COMBUSTION PERFORMANCE OF VARIOUS SYNGAS COMPOSITIONS IN SWIRL COMBUSTOR

NOR AFZANIZAM BIN SAMIRAN

UNIVERSITI TEKNOLOGI MALAYSIA

COMBUSTION PERFORMANCE OF VARIOUS SYNGAS COMPOSITIONS IN SWIRL COMBUSTOR

NOR AFZANIZAM BIN HJ. SAMIRAN

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy (Mechanical Engineering)

Faculty of Mechanical Engineering
Universiti Teknologi Malaysia

SEPTEMBER 2017

To my beloved parents, wife and sibling

ACKNOWLEDGEMENT

The completion of this thesis could not have been possible without the participation and assistance of many people whose name may not all be enumerated. Their contributions are sincerely appreciated and gratefully knowledge. I would like to express my deep appreciation and indebtedness particularly to the following:

My main thesis supervisor, Professor Dr. Mohammad Nazri Mohd. Jaafar, who was like my own father which contribute his endless support in terms of advices and facilities, kind and understanding spirit for my phD journey. My Co-supervisor Dr. Chong Cheng Tung for his guidance, motivation and the best teacher I ever have. My knowledge, expertise and skill were not at this stage without his presence.

My special thanks to my colleagues in the gas turbine lab and combustion lab for their kind assistance, sharing and laughter. They are, Ting, Leong, Win Hon, Yaseer, Chan, Amin, Ismail, Shahiran, Daie and Azwarie. To all Technician in Aerolab and combustion lab especially, Mr. Rosli, Mr. Hilmi and other technician. I am also thankful and indebted with their willingness in sharpening my practical skills.

My sincere thanks go to my dear parents. Their sacrifices to raise me and become success cannot possibly be repayable. My special thanks also for my siblings for their endless support, advice and opinion.

My sincere appreciation go to my dear wife, Siti Nur Aisah Ahmat for her patience, love, care, invaluable support, and everything for this long journey. Her kind support and encouragement is my strength.

Above all, to the great almighty, Allah, the author of knowledge and wisdom, and my beloved prophet, Muhammad peace be upon him, my sincere love and grateful to them for their countless love and mercy.

ABSTRACT

The challenge of using syngas in combustion system is the composition variability and low calorific value. Syngas mainly consists of H_2 and CO and other sub component such as N_2, CO_2 and H_2O. High H_2-enriched syngas would result in high NOx production for some combustion cases. Whereas high CO concentration is posed with stability issues. The presence of sub-component as a diluent improves the emission characteristic but slows down the chemical reaction rate and calorific values. The variability in syngas strongly depends on the type of gasification technique, feedstock and oxidation agent. The present study therefore aims to investigate the combustion performance of different configuration in composition of syngas using premixed swirl mode technique. Various simulated syngases of CO and H_2-dominant syngas or CO-rich and H_2-rich syngas were used as fuels to evaluate the performance of emissions, diluent effects, lean blowout limit and flame structure. Further investigation on combustion of syngas was fundamentally conducted using numerical approach in which a comparative study on flame structure and reaction zone species were evaluated between those syngas fuels. Measurement by gas analyser was used to evaluate the performance of combustion emission and direct photography was used to analyse the flame appearance. Lean blowout test was performed by gradually reducing the fuel flowrate until flame blowout occur. For numerical method, two different combustion models namely flamelet generated manifold (FGM) and chemical equilibrium (CE) models were implemented to predict the combustion characteristic of syngas and the result obtained was then validated with experimental results. The results indicate that high CO-rich syngas shows evidently less NOx and CO emissions as compared to the other dominant CO fuel. Higher fraction of CO_2 dilution results in reduction of NOx emissions, with pronounced impact on fuel-rich cases. There was minimal effect on CO emissions with increased dilution of CO_2. The lean blowout limit test shows that higher CO content results in blowout at higher equivalence ratio. Addition of hydrocarbon fuel such as CH_4 or hydrogen extends the blowout limit as the flammability limit is stretched to ultra-lean region. Dilution of unreactive CO_2 in syngases results in higher lean blowout limit. Higher fraction of H_2 in syngas produces both lower NOx emission and lean blowout limits. The optimum characteristic of high H_2-rich syngas is also validated by numerical approach using FGM method. The numerical computation found that the increasing content of H_2 in syngas results in lower flame temperature, subsequently leading to reduced flame height and lower NO emissions.

ABSTRAK

Kepelbagaian komposisi dan nilai kalori yang rendah adalah antara cabaran menggunakan bahan api gas sintesis. H_2 dan CO merupakan komposisi utama gas sintesis selain elemen sampingan seperti N_2, CO_2 dan H_2O. Kandungan H_2 yang tinggi di dalam gas sintesis menyebabkan pengeluaran NOx yang tinggi untuk kes-kes pembakaran tertentu. Manakala kandungan CO yang tinggi pula menimbulkan isu kestabilan. Kehadiran komponen sampingan sebagai pelarut dapat memperbaiki ciri emisi tetapi pada masa yang sama memperlahankan kadar tindak balas kimia dan nilai kalori. Kepelbagaian komposisi gas sintesis amat dipengaruhi oleh jenis teknik penggasan, biojisim dan agen pengoksidaan. Kajian dijalankan untuk mengkaji prestasi pembakaran gas sintesis menggunakan teknik pusaran pracampuran. Penyelakuan gas sintesis mengikut komposisi CO dan H_2-dominan gas sintesis atau CO dan H_2-kaya gas sintesis telah digunakan sebagai bahan api untuk mengukur prestasi emisi, kesan pelarut, had pemadaman cair dan struktur api. Kajian lebih asas mengenai pembakaran gas sintesis juga dilanjutkan dengan kaedah berangka di mana kajian perbandingan keatas struktur api dan spesies di dalam zon tindak balas dinilai terhadap semua jenis gas sintesis tersebut. Penganalisis gas telah digunakan untuk mengukur prestasi emisi pembakaran dan fotografi langsung digunakan untuk menganalisis susuk api pembakaran. Had pemadaman cair diuji dengan mengurangkan kadar aliran bahan api sehingga pemadaman nyalaan berlaku. Bagi kaedah berangka, dua model pembakaran iaitu model manifold flamelet terjana (FGM) dan keseimbangan kimia (CE) telah dilaksanakan untuk meramalkan ciri pembakaran gas sintesis dengan keputusan eksperimen sebagai rujukan. Keputusan menunjukkan CO-kaya yang tinggi menghasilkan NOx dan CO yang rendah berbanding bahan api CO dominan yang lain. Kandungan CO_2 yang tinggi memberi kesan ketara kepada pengurangan NOx terutama dalam keadaan percampuran kaya. Peningkatan CO_2 memberikan kesan yang minimum keatas emisi CO. Kandungan CO yang tinggi di dalam gas sintesis menyebabkan had pemadaman berada pada nisbah kesetaraan yang tinggi. Ujian had pemadaman cair juga menunjukkan kandungan CO yang tinggi menyebabkan pemadaman berlaku pada nisbah kesetaraan yang tinggi. Penambahan bahan api hidrokarbon seperti CH_4 atau hidrogen melanjutkan had pemadaman memandangkan had kebolehbakaran diregangkan sehingga ke rantau ultra cair. Pencairan oleh komponen tidak reaktif CO_2 di dalam gas sintesis meningkatkan had pemadaman cair. Gas sintesis yang mempunyai kandungan H_2 yang paling tinggi menghasilkan kedua-dua NOx dan had pemadaman nyalaan cair yang rendah. Ciri optimum yang dimiliki oleh H_2-kaya yang tinggi ini juga telah disahkan oleh kaedah berangka menggunakan model FGM. Kaedah pengiraan berangka juga mendapati peningkatan kandungan H_2 di dalam gas sintesis menyebabkan penurunan suhu dan ketinggian nyalaan seterusnya menurunkan kandungan NOx.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

BFB	–	Bubbling fluidize Bed
CCE	–	Carbon Conversion Efficiency
CCGT	–	Combined Cycle Gas Turbine
CCS	–	Carbon Capture Storage
CE	–	Chemical equilibrium
CFB	–	Circulating Fluidized Bed
CFD	–	Computational Fluid Dynamic
CGE	–	Cold Gas Efficiency
CHP	–	Combined Heat and Power
DNS	–	Direct Numerical Simulation
EDC	–	Eddy Dissipation Concept
EDM	–	Eddy Dissipation Model
EFB	–	Empty Fruit Bunch
FB	–	Flashback
FGM	–	Flamelet Generated manifold
FT	–	Fischer-Tropsch
GC	–	Gas Chromatograph
HHV	–	High Heating Value
IGCC	–	Integrated Gasification Combined Cycle
IRZ	–	Internal Recirculation Zone
LBO	–	Lean Blowout
LES	–	Large Eddy Simulation
LHV	–	Low Heating Value

