EFFECTS OF PRE-TURBOCHARGER TURBINE WATER INJECTION ON THE PERFORMANCE OF SPARK-IGNITION ENGINE

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DEDICATION

Dedicated to my beloved parents, who had been supporting my decision, giving me the freedom to learn and do the things I wanted. It is also dedicated to my one and only brother, Edward, who always talk to me openly.

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ABSTRACT

Following the stringent emission legislation in the major automotive markets, the downsized boosted engine becomes the engine design trend that almost all automakers have been adopted. A turbocharged engine has the disadvantages of high exhaust gas temperature at medium to high engine load and engine speed operations. Fuel enrichment is the common strategy used to control the high exhaust temperature within the permissible thermal limit of the catalytic converter and turbine vane. Water injection strategies have been proven to be a promising technique to improve the performance of boosted engine while reducing the NOx emission via the latent heat of vaporization of water. Plenty of water injection research was conducted on in-cylinder and intake port water injection. However, the water injection research on the spark ignition engine exhaust system section is still lacking. This research proposed a pre-turbocharger turbine water injection concept to reduce the turbine inlet temperature. In turn, the stoichiometric engine operation could be achieved at the medium-high load and speed engine operation without resorting to fuel enrichment strategy in reducing the exhaust gas temperature. The purpose of this study was to investigate the effect of injecting water into the exhaust gas at the pre-turbine of a turbocharged spark-ignition engine. This study was initiated by experimenting using a 1.3-litre 4-cylinder turbocharged engine on a test bench to collect engine data for Computational Fluid Dynamics (CFD) baseline model validation. Simultaneously, a one-dimensional engine model was then developed based on the 1.6-litre 4-cylinder turbocharged engine experiment using AVL BOOST software. The CFD model was used to investigate the effects of water injection pressure, pipe diameter and water injector location. The CFD results showed that a 50 mm connecting pipe with 4 bar of injection pressure gives the most exhaust temperature drops. The CFD results were then applied to the one-dimensional engine model. The engine model simulation results showed that the fuel consumption can be reduced up to 13% at 4,000 rpm during wide-open throttle and 75% engine load. This research proved the potential of using water injection at the pre-turbine turbocharger to reduce the fuel consumption of a turbocharged spark-ignition engine. The pre-turbocharger turbine water injection is a new approach, requiring further optimisations and improvements to fulfil the market demand for a fuel-efficient vehicle with stringent emission regulations.

ABSTRAK

Disebabkan undang-undang pelepasan yang ketat di pasaran automotif utama, enjin yang diperkecil menjadi trend reka bentuk enjin yang hampir diadaptasi oleh semua pembuat kenderaan. Enjin pengecas turbin mempunyai kelemahan suhu gas ekzos yang tinggi sewaktu operasi beban enjin yang sederhana tinggi. Pengayaan bahan api ialah strategi umum yang digunakan untuk mengawal suhu ekzos yang tinggi dalam had terma yang dibenarkan untuk penukar pemangkin dan ram turbin. Strategi suntikan air telah terbukti sebagai teknik yang menjanjikan peningkatan prestasi engine pengecas turbin sambil mengurangkan pelepasan NOx melalui haba pendam pengewapan air. Terdapat banyak penyelidikan suntikan air yang dilakukan pada suntikan air dalam silinder dan port pengambilan. Namun demikian, kajian suntikan air pada bahagian sistem ekzos enjin pencucuhan bunga api masih berkurangan. Konsep yang baru dicadangkan dalam penyelidikan ini, iaitu suntikan air pra-pengecas turbin bertujuan untuk mengurangkan suhu salur masuk turbin. Sebaliknya, operasi enjin stoikiometrik dapat dicapai tanpa menggunakan strategi pengayaan bahan api dalam mengurangi suhu gas ekzos pada pengoperasian enjin dalam kelajuan tinggi dan beban tinggi. Tujuan kajian ini adalah untuk mengkaji kesan penyuntikan air ke dalam gas ekzos pada pra-turbin enjin pencucuhan bunga api pengecas turbin. Kajian ini dimulakan dengan melakukan eksperimen dengan menggunakan enjin pengecas turbin 4 silinder 1.3 liter di bangku uji untuk mengumpulkan data enjin untuk pengesahan model asas Dinamik Bendalir Pengkomputeran (CFD). Model enjin satu dimensi dikembangkan berdasarkan eksperimen enjin pengecas turbin 4 silinder 1.6 liter dengan menggunakan perisian AVL BOOST secara serentak. Model CFD digunakan untuk menyiasat kesan tekanan suntikan air, diameter paip dan lokasi penyuntik air. Hasil CFD menunjukkan bahawa paip penghubung yang lebih besar dengan tekanan suntikan 4 bar memberikan penurunan suhu ekzos yang paling banyak. Hasil CFD kemudian diterapkan pada model enjin satu dimensi. Hasil simulasi model enjin menunjukkan bahawa penggunaan bahan api dapat dikurangkan sehingga 13% pada 4,000 rpm semasa pendikit terbuka luas dan 75% beban enjin. Hasil daripada penyelidikan ini membuktikan potensi menggunakan suntikan air pada pra-pengecas turbin dapat mengurangkan penggunaan bahan api enjin pencucuhan percikan turbo. Suntikan air pra-turbin pengecas adalah pendekatan baru yang memerlukan pengoptimuman dan peningkatan lebih lanjut bagi memenuhi permintaan pasaran kenderaan yang efisien bahan api dengan peraturan pelepasan yang ketat.

