DESIGN AND SIMULATION OF AN EXHAUST BASED THERMOELECTRIC GENERATOR (TEG) FOR WASTE HEAT RECOVERY IN PASSENGER VEHICLES

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Clarkson and Nissan parameters, respectively. Columns (II) and (IV) contain the experimental results produced by Clarkson and Nissan prototypes, respectively

ABSTRACT

The increasing demand for electric power in passenger vehicles has motivated several research focuses since the last two decades. This demand has been revoluted by the unrelenting, rapidly growing reliance on electronics in modern vehicles. Generally, internal combustion engines lose more than 35% of the fuel energy in exhaust gas. Comparing this huge loss to every day's growing oil price, one could understand how the recovery of such losses could help the economy, as well as providing the additional power sources required by contemporary vehicle systems. There are three fundamental advantages of thermoelectric generators (TEGs) over other power sources are three; they do not have any moving parts as they generate power using Seebeck solid-state phenomena, they have a long operation lifetime, and they can be easily integrated to any vehicle's exhaust system.

This thesis presents a novel TEG concept aims to resolve the thermal and mechanical disputes faced by the research community. A novel procedure for designing exhaust based TEG is presented as well. Several simulation models are used to analyze the TEG performance. The significance of the novel TEG is discussed through a detailed comparison with experimental results from Clarkson University and Nissan Motors TEG prototype tests. The simulation results showed a huge increase in the energy density achieved by the novel TEG to reach 11.92 W/kg.

ABSTRAK

Peningkatan permintaan terhadap kuasa elektrik di dalam kenderaan penumpang telah memotivasi beberapa fokus penyelidikan semenjak beberapa dekad yang lalu. Permintaan ini telah direvolusikan oleh peningkatan kebergantungan yang mendadak terhadap peralatan elektronik dalam kenderaan penumpang seperti sistem telekomunikasi, modul kawal enjin, penderia hindar perlanggaran, dan peranti pelayaran satelit. Amnya, enjin pembakaran dalam kehilangan tenaga bahan api melebihi 35% dalam gas ekzos.Membanding kehilangan ini dengan peningkatan harag bahan api, adalah difahami bagaimana penggunaan semula kehilangan ini dapat membantu dari segi ekonomi disamping membekalkan sumber tenaga tambahan yang diperlukan oleh sistem kenderaan sedia ada. Terdapat 3 asas kelebihan penjana termaelektrik (TEG) berbanding sumber kusasa yang lain; ia tidak mempunyai bahagian yang bergerak kerana ia menjana kuasa menggunakan fenomena keadaan pejal seebeck, ia mempunyai jangka hayat operasi yang lama dan ia mudah untuk disatukan kepada sistem ekzos mana-mana kenderaan.

Tesis ini membentangkan konsep baru TEG yang mensasarkan penyelesaian terhadap permasalahan terma dan mekanika yang dihadapi oleh komuniti penyelidikan. Prosedur baru unutk merekabentuk sistem ekzos berdasarkan TEG juga dibentengkan. Beberapa odel simulasi digunakan untukk menganalisa prestasi TEG. Kepentingan TEG dibincangkan bersama perbandingan teliti dengan keputusan ujikaji dari Universiti Clarkson dan ujian prototaip TEG dari Nissan Motors. Keputusan simulasi menunjukkan peningkatan ynag besar dalam ketumpatan tenaga yang dicapai oleh TEG ini yang mencecah 11.92 W/kg.

