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Design and Thermal Analysis of Free Piston Linear Generator using In Range Extended Electric Vehicles

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Abstract: ***Today, battery electric vehicles (BEV) have zero emission (tank to wheel) and very high efficiency. However, the most important obstacle of BEV is insufficient range. This disadvantage can be eliminated in term of range extender systems. Range extender system like generator can charge battery when required. Free Piston Linear Generator (FPLG), Wankel engine, Piston Internal Combustion Engine, Gas Turbine Engine and Fuel Cell Engine can be used as range extender unit. In this study, opposed-piston free-piston linear generator which can be used in low weight electric vehicles, which has spark ignition, 153 cm3 volume, and gasoline direct fuel injection was designed via SOLIDWORKS® software. Thermal analysis of the engine were performed by means of ANSYS® software using temperature in the literature. Finally, the engine design is determined to suit thermal operating conditions. It is find out that this system can be used as a range extender unit.***

Index Terms: ***Finite Element Method, Thermal Analysis, Free Piston Linear Generator, Computer Aided Design.***

I. INTRODUCTION

Energy sources of conventional Internal Combustion Engines (ICE), oil reserves, are gradually in decreasing. Also, adverse effects of conventional ICE on the environment have led to many car manufacturers to product electric car. The inefficiency in ICE's with low speed and, despite inefficient work with the reason of stop-start urban traffic, energy with regenerative braking, the electric car back in the storage and low speed is an advantage with less energy consumption. While the conventional ICE cars have low efficiency in both too low and too high engine speed and in start-stop city traffic, the electric cars have regenerative braking and consume less energy in low speed. ICEs have different efficiencies a torques with different speeds, so it cannot operate with maximum efficiency, continuously. Unlike ICE, electric motors can give maximum torque in a wide speed ranges and can work with maximum efficiency in a wide torque ranges.

The forthcoming of electric vehicles are promising, because electric vehicles have no emission during operation. However, current battery technology is not at the desired level owing to short range and long charging times, which is the biggest obstacle in the development of battery electric vehicles. Although Electric cars for daily use are sufficient, they are still not suitable for long-distance travel. For this reason, to solve this problem, in the place of adding some battery unit to electrical car,

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Which causes both an extra weight to car and extra costs, it can be added a range extender unit. Range extender unit has fuel station in anywhere and it can be charge to car's battery while driving. In this way, car which is both can charge from mains and, if needed, FPLG can charge the batteries using gasoline, diesel or LPG. Vehicle will be made suitable for long trips [1, 3]. Furthermore, range extender can be made portable.

Many engines can be used as range extender unit such as internal combustion engines, gas turbine engines, wankel engines, and fuelcell engines etc. However, free piston linear engine may be smaller volume, lighter, and also high efficiency. Because these engines do not have the crank-rod mechanism although it works like a conventional internal combustion engines. Linear motion of pistons directly converted to electrical energy by means of the linear alternator instead of converting circular motion. Hence efficiency does not loss and weight and volume do not increase due to auxiliary units (Fig.1).

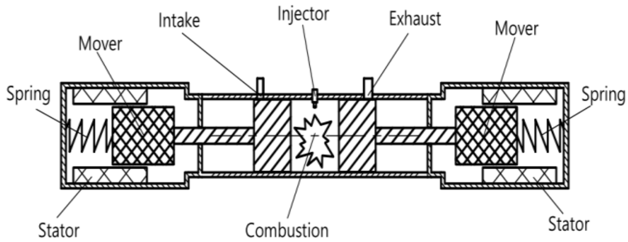

Figure 1. Illustration of the part of the free-piston linear generator

Free piston linear engine and generator have been designed and produced as prototype since the mid-twentieth century. Especially, companies such as Pempek Systems (Australia), Volvo, DLR (Germany), Micron AG (Switzerland) and Toyota have made free-piston linear generator design [4]. Table 1 shows the basic characteristics of the FPLG [2].

