STUDY ON WASTE HEAT RECOVERY FROM EXHAUST GAS OF THE NATURALLY ASPIRATED SPARK IGNITION ENGINE

BY

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A thesis submitted in fulfillment of the requirement for the degree of Doctor of Philosophy (Engineering)

Kulliyyah of Engineering
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JANUARY 2017

ABSTRACT

The number of motor vehicles continues to grow globally and therefore increases reliance on the petroleum and increases the release of carbon dioxide into atmosphere which contributes to global warming. To overcome this trend, new vehicle technologies are introduced to achieve better fuel economy without increasing harmful emissions. For internal combustion engine (ICE) in most typical gasoline fuelled vehicles, it was estimated that 21% of the fuel energy is wasted through the exhaust at the most common load and speed range. The waste heat from exhaust gases represents a significant amount of heat energy, which has conventionally been used for combined heating and power applications. In this study, the waste heat recovery mechanism (WHRM) is developed for a naturally aspirated spark ignition engine. The performance of a naturally aspirated spark ignition engine equipped with the WHRM is explored, in terms of the engine performance and the generated power from WHRM. The experimental works were conducted by using an experimental vehicle, which implemented the WHRM on two mechanisms: gas turbine and steam turbine mechanisms. First, the experimental vehicle run on-road test without WHRM to explore the engine performance and the amount of heat energy from exhaust waste heat as a reference condition. Then, the experimental vehicle run on-road test with gas turbine mechanism steam turbine mechanism of WHRM. The major contributions of this study includes in conducting the experimental work of novel waste heat recovery mechanism, and implementing on the experimental vehicle (naturally aspirated spark ignition engine) with on-road test, which can reveal the performance of engine and waste heat recovery mechanism on the real condition. Heat energy from exhaust waste was found in range of 500 W up to 23 kW that obviously worthy to recover this heat energy. For WHRM, It is found that the gas turbine mechanism of waste heat recovery can reach up to 110 W, and occurs in short period of time around 1 to 4 second. Meanwhile the steam turbine mechanism can reach up to 29 W, but occurs in longer period of time, for example in 10 s. It also found that the gas turbine mechanism causes the power of engine to slightly drop, while the steam turbine mechanism of waste heat recovery does not affect the performance of engine. A new model for heat energy from exhaust waste heat and power generated from WHRM are proposed here to explain the possible enhancement, by using the engine speed, throttle angle, exhaust temperature, ambient temperature, and air flow rate as the data input in multiple regression method and Artificial Neural Network (ANN). For heat energy and both gas turbine and steam turbine mechanisms, the model of heat energy and generated power are found to be more in good agreement with experimental data using ANN with comparison to multiple regression method.

