UNIVERSITI PUTRA MALAYSIA

DESIGN OF HOMOGENOUS CNG-H AND AIR MIXER FOR DIESEL ENGINES USING PARTICLE SWARM OPTIMISATION

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By

HUSSEIN ADEL MAHMOOD

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

February 2018

DEDICATION

To my dear Country Iraq and my marvellous family,

My beloved father and my dear mother,

My loving wife and my children,

All the people in my life who touch my heart

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirements for the degree of Doctor of Philosophy

DESIGN OF HOMOGENOUS CNG-H AND AIR MIXER FOR DIESEL ENGINES USING PARTICLE SWARM OPTIMISATION

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February 2018

Chairman : Nor Mariah binti Adam, PhD, PE
Faculty : Engineering

A mixer is a device for mixing the proper amount of fuel with air before admission to the combustion chamber. Although an air–fuel mixer easily converts a diesel engine into a dual-fuel engine, and a petrol engine to a bi engine, the problem with gaseous mixers is the inability to prepare a homogeneous mixture of air and gaseous fuel at various engine speeds, and weak performance in controlling the AFR (air-fuel ratio) at various engine speeds. According to previous studies, no mixer has yet been designed for mixing H-CNG-air for tri-fuel engines (H-CNG-Diesel engines). Moreover, the existing available mixers were unable to work under different engine modes (such as dual fuel or bi engine), different capacities of engine, or different mix of gaseous fuels. In this present work, a new air–H-CNG mixer was designed and developed to be suitable for mixing air with (Hydrogen), (CNG) and (HCNG) under different modes (bi-engine, dual fuel engine, tri-fuel engine). In addition, this new mixer will allow super homogeneous mixing for gaseous fuels with air according to different engine speeds. The new mixer has been designed such that the mixer can be easily connected with an Electronic Control Unit (ECU) for accurate control of the air–gaseous fuel ratio for different engine speeds. The methodology includes theoretical analysis, numerical analysis and experimental work to validate the results of the numerical study. In the numerical part, 14 models of mixers with 116 cases were computer simulated to investigate the effects on the homogeneity and distribution of the mixture according to diameter size, location, and number of holes. The performance of the new mixer models was studied using (ANSYS FLUENT) with different air–gas fuel ratios (six cases), using a fully open valve, and with an engine speed of 4000 rpm. The results of the simulation indicated that the lowest UI (uniformity index) values compared with other models were obtained for a gaseous fuel range between 0.651 and 0.5107 using the different gaseous fuels with the existing mixer. By contrast, the highest UI values range between 0.954

and 0.939, and were obtained using the different gaseous fuels with model 6/case 47. The simulation results show that the new mixer exhibits superior performance in terms of achieving a homogenous mixture (CNG–air, H-air, and HCNG–air) at various engine speeds; the UI values range between 0.9336 and 0.967 under different AFR_{CNG}, (0.941 to 0.974) under different AFR_{H}, and (0.935 to 0.971) under AFR_{HCNG}. Moreover, the new mixer shows a high level of accuracy in controlling the AFR according to the engine speed. In the practical investigation, the new air–fuel mixer (model 6, case 47) was fabricated based on the numerical analysis, and also on the new design for the movable mechanism, which consists of a small bevel gear, a large bevel gear, a power screw, a valve, bolts and seals. According to the numerical and practical results for the new mixer under different engine speeds (1000–4000), and an air–CNG ratio of 34.15, a meaningful agreement is reached between the experimental and numerical values for AFR_{CNG} (R^2 = 0.96 and CoV = 0.001494). In the theoretical part, two empirical models were proposed to estimate the UI of the gaseous fuel inside the new mixer models, and the valve displacements inside the new mixer model (model 6, case 47) based on the PSO technique. The results of the empirical models demonstrate the power of the PSO technique to solve the problem of heterogeneous mixtures inside the mixer, and to control the AFR inside the mixer, thereby enhancing the engine performance.

