UNIVERSITI PUTRA MALAYSIA

NOVEL HEAT EXCHANGER FOR COLD AIR INTAKE ON SPARK IGNITION ENGINE PERFORMANCE

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By

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The engine intake charge air (EICA) system enhancement technology plays an essential part in vehicle engine performance developments and pollution reduction.

The increase in ambient temperature due to global warming and climate change introduced a significant influence on vehicle performance. Same while, EICA temperature increasing affects the engine complete combustion due to the oxygen density per volume reduction in air. Thus, EICA cooling technology becomes one of the best solutions for temperature reduction through intercooler units. This research introduces the influence of direct combustion volumetric effect using a new designed evaporative intercooler heat exchanger (EIHE), direct intercooler device used for engine intake charge air cooling (EICAC) in non-turbocharged vehicles spark-Ignition engines (SI-engines), contributing a new technique method in heat-exchanger designing.

Most of the previous studies of conventional intercoolers heat-exchangers (IHE) devices demonstrated a significant influence of EICAC on engine performance. However, it presented low efficient or non-operational in vehicle slow driving speed or stand-still operation. Furthermore, the designs showed non-flexibility in size and low cooling capacity. Therefore, there is a need for a better IHE design with flexibility in size designing suitable for most vehicles, able to function in all environments and weather conditions, with the ability of vehicle performance enhanced. The new design should be functional in both vehicle low-speed driving or stand-still parking operation.

Refrigerant medium system technology becomes significant in heat transfer property which helps to design subcooling heat-exchanger. The new EIHE device utilizing the refrigerant medium which presented a better performance than the water cooled IHE reaching lower cooling range temperature and functional in all vehicle condition.

The Computational Fluid Dynamics (CFD) simulation was used using ANSYS FLUENT to simulate various EIHE models performance with different air flow rate and temperatures. The EIHE geometry shell-and-tube was designed from steel metal, based on criteria of space available inside the vehicle engine bay. The simulation results presented a significant improvement in cooling performance with temperature reduction lower than the inlet temperatures, offering a very low-pressure drop coefficient. The EIHE design was experimentally validated. For the experimental part, the EIHE device was tested both in the laboratory and real-world. The EIHE operation and performance evaluation investigated in real-world tests. The tests result generally presented a significant cooling performance capability by the developed EIHE almost efficient of 49% - 50% reduction in temperature. The applied vehicle test results presented a significant enhanced improvement in the max power wheel and max torque increasement, and test results of real-world test utilizing the EIHE presented a significant emission reduction of 12.86% of CO, 29.32% CO_2, and 29.41% HC. In conclusion, the new designed EIHE successfully meet the required objectives.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PENUKAR HABA NOVEL BAGI MASUKAN UDARA SEJUK KE ATAS PRESTASI ENJIN CUCUHAN API

Oleh

PSHTIWAN MOHAMMAD SHARIF SHWAN

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Teknologi peningkatan sistem udara caj ambilan enjin (EICA) memainkan peranan yang penting dalam perkembangan prestasi enjin kenderaan dan pengurangan pencemaran. Peningkatan dalam suhu ambien disebabkan pemanasan global dan perubahan iklim menghasilkan pengaruh yang signifikan ke atas prestasi kenderaan. Di samping itu, peningkatan suhu menjejaskan enjin pembakaran yang sempurna akibat pengurangan ketumpatan oksigen per isi padu dalam udara. Oleh itu, teknologi penyejukan EICAC merupakan salah satu penyelesaian terbaik untuk pengurangan suhu melalui unit pendingin antara. Penyelidikan ini mengutarakan pengaruh kesan volumetrik pembakaran langsung , menggunakan penukar pendingin antara evaporatif (EIHE) reka bentuk baharu, peranti pendingin antara langsung yang digunakan untuk penyejukan udara caj saluran ambilan enjin (EICAC) dalam enjin cucuhan bunga api kenderaan (enjin SI) bukan pengecas turbo, menyumbang suatu kaedah teknik baharu dalam reka bentuk penukar haba. Kebanyakan kajian terdahulu mengenai peranti penukar haba pendingin antara yang konvensional (IHE) memperlihatkan pengaruh EICAC yang signifikan ke atas prestasi enjin. Walau bagaimanapun, ia mengutarakan keefisienan yang rendah atau tak operasional dalam kenderaan kelajuan pemanduan perlahan atau operasi tak bergerak. Di samping itu, reka bentuk tersebut menunjukkan tidak fleksibiliti dari segi saiz dan kapasiti penyejukan rendah. Oleh sebab itu, terdapat keperluan untuk reka bentuk IHE yang lebih baik dengan fleksibiliti dari segi mereka bentuk saiz yang sesuai bagi kebanyakan kenderaan, dapat berfungsi dalam semua persekitaran dan keadaan iklim, dengan keupayaan prestasi kenderaan dipertingkat. Reka bentuk baharu tersebut harus berfungsi dalam kedua-dua kenderaan pemanduan kelajuan rendah atau ketika operasi parkir tanpa bergerak. Teknologi sistem medium refrigeran menjadi signifikan dari segi sifat penukar haba yang membantu bagi mereka bentuk penukar haba subpenyejuk. Peranti EIHE yang baharu menggunakan medium refrigeran yang memperlihatkan prestasi yang lebih baik daripada IHE penyejuk air mencapai suhu julat penyejukan yang lebih rendah dan berfungsi dalam semua keadaan kenderaan.