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LIST OF ABBREVIATIONS

1D	-	One-Dimensional
3D	-	Three-Dimensional
AFR	-	Air Fuel Ratio
AHRR	-	Apparent Heat Release Rate
BEV	-	Battery Electric Vehicle
BSFC	-	Brake Specific Fuel Consumption
CAD	-	Crank Angle Degree
CI	-	Compression-Ignition
CO	-	Carbon Monoxide
CO_2	-	Carbon Dioxide
CR	-	Compression Ratio
DWI	-	Direct Water Injection
ECU	-	Engine Control Unit
EE	-	Eulerian-Eulerian
EGR	-	Exhaust Gas Recirculation
EV	-	Electric Vehicle
FCV	-	Fuel Cell Vehicle
FMEP	-	Friction Mean Effective Pressure
HCCI	-	Homogeneous Charge Compression Ignition
ICE	-	Internal Combustion Engine
IMEP	-	Indicated Mean Effective Pressure
LE	-	Lagrangian-Eulerian
PNH	-	Patton, Nitschke and Heywood
PTWI	-	Pre-turbocharger Turbine Water Injection
PWI	-	Port Water Injection
RANS	-	Reynold-Averaged Navier Stokes
ROHR	-	Rate of Heat Release
SI	-	Spark-Ignition
TDC	-	Top Dead Centre
TIT	-	Turbine Inlet Temperature

VVT	-	Variable Valve Timing
WI	-	Water Injection
WOT	-	Wide Open Throttle

LIST OF SYMBOLS

Roman Symbol

A_w	-	Port Surface Area
d_p	-	Droplet Diameter
$\dot{m}_T$	-	Turbine Mass Flow
h_v	-	Valve Lift
F_B	-	Buoyant Force
F_D	-	Drag Force
F_P	-	Pressure Gradient Force
F_R	-	Rotation Force
F_{VM}	-	Virtual And Added Mass Force
N_c	-	Number Of Computational Particles
N_{pc}	-	Nominal Number of Particles Per Grid Cell
N_u	-	Nusselt Number
P_C	-	Compressor Power Consumption
P_T	-	Power Provided by Turbine
Q_C	-	Convective Heat Transfer
Q_R	-	Radiation Heat Transfer
T_c	-	Gas Temperature in The Cylinder
T_d	-	Downstream Temperature
T_u	-	Upstream Temperature
T_w	-	Port Wall Temperature
T_{wi}	-	Wall Temperature
U_p	-	Initial Particle Velocity
V_D	-	Displacement Per Cylinder
W_G	-	Molecular Weight of Vapour
W_c	-	Molecular Weight of Mixture in Continuous Phase
X_S^V	-	Equilibrium Vapour Mole Fraction of The Evaporating Component at The Droplet Surface