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

REKA BENTUK PENGADUN CNG-H-UDARA HOMOGEN UNTUK ENJIN TIGA-BAHAN API MENGGUNA KAEAAH PENGOPTIMUM SWARM PARTIKAL

Oleh

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Pengadun ialah suatu alat untuk mencampurkan sejumlah bahan api yang sesuai dengan udara sebelum masuk ke ruang pembakaran. Walaupun pengadun udara-bahan api mudah menukarkan enjin diesel ke enjin dwi-bahan api dan enjin petrol untuk menjadi dwi-enjin, masalah dengan pengadun gas adalah ketidakupayaannya menyediakan adunan homogen udara dan bahan api gas pada pelbagai kelajuan enjin dan prestasi yang lemah mengawal AFR (nisbah udara-bahan api) pada pelbagai kelajuan enjin. Menurut kajian-kajian lampau, tidak ada pengadun yang direka untuk mencampurkan H-CNG-Udara untuk enjin-enjin tiga-bahan api (enjin H-CNG-Diesel). Selain itu, pengadun-pengadun yang ada tidak dapat bekerja di bawah mod enjin yang berbeza (enjin dwi-bahan api, enjin dwi), kapasiti enjin yang berbeza dan bahan api gas yang berlainan. Di dalam kajian ini, pengadun udara-H_2-CNG yang baru telah direka dan dibangunkan untuk menjadi sesuai bagi mencampurkan udara dengan (Hidrogen), (CNG) dan (HCNG) di bawah mod-mod berbeza (dwi-enjin, enjin dua bahan api, enjin tiga-bahan api). Sebagai tambahan pengadun baru ini akan memberikan pencampuran superhomogen untuk bahan api gas dengan udara mengikut kelajuan enjin. Pengadun baru ini direka dengan cara yang tertentu di mana pengadun boleh dengan mudah disambungkan dengan Unit Kawalan Elektronik (ECU) untuk mengawal dengan tepat nisbah udara-bahan api bergas untuk kelajuan enjin yang berbeza. Metodologi kajian merangkumi analisis teori, analisis berangka dan kerja eksperimen untuk mengesahkan hasil dari kajian berangka. Di dalam bahagian berangka, 14 model pengadun dengan 116 kes dicipta untuk menyiasat kesan saiz diameter, lokasi, dan bilangan lubang di dalam pengadun ke atas kehomogenan dan agihan campuran dengan menggunakan suatu perisian. Prestasi model pengadun baru telah dikaji dengan menggunakan (ANSYS FLUENT) dengan nisbah udara-bahan api gas yang berbeza (enam kes), injap terbuka sepenuhnya,

dan dengan kelajuan enjin 4000 rpm. Keputusan simulasi menunjukkan bahawa nilai UI (indeks keseragaman) terendah berbanding dengan model-model lain bagi bahan api gas berjulat antara 0.651 dan 0.510776 untuk bahan api bergas yang berbeza yang telah diperoleh dengan menggunakan pengadun yang sedia ada. Sebaliknya, nilai UI tertinggi berjulat di antara 0.954 dan 0.939 dengan bahan api bergas yang berbeza yang telah diperoleh dengan menggunakan model 6/kes 47. Keputusan simulasi menunjukkan bahawa pengadun baru itu menunjukkan prestasi lebih baik dari segi mencapai campuran homogen (CNG-udara, H-udara, dan HCNG-udara) pada pelbagai kelajuan enjin; yang mana, nilai UI berjulat antara 0.9336 dan 0.967 dengan AFR_{CNG} yang berbeza, (0.941-0.974) dengan AFR_{H} berbeza dan (0.935-0.971) dengan AFR_{HCNG}. Tambahan pula, pengadun baru tersebut menunjukkan ketepatan yang tinggi untuk mengawal AFR mengikut kelajuan enjin. Dari segi praktikal, pengadun udara-bahan api baru itu (model 6 kes 47) telah dibuat berdasarkan analisis berangka dan juga berdasarkan reka bentuk baru untuk mekanisme mekanikal boleh gerak yang terdiri daripada suatu gear serong kecil, gear serong besar, skru kuasa, injap, bolt dan kedap. Menurut keputusan berangka dan eksperimen untuk pengadun baru itu dengan kelajuan enjin yang berbeza (1000-4000) dan nisbah udara-CNG 34.15, persetujuan yang bermakna telah dicapai antara nilai eksperimen dan berangka untuk AFR_{CNG} (R^2= 0.96 dan CoV = 0.001494). Di bahagian teori, dua model empirikal (dua persamaan) dicadangkan untuk menganggarkan UI bahan api bergas di dalam pengadun model baru dan anjakan injap di dalam model pengadun baru (model 6 kes 47) berdasarkan teknik PSO. Hasil model-model empiris menunjukkan kuasa teknik PSO untuk menyelesaikan masalah campuran heterogen di dalam pengadun dan untuk mengendalikan AFR di dalam pengadun, dengan itu meningkatkan prestasi enjin.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfillment of the requirement for the Degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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LIST OF ABBREVIATIONS

