DEVELOPMENT OF LOW EMISSION OIL BURNER

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A thesis submitted in fulfilment of the
Requirements for the award of the degree of
Master of Engineering (Mechanical)

Faculty of Mechanical Engineering
Universiti Teknologi Malaysia

FEBRUARY, 2005

To

My inspirational father

My beloved mum

My brothers and sisters

My nephews and nieces

Your support gave me the strength

ACKNOWLEDGEMENTS

I would like to take this opportunity to thank my supervisors, Associate Professor Dr. Mohammad Nazri Mohd. Jaafar and Professor Ir. Dr. Farid Nasir bin Haji Ani of Faculty of Mechanical Engineering, UTM for their constant guidance, inspiration, support and precious suggestions and supervisions in performing and completing this research study.

I would like also to thank the staff of the Thermodynamic and Combustion Laboratory for their cooperation and assistance during the experimental testing. Special thank to the Ministry of Science, Technology and Environment, Malaysia for the financial support through IRPA research grants.

The understanding, patience and moral support of my parents, Appalanidu Akiah and Jayalechumy Apparoo and family members are deeply acknowledged. Special thank to Khandoker Abul Hossain, Mohd Ridzuan Mansor, Lukeman Yusoff, Ekhwan Hakim Sukadarin and Abd. Razak Abd. Hamid for helping in discussions during the research was conducted. My sincere appreciations also extend to all my colleagues, friends and others who have provided assistance at various occasions. Their views and tips are useful indeed. Unfortunately, it is not possible to list all of them in this limited space.

ABSTRACT

Recently, most of the gas turbine combustion research and development involves in lowering the emissions emitted from the combustor. Emission causes adverse affect to the world and mankind especially. Main concern of the present work is to reduce the NO_x emission since the CO emission could be reduced through homogeneous mixing of fuel and air. Homogeneous mixing of fuel and air is also needed in order to reduce NO_x emission. A liquid fuel burner system with radial air swirler vane angle of 30^o, 40^o, 50^o and 60^o has been investigated using 163mm inside diameter combustor. Orifice plates with three different sizes of 20mm, 25mm and 30mm were inserted at the back plate of swirler outlet. All tests were conducted using diesel as fuel. Fuel was injected at two different positions, i.e. at upstream and downstream of the swirler outlet using central fuel injector with single fuel nozzle pointing axially outwards. Experiment has been carried out to compare between three emissions NO_x, CO and SO_2. NO_x reduction of about 53 percent was achieved for orifice plate of 20mm with downstream injection compared to orifice plate of 20mm with upstream injection. CO_2 and SO_2 was reduced about 26 percent and 56 percent respectively for the same configuration. This comparison was taken using swirler vane angle of 60^o. The overall study shows that bigger swirler vane angle produce lower emission results compared to the smaller ones. Smaller orifice plates generate better emission reduction. Meanwhile, downstream injection position significantly decreases the emission results compared to upstream injection position. Combination of smallest orifice plate and biggest swirler vane angle with downstream injection produce widest and shortest flame length. Lowest emission results were found in the smallest orifice plate using biggest swirler vane angle with downstream injection. The temperature of the flame increases along the combustion chamber and decreases back towards the combustor exit once it reaches the peak.

