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NUMERICAL SIMULATION OF MIXING CHARACTERISTICS OF CNG-AIR MIXER FOR DUAL-FUEL VEHICLE

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By

HASSAN SADAH MUHSSEN

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Master of Science

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DEDICATED

My dear father, Sadah Muhssen,

My beloved mother, Ibtisam Khayoon,

My loving wife, Zainab Atiyah,

Faithful brothers, sisters, children, relatives, & friends

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Master of Science

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Chairman : Siti Ujila Masuri, PhD
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A compressed natural gas (CNG)-air mixer is a device like a carburettor positioned at the air intake manifold of the engine to mix CNG with incoming air at proper amounts of CNG and air prior to entering the combustion chamber. According to literature, the best design of CNG-air mixer is one that is able to meet the conditions of 1) supply the engine with a homogeneous mixture of CNG and air, 2) with air and CNG with the required air fuel ratio (AFR), and 3) without reduction of the air intake manifold size. The homogeneous mixture occurs when the uniformity index (UI) of methane mass fraction (M_{Ch4}) =1.0. From previous studies, there is no design of CNG-air mixer which could satisfy all the above three conditions at the same time.

This research carried out a computational fluid dynamics (CFD) study to design a CNG-air mixer for CNG-diesel dual fuel (DDF) engine. The objectives of this study were to examine the performance of existing Secondary Fuel Premixing Controller (SFPMC) commercial mixer and modify it in terms of air fuel ratio (AFR) and CNG-air mixture homogeneity (CAMH).

The validity and reliability procedures of the simulation results were carried out using the grid independent test, and verification by comparing the results with the literature.

Results from simulation indicated that the original mixer (model 1) was unable to control AFR due to the shaft design of the control valve. Furthermore, this mixer could not provide a homogeneous mixture of CNG and air due to the mixer's internal

design, position and directions of the CNG holes. Therefore, the mixer design was modified in terms of AFR and CNG-air mixture homogeneity. Design modification of the control valve shaft was the first method to control AFR, while the second modification involved removing the control valve and also assuming that the gas flow rate is controlled by the electronic flow controller and electronic control unit (ECU). For the mixture homogeneity, there were 10 alternative designs that were tested (models 2-11) to achieve the desired design. The uniformity index (UI) of methane mass fraction (M_{Ch4}) was the approach used to quantify CNG spread on the mixer outlet. The UI of M_{Ch4} represents how M_{Ch4} varies over a plane surface, where a value of 0 and 1 indicate the lowest and highest uniformity of gas spread, respectively. Based on the results obtained from mixer models 1-11, it can be concluded that models 8 and 11 showed a superior performance in terms of UI. The minimum UI of M_{Ch4} at the outlet of these two mixer models was not less than 0.96 at various engine speeds of 1000, 1500, 2000, 3000, and 3600 rpm, and 0.87 at various AFRs of 10, 17.2, 20, 30, and 40. On the other hand, at the outlet of original mixer, the maximum UI of M_{Ch4} was not higher than 0.57 at various engine speeds, and 0.58 at various AFRs. In terms of AFR, the optimized mixer with a new control valve shaft showed better controlling of AFR at the various engine speeds compared with the original mixer.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Sarjana Sains

SIMULASI BERANGKA CIRI-AM MENCAMPUR PENGADUN CNG-UDARA UNTUK KENDERAAN DWI-BAHAN BAKAR

Oleh

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Pengadun gas asli termampat (CNG)-udara adalah alat seperti karburetor yang diletakkan di pancarongga pengambilan udara enjin untuk mencampur CNG dengan udara masuk pada jumlah CNG dan udara yang sesuai sebelum memasuki kebuk pembakaran. Menurut literatur, reka bentuk yang paling sesuai untuk pengadun CNG-udara adalah sesuatu yang dapat memenuhi syarat-syarat 1) membekalkan enjin dengan campuran homogen CNG dan udara, 2) dengan udara dan CNG pada nisbah udara bahan bakar yang diperlukan (AFR), dan 3) tanpa pengurangan saiz pancarongga pengambilan udara. Campuran yang homogen berlaku apabila indeks keseragaman (UI) bagi pecahan jisim metana (M_{Ch4}) =1.0. Dari kajian sebelum ini, tidak ada reka bentuk pengadun CNG-udara yang boleh memenuhi kesemua tiga-tiga syarat di atas secara serentak.

