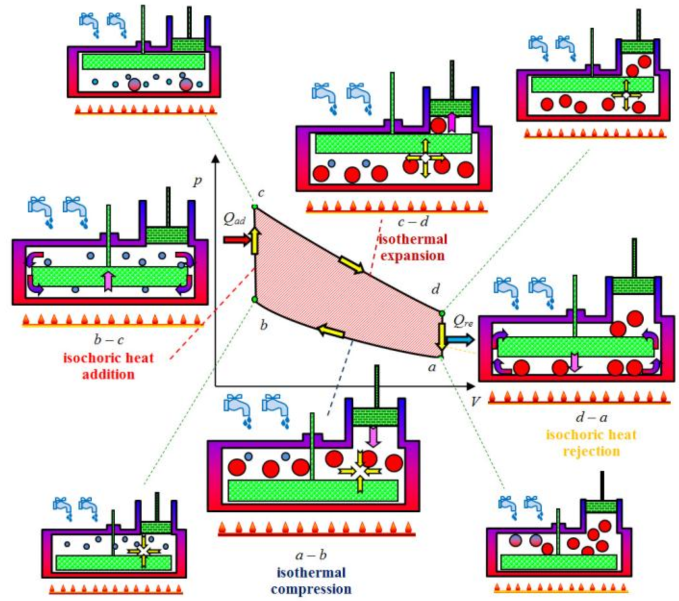

Figure 3 Ideal Stirling cycle

Diesel Engine Cycles

In a Diesel (compression-ignition) engine, the used ideal cycle is the Diesel cycle (1 – a – b – c – d – a – 1) shown in Figure 2. The air is compressed adiabatically at a ratio between 15 and 40 (line: a – b). This compression raises the temperature to the ignition temperature of the fuel mixture which is formed by injecting fuel once the air is compressed. The ideal cycle is modeled as a reversible adiabatic compression followed by a combustion process at constant pressure – isobaric heat addition (line: b – c), then an adiabatic expansion as a power phase (line: c – d) and an exhaust – isochoric heat rejection (line: d – a). The process is reinitiated by fresh air admission (line: a – 1 – a).The heat addition Q_{ad} and heat rejection Q_{re} and the Diesel engine thermal efficiency η_D can be calculated from the mass m of the working fluid, temperature T at several points and specific heat capacity at constant volume c_v and pressure c_p

$$Q_{ad} = mc_p(T_c - T_b) \quad (1)$$
$$Q_{re} = mc_v(T_d - T_a) \quad (2)$$
$$\eta_D = \frac{Q_{ad}-Q_{re}}{Q_{ad}} = 1 - \frac{1}{\kappa}\frac{(T_d-T_a)}{(T_c-T_b)} \quad (3)$$

The combustion (heat addition) in Diesel engine influences the mechanical and thermal load. During the working cycle various engine components are exposed to variable temperatures. Fresh air enters the engine at temperature that varies from 30 to 60 °C, the temperature of working fluid during combustion increases to 2400 °C and the exhaust gasses leave the combustion chamber at a temperature from 700 to 900 °C. Therefore, the maximal temperature of the working cycle is about 2400 °C and the temperature difference is about 2350 °C.

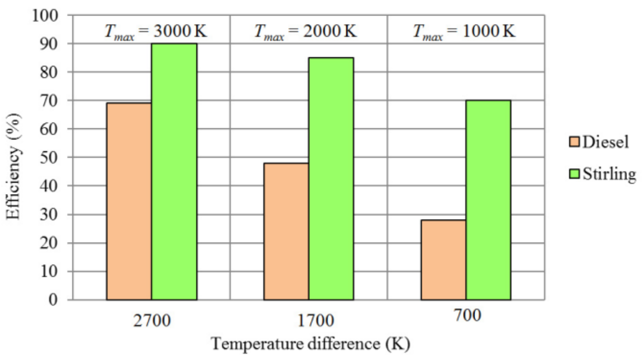

Figure 4 Thermal efficiency of Diesel and Stirling engine

Stirling engine cycle

The ideal cycle (a – b – c – d) of the displacer type Stirling engine is presented in Figure 3. During the isochoric heat addition (line: b – c), the displacer moves to the cooled chamber side, causing the working gas to flow to the heated side of the displacer chamber. Since the volume is constant, the gas pressure increases with the temperature increase. During the isothermal expansion process (line: c –d), most of the working gas is at the heated side, therefore expanding and pushing the power piston. Since the gas expands at an approximately constant temperature, the pressure decreases.