ABSTRAK

Masa kini, kebanyakan kajian dan pembangunan ke atas pembakaran turbin gas melibatkan pengurangan emisi dari pembakar. Pencemaran memberi kesan negatif kepada dunia dan manusia khususnya. Dalam projek ini, perhatian diberikan kepada pengurangan emisi NO_x kerana emisi CO dapat dikurangkan melalui percampuran yang baik di antara bahan api dan udara. Percampuran yang baik juga diperlukan untuk mengurangkan emisi NO_x. Pembakar berbahan api cecair menggunakan pemusar udara aliran jejarian bersudut 30^o, 40^o, 50^o dan 60^o dikaji menggunakan pembakar berdiameter dalam 163mm. Tiga plat orifis bersaiz 20mm, 25mm dan 30mm dipasang di bahagian keluar pemusar udara. Ujikaji dijalankan menggunakan bahan api diesel. Bahan api dibekalkan pada dua kedudukan pancitan, yakni di belakang dan di hadapan pemusar udara menggunakan pemancit bahan api berlubang tunggal menghala arah paksi. Ujikaji dijalankan keatas tiga jenis pencemar iaitu NO_x, CO dan SO_2. Emisi NO_x dapat dikurangkan sebanyak 53 peratus bagi plat orifis 20mm menggunakan pancitan di hadapan pemusar udara berbanding plat orifis 20mm menggunakan pancitan di belakang pemusar udara. CO dan SO_2 pula dapat dikurangkan sebanyak 26 dan 56 peratus masing-masing untuk konfigurasi yang sama. Ujikaji menunjukkan emisi yang rendah bagi pemusar udara bersudut besar berbanding pemusar udara bersudut kecil. Plat orifis bersaiz kecil memperoleh nilai emisi yang rendah. Pancitan di hadapan pemusar udara menunjukkan pengurangan emisi yang lebih baik berbanding pancitan di belakang pemusar udara. Saiz api yang pendek dengan bukaan yang besar diperoleh apabila pemusar udara besudut besar, plat orifis yang kecil dan pancitan di hadapan pemusar udara digunakan. Kombinasi pemusar udara bersudut paling besar, plat orifis bersaiz paling kecil dengan pancitan di hadapan pemusar udara menghasilkan emisi paling rendah. Suhu pembakaran meningkat sepanjang kebuk pembakaran dan seterusnya berkurangan menghala mendekati hujung keluar kebuk pembakar apabila suhu maksima tercapai.

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A	-	cross sectional area
C_c	-	contraction coefficient
C_D	-	discharge coefficient
d_o	-	Initial jet diameter
d	-	hub diameter
D	-	diameter
et al.	-	and others
g	-	acceleration due to gravity (9.81 m/s^2)
G_θ	-	axial flux of angular momentum
G_x	-	axial flux of axial momentum
h	-	height
HP	-	horse power
i.e.	-	id est (that is)
I_e	-	intensity of rotation
L	-	length
$\dot{m}$	-	mass flow rate
m	-	mass
M	-	Airflow Mach number
n	-	quantity
P	-	pressure
q	-	volumetric flow rate
r	-	radius
R	-	gas constant (8.31 J/ mol K)
Re	-	Reynolds number
s	-	vane thickness

S	-	swirl number
T	-	temperature
vs.	-	versus
V	-	Volume
V	-	velocity
We	-	Weber number
x	-	distance
Z	-	Z number
^{o}C	-	degree Celsius
^{o}	-	degree
$\sum$	-	summation
Δ	-	differential
α	-	vane angle
σ	-	stress
π	-	phi $\left(\frac{22}{7}\right)$
λ	-	wavelength
θ	-	angle
ρ	-	density
μ	-	dynamic viscosity
γ	-	ratio of specific heat
C	-	carbon
CH	-	methylidyne
CH_2	-	methylene
CH_4	-	methane
CHO	-	formyl radical
CN	-	cyano radical
CO	-	carbon monoxide
CO_2	-	carbon dioxide
$C_{12.5}H_{22.2}$	-	Diesel
H	-	hydrogen
H_2	-	Hydrogen
HCN	-	hydrogen cyanide

H_2CN	-	amidogen, methylene-
HO_2	-	hydrogen dioxide
NCO	-	isocyanato radical
N	-	nitrogen
N_2	-	nitrogen
NO	-	nitrogen oxide
NO_2	-	nitrogen dioxide
N_2O	-	nitrous oxide
NO_x	-	oxides of nitrogen
O	-	oxygen (atom)
O_2	-	oxygen (Gas)
OH	-	hydroxyl radical
O_3	-	ozone
SO_2	-	sulphur dioxide
AFR	-	air fuel ratio
ASME	-	American Society of Mechanical Engineers
CFC	-	chlorofluorocarbon
EGR	-	exhaust gas recirculation
EQR	-	equivalence ratio
FAR	-	fuel air ratio
FGR	-	flue gas recirculation
FLR	-	filter, lubricator and regulator
HHV	-	higher heating value
ppm	-	part per million
RQL	-	rich-burn quench lean-burn
SMD	-	Sauter mean diameter
SCR	-	selective catalytic reduction
SNCR	-	selective non-catalytic reduction
UHC	-	unburned hydrocarbon

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CHAPTER I

INTRODUCTION

1.1 Background

Global environmental problems such as global warming, acid rain, ozone layer depletion and photochemical smog have become serious problems all over the world. Pollution and environmental degradation are discussed in a great deal today, but it is often spoken of in a way that is disconnected from its cause. Conventional energy processes can cause major problems to the environment, and it is important to consider energy issues alongside environmental issues in order to seek solution effectively.