X_{vap}^{V}	-	Mole Fraction of The Evaporating Component in The Gas Phase
c_m	-	Mean Piston Speed
c_p	-	Specific Heat Capacity of The Wall Layer
c_u	-	Circumference Velocity
d_{hyd}	-	Hydraulic Diameter
d_e	-	Measure of Fineness
m_p	-	Particle Momentum
q_w	-	Wall Heat Flow
w_j	-	Mass Fraction of The Species J In the Gas Phase
vT_{oil}	-	Viscosity As a Function of Oil Temperature
c_v	-	Specific Heat Capacity of The Gas (At Constant Volume)
D_{cyl}	-	Cylinder Bore
D	-	Mean Droplet Size
d	-	Particle Diameter
d_{vi}	-	Inner Valve Seat Diameter
E	-	Energy
F	-	Flux Vector
h	-	Specific Enthalpy
H	-	Latent Heat of Evaporation
k	-	Turbulent Kinetic Energy
m	-	Mass
M	-	Total Element Number
P_{inj}	-	Injection Pressure
P	-	Pressure
R	-	General Non-Linear Source
R	-	Mass Fraction
S	-	Mass Source
T	-	Temperature
u	-	Mean Mass Weighed Gas Velocity
U	-	State Vector
V	-	Effective Injector Velocity
v	-	Volume

x	-	Coordinate Along the Pipe Axis
x	-	Displacement
D	-	Mass Diffusion Rate
Sh	-	Sherwood Number
k	-	Isentropic Exponent

Greek symbols

α_{gw}	-	Heat Transfer Coefficient Between Gas and Wall
α_p	-	Heat Transfer Coefficient in The Port
η_{TC}	-	Overall Turbocharger Efficiency
η_m	-	Mechanical Efficiency of Turbocharger
η_s	-	Isentropic Efficiency
λ_g	-	Thermal Conductivity (Gas)
ϕ_p	-	Generic Transported Variable
Δ	-	Change of Any Changeable Quantity
γ	-	Rosin Rammler Power
δt	-	Timestep
ρ	-	Density
τ	-	Linearization Coefficient
ϵ	-	Turbulence Dissipation Rate

Subscripts and superscripts

1	-	Compressor Inlet
2	-	Compressor Outlet
3	-	Turbine Inlet
4	-	Turbine Outlet
a		Target Variable
A	-	Caused By Axial Change in The Cross-Section of The Pipe
AUX	-	Auxiliary Loss

b		Reference Variable
C	-	Compressor
c	-	Cylinder
CS	-	Crankshaft
f	-	Value Of The Φ in the Surrounding Fluid
IP	-	Injection Pump
n	-	New
o	-	Old
p	-	Particle
P	-	Piston (Reciprocating) Group
R	-	Inclusive Of Homogeneous Chemical Reaction, Heat and Mass Transfer Term Between the Gas And Solid Phase As Well As Friction
T	-	Turbine
TC	-	Turbocharger
TOT	-	Total
vap	-	Vapour
VT	-	Valve Train
w	-	Wall

CHAPTER 1

INTRODUCTION

The first chapter will provide a brief overview of the research. First and foremost, the background of the current regulation and how it leads to the shift of engine design trends will be presented, followed by the problem statement and research gap, which lead to the motif of this research. The research objectives and scopes will also be well-defined.

1.1 Stringent emission regulation

Vehicle emission regulation is crucial to tackle air pollution in developed countries and cities. One of the primary automotive markets, Europe, has proposed an ambitious reduction in carbon dioxide (CO_2) limit for both light and heavy-duty vehicles for the coming decade. Their Euro 6 regulation has been implemented for several years, and they have started to discuss on Euro 7 regulation which will be put into effect potentially in the year 2025 [1].

In the United States (US), their Environmental Protection Agency (EPA) and the National Highway Traffic Safety Administration (NHTSA) proposed to amend the existing Corporate Average Fuel Economy (CAFÉ) and specific greenhouse gas emission standards for passenger cars and light trucks. The amended standard will cover every vehicle coming out from 2021 to 2026 model years [2].

In 2018, China announced a 3-year action plan called the “Blue Sky” policy with a broad call to action for their local government to address various air quality goals. The critical regions involved are the major cities like Beijing, Tianjin, Hebei, Shanghai, etc. The policy ensures that China 6 fuel is introduced nationwide starting Jan 2019.

The emission regulation will only be getting stricter year by year, as shown in Figure 1.1. The car manufacturers must find their way in every possible way to gradually reduce the CO_2 emission of their fleet every year to comply with the regulation set by the major markets.