TABLE I. BASIC CHARACTERISTICS OF FPLG

Efficiency	36,6%
Packaging	470 W/l (without auxiliary units)
Power density	320 W/kg
Cost	~2100 €
Emissions	3-way-catalyst
flexibility of fuel	many fuels with full potential
Noise–vibration-harshness	Mid(full mass compensation)
Dynamics	Fast, <1s

The REXEL study estimates the weight of a free piston linear generator with a central combustion unit at 55.9 kg. This weight involves the power electronics needed to run the

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FPLG. The power density for this prototype is 350 W/kg and the volumetric power density of FPLG is 470 W/l. Former experimental studies showed that the combustion unit could easily achieve an efficiency of 36% and efficiency of engine is about 36% and cost is approximate 2100 € per unit. Yet cost can be reduced to 1500 € per unit using mass production. FPLG with modular size and low weight is a good alternative for range extender units for electric vehicles. Vehicle can extend its range up to a 300 kilometers with adding just about 100 kg (including tank etc.) [1, 2].

II. MODELING OF ENGINE

Computer-aided design (CAD) is the use of computer systems to aid in the creation, modification, analysis, or optimization of a design. CAD is used to increase the productivity of the designer, to improve the quality of design, to improve communications through documentation and to create a database for manufacturing [5]. Free piston linear engine for range extended electric vehicles was designed using CAD software (SOLIDWORKS®) in order to analyze thermal using finite element method. The basic technical characteristics of the engine which was analyzed are given in Table 2.

TABLE III. TECHNICAL SPECIFICATIONS OF ENGINE

Engine Type	Free Piston Linear Engine
diameter of cylinder (mm)	46
Stroke (mm)	46
Compression ratio	10:1
Volume of engine (cm^3)	153

Piston, cylinder, wrist pin and rod were redesigned based on the design in the literature (Fig. 2) [1, 6].

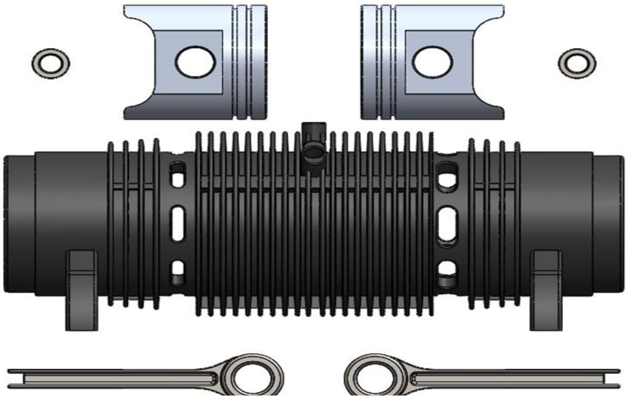

Figure 2. Design of Free piston linear engine

TABLE IIIII. MATERIAL SPECIFICATION OF THE ENGINE PARTS

S.	Part name	Number of part in engine	Material
1	Piston	2	AlSi
2	Cylinder	1	GGG40
3	Wrist pin	2	AISI 4140
4	Rod	2	AISI 4140

Temperature in cylinder change between 100oC and 2500oC and Pressure in cylinder change between 0.8 and 70 bar [18]. So, Cylinder to withstand these conditions are usually made of ductile cast iron grade or steel.

In our design, GGG40 material is selected benefiting from literature, due to damping capacity, good wear and temperature resistance, good machinability, and inexpensive to produce. For cooling, fins were added to cylinder.

By reason of moving at different speed and direction in cylinder, piston should be made of the lightweight material in order to decrease inertia force. Piston of gasoline engines are usually made of AlSi including 12% silicon. As ratio of silicon in AlSi go up, thermal expansion, wear rate and machinability go down [18]. In our design, AlSi12CuNi is selected. Piston are designed as D-cup.

By virtue of free-piston linear engine, only axial forces come to rod. Thus, it is exposed to less load than conventional engines. AISI 4140 is selected for rod material. Rod has unusual shape, because engine designed has not crankshaft.

As FPLG has not crankshaft, rod does not angular movements. So rod pin fix rod and piston. Moreover rod pin, rod and piston can be monolithic. However; it is designed conventionally.

Piston, rod, rod pin and cylinder are designed according to the desired properties benefiting from the literature. Alternator is drawn as represent. Then, parts designed are assembled (Fig. 3 and 4).