The increasing use of gas turbine power plants for electricity generation, motor vehicles and other industrial application causes atmospheric pollution. For several decades, the gas turbine has been the prime movers for aircrafts, due to the tremendous advantages in term of speed, fuel economy and passenger comfort.

The combustion of fossil fuels is also a major contributor of four main environmental concerns. These environmental problems are caused by air pollution that contains oxides of nitrogen, carbon monoxide and oxides of sulphur. These environmental problems concern has prompted many governing bodies to legislate new regulations regarding emissions from combustion process in the hope that these environmental problems will be reduced.

1.2 Review of Previous Works

Past researchers who studied on the effect of varying the swirl strength were mainly interested on the flow pattern and temperature profiles resulted from varying the swirl strength. They were emphasizing the effect of swirl on the generation of torroidal central recirculation zones and flame geometry rather than the effect of swirl strength on emissions formation.

Mikus, T. and Heywood, J.B. (1971) in their work on automotive gas turbine concluded that leaning out the primary zone or reducing the residence time of conventional combustor designs using conventional fuel injection techniques was unlikely to reduce NO emissions enough to meet emissions standard. This was due to the presence of stoichiometric fuel and air ratio in parts of the flow within the primary zone even if the excess air was present. To achieve a significant reduction in NO emissions, combustors need to be developed with both a leaner and more homogeneous fuel and air ratio distribution in the primary zone that is attainable in conventional designs.

Mestre (1974) compared the effect of swirling and non-swirling system on combustion. He demonstrated that swirl helps to improve combustion efficiency, decreases all pollutants and increases flame temperature. He also observed that during the present of swirl, a shorter blue flame was observed indicating good mixing while non-swirling system showed a longer yellow flame indicating that there is still some fuel left unvapourized.

A series of combustor tests were conducted by Mularz et. al. (1975) to evaluate three improved designs of swirl-can combustor modules, using axial swirlers and their objectives were to obtain low levels of exhaust pollutants while maintaining high combustion efficiency at combustor operating conditions. He came with an opinion that swirl-can modules consisted of three components; a carburettor, an inner swirler and a flame stabiliser. The functions of the module were to mix fuel and air, swirl the mixture, stabilise combustion in its wake and provide large interfacial mixing areas between the bypass air around the module and combustion gases in its wake. They found that swirl-can combustor model performed with high combustion efficiency at all conditions tested but the NO_x emissions were still higher than the maximum allowable level of 20ppm which was needed to achieve the 1979 Environmental Protection Agency (EPA) emissions standards.

Meanwhile, Ballal and Lefebvre (1979), in their study, stressed that for a premixed flame, the weak extinction limits were governed mainly by inlet air temperature, to a lesser extent by air velocity and turbulence level and were almost independent of pressure.

Past researchers also have studied the effect of varying the vane angle, which in turn vary the swirl number, on combustion performance. Claypole and Syred (1981) investigated the effect of swirl strength on the formation of NO_x. At swirl number of 3.04, much of the NO_x in the exhaust gases was recirculated into the flame front. The total emissions of NO_x were reduced, however, at the expense of reduced combustion efficiency.

Noyce and Sheppard (1982) investigated the influence of equivalence ratio on air and fuel mixing. They suggested that at low and high power conditions the high CO emissions could be minimised by better mixing.