LPG	–	Liquid Petroleum Gas
MF	–	Mesocarp Fibers
OPF	–	Oil Palm Fronds
PDF	–	Probability Density Function
PKS	–	Palm Kernel Shells
PREMIER	–	Premixed Mixture Ignition in the End-Gas Region
RANS	–	Reynolds Average Navier-Stokes
RE	–	Renewable Energy
RSM	–	Reynolds Stress Model
RSP	–	Rubber Seed Pericarp
SCR	–	Selective Catalytic Reduction
SIMPLE	–	Semi-Implicit Method for Pressure-Linked Equations
SLFM	–	Steady Laminar Flamelet Model
TGA	–	Thermogravimetric Analysis
UHC	–	Unburned Hydrocarbon

LIST OF SYMBOLS

n	–	Number of moles fraction
ΔH	–	Entalphy [kJ/mole]
T	–	Temperature [K]
P	–	Pressure [bar]
Da	–	Damkohler number
t_c	–	Chemical time
ρ	–	Density [kg/m^3]
u	–	Velocity [m/s]
τ_{ij}	–	Viscous stress tensor
D_k	–	Species diffusion coefficient [m^2/s]
σ_h	–	Mixture Prandtl number
Sc_k	–	Schmidt number
f	–	Mass fraction
$\bar{f}$	–	Mean mixture fraction
$\overline{f'^2}$	–	Mixture fraction variance
S_N	–	Swirl number
D_h	–	Swirler hub diameter [m]
D_s	–	Swirler diameter [m]
θ	–	Angle of the swirl blade [deg]
Re	–	Reynold number
L	–	Travel length [m]
μ	–	Dynamic viscosity [kg/ms]
$X_{diluent}$	–	Dilution ratio
$V_{diluent}$	–	Volume fraction of diluent
V_{fuel}	–	Volume fraction of fuel
$\dot{m}_{fuel}$	–	Fuel mass flow rate [g/s]

$\dot{m}_{air}$	–	Air mass flowrate [g/s]
P	–	Power [kW/h]
$(A/F)_{stoic}$	–	Stoichiometric air to fuel ratio
$(A/F)_{act}$	–	Actual air to fuel ratio
MW	–	Molecular weight
$\dot{V}_{air}$	–	Volume flowrate of air [m3/s]
$\dot{V}_{fuel}$	–	Volume flowrate of fuel [m3/s]
c	–	Reaction progress variable
Y	–	Species mass fraction
$\dot{\omega}$	–	Species mass fraction rate
c_p	–	Specific heat [kJ/kg.K]
χ_c	–	Scalar dissipation rate [s^{-1}]
λ	–	Thermal conductivity [W/m.K]
ϕ	–	Equivalence ratio
τ_R	–	Residence time [s]
α	–	Thermal diffusivity [m^2/s]
S_L	–	Laminar flame speed [m/s]
ϕ_{bo}	–	Blowout equivalence ratio
S_k	–	Source term of species, k
G_p	–	Amount of product gas produced per unit weight of fuel (Nm^3 kg $fuel^{-1}$)

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

The world energy demand and environmental concerns on pollutant emissions have raised an interest in development of renewable energy. Synthetic gas (or syngas) is considered as one of the potential alternative fuels in the future. Syngas is expected to play an important role in the diversification of energetic sources since it is produced from gasification of coal where the reserves are widely abundance [1]. It is also produced from gasification of multiple solid feedstocks such as organic waste and renewable biomass [1, 2]. Gasification involved a process where solid feedstock is gasified by incomplete combustion resulting in production of combustible gases [3]. Application of syngas as fuel reduced the emission of CO_2 and other pollutant components as compared to conventional fuels [2]. Syngas composition typically varies depending on the gasification process and the feedstock type. The main component of syngas is H_2 and CO and the volume percentages could be CO-rich or H_2-rich. Syngas also contain diluents such as N_2, CO_2 and H_2O, and hydrocarbon content, mainly CH_4 [4]. Syngas is a cleaner gas but it has low calorific value which only accounts for 30% as compared to conventional natural gases [2].

Syngas can be directly burned in power generation sector (boiler, engine, furnace, gas turbine, and burner) or further processed for other gaseous or liquid products. For gas turbine combustion, integrated gasification combined cycle (IGCC) is considered as one of the significant application of syngas in power generation. IGCC is a technology involving an integration of gasifier system with combined cycle gas turbine (CCGT). In IGCC, rather than H_2 alone, using syngas directly in stationary power generation gives high potential of economic value and cost effective [5]. However, current existing combustor used for traditional hydrocarbon combustion need substantial improvements to burn syngas [6]. Applying fuel and designing combustor are critical challenges to utilise the syngas fuel since the composition of syngas varies depending on the fuel sources and process technique. Since small scale power of micro turbines (<500 kWe) have the ability to burn lower calorific fuel and lean (premixed) combustion regimes, syngas have high potential to be used in this type of applications. Micro turbines are small, compact electricity generators with rated capacities in the 25 – 300kW range. Multiple units can be grouped to form larger installations often part of a micro-grid, utilizing a range of power generation technologies and storage capability. They typically use a high-speed generator/turbo alternator, resulting in high frequency AC electricity [7].

Current design of turbine burners also involves the use of swirler and combustion of lean premixed fuels. Swirl burners ensure efficient combustion conditions allowing good fluid mixing and offering long residence time for complete reaction to take place, typically used in the lean premixing of fuel and air to achieved low level of NOx emission [8]. Yet, interactions between swirling flow and operability issues of burning syngas are still poorly understood. Therefore, it is necessary to establish a framework for the combustion characteristic of syngas particularly in the presence of swirl [6].

As a conclusion, developing a practical applications technology such as gas turbines, boilers and furnaces which capable to combust H_2-rich and CO-rich syngas requires understanding of more fundamental combustion properties. The fundamental characteristic of combustion, emission and extinction of syngas flames are then requires extensive investigations. Previous works focused on premixed, non-premixed and diffusion flames in integration with the studies of syngas laminar flame speed. Research efforts in syngas turbulence flame (or swirling flame) are still not well understood, particularly on the flame structures, characteristic and emission with consideration of various syngas composition and operational condition.

1.1 Problem statement

The challenge of using syngas is the composition variability in production of syngas from coal and biomass through the gasification process which complicates the design and operation of modern combustor for boiler, furnace or gas turbine [8]. Most gasification processes typically produce syngases that are CO-rich or H_2-rich depending on feedstock. CO-rich syngas has been produced by coal gasification with blends comprising 60% CO and 30% H_2 by volume [9]. The relative molar fraction of H_2 to CO for coal-derived syngas ranges from 0.4 to 1.0 [10]. The use of catalytic gasification techniques to gasify biomass was shown to produce H_2-rich syngas with a composition of up to 50% H_2 and 17% CO by volume [11]. The volume ratio of H_2/CO in most syngas mixtures typically exceeds 0.25, where chemical kinetic and reaction mechanisms of hydrogen play a dominant role in syngas combustion. Hence, syngas generally exhibits large burning rates with small autoignition time, comparable to those of pure hydrogen combustion [4].

Apart from feedstock, the quality of syngas also depends on the gasifier type, processing technique and operating conditions of gasification process [12]. For example, slurry-feed and dry-feed syngases are CO-enriched syngases typically produced by gasifying pulverized coal/slurry water. While H_2-rich syngases are mainly produced from catalytic gasification process maximized by water-gas shift reactions and CO_2 removal [13]. H_2 and CO aside, syngas also contains diluents such as carbon dioxide, nitrogen, and methane which may affect the thermodynamic properties of the mixture if the amount is significant, leading to different combustion properties which may pose operational issues to some combustion system. Detail of some of the previous researchs which representing the different techniques and syngas composition produced were summarised as in Table 1.

Table 1.1 Previous researchs of gasification with different composition of syngas produced

Biomass type	Reactor type	Gasify-ing agent	Reaction temp. (^oC)	Finding factors	CO %	H_2 %	CH_4 %	CO_2 %	N_2 %	LHV (MJ/Nm^3)	Ref.
Oil palm frond	Down-draft fixed-bed	Preheated air	985	Preheating air improved the composition for all component (H_2, CO and CH_4)	24.9	8.5	2.02	11.8	<50	4.7	[14]
Empty fruit bunch	Fluidized bed	Air	700-1000	As temperature increased from 700 to 1000 ^oC, the H_2 content increased from 10.27 to 38.02 vol.%, CH_4 increased from 5.84 to 14.72 vol.%., CO increased from 21.87 to 36.36%.	36.4	38	14.7	10	n.a	15.6	[15]
Coal dry powder	2-stage entrained flow	O_2& H_2O	1700	The consumption of oxygen and coal consumption are lower than with the single stage gasifier	60.5	31.4	0.8	2.8	3.74	16.7	[9]

Table 1.1 (cont.)