The next phase (line: d – a) is the constant volume cooling process or isochoric heat rejection. As the displacer moves to the heated side, the working gas flows to the cooled side and rejects heat. Since the volume is constant, the gas pressure drops. During the isothermal compression process (line: a – b), most of the working gas is at the cooled side of the displacer chamber; the volume of the working gas increases as the power piston is pushed down. The gas pressure increases at a constant temperature.

In the Stirling engine, the displacer and power piston don't move intermittently but sinusoidal. Between the movement of the displacer and power piston there is a phase angle of 90 degree (Sripakagorn and Srikam2011; Walker 1980). The Stirling engine's thermal efficiency η_S can be calculated using the maximal and minimal cycle temperature (Young and Freedman 2008):

$$\eta_S = 1 - \frac{T_{max}}{T_{min}} \tag{4}$$

Comparison of Diesel and Stirling engine characteristics

On the basis of literature review, a comparison of the heat transformation into mechanical work in a Diesel internal combustion engine and a Stirling engine is presented. Attention is focused on the advantages and disadvantages of acquisition of mechanical work from the heat at high cycle temperature differences, typically for a Diesel engine, and at low temperature cycle differences, typically for a Stirling engine. The following characteristics are analyzed:

- thermal efficiency,
- mechanical and thermal loads of engine,
- material of engine components and cost,
- engine start and adaptability to working changes,
- heat source and working fluid,
- harmful emissions.

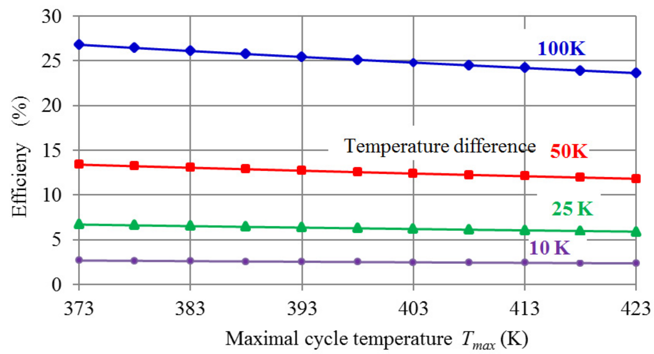

Figure 5 Thermal efficiency of Stirling engine in dependence of maximal cycle temperature and various temperature differences

Thermal efficiency

Thermal efficiency of a heat engine is the relative part of input heat that is transformed into mechanical work (Walker 1980). For the Diesel and Stirling engine thermal efficiency calculation the following equations are used: $\eta_D = 1 - \frac{1}{\kappa}\frac{(T_d - T_a)}{(T_c - T_b)}$ and $\eta_S = 1 - \frac{T_a}{T_d}$, respectively (the limit cycle temperatures need to be selected). For the lower temperature limit the ambient temperature (300 K) is used, whereas for the upper temperature limit (3000 K) the endurance of materials and calorific fuel value (Kegl 2006; Kegl 2008) are decisive. The calculated results show that at equal working fluid maximal and minimal temperatures (equal temperature difference) the thermal efficiency of the Stirling engine is higher than of the Diesel engine (Figure 4). Considering the fact that the minimal temperature for combustion process of a Diesel engine is prescribed and that the temperature at the end of expansion cannot be reduced arbitrarily, it is obvious that the Diesel engine does not function at working fluid low temperature differences. On the other hand, the Stirling engine is able to run even at low temperature differences and at low maximal temperature of the working fluid (Figure 5).