CHAPTER 1

INTRODUCTION

The expression "Energy Crisis" has become a symbol of the human concern about the increasing demands and consumption of energy on earth. For almost two hundred years, the main energy resource has been fossil fuel. The world consumption of all energy resources is forecasted to increase from 421 quadrillion Btu in 2003 to 563 quadrillion Btu in 2015 then to 722 quadrillion Btu in 2030, as shown in Figure 1.1.
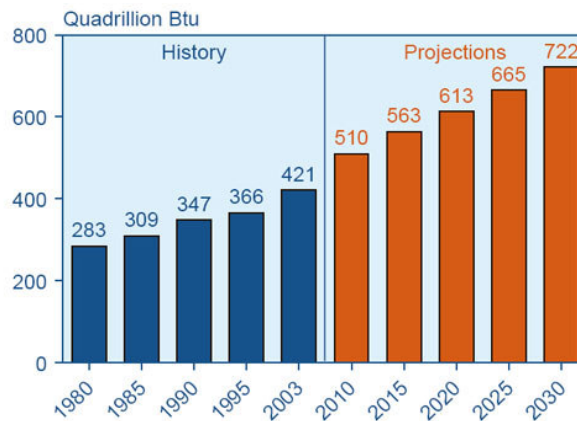

Figure 1.1 World market energy consumption 1980 – 2030, (IEO, 2006)

Fossil fuels continue to supply much of the increment in marketed energy use worldwide throughout the next two and half decades. Oil remains the dominant energy source, but its share of total world energy consumption declines from 38 % in 2003 to 33 % in 2030 as illustrated in Figure 1.2, largely in response to higher world

oil prices, which will dampen oil demand in the mid-term. Worldwide oil consumption is expected to rise from 80 million barrels per day in 2003 to 98 million barrels per day in 2015 and then to 118 million barrels per day in 2030.
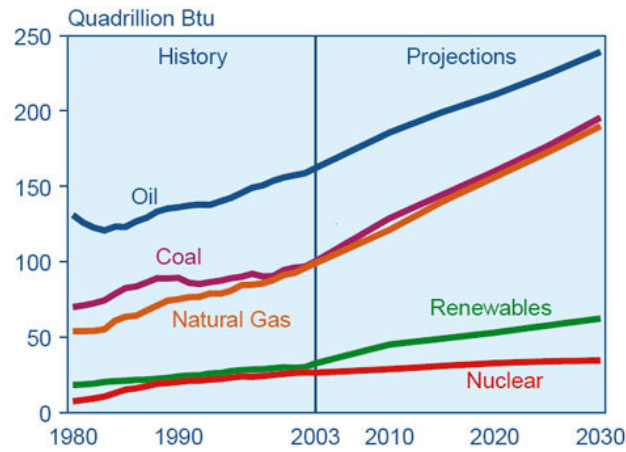
Figure 1.2: World marketed energy use by fuel type 1980 – 2030, (IEO, 2006)

1.1 Trends of energy usage in road transport sector

Most of the worldwide increase in oil demand will come from the transport sector, Figure 1.3. In the OECD[1], oil use in sectors other than transport will hardly grow at all, and will even fall in the power sector. In non-OECD countries, the industrial, residential and services sectors will also contribute to the increase in oil demand. The transport sector will account for 54% of global primary oil consumption in 2030 compared to 47% now and 33% in 1971, as demonstrated in Figure 1.3. Transport will absorb two-thirds of the increase in total oil use. Almost all the energy currently used for transport purposes is in the form of oil products. The

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[1] OECD includes all members of the Organization for Economic Cooperation and Development as of February 1, 2006, as follows:
OECD Europe
OECD Europe consists of Austria, Belgium, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Luxembourg, the Netherlands, Norway, Poland, Portugal, the Slovak Republic, Spain, Sweden, Switzerland, Turkey and the United Kingdom.
OECD North America
OECD North America consists of the United States of America, Canada and Mexico.
OECD Pacific
OECD Pacific consists of Japan, Korea, Australia and New Zealand.
OECD Asia
OECD Asia consists of Japan and Korea.
OECD Oceania
OECD Oceania consists of Australia and New Zealand.