Figure 3. FPLG assembled

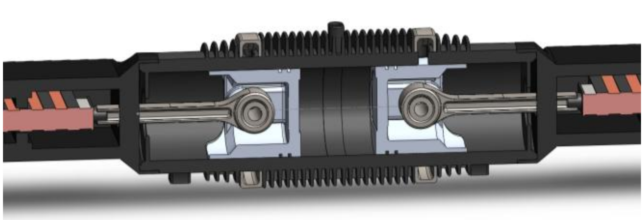

Figure 4. Section view of FPLG designed

III.THERMAL ANALYSIS OF ENGINE PARTS

A. Mathematical Formulation

The temperature T(x, y, z, t) as a function of coordinate system parameters and time satisfies a parabolic differential equations. It can be expressed as follows called heat equation,

$$k_x \frac{\partial^2 T}{\partial x^2} + k_y \frac{\partial^2 T}{\partial y^2} + k_z \frac{\partial^2 T}{\partial z^2} + Q = \rho c_p \frac{\partial T}{\partial t} \tag{1}$$

where Q(x, y, z, t) is the source or sink rate of heat in a domain (W/m^3), c_p is the specific heat at constant pressure (kJ/kg^oC) and k is the thermal conductivity (W/m^oC). The essential boundary condition on the boundary and the natural boundary condition can be defined, respectively, as

$$T(x, y, z, t) = T_1(x, y, z, t) \tag{2}$$

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$$k_n \frac{\partial y}{\partial x} + q_p + h(T - T_\infty) + \sigma\varepsilon(T^4 - T_\infty^4) = 0 \qquad (3)$$

where k_n is the thermal conductivity normal to the surface, qp (x, y, z, t) is a prescribed flux (W/m2), h is the heat transfer coefficient for convection (W/m2C), σ is Stefan–Boltzmann constant (W/m2C4), ε is the emissivity and T∞ is the ambient temperature for convection and/or radiation. Boundary condition becomes nonlinear when radiation is included or the convective heat transfer coefficient is temperature dependent. Besides the boundary conditions, the initial condition must be specified for a heat transfer analysis:

$$T(x, y, z, 0) = T_{in}(x, y, z) \qquad (4)$$

B. Finite Element Formulation

The domain is broken into a set of discrete volumes or finite elements that are generally unstructured; in 2D, they are usually triangles or quadrilaterals, while in 3D tetrahedral or hexahedra are most often used. The distinguishing feature of finite element method (FEM) is that the equations are multiplied by a weight function before they are integrated over the entire domain [7, 19].

This approximation is then substituted into the weighted integral of the conservation law and the equations to be solved are derived by requiring the derivative of the integral with respect to each nodal value to be zero; this corresponds to selecting the best solution within the set of allowed functions. The result is a set of non-linear algebraic equations [7].

The basis of the finite element method is a piecewise polynomial approximation for the temperature field within each element:

$$T = \sum_{i=1}^{n} N_i T_i$$

where Ni are basis functions dependent only on the type of the element and its size and shape, and ‘‘n’’ represents the node number that each element has. Physically, Ti(t) are nodal values of the temperature at time t, and mathematically, they are undetermined coefficients. Basically, by using different techniques, Eq. (1) can be reduced to

CT+KT=F

in which (K) is an effective conductivity (stiffness matrix) and (F) is an effective load (residual vector). For steady-state analysis, effective load becomes zero. By solving the system, the temperature distribution on the domain is determined [8, 9].

C. Thermal Analysis using Finite Element Method

Numerical analysis was performed to evaluate the temperature gradients in FPLG. The finite element mesh of the FPLG model using ANSYS® is shown in Fig. 5. In the thermal analysis, 209,721 elements are used. 378,597 nodes are also used in thermal analysis.

In this research, thermal boundary conditions were determined by examining the similar works in literature. The temperature values in the cylinder were taken to be average of ICE [9-14].

