DYNAMIC MODELING OF WASTE ENERGY HARVESTING SYSTEM FOR SPARK IGNITION INTERNAL COMBUSTION ENGINE

BY

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A thesis submitted in fulfilment of the requirement for the degree of Master of Science in Automotive Engineering

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ABSTRACT

Several methods for waste thermal energy recovery from IC engine have been studied by using supercharger or turbocharger or combined. This study presents an innovative approach on power generation from waste of IC engine based on coolant and exhaust. The waste energy harvesting system of coolant ($weHS^c$) is used to supply hot air at temperatures in the range of 60-70°C directly into the engine cylinder, which would be useful to vaporize the fuel droplets into the cylinder. Increase in fuel vaporization helps to improve the engine thermal efficiency by 1% to be 29% at 4000 rpm due to reduction in fuel consumption. The waste energy harvesting system of exhaust ($weHS^{ex}$) has been developed with integrating fuzzy intelligent controlled micro-faucet emission gas recirculation (MiF-EGR). In this study the MiF-EGR has been used to maintain the intake air temperature at 70°C and reduce higher intake temperature by allowing exhaust gas flow to the engine cylinder chamber thus increase the engine volumetric efficiency. The performance of $weHS^c$ and $weHS^{ex}$ equipped engine has been investigated by using GT Suite software for optimum engine speed at 4000 rpm. The result shows that specific fuel consumption of engine has improved by 2% due to vaporization of fuel droplets. Reduction of hydrocarbon (HC) formation inside the engine combustion chamber has been reduced by 9% at 4000 rpm thus control the emission level. Volumetric efficiency also has been improved in overall by 2.2%. Lastly, the brake power has increased by 8% due to the fuel atomization and vaporization at engine intake temperature of 70°C.

ملخص البحث

وقد تم دراسة عدة طرق لاستخلاص بقايا الطاقة الحرارية من محرك الاحتراق الداخلي باستخدام الشحان أو الشاحن التوربيني أو كلاهما. تقدم هذه الدراسة نهجا مبتكرا لتوليد الطاقة من بقايا محرك الاحتراق الداخلي معتمدا على المبرد والعادم. يتم استخدام نظام حصاد بقايا الطاقة من المبرد ($weHS^c$) لتزويد الهواء الساخن عند درجة الحرارة التي تتراوح ما بين 60 – 70 درجة سلزيوس، مباشرة في أسطوانة المحرك، التي من شأنها مفيدة لتبخير قطرات الوقود في الأسطوانة. الزيادة في تبخير الوقود يساعد على تحسين الكفاءة الحرارية للمحرك بنسبة 1% لتكون 29% في ٤٠٠٠ دورة في الدقيقة جراء انخفاض في استهلاك الوقود. وقد تم تطوير نظام حصاد بقايا الطاقة من العادم ($weHS^{ex}$) مع دمج الصنبور المجهري لإعادة تدوير انبعاثات الغاز بتحكم المنطق الترجيحي (MiF-EGR). في هذه الدراسة استخدمت MiF-EGR للحفاظ على دخول الهواء بالدرجة الحرارة 70 درجة سلزيوس وتخفيض دخول الهواء الأكثر حرارة من خلال السماح بتدفق غاز العادم إلى غرفة أسطوانة المحرك وبالتالي ترتفع الكفاءة الحجمية للمحرك. وقد تم تحقيق فعّالية المحرك المجهز بـ $weHS^c$ و$weHS^{ex}$ باستخدام برنامج GT Suite لتقييم السرعة المثلى للمحرك عند ٤٠٠٠ دورة في الدقيقة. وتظهر النتائج أن استهلاك الوقود الخاص للمحرك تحسن بنسبة 2% وذلك بسبب تبخر قطرات الوقود. تم تخفيض تشكيل هيدروكربون (HC) داخل غرفة احتراق المحرك بنسبة 9% في ٤٠٠٠ دورة في الدقيقة وبالتالي يسيطر على مستوى الانبعاثات. وكذلك تم تحسين الكفاءة الحجمية بشكل إجمالي بنسبة 2،2% .وأخيرا، زادت قوة الفرملة بنسبة 8% بسبب الانقسام الذّرّيّ للوقود وتبخره عند 70 درجة سلزيوس من درجة حرارة مسرب المحرك.