share of oil in transport energy demand will remain almost constant over the projection period, at 95%, despite the policies and measures that many countries have adopted to promote the use of alternative fuels such as biofuels and compressed natural gas. (WEO, 2004)
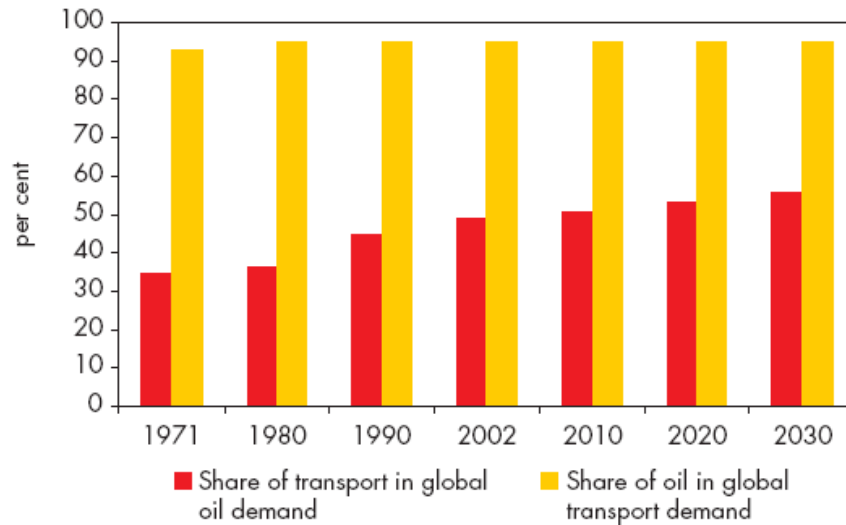
Figure 1.3. Reciprocal transport and oil demands

Demand for road transport fuels is growing dramatically in many developing countries, in line with rising incomes and infrastructure development. The passenger-car fleet in China – the world's fastest growing new-car market – grew by more than 9% per year in the five years to 2002, compared to just over 3% in the world as a whole as reported by Rueil and Malmaison (2003). Preliminary data show that more than two million new cars were sold in China in 2003. The scope for continued expansion of the country's fleet is enormous: there are only 10 cars for every thousand Chinese people compared with 770 in North America and 500 in Europe. Other Asian countries, including Indonesia and India, are also experiencing a rapid expansion of their car fleets. Freight will also contribute to the increase in oil use for transport in all regions. Most of the increased freight will travel by road, in line with past trends. The total vehicle stock in non-OECD countries is projected to triple over the projection period to about 550 million, but will still be about 25% smaller than that of OECD countries in 2030.

As for Malaysia, the final energy consumption grew at a fast rate of 5.6 % between 2000 and 2005 to reach 38.9 MTOE[2] in 2005. A substantial portion of the energy consumed was from oil (63 %) which was mainly utilized in the transport and industrial sectors. Natural gas consumption also increased in a rapid manner to fuel electricity demand. The share of natural gas in total installed electricity generation capacity remains high at 70 % in 2005, but has fallen slightly from 77 % in 2000.

Despite the government's efforts to increase the share of coal in the electricity generation mix, the share of coal only reached 22 % in 2005. Over the coming 50 years, final energy demand is projected to grow at 3.9 % per year, reaching 98.7 MTOE in 2030, nearly three times the 2002 level. The industry sector will have the highest growth rate of 4.3 %, followed by transport at 3.9 %, residential at 3.1 % and commercial at 2.7 %, Figure 1.4, (APEC 2007).
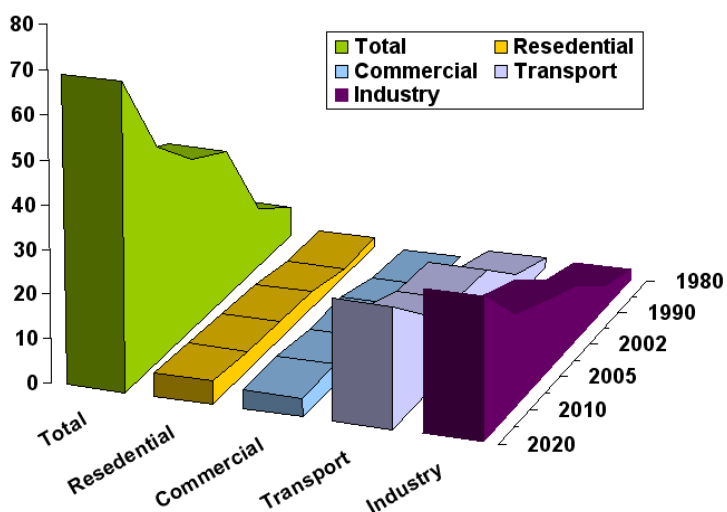
Figure 1.4: Malaysia final energy demand by sector 1980-2020, (APEC 2007).