AFR	Air–fuel ratio
AFRs	Air–fuel ratios
BSFC	Brake-specific fuel consumption
CFD	Computational fluid dynamics
CH_4	Methane
CNG	Compressed natural gas
CO	Carbon monoxide
CO_2	Carbon dioxide
CR	Compression ratio
DDF	Diesel dual fuel
DF	Dual-fuel
DOC	Diesel oxidation catalyst
DPF	Diesel particulate filter
ECU	Electronic control unit
EGR	Exhaust gas recirculation
EPA	Environmental Protection Agency
EU	The European Union Economic Area
GIT	Grid independent test
H_2	Hydrogen
HC	Hydrocarbon
HCNG	Blend of hydrogen and Compressed natural gas
H_2O	Water
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
OECD	Organization for Economic Cooperation and Development
PM	Particulate matter
PSO	Particle swarm optimization
RR	Replacement ratio
SCR	Selective catalytic reduction
SO_2	Sulphur dioxide
UI	Uniformity index
UPM	Universiti Putra Malaysia

LIST OF SYMBOLS

A	The totally brick area (mm^2)
A	The area of the pressure outlet boundary(mm^2)
A	The surface area for valve(mm^2)
Ai	the local cell area (mm^2)
Af	Area of the fuel inlet (mm^2)
A_{hole}	Sum of the area of holes (mm^2)
ah	The angle of the holes
B	Friction angle in trap thread
CNG%	The substitute ratio of CNG with diesel by energy CNG.
C_v	Specific heat at constant volume
Cμ	Empirical constant
C_1	Constant of turbulence model
C_2	Constant of turbulence model
D	Dimension of particles
d_1	The minor diameter(mm)
d_2	Pitch Diameter (mm)
df	Diameter of the fuel inlet(mm)
d_{hole}	Diameter of the hole(mm)
dp	The change in pressure(Pa)
ES	Engine speed (rpm)
F	The force that supplied on the valve head (N)
F	Force (N)
F_{axial}	Axial force that will supply on the valve (N)
F_f	Friction force (N)
F_1 *to* F_{12}	Unknown coefficients
gbest	Global best position of all particles
i	The local cell
i	Gear ratio
K	Stiffness of spring
k'	The fluctuating velocity in z axis
l	The lead

LHV_D	The lower heating values of diesel (MJ/kg)
LHV_{CNG}	The lower heating values of Compressed natural gas(MJ/kg)
LHV	The lower heating values(MJ/kg)
$LHV_{gaseous}$	The lower heating values of gaseous fuels(MJ/kg)
LNG	Liquefied natural gas
ḿ	The current computed mass flow rate at pressure outlet boundary(kg/s)
m_a	The mass flow rate for air (kg/s)
$ḿ_{CNG}$	The mass flow rate for the natural gas (kg/s)
$ḿ_D$	The mass flow rate for diesel (kg/s)
m_f	The mass flow rate for fuel (kg/s)
MFR_{diesel}	Mass flow rate for diesel (kg/s)
MFR_H	Mass flow rate for hydrogen (kg/s)
MFR_{CNG}	Mass flow rate for CNG (kg/s)
MFR_{air}	Mass flow rate for air (kg/s)
m_g	The mass flow rate for gaseous fuel (kg/s)
$ḿ_{gaseous}$	The mass flow rates of gaseous fuels (kg/s)
M_{LBG}	The torque for large bevel gear (N.mm)
m_{req}	The required mass flow rate (N.mm)
M_{PS}	The torque for power screw (N.mm)
M_{SBG}	The torque for small bevel gear (N.mm)
M_{SM}	The torque for stepper motor
Ms	The torque for shaft(N.mm)
m_T	The mass flow rate of mixture (kg/s)
N	Number of particles
N	The engine speed (Rpm)
n	Number of holes
n	The number of cells
NG	Natural gas
Nh	The number of holes
NOx	Nitric oxide
Pbest	The best last location of jth particle
P	Pressure supply on the surface area for valve(kpa)