Kajian ini adalah satu kajian menggunakan pengkomputeran dinamik bendalir (CFD) untuk mereka-bentuk pengadun CNG-udara bagi enjin CNG-diesel dwi-bahan bakar (DDF). Objektif kajian ini adalah untuk mengkaji prestasi pengadun dagangan Pengawal Pra-Adunan Bahan Bakar Sekunder yang sedia ada dan mengubahsuainya dari segi nisbah udara bahan bakar (AFR) dan kehomogenan campuran CNG-udara (CAMH).

Prosedur kesahan dan kebolehpercayaan bagi keputusan simulasi telah dijalankan menggunakan grid ujian bebas, dan penentusahan oleh perbandingan keputusan dengan literatur.

Keputusan daripada simulasi menunjukkan bahawa pengadun asal (model 1) tidak dapat mengawal AFR disebabkan oleh reka bentuk shaf injap kawalan yang tidak

sesuai. Tambahan pula, pengadun ini tidak dapat menyediakan campuran homogen CNG dan udara disebabkan oleh reka bentuk dalaman, kedudukan dan arah lubang CNG. Oleh itu, reka bentuk pengadun telah diubahsuai dari segi AFR dan kehomogenan campuran CNG-udara. Pengubahsuaian reka bentuk shaf injap kawalan adalah kaedah pertama untuk mengawal AFR, manakala pengubahsuaian kedua melibatkan mengeluarkan injap kawalan dan juga menganggap bahawa kadar aliran gas dikawal oleh pengawal elektronik aliran serta unit kawalan elektronik (ECU). Untuk kehomogenan campuran, terdapat 10 reka bentuk alternatif yang diuji (model 2-11) untuk mencapai reka bentuk yang dikehendaki. Indeks keseragaman (UI) bagi pecahan jisim metana (M_{Ch4}) adalah pendekatan yang digunakan untuk mengukur agihan CNG pada saluran keluar pengadun. UI M_{Ch4} mewakili bagaimana M_{Ch4} berbeza agihannya di atas sesuatu permukaan, yang mana nilai 0 dan 1 masing-masing menunjukkan keseragaman bagi penyebaran gas yang paling rendah dan paling tinggi. Berdasarkan keputusan yang diperolehi daripada model pengadun 1-11, dapat disimpulkan bahawa model 8 dan 11 menunjukkan prestasi yang lebih baik dari segi UI. UI minimum M_{Ch4} di saluran keluar kedua-dua model pengadun tersebut tidak kurang daripada 0.96 pada pelbagai kelajuan enjin di paras 1000, 1500, 2000, 3000, dan 3600 rpm, dan 0.87 di pelbagai AFRs iaitu 10, 17.2, 20, 30, dan 40. Sebaliknya, di saluran keluar pengadun asal, UI maksimum MCh4 tidak melebihi 0.57 pada pelbagai kelajuan enjin, dan 0.58 pada pelbagai AFRs. Dari segi AFR, pengadun yang dioptimumkan dengan shaf injap kawalan baru menunjukkan pengawalan AFR yang lebih baik pada pelbagai kelajuan enjin berbanding dengan pengadun asal.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirements for the degree of Master of Science. The members of the Supervisory Committee were as follows:

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This is to confirm that:

- the research conducted and writing of this thesis was under our supervision;
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(A/F)s	Stoichiometric air fuel ratio
Ø	Equivalence ratio
3D	Three dimensions
AFR	Air to fuel ratio
BDC	Bottom dead centre
CAMH	CNG-air mixture homogeneity
CAPMC	CNG-air pre mixing controller
CFD	Computational fluid dynamics
CI	Compression ignition engine
CNG	Compressed natural gas
CO	Carbon monoxide
CO_2	Carbon dioxide
DDF	CNG-dual fuel diesel
ECU	Electronic control unit
GMSB	Gas Malaysia Sdn. Bhd.
HCAM	Homogeneous CNG-air mixture
HCNG	Hydrogen-compressed natural gas engine
L	Liter
L.H.V	Lower heating value
M_{ch4}	Methane mass fraction
MDE	Dimethyl ether
mm	Millimeters
NG	Natural gas
NGVs	Natural gas vehicles
NMHC	Non-methane hydrocarbons
NO_x	Nitrogen oxides
PM	Particulate matter
SFPMC	Secondary fuel pre mixing controller
SI	Spark ignition engine
SIMPLE	Semi-implicit method for pressure link equation
SPIT	Single point injection throttle
TBIM	Throttle body injection mixer
TCF	Trillion cubic feet
TDC	Top dead centre
UHC	Unburned hydrocarbon
UI	Uniformity index
λ	Relative air fuel ratio