Biomass type	Reactor type	Gasify-ing agent	Reaction temp. (°C)	Finding factors	CO %	H_2 %	CH_4 %	CO_2%	N_2 %	LHV (MJ/ Nm^3)	Ref.
Rice husk, sawdust and camphor wood	High temperature entrained flow	O_2	1400	Higher temperature favoured H_2 and CO production. Cold gas efficiency was improved by N10% when the temperature was increased from 1000 to 1400 °C. The presence of oxygen strengthened the gasification and improved the carbon conversion, but lowered the lower heating value and the H_2/CO ratio of the syngas.	>50	>30	<5	5-15	n.a	16	[16]
Lignite coal	Multiple swirl burners in entrained flow gasifier	O_2	1200-1600	Effects of rigorous mixing of oxygen and pulverized coal by the strong swirl flow complete the reactivity gasification reaction within a short residence time for low-rank coal of high reactivity.	45-55	15-20	n.a	5-15	n.a	11-14	[17]

The volumetric H_2/CO ratio of syngas is typically varies from 0.33 to 4.0. H_2 component in syngas exhibits clean combustion, high flame propagation speed and wide flammability limits. H_2 has laminar combustion speed approximately eight times to that of natural gas, hence reduces residence time of combustion and thereby the efficiency [3]. However, high hydrogen content also resulting high production of NOx correspondingly to the increasing temperature of flame [10]. The presence of diluent gases, such as N_2, CO_2 and H_2O, is significantly representing 4 to 60% of the final compositions [2]. For pre-mixed flames, the addition of diluent in fuel effectively results in the reduction of NOx emission [18]. However, diluent components slow down the chemical reaction rate as well as calorific value, thus reducing laminar flame speed, increase flame thickness and reduce the flame temperature [18]. Additionally, the degree of the diluent effectiveness and the presence purpose are not thoroughly investigated. Lack in study of diluent with various percentages caused the effect on the syngas flame and emission not well understood. Therefore, it is important to develop flexible combustion system which capable to operate at a broad range of syngas composition with high efficiency and low pollutant emissions.

Swirl technology in combustion has long being studied as an effective way to induce flow recirculation to provide better mixing of fuel and air, hence perfect combustion. However, high swirl could also increase the production of NOx since high recirculation zone increase local temperature especially for H_2-enrich gases [19]. Therefore it is necessary to study the effect of H_2 and diluent compositions in syngas with the presence of swirling features on the combustion performance.

1.2 Objectives

The main objectives of the present research are

1. To experimentally evaluate the effects of syngas composition variability on emission performance and investigates the effect of dilution component on reduction of emission.

2. To study the stability limit of syngas flame through the lean blowout limit test and investigate the effect of dilution component on stability performances.

3. To evaluate the characteristic of combustion model by performing a computational fluid dynamic (CFD) simulation analysis on combustion of syngas and validate with experimental results

4. To fundamentally investigate the characteristic of syngas flame in reaction zone through CFD simulation analysis.

1.3 Scopes

In this study, the first section investigate the effects of variability composition of simulated syngas on combustion characteristic using experimental and numerical method. Composition of syngas (H_2/CO) varied from H_2-rich to CO-rich syngas. H_2/CO ratio are 100/0, 75/25 and 55/45 for H_2-rich and 0/100, 25/75 and 45/55 for CO-rich. The presence of dilution species including CO_2 and CH_4 are used to improve the characteristic of combustion including emission and lean blowout limit. The degree of dilution ranges from 0 to 25%. In general, the experiment is conducted into three parts. The first part focuses on emission measurement by using gas analyzer. The second part evaluate the flame structure and the third part is investigation on lean blowout limit for each of the syngas composition. All results from the syngas combustion are compared with pure gases of H_2, CO and CH_4 for baseline. Experimental study is conducted using lab scaled combustor which operates at atmospheric condition. CFD simulation is used to validate the experimental data with numerical data. In this study, combustion of syngas is modelled using chemical equilibrium (CE) and flamelet generated manifold (FGM) model. The accuracy for both modeled are evaluated with experimental result as a baseline. The study focused on fuel variability performance. The effect of combustor design and system on combustion performance is out of scope.

The second section investigated the effect of various biomass feed on variability composition of syngas produced via gasification. Downdraft fixed bed was used as a gasification method. Treated and untreated biomasses were used as a feedstock and the variability composition of syngas produced was compared. The last section was an evaluation of syngas variability composition produced from various type of treated biomass. The study only evaluated the quality of syngas produced whereas the reactor system performance was not in research interest.

1.4 Limitation of the research

The research aims to evaluate how variety in composition of syngas would affect the combustion performance. Hence, composition of syngas is modelled using standard gas to carefully study each of the component changes. The standard gas is however limited for four types of main gases (CO, H_2, CO_2 and CH_4) which normally dominant in most typical syngas. Other component such as Ar, H_2S and COS are difficult to model as the concentration is typically very small in syngas. Small concentration complicates the flow setup. Apart of four dominant components of gases in syngas, other dominant component such as H_2O, O_2 and N_2 were not involved in this model. The presence of H_2O and O_2 components are not consistent in syngas. Therefore, both components are not considered as frequently existed component of syngas in this study. The concentration of N_2 is very high (>50%) in a syngas which typically produced by air-blown gasification. High concentration of N_2 limiting the concentration of other reactive gases in a total volumetric percentage. Hence, the concentration setup allows only a small change for reactive gases. The small changes is thus caused the different in a combustion performance is insignificant and difficult to observe. Thus, syngas is modeled using most prevalent and reactive component only.

A simulation for syngas combustion is using only one type of turbulence model which is standard k-epsilon. Other model such as realizable k-epsilon, RMS and LES are not conducted due to time constraint and requirement of high performance computer to run such a complicated fuel with different composition like syngas.

For production of syngas, a small scale downdraft reactor is employed to gasify different type of biomass. The gasification process uses both untreated and treated (torrefied) biomass. The same temperature of torrefaction is used for all type of biomass in this study. Hence, the variable of feedstock type only restricted for biomass type rather than torrefaction level. In addition, the biomass is feeding to the gasifier by batch rather than continuous feeding systems. Hence, fuel flowrate is measured manually as the system does not require a flow controller.

1.5 Research Flowchart

Figure 1.1 and Figure 1.2 show a flowchart of research work. Current study will be conducted into two major parts. The first part focused on experimental works and numerical study of emission test, lean blowout limit and flame shape which were investigated using different type of syngas composition at various condition of equivalence ratio. Characteristic of syngas combustion will be evaluated numerically by Ansys Fluent software. Result of temperature profile and species product will be compared with experimental result for validation. The second part focused on gasification process to produced different composition of syngas using different type of biomass feed.

1.6 Thesis outline

The present thesis consists of 5 main chapters. Chapter 1 described briefly the Introduction, problem statement, objectives, scopes, limitation of the research, research flowchart and thesis outline. The background study of syngas composition was thoroughly reviewed in this section. The structures and plan of research also illustrated through objectives, scopes, limitation and flowchart.

Chapter 2 performed a critical literature study on both combustion and production of syngas. For combustion of syngas, previous works involving the effects of composition variability on emission and lean blowout (LBO) limit were reviewed. In CFD section, performance of flamelet generated method (FGM) in modelling syngas combustion was also reviewed. The production of syngas section critically reviewed different type of gasifier and feedstock which have been used in the previous research.

Chapter 3 presented a method of research for both experimental and numerical works. Detail burner and gasifier setup are described briefly in this section. Measurement equipment and method are also presented for both combustion and gasification process. The different combustion modelling are thoroughly described for numerical simulation section.

Chapter 4 described the results and discussion for all experimental and numerical test conducted. Experimental test on combustion of syngas presented a result of emission, LBO limit and a flame structure. Whereas numerical simulation focuses on predicting the experimental results with different types of combustion model including chemical equilibrium (CE) and FGM method. For production of syngas section, the composition of product gases produced by gasification were characterized and compared among different type of biomasses.

Finally, conclusion and a summary of the research study are comprised in chapter 5. This chapter also includes a recommendation of future work of implementing clean syngas fuel in various combustion techniques. Various gasification technique and improving biomass properties are also suggested to increase the production of syngas.