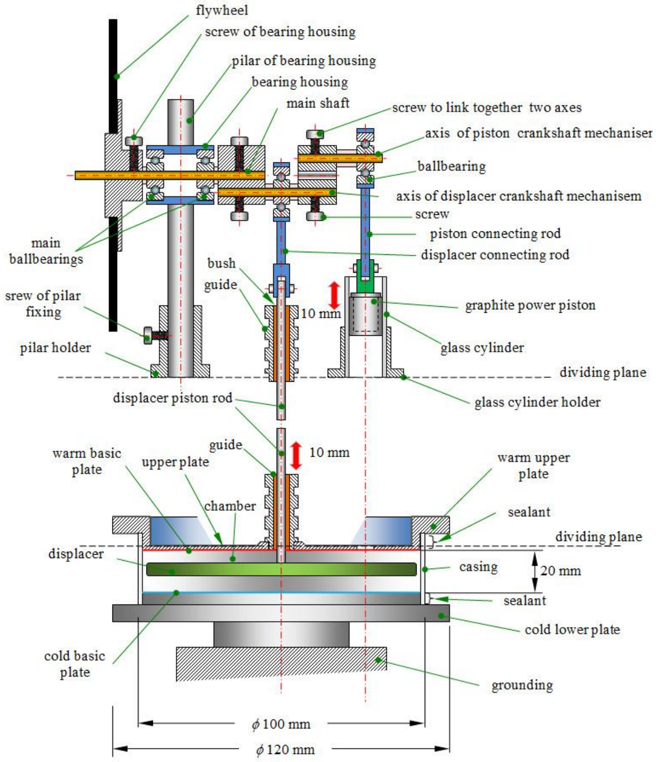

Figure 6 Details of the Stirling engine

Mechanical and thermal loads.

During the combustion process in a Diesel engine, the piston supports a high load. For example, for a piston diameter $d = 125\ \text{mm}$ and maximal in-cylinder pressure $p = 130\ \text{bar}$, one can calculate the force

$$F = p \cdot \pi \left(\frac{d^2}{4}\right) \qquad (5)$$

acting on the piston (Kegl 2008).This force of $159.5\ \text{kN}$ loads the piston 1000-times in one minute at engine speed of 2000 rpm in a 4-stroke Diesel engine. With the same frequency the maximal temperature of 2500 K is reached. At equal temperature and pressure of the working fluid, the mechanical and thermal loads in a Stirling engine are similar to those of a Diesel engine. However, it has to be kept in mind, that the Stirling engine does not need such high temperatures and pressures.

Material of engine components and costs.

In a Diesel engine, the combustion temperatures of the working fluid (over 2500 K) are substantially higher than the engine piston temperatures the surface, up to 750 K). The maximal fluid temperature is allowed to be substantially higher than the maximal acceptable temperature of the materials of the piston and other engine parts because in the Diesel engine the heat is not added through the engine elements. Consequently, the aluminum alloys are a suitable material as well. In the Stirling engine, the temperature of some engine elements is higher than the working temperature because heat is added through the engine elements. For this reason, the requirements for the materials are quite strong in case of a high temperature Stirling engine. It is, therefore, necessary that the heated part of the displacer chamber (warm basic plate) is built from heat resistant and highly heat conductive materials. This special requirement on the employed materials may result in higher costs.

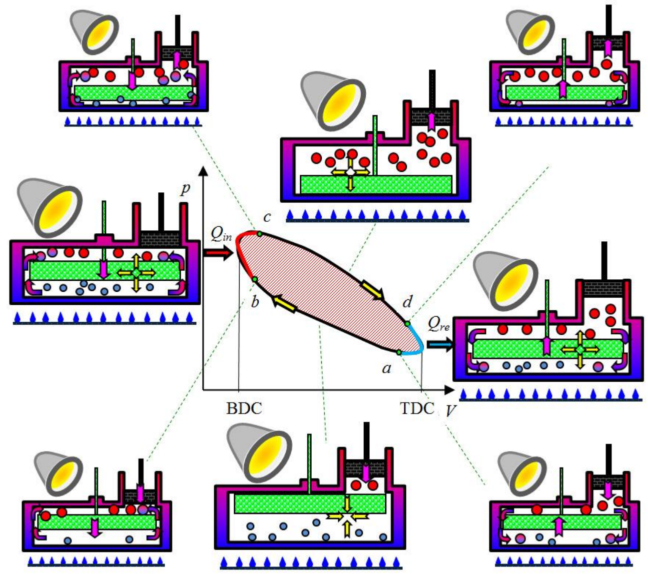

Figure 7 The characteristic phases of real Stirling engine cycle

Engine start and adaptability to working changes.