CHAPTER 1

INTRODUCTION

1.1 Background

High thermal efficiency, durability, low carbon dioxide emission, reliability, high torque, and fuel economy are the factors that have made the diesel engines the preferred choice for passenger transport, trucks, and power generation operations (Chintala & Subramanian, 2013). In contrast, high localized temperature and combustion with heterogeneous air-fuel mixture have made the diesel engine produce a high level of nitrogen oxides emission and particulate matter emission (Chintala & Subramanian, 2013). Previous investigations have shown that people are prone to heart and lung diseases when exposed to exhaust particulate matter emission (Azad, Uddin, & Alam, 2012; Chintala & Subramanian, 2013). Many types of alternative fuels like alcohol, CNG, LPG, biogas, producer gas, and hydrogen were studied widely in the literature (Lata, Misra, & Medhekar, 2012). The factors such as high auto-ignition temperature, clean nature of combustion, and high availability at attractive prices make natural gas a good alternative fuel for diesel and gasoline engines (R. G. R. Papagiannakis et al., 2010). Compressed natural gas (CNG) is one of the natural gas forms, with some properties that make it an attractive alternative fuel for diesel fuel such as high octane number, high hydrogen to carbon rate, and leaner burn due to wide ignition limit (Kamil, Rahman, & Bakar, 2011).

Although CNG plays a significant role in reducing combustion emissions, the problems of high rate of NO_x and PM (particulate matter) emissions have been taken into account in recent times (T. F. Yusaf, Buttsworth, Saleh, & Yousif, 2010). CNG-diesel dual fuel (DDF) system has been developed to decrease NO_x and particulate matter emissions of diesel engines (Chintala & Subramanian, 2013; N. Kapilan, 2010; T Yusaf, Baker, Hamawand, & Noor, 2013). The work principle of the DDF engine is represented by the burning amount of the premixed CNG-air mixture by injecting a small amount of diesel “pilot” fuel inside the engine combustion chamber near the end of the compression stroke (Khan, Yasmin, & Shakoor, 2015b). CNG-air mixer is used to convert the diesel engine to DDF engine without more engine modifications. The main purpose of the mixer is to obtain a homogeneous mixture and suitable ratios of air and CNG as required by the engine (Abagnale et al., 2014; Chang, Yaacob, & Mohsin, 2007; Gorjibandpy & Sangsereki, 2010; Talal Yusaf & Yusoff, 2000). Venturi mixer, throttle body injection mixer (TBIM), venturi mixjector, and secondary fuel pre-mixing controller (SFPMC) are the devices that are used to mix the CNG and air prior to entering the engine combustion chamber.

All these mixing devices have been investigated extensively except the latter type, which is SFPMC. From the results of investigation of mixing devices except the

SFPMC, there was no mixer found that is optimized to provide a homogeneous CNG-air mixture (HCAM) at various engine speeds and various AFR without throttling engine air inlet. SFPMC mixer can be investigated and developed for a CNG-dual fuel diesel engine. Hence, this study focused on the modeling, testing and improving the mixing quality of CNG-air mixture in SFPMC mixer.

1.2 Problem Statement

All the CNG-air mixing devices like venturi mixer, venturi mixjector and throttle body injection mixer (TBIM) have been much investigated except the secondary fuel pre-mixing controller (SFPMC). The results of previous studies on the venturi showed a weakness in its performance in terms of CNG-air mixture homogeneity (CAMH) and AFR controlling at various engine speeds. In the venturi mixer the gas is rich at the wall regions and lean at the axial region; also the mixer should be long enough to provide homogenous mixture of CNG and air. Moreover, AFR is controlled by mixer design not as required by the engine due to stationary parts of the venturi mixer (MM & MRM, 2008; Mohsin, 2008; Ramasamy, 2006; T Yusaf et al., 2013; Talal Yusaf & Yusoff, 2000). For these two reasons, TBIM and venturi mixjector were the two suggested mixers to improve the CAMH and AFR controlling. TBIM is workable only with engine with throttle body and the CAMH depended on the butterfly valve position and gas injection frequency (Chang et al., 2007; Mohsin, 2008). On the other hand, venturi mixjector is a venturi mixer which uses electronic gas injectors to control AFR. Although this mixer controlled AFR and improved engine performance, but it is still venturi shaped which chokes the engine air intake. Moreover, CAMH occurs at intake manifold and the mixing is not completed at the mixer outlet (Supee, Shafeez, et al., 2014). Therefore, there is a need for analytical study of SFPMC mixer to work with 3.168 liter diesel engine.