Simulasi Dinamik Bendalir Komputational (CFD) telah dilaksanakan menggunakan ANSYS FLUENT bagi mensimulasi pelbagai prestasi model EIHE dengan kadar aliran udara dan suhu yang berbeza. Kelompang dan tuib geometri EIHE telah direka bentuk daripada logam keluli, berdasarkan kriteria ruang yang terdapat dalan ruang enjin kenderaan. Dapatan simulasi memperlihatkan penambahbaikan yang signifikan dari segi prestasi penyejukan dengan pengurangan suhu yang lebih rendah daripada suhu masukan, mengemukakan suatu koefisien kejatuhan tekanan yang sangat rendah. Reka bentuk EIHE telah disahkan secara eksperimental. Bagi bahagian eksperimental, peranti EIHE telah diuji di kedua-dua makmal dan dunia sebenar. Operasi EIHE dan penilaian prestasi telah diselidiki dalam ujian dunia sebenar. Dapatan ujian umumnya memperlihatkan kapabiliti prestasi penyejukan yang signifikan oleh EIHE yang dibangunkan, hampir efisien, iaitu 49% - 50% pengurangan dalam suhu. Dapatan Ujian kenderaan yang diaplikasikan memperlihatkan pembaikan dipertingkat yang signifikan dalam roda kuasa maksimum dan kenaikan kilas maksimum, dan dapatan ujian bagi ujian dunia sebenar yang menggunakan EIHE memperlihatkan pengurangan buangan yang signifikan, iaitu 12.86% CO, 29.32% CO_2, dan 29.41% HC. Kesimpulannya, reka bentuk EIHE yang baharu berjaya memenuhi objektif yang diperlukan.

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LIST OF ABBREVIATIONS

CAC	Charge air cooling
CFD	Computational Fluid Dynamics
CFM	Cubic feet meter
CO	Carbon monoxide
CO_2	Carbon dioxide
COP	Coefficient of Performance
DOE	Design of Experiment
EICA	Engine intake charge air
EICAC	Engine intake charge air cooler
EIHE	Evaporative intercooler heat exchanger
EPA	Environmental Protection Agency
EU	The European Union Economic Area
FEM	Finite Element Method
FVM	Finite Volume Method
H_2	Hydrogen
H_2O	Water
HC	Hydrocarbon
HE	Heat exchanger
IHE	Intercooler heat exchanger
IPCC	Intergovernmental Panel on Climate Change
MAE	Mean Absolute Error
PM	Particulate matter
R^2	Coefficient of Determination

UPM	Universiti Putra Malaysia
VCRC	Vapor compression refrigeration cycle
VCRC	vapour compression refrigeration cycle