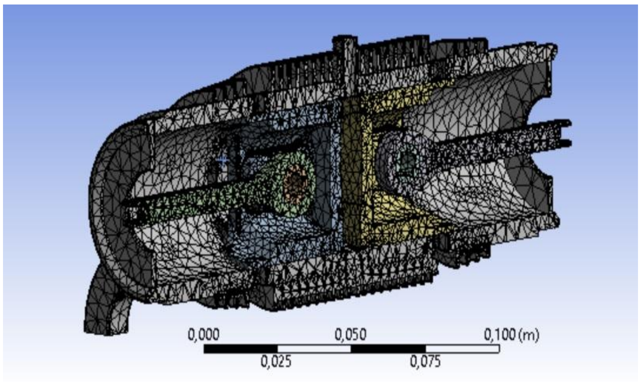

Figure 5. Finite element mesh of FPLG designed

Properties of FPLG materials used in thermal analysis are shown in Table 4 [15-17].

TABLE IVV. PROPERTIES OF MATERIALS OF FPLG

Material	Thermal cond. (W/m°C)	Thermal expanse. (10^{-6}/°C)	Den. (kg/m^3)	Spec. heat (J/Kg °C)	Poisson's ratio	Young's mod. (GPa)
GGG40	42	11	7200	447	0,28	168,5
AlSi	155	21	2700	960	0,28	80
AISI 4140	43	11,8	7850	450	0,29	205

Thermal boundary conditions are shown in Fig. 6 and Table 5. Piston thermal boundary conditions consist of the combustion side thermal boundary condition (A), upper ring land (B), lower ring land (C), skirt surface thermal boundary condition (D), outside of cylinder thermal boundary condition (E), surface of rod and rod pin thermal boundary condition (F), inside of cylinder thermal boundary condition (G) and surface of combustion chamber thermal boundary condition (H) [9-14].

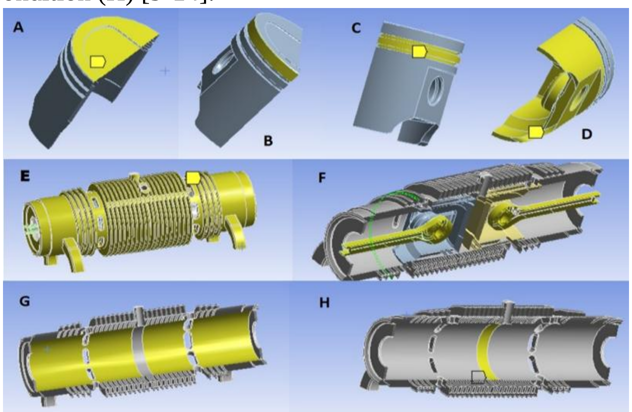

Figure 6. FPLG thermal boundary conditions

TABLE V. FPLG THERMAL BOUNDARY CONDITIONS

	Temperature (°C)	Convection coefficient (W/m^{2}K)
A	650	800
B	300	230
C	110	200
D	85	400
E	50	60
F	85	400
G	85	400
H	650	800

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IV. RESULTS AND DISCUSSION

In order to evaluate the temperature gradients of the FPLG parts, numerical analyses were carried out. Minimum-maximum temperatures and heat fluxes values of piston and cylinder that is found in thermal analyses are shown in Table 6. Maximum temperature of combustion chamber is 231.56^{o}C in the top surface of pistons. Maximum heat flux of combustion chamber is 1.09*106 W/m^{2} and minimum heat flux of combustion chamber is 4.76*104 W/m^{2}.

The resulting temperature distributions given in Fig. 7 and the resulting heat flux distribution are illustrated in Fig. 8. Temperature distribution in the top and side surface of piston is demonstrated Fig. 7 and Fig. 8, respectively.

Fig. 9 was shown that the surface temperature of the piston decreases from the center to the edge of the piston. The temperature at the center was found as 223^{o}C, it decreased by ~10% and reached to 207^{o}C at the edge of the piston. It indicates that the temperature distribution of the piston surface tends to decrease from the center to the edge of the piston. This situation is valid for the spark ignition engines at real working condition.