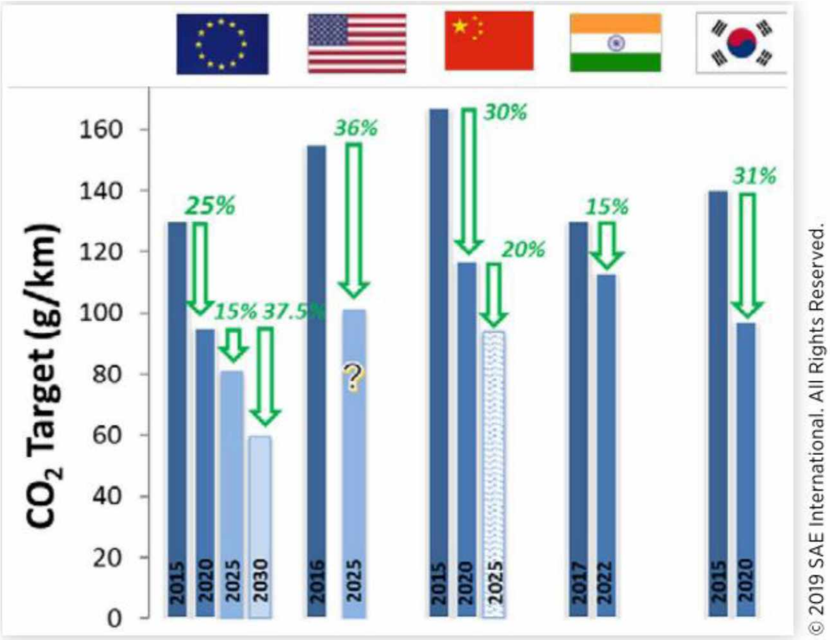

Figure 1.1 CO_2 target for light-duty vehicles in significant markets [1]

1.2 Engine downsizing trend

Due to the stringent emission standard, engine downsizing has been the engine design trend for the past decade. For example, the market share of the boosted downsized engine for light transportation in a vast market like the US has been increasing in recent years, as shown in Figure 1.2. This momentum is expected to continue for the coming years. Turbochargers are being used to compensate for the power loss from the downsized engine. The boosted engine can produce a flatter torque curve which improves the performance and efficiency at part load operation [3]. However, this downsized boosted engine has some drawbacks to overcome.

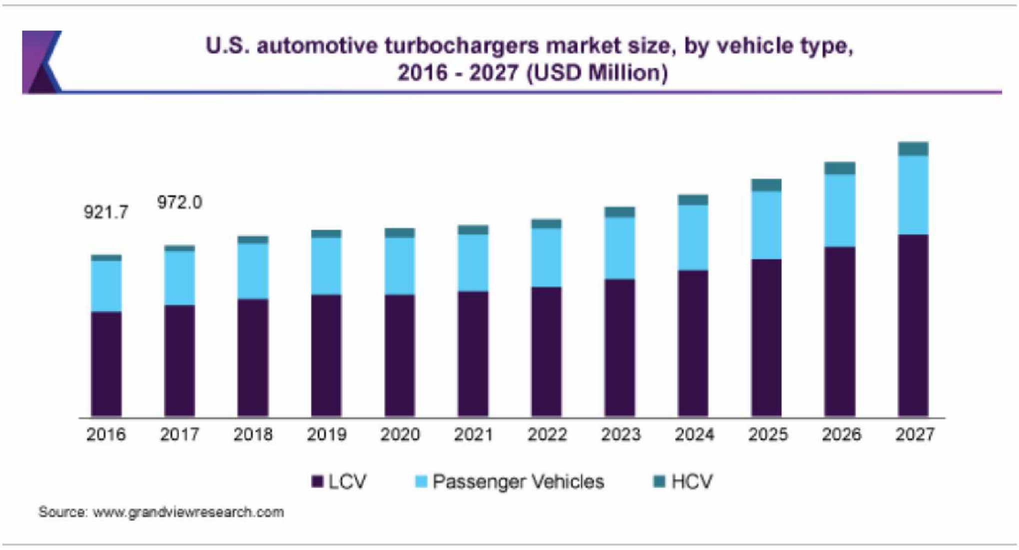

Figure 1.2 Market share of the automotive turbocharger in the US [4]

Firstly, the compressed intake air causes the boosted engine to operate at higher indicated mean effective pressure (IMEP). This promotes engine knocking in the combustion chamber, which will damage the engine if it occurs for a prolonged period. The compression ratio (CR) reduction and spark retard are required to prevent engine knock, leading to the deficit in engine efficiency. Hence, engine knocking is the limiting factor of extracting potential performance from a high power density engine [5].