LIST OF NOMENCLATURES

A	Area (mm^2)
a	Acceleration
$Ref._{in}$	Refrigeration inlet
$Ref._{out}$	Refrigeration outlet
Air_{in}	Air inlet
Air_{out}	Air outlet
σ_{sensor}	Error in the measuring sensor
$\sigma_{instrument}$	Error in the measuring instrument
$\propto$	Helix angle or lead angle
η	The efficiency
η_{th}	The thermal efficiency for engine
λ	Lambda
ρ	Fluid density(kg/m^3)
σ_c	The compression stress (N/mm)
Δp	Pressure loss due to friction (Pa)
f_D	Darcy friction factor (unitless)
L_{tube}	Tube length (m)
D	Hydraulic diameter of the pipe D (m)
V	Fluid flow average velocity (m/s)
A_{tube}	the cross-section of the EIHE fitting cover (m^2)
ρ	the density
U	the time-average velocity in the x-direction

$T_{air\ in}$	Air inlet temperature
$T_{air\ out}$	Air outlet temperature
$T_{ref.}$	Refrigerant temperature
W	the time-average velocity in the Z-direction
μ_{eff}	the effective viscosity, laminar and turbulent stresses
Γ_{eff}	the effective exchange coefficient for heat
C_v	the specific heat at a constant volume
R	the universal gas constant
v_{air}	the air velocity (m/s)

CHAPTER 1

INTRODUCTION

1.1 Background

Environment and greenhouse effects presented a global issue of pollution, as gases are released into the atmosphere, leading to global climate change and global warming (N. Sharma et al. 2018). The increase of ambient temperature and engine emissions recognized as a potential problem globally, which needs serious attention (Sutherland *et al.*, 2019). Global warming and greenhouse with climate change and desertification all lead to environmental pollutions and increasing the atmospheric temperature, unstable weather, and an increase in ocean levels (Xiang *et al.*, 2019). Most countries suffering from weather temperature increasing are Middle East countries, where a high ambient temperature recorded in summertime (Salimi and Al-Ghamdi, 2020).

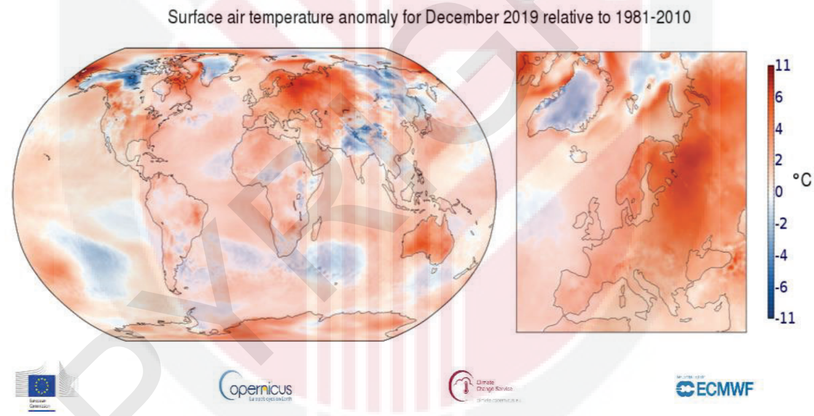

Figure 1.1 : Surface air temperature anomaly for December 2019 relative to the December average for the period 1981-2010 (Copernicus and ECMWF, 2019)

The European Centre for Medium-Range Weather Forecasts (ECMWF), Simulated of the earth's surface global warming status of air temperature increasing shown in Figure 1.1 Furthermore, NOAA's National Centers for Environmental Information (NCEI) provides public access to global climate observation and historical weather data and information reported in 2019 (Allegra et al. 2019). Data illustrated in Figure 1.2 shows ambient temperature in most of the countries increased above the average temperature between 5°C to 6°C.

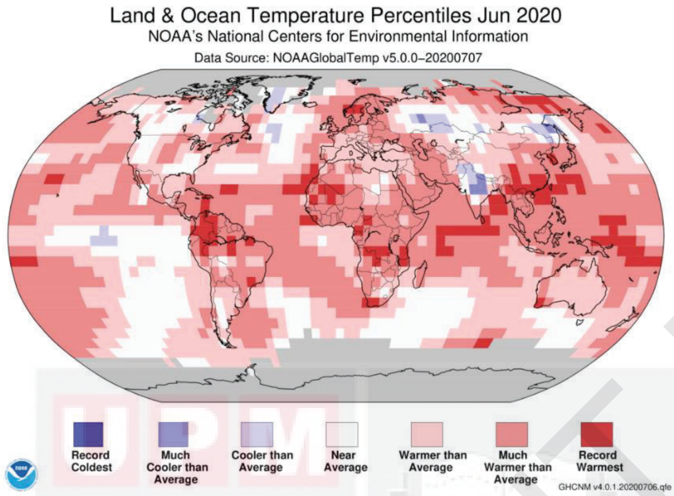

Figure 1.2 : Global climate report -June 2020 blended land and sea surface temperature percentiles (Climate, 2020)