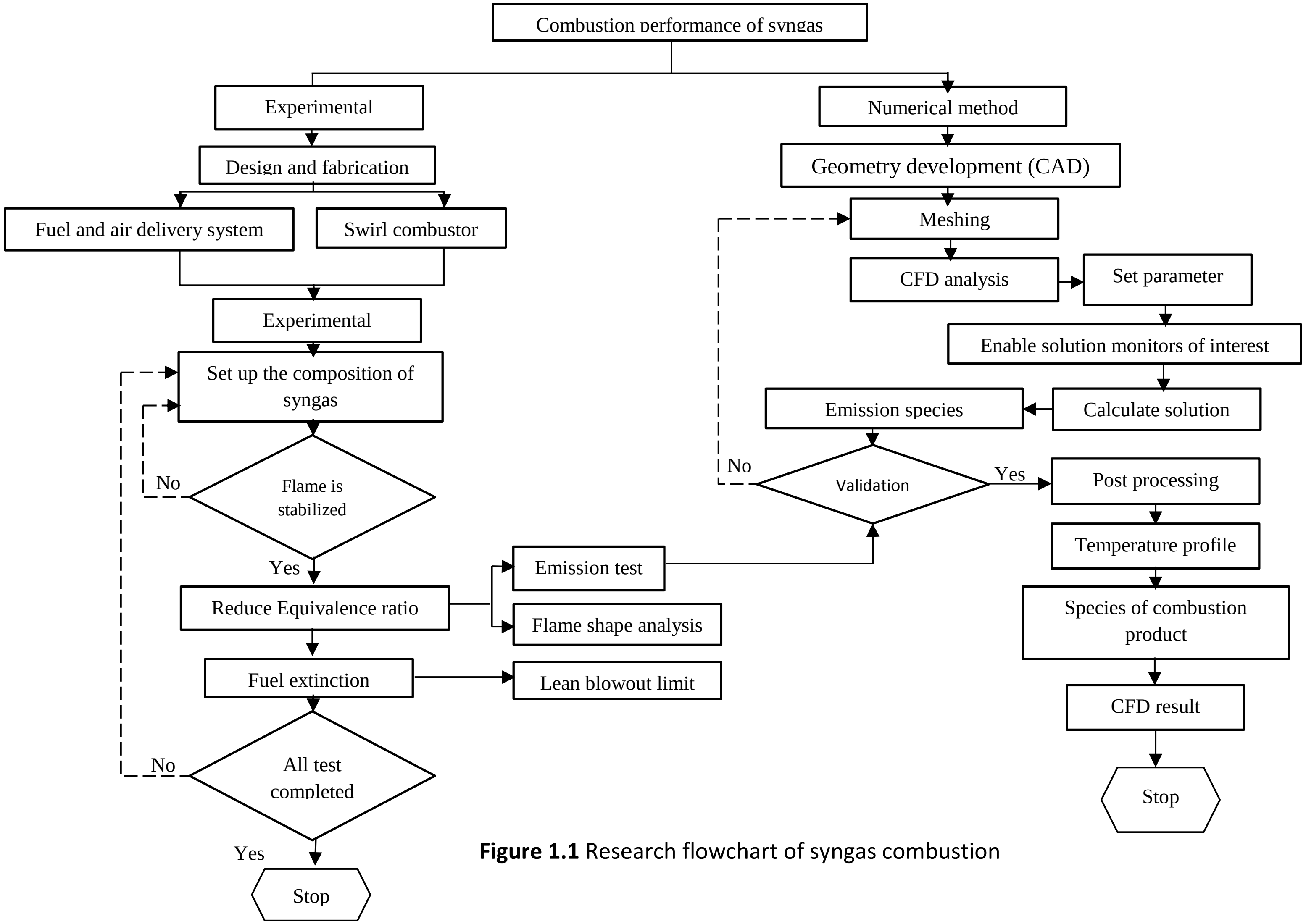

Figure 1.1 Research flowchart of syngas combustion

REFERENCES

[1] Lee, MC, Seo, SB, Yoon, J, Kim, M, and Yoon, Y. Experimental study on the effect of N2, CO2, and steam dilution on the combustion performance of H2 and CO synthetic gas in an industrial gas turbine. *Fuel* 2012; 102: 431-38.

[2] Burbano, HJ, Pareja, J, and Amell, AA. Laminar burning velocities and flame stability analysis of H2/CO/air mixtures with dilution of N2 and CO2. *Int. J. Hydrogen Energy* 2011; 36(4): 3232-42.

[3] Azimov, U, Tomita, E, Kawahara, N, and Harada, Y. Effect of syngas composition on combustion and exhaust emission characteristics in a pilot-ignited dual-fuel engine operated in PREMIER combustion mode. *Int. J. Hydrogen Energy* 2011; 36(18): 11985-96.

[4] Boivin, P, Jiménez, C, Sánchez, AL, and Williams, FA. A four-step reduced mechanism for syngas combustion. *Combust. Flame* 2011; 158(6): 1059-63.

[5] Shih, H-Y and Hsu, J-R. A computational study of combustion and extinction of opposed-jet syngas diffusion flames. *Int. J. Hydrogen Energy* 2011; 36(24): 15868-79.

[6] Ranga Dinesh, KKJ, Luo, KH, Kirkpatrick, MP, and Malalasekera, W. Burning syngas in a high swirl burner: Effects of fuel composition. *Int. J. Hydrogen Energy* 2013; 38(21): 9028-42.

[7] Delattin, F, Lorenzo, GD, Rizzo, S, Bram, S, and Ruyck, JD. Combustion of syngas in a pressurized microturbine-like combustor: Experimental results. *Applied Energy* 2010; 87(4): 1441-52.

[8] Ding, N, Arora, R, Norconk, M, and Lee, S-Y. Numerical investigation of diluent influence on flame extinction limits and emission characteristic of lean-premixed H2–CO (syngas) flames. *Int. J. Hydrogen Energy* 2011; 36(4): 3222-31.

[9] Xu, S, Ren, Y, Wang, B, Xu, Y, Chen, L, Wang, X, and Xiao, T. Development of a novel 2-stage entrained flow coal dry powder gasifier. *Applied Energy* 2014; 113: 318-23.

[10] Mansfield, AB and Wooldridge, MS. High-pressure low-temperature ignition behavior of syngas mixtures. *Combust. Flame* 2014; 161(9): 2242-51.

[11] Chacartegui, R, Sánchez, D, Muñoz de Escalona, JM, Muñoz, A, and Sánchez, T. Gas and steam combined cycles for low calorific syngas fuels utilisation. *Applied Energy* 2013; 101: 81-92.

[12] Samiran, NA, Mohd Jaafar, MA, Ng, J, Lam, SS, and Chong, CT. Progress in biomass gasification technique - with focus on Malaysian palm biomass for syngas production. *Renewable and Sustainable Energy Reviews* 2016; 62: 1047-62.

[13] Williams, TC, Shaddix, CR, and Schefer, RW. Effect of Syngas Composition and CO2-Diluted Oxygen on Performance of a Premixed Swirl-Stabilized Combustor. *Combust Sci Tech* 2007; 180(1): 64-88.

[14] Guangul, FM, Sulaiman, SA, and Ramli, A. Gasifier selection, design and gasification of oil palm fronds with preheated and unheated gasifying air. *Bioresour Technol* 2012; 126: 224-32.

[15] M.A.A. Mohammed, AS, W.A.K.G. Wan Azlina, M.S. Mohammad Amran, A. Fakhru'l-Razi. Air gasification of empty fruit bunch for hydrogen-rich gas production in a fluidized-bed reactor. *Energy Convers. Manage.* 2011; 52 1555–61.

[16] Zhou, J, Chen, Q, Zhao, H, Cao, X, Mei, Q, Luo, Z, and Cen, K. Biomass-oxygen gasification in a high-temperature entrained-flow gasifier. *Biotechnol Adv* 2009; 27(5): 606-11.

[17] Lee, J-W, Yun, Y, Chung, S-W, Kang, S-H, Ryu, J-H, Kim, G-T, and Kim, Y-J. Application of multiple swirl burners in pilot-scale entrained bed gasifier for short residence time. *Fuel* 2014; 117: 1052-60.

[18] Liu, K and Sanderson, V. The influence of changes in fuel calorific value to combustion performance for Siemens SGT-300 dry low emission combustion system. *Fuel* 2013; 103: 239-46.

[19] Johnson, MR, Littlejohn, D, Nazeer, WA, Smith, KO, and Cheng, RK. A comparison of the flowfields and emissions of high-swirl injectors and low-

swirl injectors for lean premixed gas turbines. *Proc. Combust. Inst.* 2005; 30(2): 2867-74.

[20] Maggio, G and Cacciola, G. When will oil, natural gas, and coal peak? *Fuel* 2012; 98: 111-23.

[21] Höök, M and Tang, X. Depletion of fossil fuels and anthropogenic climate change—A review. *Energy Policy* 2013; 52: 797-809.

[22] Nicoletti, G, Arcuri, N, Nicoletti, G, and Bruno, R. A technical and environmental comparison between hydrogen and some fossil fuels. *Energy Convers. Manage.* 2015; 89: 205-13.