Q_a	The flow rate of air (m^3/s)
Q_g	The flow rate of gaseous fuel (m^3/s)
Q_T	The flowrate of mixture (m^3/s)
R	Universal gas constant ((m3 * Pa) / (K* mol))
S.f	The safety factor
SR	Substitution ratio of gaseous fuel with diesel fuel by energy
Ss	Appropriate sources and/or sinks of the variable concerned
T	The time-average Temperature (k)
U	The time-average velocity in x-direction (m/s)
u_*	The friction velocity (m/s)
$u^{\prime}$	The fluctuating velocity in x axis (m/s)
V	The time-average velocity in y-direction(m/s)
$\boldsymbol{\nu}$	The kinematic viscosity (m^2/s)
V_D	The flow rate for diesel (m^3/s)
VD	Valve displacement (mm)
v_i	The jth particle velocity in the swarm
VOL	Substitute ratio of CNG with diesel by volume fraction.
$v^{\prime}$	The fluctuating velocity in y axis (m/s)
W	The time-average velocity in Z-direction (m/s)
w	Inertia weight
Wi	The local mass fraction
w mean	The mean mass fraction
X	The distance that spring will move by (mm)
xi	The jth particle position in the swarm
XL_1	The distance between the holes and the mixer center(mm)
XL_2	The distance between the holes and the mixer center(mm)
XL_3	The distance between the holes and the mixer center(mm)
XL_4	The distance between the holes and the mixer center(mm)
y+	The distance from the wall
Z	Substitute ratio of CNG with diesel by mass fraction.

GREEK SYMBOLS

$\propto$	Helix angle or lead angle
Γ_{eff}	The effective exchange coefficient for heat.
$\boldsymbol{\eta}$	The efficiency
η_d	The volumetric efficiency for engine
$\boldsymbol{\lambda}$	Lambda
μ_{eff}	The effective viscosity which expressed the combined laminar and turbulent stresses
μ_{nut}	Coefficient of friction between nut and screw
ρ_{ave}	The computed average density at the pressure outlet boundary(kg/m^3)
$\boldsymbol{\rho}$	The flow density(kg/m^3)
ρ	Fluid density(kg/m^3)
σ_c	The compression stress (N/mm)
σ_{all}	The allowable stress(N/mm)
σ_y	The yield stress(N/mm)
$\boldsymbol{\sigma}$k	Constant of turbulence model
$\boldsymbol{\sigma\epsilon}$	Constant of turbulence model
τ_w	Wall shear stress
τ_t	Torsion stress(N/mm)
$\emptyset$	Thread angle
$\emptyset$	Equivalence ratio

CHAPTER 1

INTRODUCTION

1.1 Introduction

In recent years, fossil fuels have suffered from a sudden rise in prices because of reserve and supply limitations combined with considerable increases in demand for petroleum fuels resulting from industrialization. This sudden price increase is also a growing concern for developing nations because they expend a significant part of their national income to import petroleum products every year. Aiming to address the above concerns, researchers worldwide are searching for alternative fuels for engines (Bora *et al.*, 2013; Bose *et al.*, 2013). Diesel engines emit higher levels of nitrogen oxides (NOx) and particulate matter (PM) than spark engines due to high localized temperatures and combustion with a heterogeneous air-fuel mixture, respectively. The exhaust produced is of concern because of its impact on visibility and its potential health hazards (Alrazen *et al.*, 2016a; Chintala and Subramanian, 2013; Zhou *et al.*, 2014).