Al-Kabie (1989), on the other hand, studied the effect of radial swirler on emission reduction in gas turbine combustor. In his study, he imposes swirler expansion ratio of 1.8 to achieve adequate combustion efficiency. Al-Kabie, in his study, showed that high efficiency was not achieved in weak region until there was a significant outer expansion and associated recirculation zone. However, there was a little influence of the expansion ratio on the weak extinction limit. Alkabie have shown that if fuel is injected into the outer recirculation zone, in the corner of the dump expansion region, then NO_x emission are high as this recirculation zone has a high residence time and low refreshment rate with air. To minimise this effect for burner application, the use of an orifice restriction at the outlet of the wall fuel injector was used. The intention was to deflect any fuel in the wall region radially inwards into the shear layer. Various non-conventional fuel injection methods was studied such as swirler vane passage, radial central and wall injection were used with gaseous propane and natural gas and liquid kerosene and gas oil. The test was conducted using lean-lean two stage combustion concept. He demonstrated that there is no significant effect on NO_x emissions by varying the vane angle from 20^o to 60^o, hence varying the swirl number from 0.41 to 3.25, respectively. However, he found that at very high swirl number of 3.25, NO_x emissions were considerably higher than the rest at all associated equivalence ratios for two different inlet air temperature of 400 K and 600 K. This may be due to increased residence time in the rich stabilizing shear layer and hence increased NO_x emissions. The same effect was demonstrated when he switched from natural gas to propane. Another way to increase the strength of swirl without changing the vane angle is to decrease the vane depth of the swirler. Combustion efficiencies were also improved as the swirl strength increased. Increasing the swirl strength also extends the lean flammability limits.

Bicen et. al. (1990), have reported temperature and species measurements for annular and tubular combustors using the same axial swirler for flame stabilisation. The annular combustor was operated at an air/fuel ratio of 29 and fuelled by natural gas; it displayed a marked improvement in combustion efficiency, 94% compared to 69%, when the inlet air temperature was raised from 315K to 523K. This improvement was observed to be a result of improved fuel and air mixing. Meanwhile, the tubular combustor was operated at a leaner fuel/air ratio of 57 and fuelled by propane, showed a more modest improvement in combustion efficiency, 97.7% compared to 98.8%, when the inlet air temperature was raised from 315K to 523K. They then concluded that from detailed measurements, the increase in efficiency was due to improved mixing in the combustor. Whitelaw commented that combustor aerodynamics was more dominant characteristic compared to chemical kinetics in the primary zone combustion (Bicen, A.F. et. al, 1990).

Escott, N.H. (1993) studied the combusting flow of three method of swirling generation namely single, coswirl and counterswirl. He used three basic fuel injection modes of swirler vane passage, central and wall injection. Escott finds that low NO_x emission was achievable through central fuel injection mode, but the lowest emission results were shown by wall injection method. However, Escott insisted that the results were strongly dependent on the input temperature and pressure provided to the flow. Escott also run an experiment on simple fuel staged injection system and concluded that there was no improvement in either emission or stability compared to non-staged modes. Coswirl and counterswirl combustion system with passage fuel injection into half of the air flow improved the flame stability but with unacceptable increase in NO_x emissions. From his observation, he concluded that lower NO_x emission was generated by counterswirl system with deteriorated flame stability due to more vigorous air mixing and consequently leaner fuel occurring in the interjet shear layer.

Kim, M.N. (1995), in his study, stresses on curved blade radial swirlers with wall injection and vane passage injection. The fuels were natural gas, propane and gas oil. He concluded that vane passage injection mode produce lower emission results compared to 76mm wall injection because of wall injections mode injects the fuel in the high residence time corner recirculating zone. This created locally rich zone and high thermal NO_x. He also find that natural gas produce lower emission compared to propane due to the better fuel and air mixing between natural gas and air since natural gas has a lower molecular weight than propane which means high diffusivity action and natural gas can be quickly dispersed into turbulent region of shear layer and hence low NO_x formation.

Mohd. Radzi Mohamed Yunus (2002), studied the effect of varying swirler vane angles on emissions reduction. He found that optimum swirler vane angle for NO_x emission found to be 60^o; for CO was 80^o and for SO_2 was 70^o. He suggested that recirculation zone size and turbulence flow affects emissions significantly.

Present researches give more importance on post combustion method which could reduce double of the amount of emissions that was reduced by pre-combustion methods. But, this probably increases the cost. The raise of awareness on importance of emission reduction makes researchers to emphasize on post combustion methods.