[23] Liu, CC, Shy, SS, Chiu, CW, Peng, MW, and Chung, HJ. Hydrogen/carbon monoxide syngas burning rates measurements in high-pressure quiescent and turbulent environment. *Int. J. Hydrogen Energy* 2011; 36(14): 8595-603.

[24] Fu, J, Tang, C, Jin, W, Thi, LD, Huang, Z, and Zhang, Y. Study on laminar flame speed and flame structure of syngas with varied compositions using OH-PLIF and spectrograph. *Int. J. Hydrogen Energy* 2013; 38(3): 1636-43.

[25] Hu, E, Fu, J, Pan, L, Jiang, X, Huang, Z, and Zhang, Y. Experimental and numerical study on the effect of composition on laminar burning velocities of H2/CO/N2/CO2/air mixtures. *Int. J. Hydrogen Energy* 2012; 37(23): 18509-19.

[26] Chacartegui, R, Sánchez, D, de Escalona, JMM, Monje, B, and Sánchez, T. On the effects of running existing combined cycle power plants on syngas fuel. *Fuel Process. Technol.* 2012; 103: 97-109.

[27] Xu, D and Lewis, RS. Syngas fermentation to biofuels: Effects of ammonia impurity in raw syngas on hydrogenase activity. *Biomass Bioenergy* 2012; 45: 303-10.

[28] Alauddin, ZABZ, Lahijani, P, Mohammadi, M, and Mohamed, AR. Gasification of lignocellulosic biomass in fluidized beds for renewable energy development: A review. *Renewable Sustainable Energy Rev.* 2010; 14(9): 2852-62.

[29] Speight, JG. Gasification of Unconventional Feedstocks. in: Inc. E, Editor;2014, p. 1-29.

[30] Emami-Taba, L, Irfan, MF, Wan Daud, WMA, and Chakrabarti, MH. Fuel blending effects on the co-gasification of coal and biomass – A review. *Biomass Bioenergy* 2013; 57: 249-63.

[31] Pudasainee, D, Paur, H-R, Fleck, S, and Seifert, H. Trace metals emission in syngas from biomass gasification. *Fuel Process. Technol.* 2014; 120: 54-60.

[32] Awalludin, MF, Sulaiman, O, Hashim, R, and Nadhari, WNAW. An overview of the oil palm industry in Malaysia and its waste utilization through thermochemical conversion, specifically via liquefaction. *Renewable Sustainable Energy Rev.* 2015; 50: 1469-84.

[33] Abdul-Manan, AFN, Baharuddin, A, and Chang, LW. A detailed survey of the palm and biodiesel industry landscape in Malaysia. *Energy* 2014; 76: 931-41.

[34] Ng, WPQ, Lam, HL, Ng, FY, Kamal, M, and Lim, JHE. Waste-to-wealth: green potential from palm biomass in Malaysia. *J. Cleaner Prod.* 2012; 34: 57-65.

[35] Umar, MS, Jennings, P, and Urmee, T. Strengthening the palm oil biomass Renewable Energy industry in Malaysia. *Renewable Energy* 2013; 60: 107-15.

[36] Brachi, P, Chirone, R, Miccio, F, Miccio, M, Picarelli, A, and Ruoppolo, G. Fluidized bed co-gasification of biomass and polymeric wastes for a flexible end-use of the syngas: Focus on bio-methanol. *Fuel* 2014; 128: 88-98.

[37] Grigaitienė, V, Snapkauskienė, V, Valatkevičius, P, Tamošiūnas, A, and Valinčius, V. Water vapor plasma technology for biomass conversion to synthetic gas. *Catal. Today* 2011; 167(1): 135-40.

[38] Asadullah, M. Barriers of commercial power generation using biomass gasification gas: A review. *Renewable Sustainable Energy Rev.* 2014; 29: 201-15.

[39] Hackett, GA, Gerdes, K, Song, X, Chen, Y, Shutthanandan, V, Engelhard, M, Zhu, Z, Thevuthasan, S, and Gemmen, R. Performance of solid oxide fuel cells operated with coal syngas provided directly from a gasification process. *J. Power Sources* 2012; 214: 142-52.

[40] Yılmaz, S and Selim, H. A review on the methods for biomass to energy conversion systems design. *Renewable Sustainable Energy Rev.* 2013; 25: 420-30.

[41] Panwar, NL, Kothari, R, and Tyagi, VV. Thermo chemical conversion of biomass – Eco friendly energy routes. *Renewable Sustainable Energy Rev.* 2012; 16(4): 1801-16.

[42] Mayerhofer, M, Fendt, S, Spliethoff, H, and Gaderer, M. Fluidized bed gasification of biomass – In bed investigation of gas and tar formation. *Fuel* 2014; 117: 1248-55.

[43] Robbins, MP, Evans, G, Valentine, J, Donnison, IS, and Allison, GG. New opportunities for the exploitation of energy crops by thermochemical conversion in Northern Europe and the UK. *Prog. Energy Combust. Sci.* 2012; 38(2): 138-55.

[44] Bhaskar, T, Bhavya, B, Singh, R, Naik, DV, Kumar, A, and Goyal, HB. Thermochemical Conversion of Biomass to Biofuels.*Biofuels : Alternative Feedstock and Conversion Processes* Elsevier Inc.;2011, p. 51-77.

[45] Mohammed, MAA, Salmiaton, A, Wan Azlina, WAKG, Mohammad Amran, MS, Fakhru'l-Razi, A, and Taufiq-Yap, YH. Hydrogen rich gas from oil palm biomass as a potential source of renewable energy in Malaysia. *Renewable Sustainable Energy Rev.* 2011; 15(2): 1258-70.

[46] Couto, N, Rouboa, A, Silva, V, Monteiro, E, and Bouziane, K. Influence of the Biomass Gasification Processes on the Final Composition of Syngas. *Energy Procedia* 2013; 36: 596-606.

[47] Xie, Q, Borges, FC, Cheng, Y, Wan, Y, Li, Y, Lin, X, Liu, Y, Hussain, F, Chen, P, and Ruan, R. Fast microwave-assisted catalytic gasification of biomass for syngas production and tar removal. *Bioresour Technol* 2014; 156: 291-6.

[48] Pereira, EG, da Silva, JN, de Oliveira, JL, and Machado, CS. Sustainable energy: A review of gasification technologies. *Renewable Sustainable Energy Rev.* 2012; 16(7): 4753-62.

[49] Xu, D, Tree, DR, and Lewis, RS. The effects of syngas impurities on syngas fermentation to liquid fuels. *Biomass Bioenergy* 2011; 35(7): 2690-96.

[50] Richardson, Y, Blin, J, and Julbe, A. A short overview on purification and conditioning of syngas produced by biomass gasification: Catalytic strategies, process intensification and new concepts. *Prog. Energy Combust. Sci.* 2012; 38(6): 765-81.

[51] Zhang, L, Xu, C, and Champagne, P. Overview of recent advances in thermo-chemical conversion of biomass. *Energy Convers. Manage.* 2010; 51(5): 969-82.

[52] Suopajärvi, H, Pongrácz, E, and Fabritius, T. The potential of using biomass-based reducing agents in the blast furnace: A review of thermochemical

conversion technologies and assessments related to sustainability. *Renewable Sustainable Energy Rev.* 2013; 25: 511-28.

[53] jansohn, p. Modern gas turbine systems, high efficiency, low emission, fuel flexible power generation. 2013.

[54] Dong, L, Asadullah, M, Zhang, S, Wang, X-S, Wu, H, and Li, C-Z. An advanced biomass gasification technology with integrated catalytic hot gas cleaning. *Fuel* 2013; 108: 409-16.

[55] Nipattummakul, N, Ahmed, II, Gupta, AK, and Kerdsuwan, S. Hydrogen and syngas yield from residual branches of oil palm tree using steam gasification. *Int. J. Hydrogen Energy* 2011; 36(6): 3835-43.

[56] Dascomb, J, Krothapalli, A, and Fakhrai, R. Thermal conversion efficiency of producing hydrogen enriched syngas from biomass steam gasification. *Int. J. Hydrogen Energy* 2013; 38(27): 11790-98.

[57] Mendiburu, AZ, Carvalho, JA, and Coronado, CJR. Thermochemical equilibrium modeling of biomass downdraft gasifier: Stoichiometric models. *Energy* 2014; 66: 189-201.

[58] Xie, Q, Kong, S, Liu, Y, and Zeng, H. Syngas production by two-stage method of biomass catalytic pyrolysis and gasification. *Bioresour Technol* 2012; 110: 603-9.

[59] Zou, W, Song, C, Xu, S, Lu, C, and Tursun, Y. Biomass gasification in an external circulating countercurrent moving bed gasifier. *Fuel* 2013; 112: 635-40.

[60] Atnaw, SM, Sulaiman, SA, and Yusup, S. Syngas production from downdraft gasification of oil palm fronds. *Energy* 2013; 61: 491-501.