Many agencies and organizations, such as the U.S. Environmental Protection Agency (EPA), the Intergovernmental Panel on Climate Change (IPCC), the International Energy Agency (IEA), and the European Union Economic Area (EU), are concerned with prevention of air pollution and climate change caused by pollutant emissions. These organizations have reported that approximately 20%–30% of pollutant emissions originate from transport vehicles and that these emissions have pivotal effects on global warming and climate change. To reduce these effects, they have made the necessary legal arrangements, advanced technological developments, created several model structures, developed control systems, and organized traffic structures (Liu *et al.*, 2013; Reşitoğlu *et al.*, 2015). Using gaseous fuels (alternative fuels) in diesel engines under the dual-fuel mode (diesel as the pilot fuel and gaseous fuel as the main fuel) offers a simple way to reduce emissions and improve fuel economy (Abagnale *et al.*, 2014a; Wei and Geng, 2016; Zhang and Song, 2015). Dual-fuel combustion dramatically lowers operational costs, extends maintenance intervals and engine life, and reduces NOx and soot emissions (Abagnale *et al.*, 2014a; Li *et al.*, 2016; Maghbouli *et al.*, 2013; Mattarelli *et al.*, 2014; Papagiannakis *et al.*, 2010b; Yang *et al.*, 2015a).

Given its low cost and relative environmental friendliness, natural gas (NG) is a promising and highly attractive alternative fuel in the transportation sector. However, the CO and HC emission levels in compressed NG (CNG)–diesel engines are considerably higher than those in normal diesel engines (Demirbas, 2010; Khan *et al.*, 2015; Semin, 2008; Song *et al.*, 2017; Zurbriggen *et al.*, 2016).

Hydrogen (H) is also a promising renewable fuel because of its natural availability; it can be produced from various resources, such as fossil energy and biomass. Addition of H in a compression–ignition engine under a dual-fuel mode reduces HC, CO, and smoke emissions or particulate matter. However, the high combustion temperature increases NOx emissions (De Morais *et al.*, 2013; Deb *et al.*, 2015; Ghazal, 2013).

1.2 Problem Statement

Few studies have investigated tri-fuel engines (HCNG–diesel tri fuel engines) to enhance the performance of a conventional diesel engine. Adding H and methane (CH_4) to a diesel fuel engine reportedly reduces CO/HC emissions and NOx formation (Zhou *et al.*, 2014). Methane has a low flame propagation speed and minimal flammability, whereas H has the opposite characteristics. Thus, adding H can enhance methane combustion by making it useful in diesel engine applications. For the H—diesel dual fuel mode, rapid burning rate, increased diffusivity, and reduced H ignition energy destabilize combustion at increased engine loads, which could lead to knocking. Knocking is harmful to the mechanical durability and safety of engines. NG enrichment can stabilize and smooth the combustion of H, thereby preventing abnormal combustion. NOx emissions are increased significantly by the addition of H due to the high combustion temperature required (Alrazen *et al.*, 2016b; Choi *et al.*, 2005; Zhou *et al.*, 2014).

The most practical method of converting a diesel engine without many modifications to accept alternative gaseous fuels, is by installing a fuel–air mixer at the air inlet before the combustion chamber (Dahake *et al.*, 2016; Gorjibandpy and Sangsereki, 2010). In this arrangement, the mixture of air and gaseous fuel (CNG–H) is admitted to the combustion chamber along with the air intake and then compressed, while the diesel is used as a pilot fuel to trigger an autoignition inside the combustion chamber. This dual-fuel system can be operated as 100% diesel or as a mixture of alternative fuel (CNG-H) and diesel. The mixing efficiency and accurate determination of flow characteristics are important in the design and control of mixing devices, particularly when turbulent flows are involved. For automotion, efficient mixing (i.e., homogeneity of the mixture) between fuel vapor and air is crucial for increased combustion efficiency and fuel saving (Abdul-Wahhab *et al.*, 2015). However, homogeneity of mixtures (air and gaseous fuel) has not been addressed at various engine speed and AFR.