ملخص البحث

لا يزال تعداد السيارات في النمو على الصعيد العالمي، وبالتالي يزيد الاعتماد على النفط وبذلك يزيد من إطلاق غاز ثاني أكسيد الكربون في الغلاف الجوي الذي يسهم في ظاهرة الاحتباس الحراري. وللتغلب على هذه المشكلة، يتم إدخال تقنيات جديدة لتحقيق اقتصاد أفضل في استهلاك الوقود دون زيادة الانبعاثات الضارة بالبيئة. بالنسبة لمحرك الاحتراق الداخلي (ICE) في أكثر المركبات المزودة بالوقود، فإن التقديرات تشير إلى أن 21% من طاقة الوقود تُهدر من خلال العادم في مدى السرعة الأكثر شيوعاً. ولكنّ الحرارة المنبعثة من غازات العادم تمثل مقداراً كبيراً من الطاقة الحرارية، والتي يمكن إ ستخدا مها في تلبيه إحتياجات الطاقه داخل المركبه. في هذه الدراسة، تم تطوير آلية استرداد الحرارة (WHRM) للمحرك الانفجاري الطبيعي وَاستكشاف فعاليّة المحرك المجهّز من حيث أداء المحرك والطاقة المولدة من WHRM. وأجريت التجارب باستخدام سيارة تجريبية والتي نفذت WHRM على آليتين: آليّة توربينات الغاز والتوربينات البخارية. جرى أولاً اختبار السيارة التجريبية على الطريق دون استخدام WHRM لتقييم أداء المحرك وكمية الطاقة الحرارية والحرارة المهدرة من العادم. بعد ذلك ، تمّ اختبار السيارة التجريبية على الطريق مع توربينات الغاز والتوربينات البخارية مع WHRM. إنّ المساهمة الرئيسية لهذه الدراسة تتضمن إجراء التجارب لآليّة استرداد الحرارة، وتنفيذها على السيارة التجريبية (بمحرك انفجاري) مع اختبارها على الطريق، حيث يمكن الكشف عن أداء المحرك وآليّة استرداد الحرارة في الواقع. تم حساب الطاقة الحرارية من نفايات العادم بين 500 واط إلى إلى 23 كيلو واط والتي تستحق بوضوح استردادها. أما بالنسبة لـ -WHRM فقد وُجد أنّ آلية توربينات الغاز لاسترداد الحرارة المهدرة يمكن أن تصل إلى 110 واط، في فترة قصيرة من الزمن تتراوح بين الثانية إلى أربع ثوانٍ. وفي الوقت نفسه يمكن لآلية التوربينات البخارية أن تصل إلى 29 واط، ولكن في فترة أطول من الزمن، على سبيل المثال خلال عشر ثوانٍ. كما وُجد أن آلية توربينات الغاز تسبب في انخفاض قوة المحرك قليلاً، في حين أن آلية التوربينات البخارية لم تؤثر على أداء المحرك. وعليه فقد تم اقتراح نموذج جديد للطاقة الحرارية من العادم لشرح امكانية التحسين، باستخدام سرعة المحرك، وزاوية دواسة الوقود ودرجة حرارة العادم، ودرجة الحرارة المحيطة، ومعدل تدفق الهواء كبيانات إدخال في الشبكات العصبية الاصطناعية (ANN). وكانت نتائج هذا النموذج في اتفاق جيد مع البيانات التجريبية.

APPROVAL PAGE

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DECLARATION

I hereby declare that this dissertation is the result of my own investigations, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at IIUM or other institutions.

Safarudin Gazali Herawan

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ACKNOWLEDGEMENTS

Firstly, it is my utmost pleasure to dedicate this work to my dear parents and my family (Eva Kaniawati: my wife, Ahmad Razaq Gazali, Ibrahim Noor Gazali and Abdul Aziz Gazali: my children) who granted me the gift of their unwavering belief in my ability to accomplish this goal: thank you for your support and patience.

I wish to express my appreciation and thanks to those who provided their time, effort and support for this project. To the members of my dissertation committee, thank you for sticking with me.

Finally, a special thanks to Professor Dr. Ahmad Faris bin Ismail for his continuous support, encouragement and leadership, and for that, I will be forever grateful.

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LIST OF SYMBOLS

C_{pg}	Specific heat of air (J/kg.^{o}C)
d_c	Diameter of copper tube (mm)
$h_{w,in}$	Inlet water enthalpy (J/kg)
$h_{w,out}$	Exit water enthalpy (J/kg)
L	Length of copper tube (cm)
L_{coil}	Length of helical coil heat exchanger (cm)
$\dot{m}_g$	Exhaust gases mass flow rate (kg/s)
$\dot{m}_w$	Mass flow rate of water (kg/s)
N	Engine speed (rpm)
N_c	Number of turns of helical coil
N_{ST}	Steam turbine speed (rpm)
N_T	Power turbine speed (rpm)
P_L	Power load (W)
p	Pitch between turned coil (mm)
$\dot{Q}_{exh}$	Energy of waste heat from the exhaust system (W)
Q_w	Waste heat energy (W)
r	Curvature radius of helical coil (mm)
r_{xy}	Pearson r value
S_x	Standard deviation for x
S_{xy}	Covariance
S_y	Standard deviation for y
T_{amb}	Ambient temperature (^{o}C)

T_{exh}	Exhaust temperature (^oC)
T_g	Exhaust gases temperature (^oC)
$T_{g,in}$	Exhaust gases temperature before the waste heat recovery device (^oC)
t_α	Throttle angle (^{o})
U_o	Overall heat transfer coefficient
$\dot{V}$	Volume flow rate of air (m^3/min)
V_L	Voltage load (V)
V_a	Air flow rate (m^3/min)
V_v	Vehicle speed (km/h)
W_{gt}	Power generated (W)