APPROVAL PAGE

I certify that I have supervised and read this study and that in my opinion, it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a thesis for the degree of Master of Science in Automotive Engineering.

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DECLARATION

I hereby declare that this thesis 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.

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To my beloved husband, Mohd Hazrol Shahril, my father, Hj. Abdul Razak Yaacob, my parents in law Hj. Hasan Abdul Rahman and Hajah Che Limah Awang, my lovely kids, Aisyah Sofiyyah and Ameer Sufyan and my siblings,

And honourable Supervisor Associate Professor Dr. Md. Ataur Rahman and my co-Supervisor Dr. Sanisah Saharin

And

To the memory of my Late Mother, Samsiah Mohamed who devoted her love to me.

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LIST OF SYMBOLS

$m_{a,th}$	Air mass flow rate (theoretical)	kg/s
A	Area normal to thedirection of heat	m^2
B	Cylinder bore size	m
V_c	Clearance volume	m^3
h	Convection heat transfer coefficient	W/m^2K
b	Cylinder bore	m
V_d	Displacement volume	m^3
Δx	distance of heat transfer	m
η_e	Effective Thermodynamic efficiency	-
w_e	Effective work	kW
$\in$	emissivity of gas	-
$\dot{Q}_{conv}$	Energy generated by engine	kW
$\dot{Q}_{ex}$, $\dot{Q}_{coolant}$,	Energy to exhaust, coolant and miscellenous	kW
$\dot{Q}_{misc}$	Energy to miscellenous	kW
N	Engine speed	rpm
h_f, h_a, h_e	Enthalpy of fuel, air and exhaust	kJ/kg
$\dot{H}_{e,ic}$	Exhaust enthalpy loss due to incomplete Combustion	kW
$m_{f,th}$	Fuel mass flow rate (theoretical)	kg/s
$\dot{Q}_{conv}$	Heat transfer through connvection	W/m^2
$\dot{Q}_{cond}$	Heat transfer through conduction	W/m^2
Q_{LHV}	Lower heating value	kJ/kg
$\dot{m}_a$	Mass flow rate of air	kg/s
$\dot{m}_f$	Mass flow rate of fuel	kg/s
S	Piston stroke length	m
λ_a	Relative air supply	kg/s
λ_f	Relative fuel supply	kg/s
c_p	Specific heat at constant pressure	W/m.K
c_v	Specific heat at constant volume	W/m.K
v	Specific volume	m^3/kg
σ	Stefan-Boltzmann constant	-

R_{st}	Stoichiometric ratio	-
T_{sca}	Supercharged air temperature	°C
k	Thermal conductivity	
F_{1-2}	View factor between gas and wall	-

LIST OF ABBREVIATIONS

AF	Air-fuel ratio
BDC	Bottom dead centre
BSFC	Brake specific fuel consumption
CC	Combustion chamber
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CR	Compression ratio
CV	Control volume
EDS	Electrically driven supercharger
EGR	Exhaust gas recirculation
EIA	Energy Information Administration USA
FA	Fuel-air ratio
FAC	Fuzzy adaptive controller
FLES	Fuzzy logic expert system
FLS	Fuzzy logic system
H_2	Hydrogen
H_2O	Water
HC	Hydrocarbon
HHV	High heating value
IC	Internal Combustion
LHRE	Low heat rejection engine
LHV	Lower heating value
MFB	Mass fraction burned
MiF-EGR	Intelligent micro faucet exhaust gas recirculation
MON	Motor Octane Number
NOx	Nitrogen Oxides
Nu	Nusselt number
PE	Position error
PHC	Partially oxidized hydro carbon
PWS	Pressure-wave supercharger
Re	Reynolds Number
RON	Research Octane Number
RPM	Revolution per minute
SI	Spark Ignition
SO_x	Sulphur Oxides
TBL	Thermal Barrier Layer
TDC	Top dead centre
TEG	Thermoelectric generator
UHC	Unburned Hydrocarbon
VCA	Variable compression ratio
VOC	Volatile organic compound
$weHS^c$	Waste energy harvesting system coolant base
$weHS^{ex}$	Waste energy harvesting system exhaust base
WOT	Wide open throttle