The exhaust gas temperature may also exceed 900°C, which will cause the exhaust manifold and turbocharger turbine side to reach an extreme temperature, as shown in Figure 1.3. The turbine inlet temperature (TIT) is the critical parameter that needs to be maintained below 930°C so that it is below the permissible thermal limit of the turbine vane and catalytic converter. Fuel enrichment is the commonly used method to control the temperature of combustion and exhaust gas. Thus, the fuel consumption of a small displacement boosted engine is higher during high load engine operation.

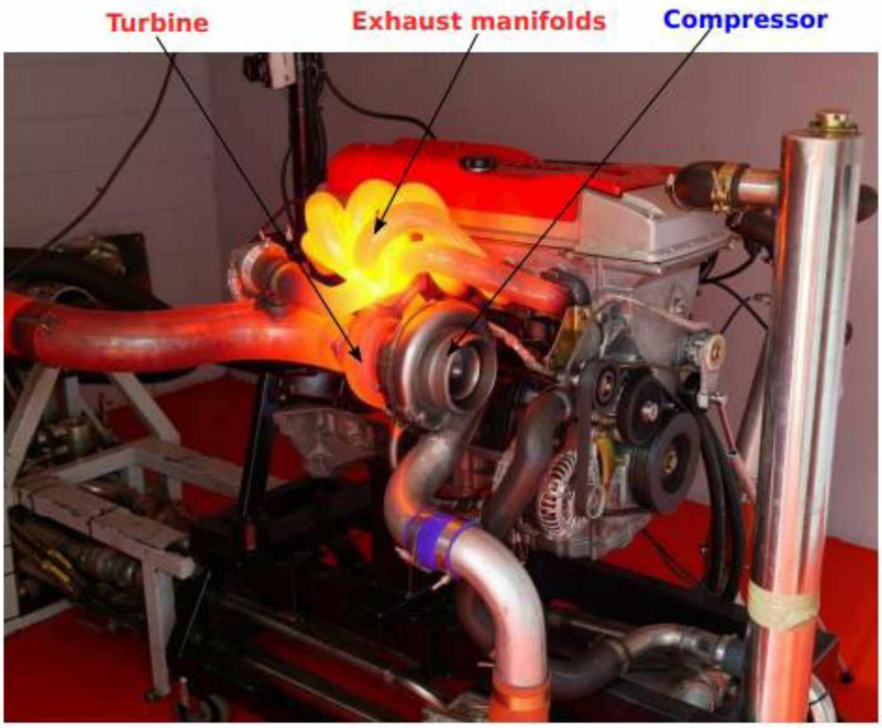

Figure 1.3 Engine is running at high load operation [6]

1.3 Problem Statement

As discussed in subchapters 1.1 and 1.2, car manufacturers face many challenges to meet the requirement of emission regulations of all the major car markets. Engine downsizing is one of the ways, but the internal combustion engine (ICE) still requires incremental improvement and breakthrough technologies to meet the emission reduction target for the coming years. Technologies such as cooled exhaust gas circulation (EGR), variable compression ratio, thermoelectric generators are some of the solutions and concepts proposed in the past five years to improve the efficiency of a turbocharged engine, up to 45% potential thermal efficiency [7], [8].

In general, water injection (WI) is a promising technology for knock suppression in the small-boosted engine. Followed by allowable spark advance, more power can be extracted from the engine. WI can also reduce the combustion temperature, which effectively reduces NOx emission. Besides, WI can also replace or reduce the fuel enrichment application, which reduces the brake specific fuel consumption (BFSC) of the engine [9]. This also allows the engine to operate on stoichiometric combustion. From here, WI is a technique that can be expected to improve engine performances without compromising fuel consumption. Furthermore, the reduction of NOx encourages the implementation of WI to meet the future exhaust emission standard.