LIST OF ABBREVIATIONS

PLDV	Passenger Light-duty Vehicle
LCV	Light Commercial Vehicle
HEV	Hybrid Electric Vehicle
EV	Electric Vehicle
A/C	Air conditioning
RCCI	Reactivity Controlled Compression Ignition
HICE	Hydrogen Internal Combustion Engine
CI	Compression Ignition
SI	Spark Ignition
IC	Internal Combustion
BSFC	Brake Specific Fuel Consumption
HPVGT	High Pressure Variable Geometry Turbine
ANN	Artificial Neural Network
ICE	Internal Combustion Engine
TEG	Thermalelectric Generator
CFD	Computational Fluid Dynamic
ORC	Organic Rankine Cycle
MAPE	Mean Absolute Percentage Error
HCCI	Homogeneous Charge Compression Ignition
EGR	Exhaust Gas Circulation
VCT	Variable Camshaft Timing
DME	Dimethyl Ether
VVA	Variable Valve Actuation
VGT	Variable Geometry Turbine
ISA	Integrated Starter-Altenator
NMPC	Nonlinier Model Predictive
HP	High Pressure
LP	Low Pressure
HD	Heavy-duty
AR	Area Ratio
EER	Exhaust Energy Recovery
WHRM	Waste Heat Recovery Mechanism
NEDC	New European Driving Cycle
WHR	Waste Heat Recovery
HT	High-temperature
LT	Low-temperature
I/O	Input Output
MLP	Multilayer Perceptron Network
RBF	Radial Basis Function
SOS	Sum of Squares
BFGS	Broyden-Fletcher-Goldfarb-Shanno
LMTD	Log mean temperature difference between inlet and exit of exhaust gas temperature and water temperature

CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND OF STUDY

In recent years, environmental and energy issues have created major interests to the public and scientists in the awareness of demand, price, and supply. From the socio-economic perspective, the increasing level of energy consumption is directly proportional to economic development and the total number of population in the world, which contribute to the increasing energy demand. In the global energy system, the fossil fuel, which consists of oil, natural gas, and coal, is the highest global energy system resources, which is 81% from the total resources and oil is the greatest resource from the fossil fuel cluster (Figure 1.1). Therefore, energy demand still relies on fossil fuel resources.

Figure 1.2 describes the oil demand, price and projection up until 2035, and Figure 1.3 shows the production of crude oil and its projection until 2035. Oil demand is always beyond its supply in the current situation and projection. This leads to increased oil price from time to time, even in the projection. The projection of oil demand and price are subjected to three scenarios. (1) The New Policies Scenario: A scenario in the World Energy Outlook that takes into account broad policy commitments and plans announced by countries, including national pledges to reduce greenhouse-gas emissions and plans to phase out fossil-energy subsidies, even if the measures to implement these commitments have yet to be identified or announced. (2) The 450 Scenario: A scenario presented in the World Energy Outlook that sets out an energy pathway consistent with the goal of limiting the global increase in temperature by 2°C by limiting the concentration of greenhouse gases in the atmosphere to around

450 parts per million of CO_2. (3) The Current Policies Scenario: A scenario in the World Energy Outlook 2010 that assumes no change in policies, which is basically 'business as usual'.

In the Current Policies Scenario, the demand and price of oil will constantly increase, however the production of oil will slightly decrease. For the new policies scenario and 450 scenario, they have set some rules and regulations to be followed by the nations to overcome the current policies scenario by enforcing clear environment and saving the resources (OECD/IEA, 2012).