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

The modern high class automobile is in the main satisfactory and can be relied upon if the driver is throughly cognizant of its working. It is needless to say that self propelling vehicles, like other machines, will never do as much for one who does not understand them as for one does. Engine makes the vehicle self propelling with combusting desired amount of air-fuel mixture in the combustion chamber. The reliability of an engine depends not so much on the proportion of the total heat converted into useful work, but rather upon of the total heat which is not so converted, and which is left over to make trouble. Fossile fuels supply nearly 80% of world demand (EIA International Energy Outlook 2010). Burning of fossile fuels in engine combustion chamber always has associated with it emissions in the form of carbon monoxide (CO), unburned hydrocarbon (UHC), nitrogen oxides (NO_x), and sulfur oxides (SO_x). Emission is one of the major contributors to the world's air pollution problem such as global worming, acid rain, smog, odors, and respiratory and health problems. Recent research and development has made major reductions in engine emissions by means of fuel automization and vaporization with heating the engine intake by electrically, increasing volumetric efficiency with the supercharger and turbocharger, introducing exhaust gas recirculation technique, and thermal electric generator. Furthermore, the interest to replace fossile fuels with renewable and sustainable energy source has reduced emissions significantly.

The heat transfer that occurs within an engine is extremely important for proper operation. Willard (2004) and Hatazawa (2004) have stated that about 35% of the total chemical energy that enters an engine in the fuel is converted to useful crankshaft work, and about 30% of the fuel energy is carried away from the engine in exhaust flow in the form of enthalpy and chemical energy. This leaves about one-third of the total energy that must be dissipated to the surroundings by some mode of heat transfer. Therefore, the true explanation for the poor performance of the engine would seem to lie in inefficient use of energy and loss of energy through heat transfer. The loss incurred through inefficient use of energy is easily understood, compressed fuel and air is ignited and is then used to propel the piston down the cylinder with explosive force for a distance of just a few inches. Fuel efficiency improvement is the overarching focus of automotive researchers and car manufacturers due to increasing demand for vehicles on the road and limited fuel source. The fundamental understanding of advanced combustion processes is about the engine able to simultaneously exhibit high efficiency and low emissions.

1.2 PROBLEM STATEMENT AND ITS SIGNIFICANCE

The rapid expansion of motor vehicle in globally dedicates the increase of energy demand in an acceleration fashion. If driving habits remain unchanged, car will have to become nearly three times more energy-efficient by 2030 just to maintain that sector's present consumption. If energy use trends are projected to year 2100, transportation would then have to be twenty times more energy-efficient, which roughly equates to 170km per liter. Environmental protection aspect is very important for an automotive industry from economic and legal perspectives, and simultaneously addressed the growing concerns of environmental safety and preservation. Some of the efforts involved are; pressures to increase fuel efficiency, to reduce exhaust emissions, and to use recyclable lightweight materials. Currently battery electric and hybrid cars are considered as the energy efficient. But, the problems of these technologies are the batteries recharging time, maintenance cost and disposal. The disposal of batteries might make bio-dreadful condition which is harmful for the humans and others living things. Advanced power systems and reduced vehicle road-loads are necessary in order to make significant gains in motor vehicles energy.