Many studies have indicated that the mixture formation of gaseous fuel with air is more critical than with liquid fuel due to the former's considerably lower density and limited fuel penetration. Even though gaseous fuel can easily mix with air due to its high diffusivity, this type of fuel may have insufficient time for mixing, particularly at substantially high engine speeds, thereby resulting in poor mixture formation (Chintala and Subramanian, 2013).

Mixers are classified as either venturi or non-venturi. A venturi gas mixer involves the venturi effect, which is a particular case of Bernoulli's principle concerned with mixing air and gaseous fuel so that the gaseous fuel and air enter the mixer without mechanical control (Ramasamy *et al.*, 2010b; Yusaf *et al.*, 2013; Yusaf and Yusoff, 2000). Meanwhile, a non-venturi mixer controls the amounts of fuel and air that enter the mixer by connecting the device to a butterfly valve or by employing another mechanical solution (Anil *et al.*, 2006b; Banapurmath *et al.*, 2011; Reddy and Reddy, 2014). In addition, few researchers attempted to connect the mixer directly to an electronic control unit (ECU) for diesel cars (Banapurmath *et al.*, 2011; Gorjibandpy and Sangsereki, 2010; Reddy and Reddy, 2014; Supee *et al.*, 2014b).

Most non-venturi mixers are suitable to work with gasoline engines under bi-engine mode (gasoline or producer gas), whereas only some are suitable to work with diesel engines under the dual-fuel mode (diesel-producer gas dual-fuel engine). Moreover, most non-venturi mixers were designed to mix air with producer gas but not with other gaseous fuels. In addition, non-venturi mixers also cannot create homogenous mixtures nor control AFR at a variety of engine speeds (Anil *et al.*, 2006b; Banapurmath *et al.*, 2011; Reddy and Reddy, 2014).

Few researchers investigated the effect of adding H as a third fuel to the dual-fuel engine (CNG–diesel)(Alrazen *et al.*, 2016b; Chintala and Subramanian, 2013). Presently, no commercially available mixer that has been designed for mixing H-CNG-Air for a tri fuel engine (H-CNG-Diesel engine) Thus, there is a need for designing a new mixer which is suitable for working with tri fuel engines (CNG-H-Diesel). The combustion efficiency, engine performance, and emission reduction of gases in dual-fuel engines are directly proportional to the degree of homogeneous mixing. These properties depend on the design (size, shape) and the control mechanism of the mixer. In addition, there is limited work on empirical equations to estimate the homogeneity of the mixture depending on different parameters (diameter of holes, location of hole and number of holes) that are governed by the design of gaseous mixer.

1.3 Objective of Study

The aim of this work is to design a new air–H_2–CNG mixer that is suitable for mixing air with H, CNG, and a blend of CNG and H. This new mixer should allow the super homogeneous mixing of gaseous fuel with air (uniformity index (UI) > 0.9) according to a range of engine speeds. The new mixer is developed to be connected easily with an ECU for the accurate control of the air–gaseous fuel ratio (AFR) at different engine speeds. This new mixer can work under different engine modes (bi- engine, dual fuel engine and tri fuel engine). The specific objectives of this work are as follows:

1. To determine the mixing characteristics of air–CNG–H and flow behaviors under different engine speeds and AFRs by developing predictive models (numerical model) through using computational fluid dynamics (CFD).

2. To propose an empirical relationship (empirical equations) to predict mixture homogeneity and air–gaseous ratios based on particle swarm optimization (PSO).

3. To design and fabricate a new air–HCNG mixer that is suitable for mixing air with H, CNG, and blend of CNG and H.

4. To evaluate the performance of the new fabricated air–HCNG mixer.

1.4 Scope of Work

1- The new air–HCNG mixer is designed for four cylinders, four strokes, and 3.2 L capacity, and it is suitable to work with various engine speeds (1000, 2000, 3000, and 4000 rpm).

2- The new air–H–CNG mixer is designed for mixing air with H, CNG, and blend of CNG and H under different AFRs [AFR_{CNG} (17.25, 19.08, 20.7, 22.89, 24.502, 29.40, 34.1584, and 40.990), AFR_{H} (34.39, 41.268, 89.7130, and 74.760), AFR_{HCNG} (39.9821, 47.9675, 51.3157, and 60.7071)], various replacement ratios (RR) for gaseous fuel with diesel fuel [RR_{CNG} (100%, 90%, 70%, and 50%), RR_{H} (50% and 100%), RR_{HCNG} (50%)], and two lambdas (1 and 1.2). AFR equations used are those available in the FLUENT software.