The Engine intake charge air (EICA) systems significantly introduced an enhancement of engine pollution reduction. However, this technique was successfully adopted but still there is need for better heat exchanger designs with flexibility is size and shapes with better cooling performance with reasonable cost manufacturing. Most of conventional IHE in the market couldn't reach the required design performance for optimum engine pollution reduction and economically are very expensive to purchased.

1.2 Problem Statement

Few studies in EICA thermal management technology were conducted to enhance the air property of engine combustion by improving its temperature significantly for a better air density (Di Battista et al. 2018; Krishnamoorthi et al. 2019; Farzam et al. 2020). The most practical method of the EICA cooling technique without engine modification is by external parameter enhancement and add-on installation components (Zhuang, W et al. 2020). However, there is a need to evaluate and investigate the EICA lower temperature variation effect on the engine performance in the absence of the compression system supercharger and turbocharger. Furthermore, the new Evaporative intercooler heat exchanger (EIHE) classified as a new technology method for hyper cooling EICAC were founded from previous studies it was conducted on diesel engine power and emission enhancement by (Grönman et al. 2016) using compressed air turbine expansion technique design, which faces the issue of large size and low cooling capacity compared to its scale. And some of the studies mainly completed in design stages only, or with the simulation, used to protect the idea.

Available IHE in the market technically face the issue of large size, non-flexible of use with other engines, and showed low performance at low engine speed, maintenance and utility problems, and there is a need to contribute new design technique of IHE. Furthermore, there were incomplete or failed attempts to integrate the IHE directly with the vehicle air-conditioning system. But due to unavailable suitable facility and technology at that time, it was abended or failed, and most of the designers investigated the EICA cooling influence in laboratories with an external refrigerant system source (Cipollone et al. 2017). Commercially, the conventional IHE's available in the market have disadvantages in operation, low thermal capacity, size challenge, high cost, and leaking. A new higher performance IHE will help to improve the vehicle performance and reduce the emissions, especially present century recorded a significant increase in vehicles produced in the world to fulfill the market demand. The amount of vehicles globally shows a massive number of personal ownership of vehicles on the road (N. Menon et al. 2019). The increase of ambient temperature variation affects the SI-engine performance (Gong et al., 2019), cause the engines to consume extra fuel due to incomplete combustion (Pugh et al., 2019), and this leads to a higher exhaust emission (Nanthagopal et al. 2019).

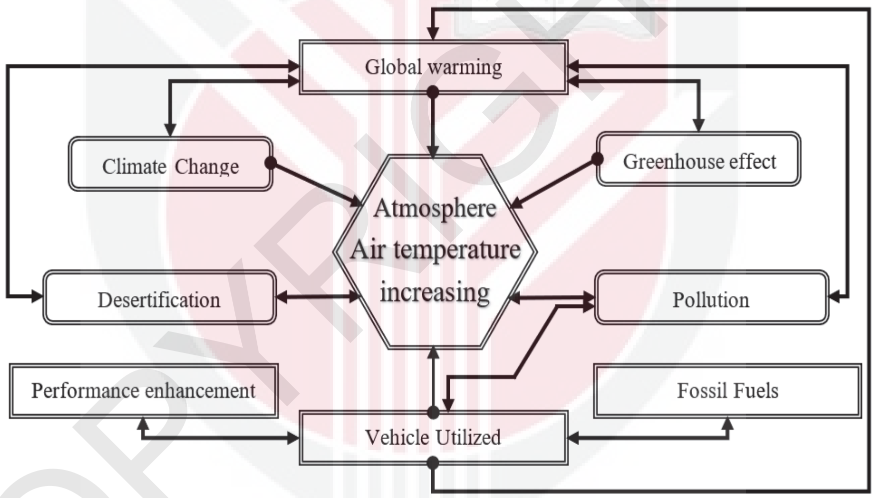

Figure 1.3 : Parameters influence the atmosphere air temperature increasing

Figure 1.3 demonstrated that most characterized parameters influence the atmospheric temperature increase. The engine intake charge air EICA cooling technology using the IHE used to improve the engines for better performance and emissions levels.