The transportation sector of Malaysia is heavily reliant on the road transport sub-sector. In 2002 for example, energy demand for road transport represented 86 % of the total transport energy demand. Urban transport such as in Kuala Lumpur is heavily dependent on passenger vehicles, since rail infrastructure has not yet been well developed to connect the city centre with the residential suburbs. Inter-city passenger and freight movement depends on road transport, because of the limited availability of rail transport (APEC, 2006). Passenger vehicle ownership has been

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[2] MTOE: Million Tons of Oil Equivalent   1 TOE = 4.5 x10^7 KJ

promoted as Malaysia considers the auto manufacturing industry as an important driver for economic development. As a result, Malaysia has a relatively high growing rate of passenger vehicle ownership, see Figure 1.5. The recess in the vehicle number growth rate in the period between 1997 and 1999 reflects the economical crisis occurred in that period. However, the escalating number of passenger vehicles over 50 years from 53 vehicles per 1,000 populations in 1980, through 180 vehicles in 2002 to a predicted value of 347 vehicles per 1,000 populations in 2030; reflects the long-term unrelenting reliance on road transport (IEA, 2006) and (JPJ, 2002)
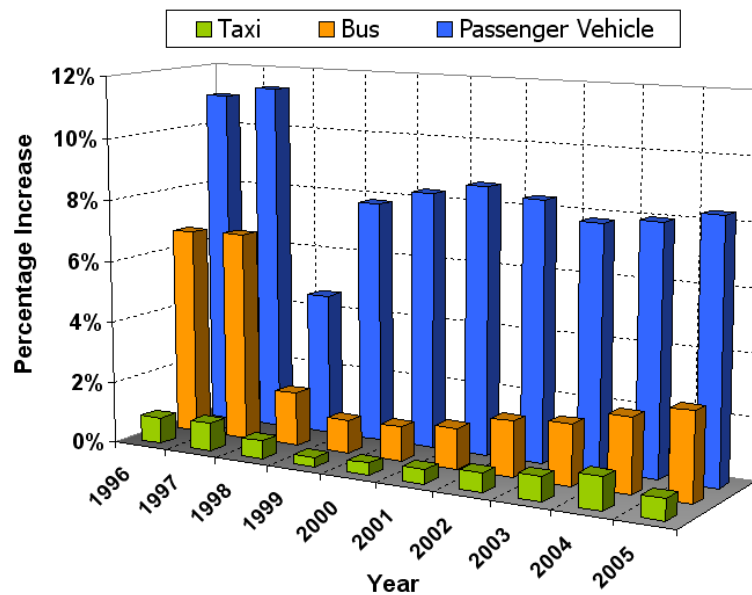
Figure 1.5: Annual growth of passenger vehicle ownership in Malaysia 1996-2005

Energy demand in road transport is projected to grow at an annual rate of 3.5 %. By fuel type, the trend of growth will show significant differences, with gasoline growing at 2.9 % per year, diesel at 4.2 % per year, and natural gas at 9.2 % per year. In 2000 the annual gasoline consumption per capita[3] in Malaysia was 358 (Liters per Person), this number has increased by 1.8% in three years to become 364.9 in 2003[4] [5], while the total gasoline consumption for the transportation sector in 2003 was 8916 million liters[5]. Beside the increase in the number of vehicle ownership, the

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[3] Motor gasoline consumption per capita measures the average volume of motor gasoline consumed by a specified country per person for use in the transportation sector.
[4] The World Resources Institute calculates per capita energy consumption with population data from the United Nations Population Division.
[5] Nearly all (>99%) of the gasoline consumption listed here is used in road transport. Motor gasoline is used in spark-ignition engines (e.g. the engines of most passenger cars) and includes both leaded and unleaded grades of finished gasoline, blending components, and gasohol. Motor gasoline may include additives, oxygenates and octane enhancers, including lead compounds such as TEL (Tetraethyl lead) and TML

increase in electric power demand in modern vehicles forms a significant factor, which boosts the vehicle fuel consumption.