[61] Lahijani, P and Zainal, ZA. Gasification of palm empty fruit bunch in a bubbling fluidized bed: a performance and agglomeration study. *Bioresour Technol* 2011; 102(2): 2068-76.

[62] Moghadam, RA, Yusup, S, Uemura, Y, Chin, BLF, Lam, HL, and Al Shoaibi, A. Syngas production from palm kernel shell and polyethylene waste blend in fluidized bed catalytic steam co-gasification process. *Energy* 2014; 75: 40-44.

[63] Khan, Z, Yusup, S, Ahmad, MM, and Rashidi, NA. Integrated catalytic adsorption (ICA) steam gasification system for enhanced hydrogen production using palm kernel shell. *Int. J. Hydrogen Energy* 2014; 39(7): 3286-93.

[64] Aziz, M, Prawisudha, P, Prabowo, B, and Budiman, BA. Integration of energy-efficient empty fruit bunch drying with gasification/combined cycle systems. *Applied Energy* 2015; 139: 188–95.

[65] Sivasangar, S, Zainal, Z, Salmiaton, A, and Taufiq-Yap, YH. Supercritical water gasification of empty fruit bunches from oil palm for hydrogen production. *Fuel* 2015; 143: 563–69.

[66] Taufiq-Yap, YH, Sivasangar, S, and Salmiaton, A. Enhancement of hydrogen production by secondary metal oxide dopants on NiO/CaO material for catalytic gasification of empty palm fruit bunches. *Energy* 2012; 47(1): 158-65.

[67] Bazargan, A, Kostić, MD, Stamenković, OS, Veljković, VB, and McKay, G. A calcium oxide-based catalyst derived from palm kernel shell gasification residues for biodiesel production. *Fuel* 2015; 150: 519-25.

[68] Asadullah, M, Adi, AM, Suhada, N, Malek, NH, Saringat, MI, and Azdarpour, A. Optimization of palm kernel shell torrefaction to produce energy densified bio-coal. *Energy Convers. Manage.* 2014; 88: 1086-93.

[69] Asadullah, M, Ab Rasid, NS, Kadir, SASA, and Azdarpour, A. Production and detailed characterization of bio-oil from fast pyrolysis of palm kernel shell. *Biomass Bioenergy* 2013; 59: 316-24.

[70] Ogi, T, Nakanishi, M, Fukuda, Y, and Matsumoto, K. Gasification of oil palm residues (empty fruit bunch) in an entrained-flow gasifier. *Fuel* 2013; 104: 28-35.

[71] Ismail, K, Yarmo, MA, Taufiq-Yap, YH, and Ahmad, A. The effect of particle size of CaO and MgO as catalysts for gasification of oil palm empty fruit bunch to produce hydrogen. *Int. J. Hydrogen Energy* 2012 3 7 3639 - 44.

[72] Kalinci, Y, Hepbasli, A, and Dincer, I. Comparative exergetic performance analysis of hydrogen production from oil palm wastes and some other biomasses. *Int. J. Hydrogen Energy* 2011; 36(17): 11399-407.

[73] Xiao, X, Cao, J, Meng, X, Le, DD, Li, L, Ogawa, Y, Sato, K, and Takarada, T. Synthesis gas production from catalytic gasification of waste biomass using nickel-loaded brown coal char. *Fuel* 2013; 103: 135-40.

[74] Hurley, S, Xu, C, Preto, F, Shao, Y, Li, H, Wang, J, and Tourigny, G. Catalytic gasification of woody biomass in an air-blown fluidized-bed reactor using Canadian limonite iron ore as the bed material. *Fuel* 2012; 91(1): 170-76.

[75] Luo, S, Xiao, B, Hu, Z, Liu, S, Guo, X, and He, M. Hydrogen-rich gas from catalytic steam gasification of biomass in a fixed bed reactor: Influence of temperature and steam on gasification performance. *Int. J. Hydrogen Energy* 2009; 34(5): 2191-94.

[76] Corujo, A, Yermán, L, Arizaga, B, Brusoni, M, and Castiglioni, J. Improved yield parameters in catalytic steam gasification of forestry residue; optimizing biomass feed rate and catalyst type. *Biomass Bioenergy* 2010; 34(12): 1695-702.

[77] Skoulou, VK and Zabaniotou, AA. Co-gasification of crude glycerol with lignocellulosic biomass for enhanced syngas production. *J. Anal. Appl. Pyrolysis* 2013; 99: 110-16.

[78] Hanaoka, T, Hiasa, S, and Edashige, Y. Syngas production by CO2/O2 gasification of aquatic biomass. *Fuel Process. Technol.* 2013; 116: 9-15.

[79] Emission limit values : Combustion plants in EU and USA. Official Journal of the European Communities, 2001. 12-17.

[80] Licata, A, Hartenstein, HU, and Terracciano, L, Comparison of U.S. EPA and European Emission Standards for Combustion and Incineration Technologies. 1997. p. 701-20.

[81] Kuklinska, K, Wolska, L, and Namiesnik, J. Air quality policy in the U.S. and the EU – a review. *Atmospheric Pollution Research* 2015; 6(1): 129-37.

[82] Taamallah, S, Vogiatzaki, K, Alzahrani, FM, Mokheimer, EMA, Habib, MA, and Ghoniem, AF. Fuel flexibility, stability and emissions in premixed hydrogen-rich gas turbine combustion: Technology, fundamentals, and numerical simulations. *Applied Energy* 2015; 154: 1020-47.

[83] Williams, TC, Shaddix*, CR, and Schefer, RW. Effect of Syngas Composition and CO2-Diluted Oxygen on Performance of a Premixed Swirl-Stabilized Combustor. *Combust. Sci. Technol.* 2007; 180(1): 64-88.

[84] Zhang, Y, Shen, W, Zhang, H, Wu, Y, and Lu, J. Effects of inert dilution on the propagation and extinction of lean premixed syngas/air flames. *Fuel* 2015; 157: 115-21.

[85] Joo, S, Yoon, J, Kim, J, Lee, M, and Yoon, Y. NOx emissions characteristics of the partially premixed combustion of H2/CO/CH4 syngas using artificial neural networks. *Appl. Therm. Eng.* 2015; 80: 436 - 44.

[86] Lambert, K Flammability limits. 2016. 1-10.

[87] Kala, B. Combustion stability. 2012 [cited 2017.

[88] Lefebvre, AH and Ballal, DR. Gas Turbine Combustion Alternative Fuel and Emissions. Boca Raton: CRC Press, Taylor & Francis Group;2010.

[89] Wu, Y. Flame Lift-Off and Blow-Out Stability Limits and Their Application in Gas Burners. in: Lackner M, Winter F, and Agarwal AK, Editors.*Handbook of Combustion*: WILEY-VCH;2010, p. 121-39.

[90] Lee, MC, Seo, SB, Chung, JH, Kim, SM, Joo, YJ, and Ahn, DH. Gas turbine combustion performance test of hydrogen and carbon monoxide synthetic gas. *Fuel* 2010; 89(7): 1485-91.

[91] Ouimette, P and Seers, P. NOx emission characteristics of partially premixed laminar flames of H2/CO/CO2 mixtures. *Int. J. Hydrogen Energy* 2009; 34(23): 9603-10.

[92] Watson, GMG, Munzar, JD, and Bergthorson, JM. NO formation in model syngas and biogas blends. *Fuel* 2014; 124: 113-24.

[93] Alavandi, S. Experimental study of combustion of hydrogen–syngas/methane fuel mixtures in a porous burner. *Int. J. Hydrogen Energy* 2008; 33(4): 1407-15.

[94] García-Armingol, T and Ballester, J. Operational issues in premixed combustion of hydrogen-enriched and syngas fuels. *Int. J. Hydrogen Energy* 2015; 40(2): 1229-43.

[95] Safer, K, Tabet, F, Ouadha, A, Safer, M, and Gökalp, I. Combustion characteristics of hydrogen-rich alternative fuels in counter-flow diffusion flame configuration. *Energy Convers. Manage.* 2013; 74: 269-78.

[96] Habib, MA, Mokheimer, EMA, Sanusi, SY, and Nemitallah, MA. Numerical investigations of combustion and emissions of syngas as compared to methane in a 200MW package boiler. *Energy Convers. Manage.* 2014; 83: 296-305.

[97] Liu, C-R and Shih, H-Y. Model Analysis of Syngas Combustion and Emissions for a Micro Gas Turbine. *J. Eng. Gas Turbines Power* 2014; 137(6): 061507.

[98] A., RG, H., Ck, and T., WN. Syngas Utilization. in: Lieuwen T, yang V, and Yitter R, Editors.*Synthesis Gas Combustion-Fundamentals and Applications*: Taylor & Francis Group;2010, p. 200–02.