1.3 Problem Statement

Current researchers hastily moved their intension to post combustion methods as they found out that post combustion methods could possibly reduce emissions twice of the pre combustion methods. But, take note that this would heavily increase the cost which would discourage the industries to venture in. Besides that, post combustion methods at present situation were almost impossible to apply in aircraft engines as it would increase the engine weight which opposes the aircraft applications requirement of producing low weight-high trust engines. This research concerns on the above mentioned problems and carried out a study to discover a better solution on reducing emission from gas turbine, mainly for aircraft applications.

1.4 Objective of Research

The objective of this research is to develop a low emission liquid fuel burner. The main concern is on reducing NO_x emission, as the controlling technique for CO and SO_2 emission has already been included in the NO_x controlling techniques. The idea is to prevent the formation of NO_x emission through rapid mixing combustion system. The research includes design, build and test of the combustion chamber, air-fuel atomizer, swirler and air-fuel system. Various swirler vane angles with different orifice plate diameters at two fuel injection positions will be carried out to study the emissions and temperatures characteristic.

1.5 Scopes of Research

(i) Study the literature on combustion chamber designs, rapid mixing systems, injector requirements and air fuel system.
(ii) Study the NO_x emission characteristic and controlling techniques.
(iii) Design of combustion chamber, air-fuel atomizer, swirlers and air-fuel system.
(iv) Build the combustion chamber, air-fuel atomizer, swirlers and air-fuel system.
(iv) Test of various swirler vane angles with different orifice plate diameters at two injection positions.
(v) Emissions & temperature measurements on each burner configurations.
(vi) Adjustment and modification of burner system to obtain the lowest burner emissions.

1.6 Limitation of the Study

(i) The research will be conducted using four different swirler vane angles of 30^o, 40^o, 50^o and 60^o.
(ii) Three orifice plate diameters of 20mm, 25mm and 30mm will be used for experimental testing to study the effect of orifice plate insertion.
(iii) Fuel injection is placed at two positions that is at 15mm upstream or downstream from the swirler exit.
(iv) Diesel fuel used was supplied by Universiti Teknologi Malaysia, which is obtained bulkily from Petronas fuel station.
(v) The geometry of combustion chamber, fuel injector, orifice plates and swirlers are as designed.
(vi) Fuel and injection air are pressurized constantly at 2 bar.
(vii) Flow rate of injection air is constant at 170 ℓ/m.
(viii) Swirling air flow rate will be varied from 24 CFM to 9 CFM, which is from 679.608 LPM to 254.853 LPM.

1.7 An Outline of the Study

This thesis consists of seven chapters. Chapter one describes briefly on the problem statement of current research. Problem statement reveal lacks of previous researches and illustrates the significant of this research. However, there were some limitations in the study which has been expressed.

Chapter two discusses thoroughly on the literature study. Four main items of gas turbine combustor; combustion chamber, flame stabilizer, fuel injector and air-fuel system has been discussed fundamentally. The impact of the emissions towards environment and human was explained in detail. The requirement that to be fulfilled on producing a good combustion chamber, flame stabilizer, fuel injector and air-fuel supply has been discussed for better understanding. Besides that, varieties of these four items have been highlighted in this section to study the availability and manufacturability of these items.

Meanwhile, chapter three concerns on the emissions behaviour and emissions controlling methods. Main concern of this research is to improve the NO_x emissions as CO emissions could be reduced through good mixing of air and fuel. NO_x emission control techniques have been described briefly.

Chapter four, on the other hand, emphasize on the burner design concepts. This chapter explains the requirement required to build a burner. All four main items of combustor; combustion chamber, swirler, fuel injector and air fuel system design concepts has been discussed.

Chapter five elaborates on the experimental testing setup. This chapter describes clearly on the equipments and instrumentations used for the entire experimental testings. There were also guidelines on how the experiment has been conducted.

Chapter six confers about the experimental results and discussion on the combustion performance of that carried out in the experimental testing. Results has been compared between four different swirler vane angle of 30^o, 40^o, 50^o and 60^o using three different orifice plate sizes of 20mm, 25mm and 30mm at upstream and downstream injection position. The behaviour of the emission results and temperature profiles was discussed thoroughly.

Chapter seven concludes the emission results and temperature profiles discussions. Recommendation for future work has been stressed in this chapter to provide inspiration for future researchers to continue delivering improvement in emission reduction from pre combustion burners.