Thermal management of internal combustion (IC) engine is considered a serious problem as it develops high temperatures due to combustion of the fuel but needs to keep the temperature at a controllable level in order to operate the engine safely. Ferguson and Kirkpatrick (2000) claimed that incomplete combustion occurred in IC engine is due to maximum pressure and temperature attained in the cycle itself. As mentioned by Eugene (2007), a complete vaporization and mixing of a liquid fuel in air prior to compression is an essential element of SI charge preparation and mixture ignition temperatures must be lower than their air-fuel self-ignition temperatures to prevent pre-ignition during compression. If gasoline is considered to be vaporized by 10% in intake system, it means 90% of the air fuel mixture entering the combustion chamber consists of tiny droplet of fuels and the air/fuel mixture need more pressure during compression stroke to get all the fuel to be fully vaporized. The consequence of the scenario is there will be a huge amount of unburned gas at the end of expansion stroke which lead to incomplete combustion.

Every major automobile manufacturer is currently working on waste heat recovery systems to reduce the emission of carbon dioxide (CO_2), nitrogen oxide (NO_x) and sulfur dioxide (SO_x). Several methods for waste thermal energy recovery from IC engine have been studied by using supercharger or turbocharger and /or combined. This chapter presents an innovative system of IC engine's waste energy harvesting from coolant. The heat energy is used to preheat intake air temperature to vaporize the injected fuel into the combustion chamber. Combustion process with allowable percentage of fuel vaporization will enhance the combustion of the fuels. This also reduced unburned fuel left in the clearance volume. If there is high temperature has been absorbed by unburned fuels in the clearance volume, there is high potential of knocking to occur.

1.3 RESEARCH OBJECTIVES

The main objective of this study is to develop a dynamic system to harvest waste energy of engine from coolant and exhaust which would be able to improve the thermal efficiency of engine in the range of 35-40% and reduce the emission significantly. In the conventional engine, the engine coolant jacket absorbed heat to avoid the engine block from damage and combustion occurs safely. The dissipated heat could supply to the engine as heat energy with the supercharged air for fuel automization and vaporization in the cylinder chamber and avoid engine from the formation of CO and UHC. The exhaust gas recirculation system (EGR) could control the temperature of the intake supercharged air in the range of 60-70^{0}C. The specific objectives of this study are:

1) To conduct a thermodynamic analysis of heat transfer to spark ignition (SI) engine wall.
2) To develop the waste energy harvesting system coolant base (weHS^c) with a fuzzy intelligent controlled micro faucet exhaust gas recirculation (MiF-EGR) for enhancing engine performance and control emission level.
3) To investigate the performance of the weHS^c theoretically.

1.4 RESEARCH METHODOLOGY

This study is started with the understanding of the operation of spark ignition (SI) IC engine and its thermodynamic process. The literature review focuses on the progress on heat generation and energy recovery from waste heat from engine. The modeling of waste heat harvesting system (weHS^c and weHS^{ex}) was carried out to meet the goal to vaporize partial of the fuel droplets into the combustion chamber for complete combustion. A Fuzzy block has been developed to simulate the optimum mass flow rate of coolant and supercharged air to get intake air temperature, $T_{sca} = 70°C$. Detailed methodology will be described in Chapter 3. However, the research work conducted is shown in Figure 1.1.

1.5 SCOPE OF THE RESEARCH

This research is mainly about a dynamic modeling of waste energy harvesting system coolant based. The system is supported by a Fuzzy intelligent micro faucet exhaust gas recirculation (MiF-EGR) which utilizes waste energy from exhaust. A Proton SAGA BLM 1.3L engine has been considered in the study for calculation purpose and reference model for engine performance data analysis. Various concepts from interdisciplinary areas of IC engine which relate to air cooled engine, radial engine, W engine, Opposed cylinder engine, rotary engine are beyond the scope of this research.

The scope of research is bounded by few assumptions made which is further discussed in detail in respective chapters. For ideal Otto cycle, the assumptions made are as follows:

i. The pressure of the mixture during the suction stroke and also during the exhaust stroke is the pressure of the atmosphere, and hence the ideal cycle shows no “pumping loss”.