1.3 Objective

The main objective of this study is to design a developed EIHE that can be utilized by vehicles with SI engines in order to improve their performance. The specific objectives are:

1. To design an improved EIHE utilizing new coolant type as a vehicle EICAC device.
2. To analyze the performance of a newly designed EIHE device by using computational fluid dynamics (CFD) and experimentally.
3. To validate the new EIHE and evaluate the cooled air influence on the engine performance based on laboratory test and real-world tests based on a chassis dynamometer and vehicle static stand-still tests.

1.4 Scope of the Study

1. The constructed EIHE designed to be operational in all vehicle status operations, a challenge of cooling performance while the vehicle is in a static standstill operation.
2. The constructed EIHE design was designed to utilized in vehicles with SI-engines. The IHE intended for the vehicle sample of the Proton Wira 1.5L four-cylinder SI-engine 2004 model. The device integrated into the manifold inlet charge air of the engine.
3. The selected sample vehicle is non-turbo or supercharger. The study focuses on temperature parameter influence on vehicle performance in the absence of the pressurized system.
4. The constructed EIHE developed to be used as an EICAC device to study the influence of lower intake charge air temperature within 50% on vehicle engine performance.
5. The constructed EIHE Scale is dependent on minimum charge air pressure drop of 5%.
6. Shared the refrigerant coolant with the vehicle air-conditioning system utilizing the same system component, operate as the second evaporator.
7. The EIHE designed to be operational in various vehicle engine speed of 0 to 100 km/h, and functional at different environmental temperature status.
8. Evaluate the vehicle EICAC performance by conducting the real-world driving test

1.5 Thesis Layout

This thesis consists of five chapters. The thesis first chapter starts with the introduction, including the problem statement, objectives, and scope of this work, the significance of the research, and thesis layout.

The second chapter includes the literature review search of subjects pertinent to the work. An overview of vehicle combustion performance in sparked ignition engines, introducing the influence of ambient air temperature property on engine combustion performance, utilizing intercooler heat exchanger and introduction to its types, introduction to vehicle air-conditioning system, the process of EIHE developing and selection. In this chapter, Computational Fluid Dynamic (CFD) presented with EIHE optimization. Laboratory and real-world test investigation introduced for design validating and performance evaluation.

The third chapter describes the methodology outline of this research. Firstly, a comparison analysis for existing IHE. Secondly, theoretical analysis and designing of the selected EIHE. Thirdly, the CFD numerical analysis elaborating for the modeling process of the current and new design IHE models using the ANSYS Platform. Fourthly, experimental laboratory validation of the newly designed EIHE and engine charge air measuring flowrate experimentally. The fifth, experimental tests of EIHE evaluation and cooling performance analysis. The experiments conducted with the continuation of the process to evaluate the EICAC influence engine performance in the laboratory and applied real-world tests conducted using a chassis dynamometer for the investigation. Real-world on-road drive test conducted to make sure and present actual realistic data of EICAC technology on the vehicle during the performance investigation. The eyewitness of driving observation by the author evaluating through observation of the vehicle while conducting the tests.

Chapter four presents the results achieved from numerical and CFD simulation, comparison analysis of designs, evaluation results of EIHE experimental tests. The investigation results of the engine performance influenced by the EICAC temperature variation and driving method. The results presented in visual graphical forms, tables, and statistical analyses.

Chapter five presents the conclusions derived results from this research, future recommendations of the research presented.

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LIST OF PUBLICATIONS

Publication

Sharif, P. M., Hairuddin, A. A., As' ary, A., Rezali, K. A. M., Noor, M. M., & Shareef, S. M. (2019). Development of evaporative intercooler heat exchanger for vehicle charge air enhancement using CFD simulation. Journal of Mechanical Engineering and Sciences, 13(4), 6195-6217.

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