Usually, the start of a Diesel engine does not cause problems, with the exception of very low ambient temperatures. These engines are valued also for quick adaptability to engine working changes. On the other side, the Stirling engine can work at low ambient temperature also, but not immediately. Usually, previous heating is necessary. The Stirling engines are appropriate for working at relatively constant engine speed and load and will not respond to rapid changes.

Heat source and working fluid.

The heat source in Diesel engines is the heat released during the working fluid combustion in the combustion chamber. The working fluid in a Diesel engine consists of air and fossil or alternative fuels requiring minor engine modifications (Balat and Balat 2010; Kegl 2006). On the other side, the Stirling engine can work with various heat sources, for example, the heat obtained from sun radiation, geothermal heat, heat obtained from biological and nuclear processes or superfluous heat from industrial processes. There are, however, some requirements for the working fluid of a Stirling engine. Appropriate fluids are gasses with high heat conductivity and with low specific heat

(Nice 2008). The first two choices would be hydrogen and helium which pose, however, difficulties in handling due to high inflammability and diffusion of molecules through solid metal parts in the case of hydrogen or due to helium's high price.

Working area	High temperature Difference and high maximum temperature of working fluid		Low temperature difference and high maximum temperature of working fluid	
Engine	Diesel	Stirling	Diesel	Stirling
Thermal efficiency	indifferent	advantage	not applicable	advantage
Mechanical load	indifferent	indifferent	not applicable	advantage
Thermal Load	indifferent	indifferent	not applicable	advantage
Material	indifferent	disadvantage	not applicable	advantage
Cost	indifferent	disadvantage	not applicable	advantage
Engine start	indifferent	disadvantage	not applicable	advantage
	indifferent	disadvantage	not applicable	advantage
Engine adaptability to changes	indifferent	disadvantage	not applicable	advantage
Working fluid	indifferent	disadvantage	not applicable	advantage
Heat source	indifferent	advantage	not applicable	advantage
Harmful emissions	indifferent	advantage	not applicable	advantage

Table 1 Comparison of Diesel and Stirling engine characteristics

Harmful emissions.

The most harmful emissions of a Diesel engine are CO, unburned hydrocarbons, smoke, particulates materials, NO_x and noise (Kegl 2006). For a Stirling engine the harmful emissions depend on the heat source. If the solar radiation is used as a heat source, no harmful emissions are produced. In a Stirling engine the working fluid never leaves the displacer chamber. Because the Stirling engine does not need the explosive combustion, the level of noise pollution is close to zero.

The Diesel and Stirling engines are compared at various maximal temperatures and temperature differences (Table 1). It appears that the Diesel engine is more appropriate for the transformation of heat into mechanical work at high temperature differences and high maximal temperatures of the working fluid. In spite of better thermal efficiency, variability of heat source and lower harmful emissions, other disadvantages of Stirling engine predominate. At low temperature differences and low maximal temperatures of the working fluid, however, the Diesel engine does not function and there the Stirling engine has its advantages. From this comparison, one can conclude that the applicability areas of Diesel and Stirling engines are different making them complementary rather than rival.

To understand the Stirling engine working cycle and to demonstrate its capacity to run at temperature differences of 30 ^{o}C or less and maximal temperature of 55 ^{o}C or less, a unique Stirling engine was developed and its working cycle was analyzed.

Stirling Engine Development and Working Analysis

The manufactured engine is not a duplicate of any existing engine. Its originality is due to the main shaft design and to the low maximal temperature and low temperature difference. This engine consists of:

- displacer chamber,
- cylinder with power piston,
- mechanism to transform longitudinal movement into circular movement (Figure 6).

The elaborated Stirling engine is conceived to be driven by the sun heat. For experimental purposes an electric lamp with 40 W bulb is used. This lamp warms the upper plate of the displacer chamber. After 5 to 10 minutes warming the engine can be started. At the beginning, the flywheel runs slowly but gains speed as the temperature of the upper plate increases. The working cycle of the engine is presented in Figure 7. In the $p-V$ diagram, Figure 7, the extreme positions of the graphite power piston in the glass cylinder are the top dead center (TDC) and the bottom dead center (BDC). At the compression phase, the power piston moves from TDC to the BDC. Because of heat addition the air moves the power piston from BTD to the TDC at expansion phase. It can be seen that heat addition and rejection do not occur at a constant volume, as well as the compression and expansion phases do not occur with isothermal transformation.