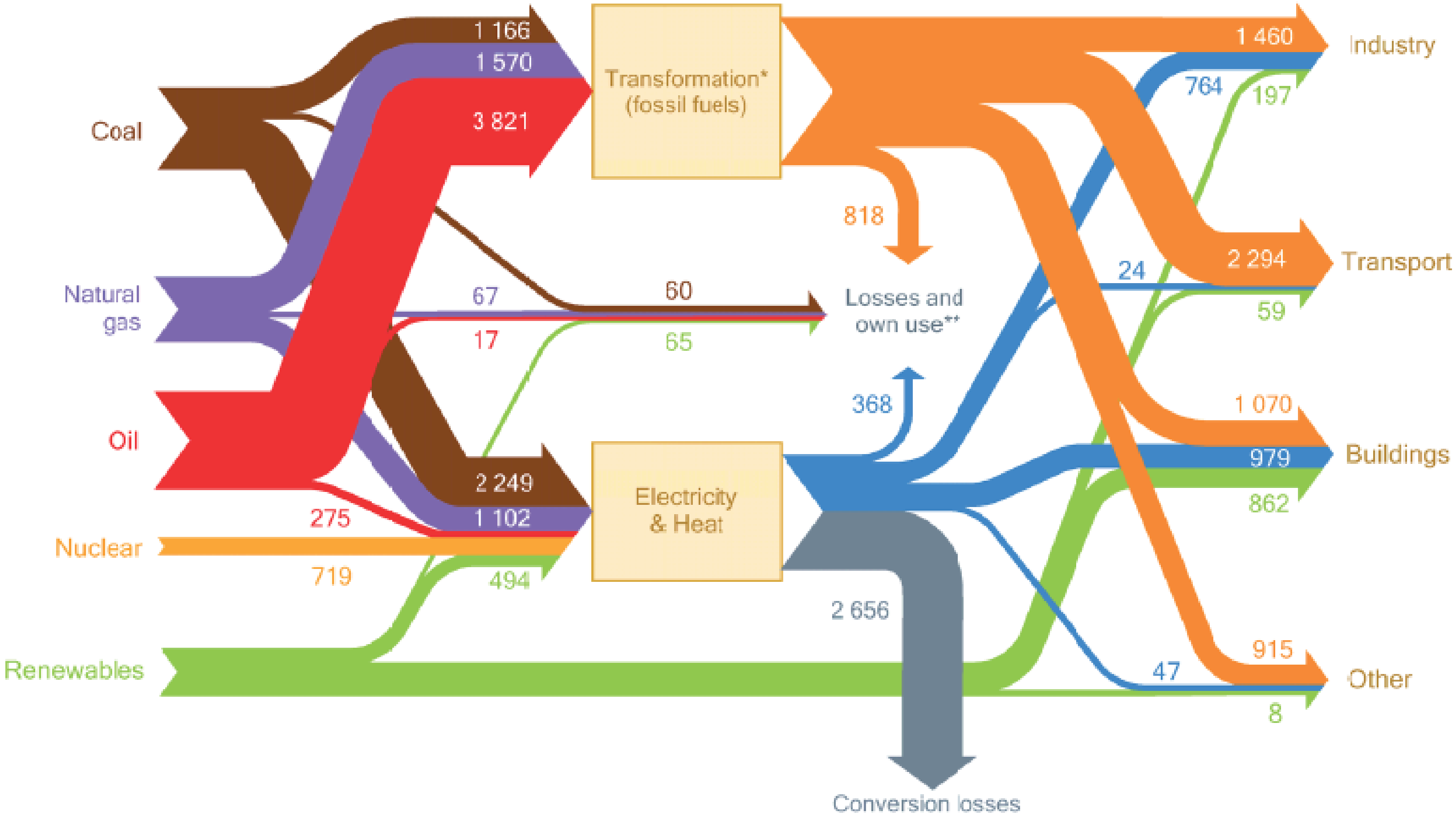

Figure 1.1 Global Energy System, 2010 (in million tonnes of oil equivalent) (OECD/IEA, 2012)