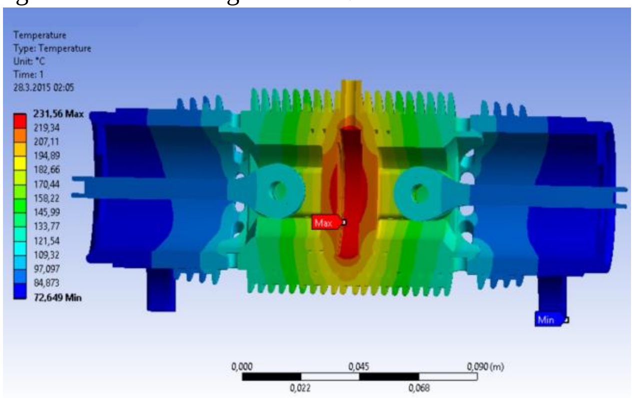

Figure 7. The resulting temperature distributions

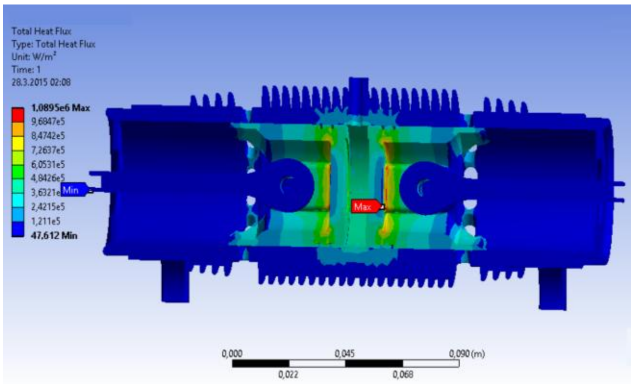

Figure 8. The resulting heat flux distribution

TABLE VI MINIMUM-MAXIMUM TEMPERATURES AND HEAT FLUXES IN PISTON AND CYLINDER

	Maximum temperature (^{o}C)	Minimum temperature (^{o}C)	Maximum heat flux (W/m^{2})	Minimum heat flux (W/m^{2})
Top surface of piston	231,56	208,62	0,7*10^{6}	0,307*10^{6}
Inside surface of cylinder	231,16	79,1	0,611*10^{6}	0,0476*10^{6}
Bottom surface of piston	217,54	188,4	1,09*10^{6}	0,0535*10^{6}

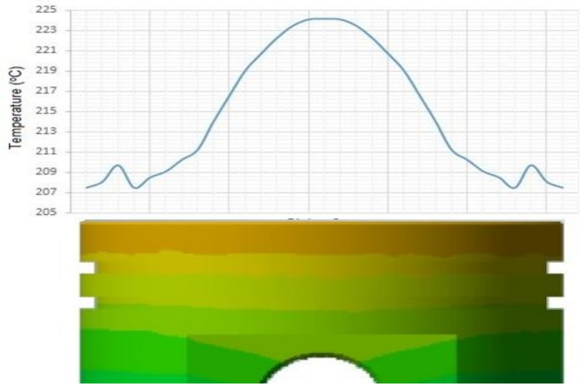

Figure 9. Temperature distribution in the top surface of piston

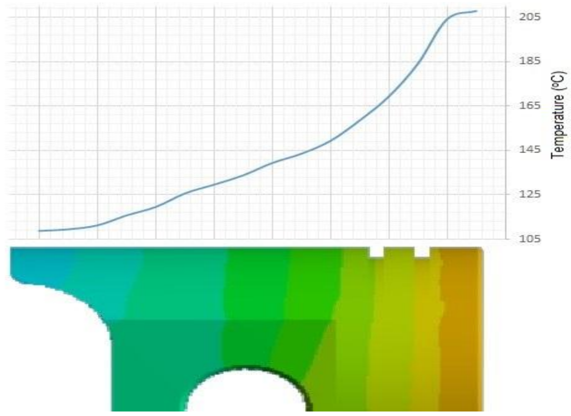

Figure 10. Temperature distribution in the side surface of piston

V. CONCLUSIONS

Although electric vehicle has advantages such as high efficiency, no emission and much quitter; it is limited by range and take about 4-6 hours to get fully charged. Range extender can eliminate these obstacles. Free piston linear generator in range extender units attract the attention with compact size, relatively simplicity and efficiency.

In this study, cylinder, piston, rod and rod pin of FPLG using in electric vehicles were designed. After defining all boundary and initials conditions in a finite element environment a thermal solution of the FPLG is achieved. According to findings of the analysis, the temperature occurred in engine is acceptable. Hence, it is clearly seen for results of analysis that, if manufactured, engine parts designed can work properly.

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