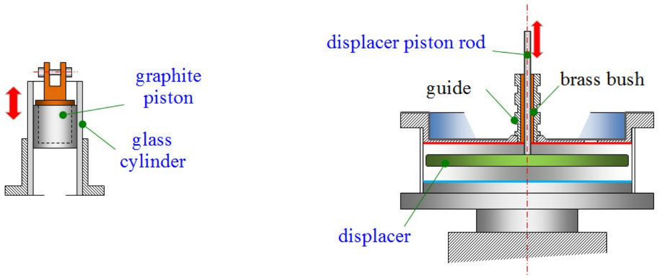

Figure 8 Critical elements of Stirling engine: graphite piston/glass cylinder, displacer piston rod/displacer

After running the engine for a few minutes, the temperatures of upper and lower plate of the displacer chamber were measured with an IR-thermometer. The average values of several measurements were:

- temperature of warm upper plate: $T_1 = 52\ °\mathrm{C}$ $(T_1 = 325\ \mathrm{K})$,

- temperature of cold lower plate: $T_2 = 28\,°\mathrm{C}$ ($T_2 = 301\,\mathrm{K}$),
- rotational speed of main shaft: $\nu = 60\,\mathrm{min}^{-1}$

The thermal efficiency of Stirling engine is calculated as:

$$\eta_S = 1 - \frac{T_2}{T_1} \quad (6)$$

The calculated thermal efficiency $\eta_S = 7{,}4\,\%$ at maximal temperature of working fluid of 52 °C and maximal temperature difference of 24 °C corresponds to the predicted one in Figure 5. It has to be kept in mind that the efficiency of a real Stirling cycle is lower than the calculated one. Furthermore, it has to be pointed out that the goal of the manufactured Stirling engine was not to achieve high efficiency, but to build a model engine which will run at low temperature differences.

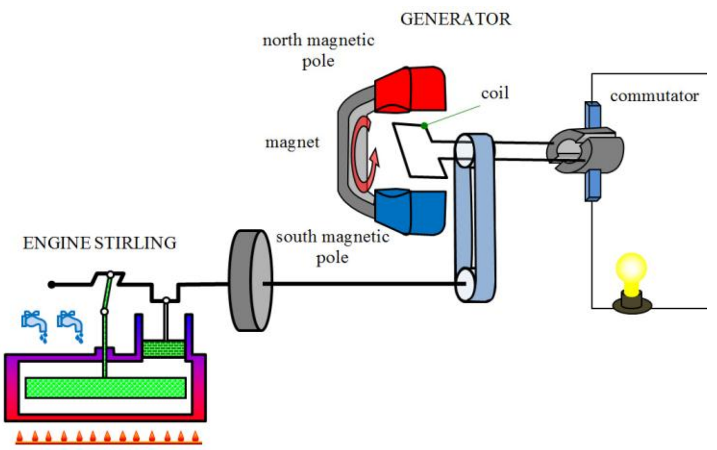

Figure 10 Electric lighting in the building with usage of generator, driven by a Stirling engine

Purpose of Manufacturing and Usage of the Stirling Engine

The basic purpose of the manufactured Stirling engine is to serve as a demonstration and educational instrument. It enables practical insight into the engine and its processes. Furthermore, it enables some construction modifications in order to tune its performance. It stimulates to think about ecology and to investigate alternative energy sources.

On the basis of our own experiences, acquired with the manufactured Stirling engine during this research work, some practical hints are briefly listed in the following:

- quality of manufacture: several components of the Stirling engine have to be carefully manufactured in order to assure efficient running of the engine,
- the selection of materials for various elements: for demonstration purposes aluminum is a very suitable material for those components where the heat transfer is very important; furthermore, aluminum is inexpensive and esthetical,
- special attention has to be put to several assembled elements, such as the graphite power piston/glass cylinder in order to assure good sliding of the piston and tightness, and the displacer piston rod/displacer assembly (Figure 8),
- friction reduction: to reduce friction, ball bearings are recommendable wherever they are possible; furthermore, the steel displacer piston rod should slide in a brass bush,

The usage of a Stirling engine is reasonable at any location where heat is dissipated and lost because the temperatures are too low to be used in some other manner. Good examples are the solar energy and the heat energy of exhaust gasses. Keeping this in mind, the Stirling engine can be used for the needs of housekeeping, industry. The developed Stirling engine can be used to produce electricity for lighting of the buildings (Figure 10).