3- The new air–HCNG mixer is designed for providing a homogeneous mixture of air and gaseous fuel (air-CNG, air-H and air-HCNG) by keeping the uniformity index (UI) of gaseous fuel at the outlet of new mixer higher than 0.91 at various engine speeds and various AFRs (Abo-Serie *et al.*, 2016).

4- Solid work software was used for modeling and designing a moveable mechanical mechanism inside the new air fuel mixer to control the amounts of air and fuel.

5- ANSYS Workbench software (FLUENT software) was used to create new mixer models and investigate the mixing characteristics of air and gaseous fuel under different AFRs and engine speeds. The flow, pressure, velocity, AFR, and properties of flow inside the mixers were studied for the three cases of mixing (CNG–air, H–air, and CNG–H–air).

6- Particle swarm optimization (PSO) was employed to estimate the uniformity index (UI) of the gaseous fuel (air–H, air–CNG, and HCNG–air) inside the new mixer models and to estimate the valve displacements inside the new mixer model. MATLAB was used to create an algorithm for PSO.

7- The existing commercial mixer and the new mixer model were tested practically under different engine speeds (1000–4000 rpm) and a CNG–AFR of 34.15, which represented 50% RR of diesel fuel with CNG fuel under a lambda value of 1, to validate the performance of the mixer (air flow, fuel flow, mixing quality, AFR, and displacement of the valve) and to validate the numerical models that were built in ANSYS software.

8- Connecting the new mixer directly with an ECU and stepper motor are not a part of this study. Moreover, the linear movement of the valve inside the new mixer model was controlled practically by using manual rotary movement for the shaft.

1.5 Significance of Research

This study contributes to improve the homogeneity ($UI > 0.9$) of mixture between air and gaseous fuel inside the mixer according to various engine speeds and control on the air and fuel ratio inside the mixer accurately at different engine speeds, by developing and constructing a new air–H–CNG mixer that is suitable for mixing air with H, CNG, and a blend of CNG and H so that the new mixer is suitable for working with dual-fuel engines (diesel –H and Diesel-CNG), bi-fuel engines (gasoline or alternative fuels) and tri-fuel engines (H-CNG-Diesel). Moreover, this study contributes to build two empirical equations to predict the homogeneity of mixture (UI) inside the new mixer model depending on change in the mixer parameters (diameter of holes, location of hole and number of holes) that are governed the design of gaseous mixer and to estimate the valve displacements inside the new mixer model (model 6/ case 47) based on particle swarm optimization method (PSO). This work shows application of PSO to develop model to predict mixture homogeneity.

1.6 Thesis Layout

This thesis is divided into five chapters. The thesis starts with the introduction in Chapter1, which includes the problem statement, objectives, and scope of this work, significance of research and thesis layout.

Chapter 2 presents an overview of dual-fuel engine (CNG–diesel, H–diesel, and CNG–diesel, and allowable replaceable ratios of alternative fuel with diesel engine) and air fuel mixer. This chapter shows Computational Fluid Dynamic (CFD) and particle swarm optimization (PSO) methods.

Chapter 3 describes the methodology outline of this research. Firstly, the numerical analysis (CFD) is elaborated for modeling process (existing mixer and new mixer models) using the ANSYS FLUENT. Secondly, the PSO algorithm is elaborated for developing empirical models to estimate mixture homogeneity and valve displacements. Thirdly, the followed methodology in designing and fabricating a new mixer model was identified. Fourthly, the method that has been used for practically testing the new and existing mixers was identified.

Chapter 4 presents the results achieved from CFD simulation for numerical models (116 cases), PSO models (two empirical equations) and experimental tests for the new and existing mixers. The results were presented in graphical forms, tables and statistical analysis.

Chapter 5 presents conclusions derived from this research together with recommendations for future research.

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