1.3 Objectives

The objectives of this study are:

1. To examine the performance of existing secondary fuel pre mixing controller (SFPMC) commercial mixer in terms of AFR and CNG-air mixture homogeneity (CAMH).
2. To improve the design of the mixer by:

(a) Provide a homogeneous CNG-air mixture by keeping uniformity index (UI) of methane mass fraction (M_{Ch4}) at the outlet of new mixer higher than 85% at various engine speeds and various AFRs.

(b) Design two new mixers in terms of controlling AFR; one with control valve (assuming the gas flowrate is mechanically controlled), and one without control valve (assuming the gas flowrate is electronically controlled).

1.4 Scope

The scope of the study is as follows:

1. SFPMC mixer is designed for 4-cyinders, 4-stroke, and 3.168 litter capacity diesel engine.
2. Engine operating at steady state with varied engine speeds 1000, 1500, 2000, 3000, and 3600 rpm.
3. Various AFR operations from rich (AFR = 10), to stoichiometric (AFR = 17.2) and to lean (AFR = 20, 30, and 40).
4. Initial mixer dimensions are taken from real commercial mixer.
5. Design two new mixers; one with control valve (to control gas flowrate mechanically), and one without control valve (to control gas flowrate electronically).
6. Using computational fluid dynamics (CFD) as analysis tool to investigate the performance of the mixer.
7. Since this study is focused on the fluid flow pattern inside the mixer, control valve mechanism (in mixer with control valve) and the flow controller (in mixer without control valve) are not a part of this study.

1.5 Significance of research

From the two primary objectives of study, the designed and best modified CNG-air mixer for DDF engine will be presented and selected. This mixer provides a homogeneous mixture of CNG and air with required AFR. Moreover, this mixer does not reduce air intake manifold to avoid engine power drop.

The correct strategies in this research to obtain the best design of the mixer in term of mixing homogeneity could be followed as a guide for mixer design. Furthermore, controlling gas flowrate mechanically by modified CNG-air mixer could be used as a guide for designing fluids flow control systems.

In addition, this research summarizes the techniques of using CFD simulation results to visualize and quantify of mixing homogeneity level of the mixture components.

1.6 Thesis Organization

Chapter 2 reviews the literature on the diesel dual fuel engine, characteristics of CNG as alternative fuel, the effects of AFR and mixture homogeneity on the engine performance, methods to show and quantify mixture homogeneity, types of CNG-air mixer and its performance in terms of AFR and homogeneity of CNG-air mixture, and finally the use of CFD as an analysis tool.

Chapter 3 describes the methodology used to model and modify the design of SFPMC real commercial mixer, and the setting up of the simulation software (ANSYS FLUENT) to examine the original mixer and the suggested alternative designs in terms of AFR and homogeneity of CNG-air mixture.

Chapter 4 presents the results and discussions on the effect of mixer design on AFR and the homogeneity of CNG-air mixture (HCAM). It begins by showing the effect of the original mixer design on the AFR and mixture homogeneity. After that, this chapter shows the comparison between the original mixer and the 10 suggested alternative designs in terms of CNG-air mixture homogeneity. Then, this chapter shows the results of a comparison between original mixer and the best two designs in terms of AFR and CNG-air mixture homogeneity.

Chapter 5 provides the general conclusions and the recommendations for future related studies.

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LIST OF PUBLICATIONS

Hassan S. Muhssen, S.U. Masuri, B.B Sahari, A.A. Hairuddin, Computational Fluid Dynamics Investigation of Air-Gas Pre Mixing Controller Mixer Designed For CNG-Diesel Dual-Fuel Engines. (Submitted to: International Journal of Automotive and Mechanical Engineering (IJAME)).

Submitted Patent under the Title of Secondary Fuel-Air Mixer for Internal Combustion Engine and Fuel Burner. Application No: PI201703422

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