[99] Shih, H-Y, Hsu, J-R, and Lin, Y-H. Computed flammability limits of opposed-jet H2/CO syngas diffusion flames. *Int. J. Hydrogen Energy* 2014; 39(7): 3459-68.

[100] Huynh, CV and Kong, S-C. Combustion and NOx emissions of biomass-derived syngas under various gasification conditions utilizing oxygen-enriched-air and steam. *Fuel* 2013; 107: 455-64.

[101] Giles, D, Som, S, and Aggarwal, S. NOx emission characteristics of counterflow syngas diffusion flames with airstream dilution. *Fuel* 2006; 85(12-13): 1729-42.

[102] Zhang, Y, Zhang, H, Tian, L, Ji, P, and Ma, S. Temperature and emissions characteristics of a micro-mixing injection hydrogen-rich syngas flame diluted with N2. *Int. J. Hydrogen Energy* 2015; 40(36): 12550-59.

[103] Wu, Y, Lu, Y, Al-Rahbi, IS, and Kalghatgi, GT. Prediction of the liftoff, blowout and blowoff stability limits of pure hydrogen and hydrogen/hydrocarbon mixture jet flames. *Int. J. Hydrogen Energy* 2009; 34(14): 5940-45.

[104] Hwang, J, Bouvet, N, Sohn, K, and Yoon, Y. Stability characteristics of non-premixed turbulent jet flames of hydrogen and syngas blends with coaxial air. *Int. J. Hydrogen Energy* 2013; 38(12): 5139-49.

[105] Sayad, P, Schönborn, A, and Klingmann, J. Experimental investigation of the stability limits of premixed syngas-air flames at two moderate swirl numbers. *Combust. Flame* 2016; 164: 270-82.

[106] Mansouri, Z, Aouissi, M, and Boushaki, T. Numerical computations of premixed propane flame in a swirl-stabilized burner: Effects of hydrogen enrichment, swirl number and equivalence ratio on flame characteristics. *Int. J. Hydrogen Energy* 2016; 41(22): 9664-78.

[107] Tunçer, O, Kaynaroğlu, B, Karakaya, MC, Kahraman, S, Çetiner-Yıldırım, O, and Baytaş, C. Preliminary investigation of a swirl stabilized premixed combustor. *Fuel* 2014; 115: 870-74.

[108] De, A and Acharya, S. Parametric study of upstream flame propagation in hydrogen-enriched premixed combustion: Effects of swirl, geometry and premixedness. *Int. J. Hydrogen Energy* 2012; 37(19): 14649-68.

[109] García-Armingol, T and Ballester, J. Influence of fuel composition on chemiluminescence emission in premixed flames of CH4/CO2/H2/CO blends. *Int. J. Hydrogen Energy* 2014; 39(35): 20255-65.

[110] García-Armingol, T, Sobrino, Á, Luciano, E, and Ballester, J. Impact of fuel staging on stability and pollutant emissions of premixed syngas flames. *Fuel* 2016; 185: 122-32.

[111] Nemitallah, MA and Habib, MA. Experimental and numerical investigations of an atmospheric diffusion oxy-combustion flame in a gas turbine model combustor. *Applied Energy* 2013; 111: 401–15.

[112] Mayr, B, Prieler, R, Demuth, M, Potesser, M, and Hochenauer, C. CFD and experimental analysis of a 115kW natural gas fired lab-scale furnace under oxy-fuel and air–fuel conditions. *Fuel* 2015; 159: 864-75.

[113] ANSYS Fluent Theory Guide. 2013.

[114] Versteeg, HK and Malalasekera, W. An introduction to computational fluid dynamics: the finite volume method. 2nd ed.: Pearson Education .Ltd;2007.

[115] Krieger, GC, Campos, APV, Takehara, MDB, Cunha, FAd, and Veras, CAG. Numerical simulation of oxy-fuel combustion for gas turbine applications. *Appl. Therm. Eng.* 2015; 78: 471 - 81.

[116] Alfaro-Ayala, JA, Gallegos-Muñoz, A, Uribe-Ramírez, AR, and Belman-Flores, JM. Use of bioethanol in a gas turbine combustor. *Appl. Therm. Eng.* 2013; 61(2): 481-90.

[117] Mayr, B, Prieler, R, Demuth, M, and Hochenauer, C. The usability and limits of the steady flamelet approach in oxy-fuel combustions. *Energy* 2015; 90: 1478-89.

[118] Ranga Dinesh, KKJ, Jiang, X, and van Oijen, JA. Numerical simulation of hydrogen impinging jet flame using flamelet generated manifold reduction. *Int. J. Hydrogen Energy* 2012; 37(5): 4502-15.

[119] Oijen, JAV, Lammers, FA, and Goey, LPHD. Modeling of Complex Premixed Burner Systems by Using Flamelet-Generated Manifolds. *Combust. Flame* 2001; 127: 2124–34.

[120] Mukhopadhyay, S, Bastiaans, RJM, Oijen, JAv, and Goey, LPHd. Analysis of a filtered flamelet approach for coarse DNS of premixed turbulent combustion. *Fuel* 2015; 144: 388–99.

[121] Donini, A, Bastiaans, RJM, van Oijen, JA, and de Goey, LPH. Differential diffusion effects inclusion with flamelet generated manifold for the modeling of stratified premixed cooled flames. *Proc. Combust. Inst.* 2015; 35(1): 831-37.

[122] Nakod, P, Yadav, R, Rajeshirke, P, and Orsino, S. A Comparative Computational Fluid Dynamics Study on Flamelet-Generated Manifold and Steady Laminar Flamelet Modeling for Turbulent Flames. *J. Eng. Gas Turbines Power* 2014; 136(8): 081504.

[123] Nguyen, P-D, Vervisch, L, Subramanian, V, and Domingo, P. Multidimensional flamelet-generated manifolds for partially premixed combustion. *Combust. Flame* 2009; 157(1): 43-61.

[124] Verhoeven, LM, Ramaekers, WJS, van Oijen, JA, and de Goey, LPH. Modeling non-premixed laminar co-flow flames using flamelet-generated manifolds. *Combust. Flame* 2012; 159(1): 230-41.

[125] Atoof, H and Emami, MD. Numerical simulation of laminar premixed CH4/air flame by flamelet-generated manifolds: A sensitivity analysis on the effects of progress variables. *J. Taiwan Inst. Chem. Eng.* 2016; 60: 287-93.

[126] Patil, S and Montanari, F. Reynolds-Averaged Navier–Stokes and Large-Eddy Simulation Investigation of Lean Premixed Gas Turbine Combustor. *J. Eng. Gas Turbines Power* 2015; 137: 1-8.

[127] Tyliszczak, A, Boguslawski, A, and Nowak, D. Numerical simulations of combustion process in a gas turbine with a single and multi-point fuel injection system. *Applied Energy* 2016; 174: 153–65.

[128] Samiran, NA, Ng, J-H, Mohd Jaafar, MN, Valera-Medina, A, and Chong, CT. Swirl stability and emission characteristics of CO-enriched syngas/air flame in a premixed swirl burner. *Process Safety and Environmental Protection* 2017.

[129] Kumar, S and Pandey, KM. Computational Simulation and Effect of Swirl Angle on NOx Generation of 2D Swirl Burner in Gas Turbine. *International Journal of Engineering Research & Technology* 2014; 3(8): 1243-46.

[130] Vu, TM, Park, J, Kwon, OB, Bae, DS, Yun, JH, and Keel, SI. Effects of diluents on cellular instabilities in outwardly propagating spherical syngas–air premixed flames. *Int. J. Hydrogen Energy* 2010; 35(8): 3868-80.

[131] Chacartegui, R, Sánchez, D, Muñoz de Escalona, JM, Jiménez-Espadafor, F, Muñoz, A, and Sánchez, T. SPHERA project: Assessing the use of syngas fuels in gas turbines and combined cycles from a global perspective. *Fuel Process. Technol.* 2012; 103: 134-45.

[132] Tao, H-G, Chen, H-X, Xie, J-L, and Hu, Y-P. An alternative approach to quantifying fluid flow uniformity based on area-weighted average velocity and mass-weighted average velocity. *Energy Build.* 2012; 45: 116-23.

[133] Ramaekers, WJS, Albrecht, BA, van Oijen, JA, de Goey, LPH, and Eggels, RLGM. The application of Flamelet Generated Manifolds in partailly-premixed flames. in *Fluent Benelux User Group Meeting*. 2005. Wavre, Belgium: Château de Limelette: Technische Universiteit Eindhoven.

[134] Turkeli-Ramadan, Z, Sharma, RN, and Raine, RR. Two-dimensional simulation of premixed laminar flame at microscale. *Chem. Eng. Sci.* 2015; 138: 414-31.

[135] Cristina Cameretti, M and Tuccillo, R. Combustion features of a bio-fuelled micro-gas turbine. *Appl. Therm. Eng.* 2015; 89: 280-90.