Stability controls, telematics, collision avoidance systems, navigation systems, steer by-wire, electronic braking, additional powertrain/body controllers, and sensors that can automatically optimize vehicle performance are modern electronic components that require more fuel to be converted to electric power through the vehicle system (Yang, 2005).

1.2 Thermoelectric Waste Heat Recovery as a Potential Energy Efficiency Option in Ground Vehicles

Stabler (2002) reported that in gasoline powered internal combustion engines, roughly 40% of the fuel energy is wasted in exhaust gases, and 30% in engine coolant. On the other hand, in diesel powered internal combustion engines about 25% and 35% of the fuel energy are wasted in the engine exhaust and coolant systems respectively. Unfortunately, present-day engine designs may not meet all our future needs. In order to meet the rapidly increasing requirements of electrical power the OEMs are considering several alternatives like 42 volt systems, hybrid vehicles, fuel cell vehicles, and so on. One such alternative is the use of thermoelectric generators to recover the waste heat from the exhaust and/or the engine coolant. Thermoelectric generators utilize the Seebeck thermoelectric effect to generate electric current from a temperature gradient. The discovery of Seebeck effect dates back to 1821, however, the interest in utilizing this physical phenomenon in automobiles started only in the second half of the twentieth century. A full literature review about the application of Seebeck phenomena in power generation, and specifically in automobiles, is presented in chapter three.

The Department of Energy (DOE), USA, is considered the pioneer organization in vehicular thermoelectric generators research through the Freedom CAR and Vehicle Technology Program. Reports by the DOE affirm that in the next 3 to 5 years, thermoelectric generators are expected to achieve up to 10% fuel economy through offering more electric power for automobile systems. Within 8 to

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(tetramethyl lead). Motor gasoline does not include the liquid biofuel or ethanol blended with gasoline. Data are reported in liters per person.

12 years, thermoelectric generator would be able to save up to 10% and 16% in light and heavy duty trucks respectively. While hydrogen fuel cells still face obstacles in the design and implementation of their refueling facilities, thermoelectric generators, unbelievably, are predicted to be the potential alternatives of internal combustion engines after 25 years (Fairbanks 2005).

A thermoelectric generator with an efficiency of 20% would allow for a reduction in fuel consumption incrementing the useful power from a gasoline ICE to a maximum of 52% (Kushch et al. 2001). In order to achieve such efficiency from the current state-of-the art thermoelectric generators which have an efficiency of 5~8%; several challenges should be encountered. The thermoelectric generator efficiency is directly dependant on the conversion efficiency of the materials employed and the overall efficiency of the heat exchangers. Saqr *et al.* (2007) stated that while there is a rat race to produce more efficient, less expensive, and more durable thermoelectric materials, the research community is reluctantly interested in improving the thermoelectric generators' heat exchanger systems in terms of thermal and mechanical efficiencies. For the exhaust-based thermoelectric generators, the overall efficiency of the system is the product of three terms; two of them represent the thermal effectiveness of the generator heat exchangers, while the third is the thermoelectric conversion efficiency of the materials employed (Ikoma et al. 1998). There are several options to investigate in order to enhance the thermal efficiency of thermoelectric generators; including the use of highly conducting alloys, innovative heat enhancement techniques in both cold and hot side heat exchangers, and reducing the overall weight through creative and innovative assembly.