Conclusions

The paper focuses on the hypothesis that it is possible to transform heat energy at maximal temperature of 55 °C and with a temperature difference up to 30 °C into mechanical work. Heat energy at such temperatures is available for free (sun energy, exhaust gasses, etc.) and without polluting the environment. An engine, which can use such energy and transform it into mechanical work, can be ecologically and economically attractive even if running with low thermal efficiency. Therefore, in order to support the proposed hypothesis, a unique Stirling engine was developed and manufactured.

A Stirling engine exhibits several drawbacks. These are related to: choice of the materials for the elements, which conduct heat from the heat source to the working fluid (high cost, if the engine operates at high temperatures); starting of the engine; adaptability to quick changes of the load and speed; and choice of the working fluid. However, the Stirling engine has also many advantages. These are related to high thermal efficiency, variability of usable heat sources and no harmful emissions (if heat source emissions are neglected). Especially, at low maximal temperature and low temperature difference, the Stirling engine has practically no substitute.

The manufactured Stirling engine is a unique one. Special attention was given to make the small engine operable with low temperature heat source and to the design of the main crankshaft. Experience has shown that good results can only be obtained by minimizing friction in the bearings and masses of the crank mechanism. Such engine can be driven by solar heat, exhaust gasses, and similar sources. In this manner, a Stirling engine can use the energy, which would otherwise be lost.

For future improvements of the thermal efficiency of the Stirling engine the following topics promise further advances: shape variations of the displacer and heat exchangers, usage of other working fluids, and the usage of a metal displacer to act as a regenerator. The investigations and improvements of the

Stirling engine stimulate the ecological education and it can contribute to reduce global warming as well as harmful emissions.

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REFERENCES

1. Lundmark, R. (2010) European trade in forest products and fuels.Journal of Forest Economics16: 235-251.
2. Balat, M. and H. Balat (2010) Progress in biodiesel processing. Applied Energy 87: 1815-1835.
3. Cinar, C. et al. (2005) Beta-type Stirling engine operating at atmospheric pressure.Applied Energy 81:351-357.
4. Demirbas, A. (2009) Progress and recent trends in biodiesel fuels. Energy Conversion and Management 50: 14-34.
5. Edmonds ,I.and G. Smith (2011) Surface reflectance and conversion efficiency dependence of technologies for mitigating global warming. Renewable Energy 36: 1343-1351.
6. Gupta, K. K. et al. (2010) Bio-fuels for the gas turbine: A review. Renewable and Sustainable Energy Reviews 14: 2946-2955.
7. Kegl, B. (2006) Numerical analysis of injection characteristics using biodiesel fuel. Fuel 85:2377-2387.
8. Kegl, B. (2008) Effects of biodiesel on emissions of a bus diesel engine. Bioresource Technology 99:863-873.
9. Kegl, B. et al. (2008) Optimization of a Fuel Injection System for Diesel and Biodiesel Usage. Energy & Fuels 22: 1046-1054.
10. Kongtragool, B. and S.Wongwises (2003) A review of solar-powered Stirling engines and low temperature differential Stirling engines. Renewable and Sustainable Energy Reviews 7: 131-154.
11. Lin, L. et al. (2011) Opportunities and challenges for biodiesel fuel. Applied Energy 88:1020-1031.
12. Onovwiona, H. I. and V. I.Ugursalb (2006). Residential cogeneration systems: review of the current technology. Renewable and Sustainable Energy Reviews 10: 389-431.
13. Panwar, N. L. et al. (2011) Role of renewable energy sources in environmental protection: A review. Renewable and Sustainable Energy Reviews 15:1513-1524.
14. Pehan, S. et al. (2009) Biodiesel influence on tribology characteristics of a diesel engine. Fuel 88: 970-979.
15. Sripakagorn, A. and C. Srikam (2011) Design and performance of a moderate temperature difference Stirling engine. Renewable Energy 36: 1728-1733.
16. Young H. D. and R. A. Freedman (2008) *University Physics with modern physics*. Santa Barbara: Pearson Addison-Wesley.
17. Walker, G. (1980) *Stirling engines*. Oxford: Oxford University Press.