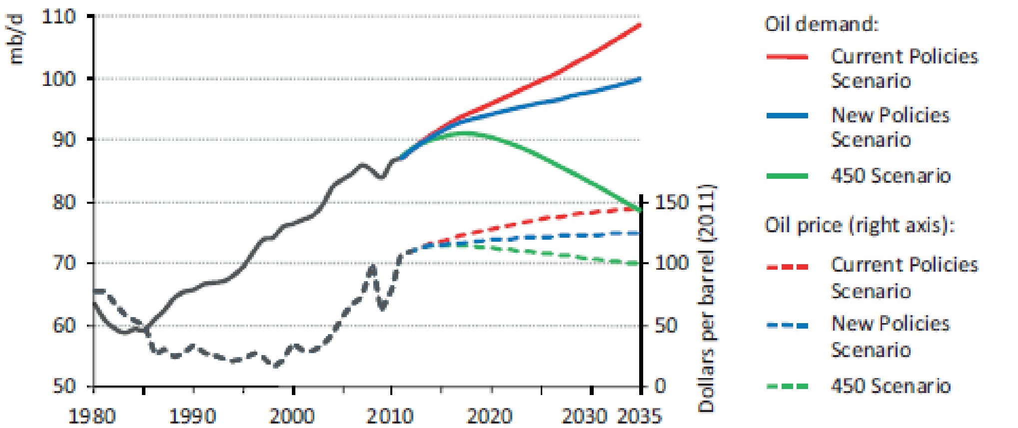

Figure 1.2 Oil demand and price in 1980 – 2035 (mb/d = million barrels per day) (OECD/IEA, 2012)

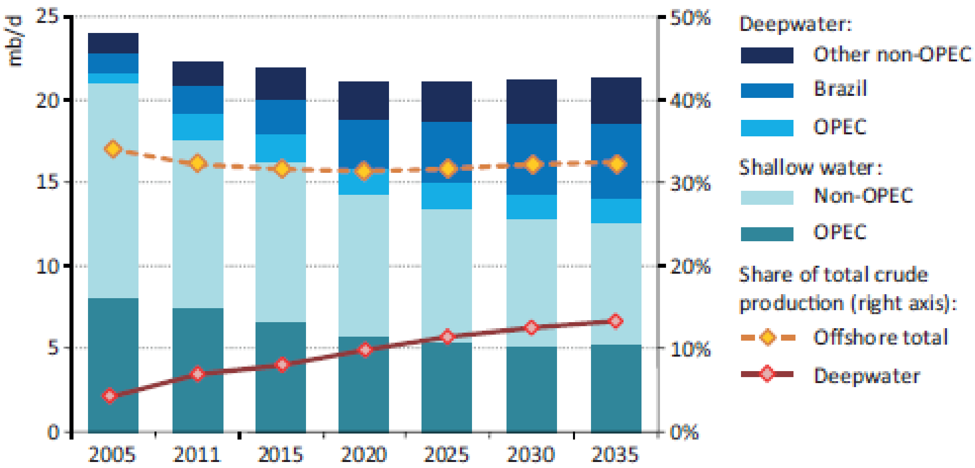

Figure 1.3 World crude oil production by physiographical location and region in the New Policies Scenario (OECD/IEA, 2012)

1.2 PROBLEM STATEMENT

By looking at the global energy system (Figure 1.1), the transport sector uses a huge part of transformation of fossil fuels. In Figure 1.4, it is clearly shown that the transport sector has grown up from 1973 just 45.5% of world oil consumption to 2011 with 62.3% of world oil consumption. This trend indicates that some actions must be taken to balance between energy demand and supply.

The demand and consumption of energy mostly come from the transport sector. Any actions that apply on this sector can contribute greatly to the world energy. Perhaps, some organizations already establish some rules and regulations with regards to this matter. For instance, the six key pillars in the policy framework assumed in the transport sector in the 450 Scenario (OECD/IEA, 2012), which are:

1. International sectoral agreements in the passenger light-duty vehicles (PLDV) sector and aviation (both domestic and international) as of 2013, which provide CO_2 emission limits for new cars and aircraft in all countries.
2. Full technology spill-over from PLDVs to light commercial vehicles (LCVs).
3. Improve efficiency of medium- and heavy-duty vehicles by 20% in 2035 relative to the New Policies Scenario.
4. Alternative fuel support policies.
5. National policies and measures in other segments of the transport sector.

This framework can become a reality when the entire nations in the world participate in order to achieve a better world for the future generation. The Efficient World Scenario is a blueprint to realize economically viable potential for energy efficiency by setting out the policies that governments need to enact to lower market barriers, thereby minimizing transaction costs and enabling necessary energy efficiency investment. This scenario covers efficiency in industry sector, transport sector, and buildings sector. The roles are to ascertain the efficiencies of the best technologies and practices available now, and to know how these are likely to evolve