1.3   Problem Statement

Publications describing experimental and theoretical investigations of automobile exhaust-based thermoelectric generators are very scarce and propriety due to the potential economic values of the system as a commercial product. In the same time, there are countable publications about these generators explicate the improvements and advances achieved by many multinational companies to produce them. For instance, BMW of North America has announced that it will launch a 10% effective thermoelectric generator through its Series 5 vehicles in the year 2010

(LaGrandeur et al. 2005). One year earlier, General motors and Clarkson University have already tested a 300 W thermoelectric generator to be applied on a Sierra Pick-Up truck in the year 2004 (Thacher et al. 2007). However, there have been no publications describing the design and testing procedures of thermoelectric generators. Although, some research work have described the use of certain software tools such as ADVISOR and FLUENT to study the effect of the generator on the engine power and to optimize the heat exchanger efficiency respectively (LaGrandeur, Crane et al. 2005)

This research mainly focuses on two aspects; first to establish a design procedure for automobile thermoelectric generators and second to apply this procedure to design and simulate a thermoelectric generator for light duty, gasoline fueled passenger vehicles. The problematic concern of developing a novel design procedure is presumed to cover several issues including the simulation and optimization of the hot-side and cold-side heat exchanger geometries and modeling the thermoelectric materials performance. Whereas the implementation of such procedure to design and simulate a new thermoelectric generator should endure a validation against one of the few published research work; in order to authenticate the proposed design procedure.

1.4   Research Objectives

The main objective of this research is to conceptualize and design an exhaust based thermoelectric generator that overcomes the thermal shortcomings found in earlier models of thermoelectric generators. The design process includes a performance simulation for the thermoelectric generator.

Secondary objectives for this research are:

1- Establish a novel procedure for design of thermoelectric generators
2- Explore the potential of thermoelectric generators as a source of electric power onboard automobiles through the previous, current and future research and commercial trends worldwide.

1.5   Research Scope

In the present research, a novel concept for a thermoelectric generator based on light-duty passenger vehicles is proposed. The proposed design is conceptualized to overcome the geometrical and thermal restrains believed to cause the ineffectiveness to former designs. The governing outlines for such novel concept are inspired from a detailed and comprehensive investigation of previous research work. The proposed concept is brought into the detailed design process through several simulations performed using COSMOSFloworks® CFD solver, and MatLab®. These simulations define the optimum dimensions and structure of the thermoelectric generator to meet the performance requirements. Additionally, the simulation processes predict the performance characteristics of the generator at certain engine operating conditions, for this reason, a simulation model for thermoelectric materials is developed. For the validation purpose of simulation results, a comparison between such results and experimental results produced by Nissan Research Center is composed.

1.6   Simulation Strategy

Working fluids in thermoelectric generators for automobile waste heat recovery are the exhaust gases and the engine cooling water for the hot and cold sides respectively. Exhaust gases temperature varies with engine speed and volumetric efficiency. While cooling water temperature varies mostly between 50 ^{o}C to 80 ^{o}C for light duty vehicles during engine part load. A MatLab® code is developed firstly to investigate the variation of exhaust flow rate with engine RPM. The pressure drop in the exhaust line is then simulated using a 3D simulation model. Thermoelectric modules from Hi-Z Inc are selected for implementation in the proposed design. A MatLab® code is developed to simulate the operating performance of the thermoelectric modules, to calculate the required number of modules at the design operating condition, and to predict the power generation profile with temperature gradient on the hot-side heat exchanger.

A MatLab® code is developed to optimize the hot-side heat exchanger geometry with regard to pressure drop and overall heat transfer coefficient. The performance of optimized heat exchanger is simulated using COSMOS® in order to

predict the performance characteristics, and to calculate the thermal efficiency of the thermoelectric generator.

1.7   Organization of thesis

This thesis contains seven chapters other than the present one. The second chapter is to shed the light on the principles of thermoelectric energy conversion in terms of molecular phenomena, mathematical formulation, materials, and generator structure. The third chapter reviews thermoelectric generator applications in a broad spectrum, however, focusing on automobile waste heat recovery specifically to highlight the major concerns and challenges facing the research community in this topic. The design concept and procedure of the thermoelectric generator is elucidated in the fourth chapter, while the fifth chapter is dedicated totally to explicate the details of the simulation strategy and processes. In the sixth chapter, the simulation results are articulated in details and compared to the experimental results produced by Nissan R&D center. Notes from such comparison are used to establish the future research recommendations outlined in chapter seven. A concise and comprehensive conclusion is presented finally.

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