WI strategies can be categorised into pre-combustion WI, direct WI (DWI), and post-combustion WI. Every design has its respective advantages and disadvantages. Under pre-combustion WI, there are port WI and intake manifold WI. Port WI is the most proposed strategy due to its versatility and easy installation. With few modifications, the gasoline fuel injection system can be directly used for water injection. Direct WI has been increasingly proposed in recent years due to the more precise water spray and evaporation control, just like direct fuel injection.

On the other hand, post-combustion WI was only proposed in the compression ignition (CI) engine. As the name suggested, the injected water does not involve combustion compared to the other two WI strategies. After all, post-combustion WI is the least exploited WI strategy. When this thesis was written, there were very few reports on the implementation of WI at exhaust manifold of CI engine found. However, there were even fewer applications onto the SI engine.

In this research, an investigation toward a newly proposed post-combustion WI strategy was carried out, known as pre-turbocharger turbine water injection (PTWI). The PTWI is used to cool down the turbine inlet temperature (TIT) instead of the combustion chamber, enabling the engine to run at stoichiometric (λ=1) conditions. This research will focus on the effects of the PTWI on the performance and fuel consumption of a spark ignition (SI) engine across the operating state.

1.4 Research objectives

The objectives of the research are:

(a) To characterise the behaviour of liquid water and exhaust gas in PTWI using three-dimensional (3D) Computational Fluid Dynamics (CFD).

(b) To investigate the effects of pre-turbine water injection on fuel consumption and engine performances using one-dimensional (1D) simulation.

1.5 Scope of research

The scope of this research covers both simulation and experiment to propose a new water injection strategy for a gasoline engine. The purpose of the experiment in this study was to validate the simulation model. The experiment was conducted on an engine test bench, and the modification was done at the turbocharger turbine upstream. All the sensitivity cases were investigated through the validated simulation models. 3D CFD simulation focuses on the water spray behaviour in the hot exhaust gas stream. The parametric study was conducted on the injector pressure (4 bar, 7 bar, 9 bar), the diameter of the turbine inlet connecting pipe (30 mm, 40 mm, 50 mm) and the distance of the injector from the turbine inlet (150 mm, 250 mm, 450 mm). For 1D engine simulation, the engine model was developed based on existing engine setup specifications on the test bench. The baseline model was then validated with engine testing results. The baseline engine model will then use the results from CFD to investigate the effect of PTWI on the engine performances and fuel consumption during 3000 rpm, 4000 rpm and 5000 rpm at 100%, 75% and 50% of engine load.

1.6 Thesis layout

The thesis is organised into five chapters. The followings are the brief outline of each chapter.

CHAPTER 1 INTRODUCTION

This chapter introduces the incoming emission regulations implemented in some major markets, followed by engine design trends to cope with the rules. Water injection is one technology that potentially improves engine efficiency, but many improvements still need to be made. Therefore, the research gap and problem statement are recognised. The objectives and scope of this research are established to fill up the research gap.

CHAPTER 2 LITERATURE REVIEW

The chapter introduces various water injection (WI) strategies that have been proposed. The author includes fuel-water emulsion as well since the water gets involved. Besides, the author also briefly discusses the application of WI on different engine configurations. The author also criticises and comments on the strength and weaknesses of each approach. The vaporisation of the water was discussed to optimise the WI research setup specifications.

CHAPTER 3 METHODOLOGY

This chapter showcases the workflow to obtain the research objectives. The author explains the experimental and simulation setup in detail. Firstly, the author describes the experimental work, test-rig design, and post-processing. Following the CFD baseline model validation, the author explains the 3D CFD setup and model used. Lastly, the author presents the 1D engine model validation and brings the result from CFD into the validated engine model for performance and fuel consumption simulation.

CHAPTER 4 RESULTS AND DISCUSSIONS

This chapter discusses 3D CFD model validation with experiment data and follows it by 1D engine model validation with the available engine testing data. The author evaluates the water spray flow over the hot exhaust gas under different sensitivity parameters. Then, the author highlights and discuss the fuel consumption and performance in 1D simulation in which the engine is running at stoichiometric condition.

CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS

The author makes sure the findings of this research achieve the objectives that have been set since the beginning. Lastly, the author closes the thesis by providing valuable recommendations for future works and researchers.

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