[136] Deng, Y, Wu, H, and Su, F. Combustion and exhaust emission characteristics of low swirl injector. *Appl. Therm. Eng.* 2017; 110: 171-80.

[137] Li, M, Tong, Y, Thern, M, and Klingmann, J. Influence of the Steam Addition on Premixed Methane Air Combustion at Atmospheric Pressure. *Energies* 2017; 10(7): 1070.

[138] Su, S-S, Hwang, S-J, and Lai, W-H. On a porous medium combustor for hydrogen flame stabilization and operation. *Int. J. Hydrogen Energy* 2014; 39(36): 21307-16.

[139] Wu, L, Kobayashi, N, Li, Z, Huang, H, and Li, J. Emission and heat transfer characteristics of methane–hydrogen hybrid fuel laminar diffusion flame. *Int. J. Hydrogen Energy* 2015; 40(30): 9579-89.

[140] Speth, RL and Ghoniem, AF. Using a strained flame model to collapse dynamic mode data in a swirl-stabilized syngas combustor. *Proc. Combust. Inst.* 2009; 32(2): 2993-3000.

[141] Whitty, KJ, Zhang, HR, and Eddings, EG. Pollutant Formation and Control. in: Lieuwen T, Yang V, and Yetter R, Editors.*Syntheis Gas Combustion*, Boca Raton: CRC Press, Taylor and Francis Group;2010, p. 169-88.

[142] Turns, SR. An Introduction to Combustion Concepts and Application. 2nd ed. Singapore: McGraw-Hill;2000.

[143] Sayad, P, Schönborn, A, and Klingmann, J. Experimental investigation of the stability limits of premixed syngas-air flames at two moderate swirl numbers. *Combust. Flame* 2015.

[144] Ruan, J and Kobayashi. Combined effects of nongray radiation and pressure on premixed CH4/O2/CO2 flames. *Combust Flame* 2001; 124: 225-30.

[145] Park, J, Bae, DS, Cha, MS, Yun, JH, Keel, SI, Cho, HC, Kim, TK, and Hae, JS. Flame characteristics in H2/CO synthetic gas diffusion flames diluted with CO2: Effects of radiative heat loss and mixture composition. *Int. J. Hydrogen Energy* 2008; 33(23): 7256–64.

[146] Walton, SM, He, X, Zigler, BT, and Wooldridge, MS. An experimental investigation of the ignition properties of hydrogen and carbon monoxide mixtures for syngas turbine applications. *Proc. Combust. Inst.* 2007; 31(2): 3147-54.

[147] Park, J, Kim, JS, Chung, JO, Yun, JH, and Keel, SI. Chemical effects of added CO2 on the extinction characteristics of H2/CO/CO2 syngas diffusion flames. *Int. J. Hydrogen Energy* 2009; 34(20): 8756–62.

[148] Davis, SG, Joshi, AV, Wang, H, and Egolfopoulos, F. An optimized kinetic model of H2/CO combustion. *Proc. Combust. Inst.* 2005; 30(1): 1283–92.

[149] Vagelopoulos, CM and Egolfopoulos, FN. Direct experimental determination of laminar flame speeds. *Symp. (Int.) Combust.* 1998; 27(1): 513-19.

[150] Dong, C, Zhou, Q, Zhao, Q, Zhang, Y, Xu, T, and Hui, S. Experimental study on the laminar flame speed of hydrogen/carbon monoxide/air mixtures. *Fuel* 2009; 88(10): 1858–63.

[151] Khan, N and Raghavan, V. Structure and reaction zones of hydrogen – Carbon-monoxide laminar jet diffusion flames. *Int. J. Hydrogen Energy* 2014; 39(34): 19832-45.

[152] Strakey, P, Sidwell, T, and Ontko, J. Investigation of the effects of hydrogen addition on lean extinction in a swirl stabilized combustor. *Proc. Combust. Inst.* 2007; 31(2): 3173-80.

[153] Glassman, I and Yetter, RA. Combustion. 4th ed. United States America: Elsevier Inc;2008.

[154] Mordaunt, CJ and Pierce, WC. Design and preliminary results of an atmospheric-pressure model gas turbine combustor utilizing varying CO2 doping concentration in CH4 to emulate biogas combustion. *Fuel* 2014; 124: 258-68.

[155] Lieuwen, T, McDonell, V, Santavicca, D, and Sattelmayer, T. Operability Issues Associated with Steady Flowing Combustors. in: Lieuwen T, Yang V,

and Yetter R, Editors.*Synthesis Gas Combustion, Fundamentals and Application*: Taylor & Francis Group;2010.

[156] Sigfrid, IR, Whiddon, R, Collin, R, and Klingmann, J. Influence of reactive species on the lean blowout limit of an industrial DLE gas turbine burner. *Combust. Flame* 2014; (161): 1365–73.

[157] Li, H-M, Li, G-X, Sun, Z-Y, Zhai, Y, and Zhou, Z-H. Measurement of the laminar burning velocities and markstein lengths of lean and stoichiometric syngas premixed flames under various hydrogen fractions. *Int. J. Hydrogen Energy* 2014; 39(30): 17371-80.

[158] Liang, W, Chen, Z, Yang, F, and Zhang, H. Effects of Soret diffusion on the laminar flame speed and Markstein length of syngas/air mixtures. *Proc. Combust. Inst.* 2013; 34(1): 695-702.

[159] Yu, G, Law, CK, and Wu, CK. Laminar Flame Speeds of Hydrocarbon+Air mixtures with H2 addition. *Combust. Flame* 1986; 63: 339-47.

[160] Li, H, Li, G, Sun, Z, Yu, Y, Zhai, Y, and Zhou, Z. Experimental investigation on laminar burning velocities and flame intrinsic instabilities of lean and stoichiometric H2/CO/air mixtures at reduced, normal and elevated pressures. *Fuel* 2014; 135: 279-91.

[161] Okafor, EC, Nagano, Y, and Kitagawa, T. Experimental and theoretical analysis of cellular instability in lean H2-CH4-air flames at elevated pressures. *Int. J. Hydrogen Energy* 2016; 41(15): 6581-92.

[162] Wang, J, Zhang, M, Xie, Y, Huang, Z, Kudo, T, and Kobayashi, H. Correlation of turbulent burning velocity for syngas/air mixtures at high pressure up to 1.0MPa. *Exp. Therm Fluid Sci.* 2013; 50: 90-96.

[163] Wang, J, Zhang, M, Huang, Z, Kudo, T, and Kobayashi, H. Measurement of the instantaneous flame front structure of syngas turbulent premixed flames at high pressure. *Combust. Flame* 2013; 160(11): 2434-41.

[164] Turns, SR. An Introduction to Combustion Concepts and Application. 3rd ed. New York: McGraw-Hill;2013.

[165] Natarajan, J and Seitzman, JM. Laminar Flame Properties of H2/CO Mixtures. in: Lieuwen T, Yang V, and Yetter R, Editors.*Synthesis Gas Combustion Fundamentals and Applications*;2010.

[166] Boushaki, T, Dhue´, Y, Selle, L, Ferret, B, and Poinsot, T. Effects of hydrogen and steam addition on laminar burning velocity of methaneeair premixed

flame: Experimental and numerical analysis. *international journal o f hydrogen energy* 2012; 37: 9412-22.

[167] Ketelheun, A, Olbricht, C, Hahn, F, and Janicka, J. NO prediction in turbulent flames using LES/FGM with additional transport equations. *Proc. Combust. Inst.* 2011; 33(2): 2975-82.

[168] Göktolga, MU, van Oijen, JA, and de Goey, LPH. Modeling MILD combustion using a novel multistage FGM method. *Proc. Combust. Inst.* 2016.

[169] Ihme, M, Shunn, L, and Zhang, J. Regularization of reaction progress variable for application to flamelet-based combustion models. *J. Comput. Phys.* 2012; 231(23): 7715-21.

[170] Oijen, JAv and Goey, LPHd, Predicting NO Formation with Flamelet Generated Manifolds, in *Proceedings of the European Combustion Meeting 2009*. 2009.

[171] Boucher, A and Bertier, N. A method to extend flamelet manifolds for prediction of NOx and long time scale species with tabulated chemistry. *Int. J. Sustainable Aviation* 2014; 1(2): 181-202.

[172] Najafi-Yazdi, A, Cuenot, B, and Mongeau, L. Systematic definition of progress variables and Intrinsically Low-Dimensional, Flamelet Generated Manifolds for chemistry tabulation. *Combust. Flame* 2012; 159(3): 1197-204.

[173] Khaleghi, M, Hosseini, SE, and Abdul Wahid, M. Investigations of asymmetric non-premixed meso-scale vortex combustion. *Appl. Therm. Eng.* 2015; 81: 140-53.