THERMAL AND FLUID FLOW ANALYSIS OF SWIRLING FLAMELESS COMBUSTION

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Dedicated to my beloved mother,

to the most precious persons in my life, my beloved wife Saja,

my sweetheart beautiful daughter Qamar and my darling son Mohammed.

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ABSTRACT

Flameless combustion is a novel combustion mode that is also to achieve ultra-low emissions of NOx and CO while producing a uniform temperature distribution and a stable combustion. In this work, a newly designed Internally Preheated Swirling Flameless Combustor (IPSFC) has been developed at the High Speed Reacting Flow Laboratory (HiREF), Faculty of Mechanical Engineering, Universiti Teknologi Malaysia (UTM) to achieve high performance combustion and low emission. The study examines the sequential development of a low emission swirling flameless vortex combustor operating from a thermal load of 7 kW to 15 kW. The swirling flameless combustor has been modified to include preheating where the fresh air passes through a helical tube that is fixed inside the combustion chamber before being injected into the flameless combustor for some experiments. The objective of this study is to investigate in detail the role of air inlet geometry with and without air preheating on the performance of the swirling flameless combustion without the addition of diluted gas. Investigation on the effect of multiple air–fuel injection configuration found that the case of SFR42 to be the best configuration for optimum flameless combustion performance. SFR42 is a swirling combustor with 4 inlets of tangential air and 12 inlets axial air with 11 inlets coaxial fuel. The lowest NOx and CO emissions are observed at the equivalence ratio of 0.8 with the value of 4 ppm and 24 ppm, respectively. In general temperature uniformity which is an important characteristic of flameless combustion is observed to vary from 0.03 to 0.06 at the different equivalence ratio. This work also demonstrated the achievement of swirling flameless combustion with and without preheated tangential air. Overall, preheated air has contributed to the increase of 5% thermal efficiency compared to the non-preheated case at the expense of 4 ppm maximum increment of NOx emission. In this thesis some simulation study is also performed to investigate the detail flow field inside the swirl combustor. The numerical investigation confirms the experimental finding on the outstanding performance of SFR42 configuration. It is found that in this configuration the bulk swirling motion was produced in the combustor for good mixing between fuel and oxidizer which in turn lead to complete combustion at low peak temperature. This results in the combustion process with low emission.

ABSTRAK

Pembakaran tanpa api adalah mod pembakaran baru yang boleh menghasilkan pelepasan NOx dan CO rendah di samping mendapatkan taburan suhu yang seragam dan pembakaran yang stabil. Dalam kajian ini, Internally Preheated Swirling Flameless Combustor (IPSFC) telah direka dan dibangunkan di Makmal Aliran Tidakbalas Berkelajuan Tinggi (HiREF), Fakulti Kejuruteraan Mekanikal, Universiti Teknologi Malaysia (UTM) bagi menghasilkan pembakaran yang berprestasi tinggi dengan pelepasan emisi yang rendah. Kajian ini memfokuskan pelepasan pembakar berpusar yang rendah beroperasi dari beban haba 7 kW kepada 15 kW. Pembakar berpusar tanpa api telah diubahsuai untuk prapemanasan di mana udara segar melalui satu tiub heliks yang diletakkan di dalam kebuk pembakaran lalu memanaskan udara tersebut sebelum dimasukan kedalam kebuk pembakaran dalam beberapa eksperiment. Objektif kajian ini adalah untuk menyiasat secara terperinci peranan geometri salur masuk udara dengan dan tanpa prapemanasan udara ke atas prestasi pembakaran berpusar tanpa api tanpa penambahan gas sebagai pencair. Siasatan ke atas kesan konfigurasi suntikan berganda udara-bahan api mendapati bahawa kes SFR42 adalah konfigurasi terbaik untuk prestasi pembakaran optimum. SFR42 adalah pembakar berpusar dengan 4 salur masuk udara tangen dan 12 salur masuk udara paksi dengan 11 salur masuk bahan api sepaksi. Pelepasan NOx dan CO paling rendah direkodkan pada nisbah kesetaraan 0.8 dengan masing-masing bernilai 4 ppm dan 24 ppm. Secara umum keseragaman suhu yang merupakan satu ciri penting dalam pembakaran tanpa api didapati berubah dari 0.03-0.06 pada nisbah yang kesetaran berlainan. Kajian ini juga menunjukkan pembakaran berpusar tanpa api dengan dan tanpa udara tangen yang diprapanaskan telah dicapai. Secara keseluruhan, udara yang diprapanaskan telah menyumbang kepada peningkatan sebanyak 5% kecekapan haba berbanding dengan kes udara yang tidak diprapanaskan tetapi dengan peningkatan pelepasan NOx maksima settingi 4 ppm. Dalam tesis ini beberapa kajian simulasi dijalankan untuk menyiasat medan aliran terperinci dalam pembakar pusaran. Kajian numerikal didapati menghalkan penemuan yang hampir sama dalam mempastkan prestasi tinggi yang dicapai oleh eksperiment pada konfigurasi SFR42. Dalam konfigurasi ini sebahagian besar gerakan berpusar dihasilkan dalam pembakar dan ini membantu pencampuran yang baik antara bahan api dan pengoksida yang seterusnya membawa kepada pembakaran lengkap pada suhu puncak rendah. Keadaan tersebut seterusnya menyebabkan proses pembakaran berlaku dengan pelepasan emisi yang rendah.

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LIST OF ABBREVIATIONS

NO_X	-	Nitrogen Oxide
CO	-	Carbon Monoxide
CO_2	-	Carbon Dioxide
N_2O	-	Nitrous Oxide
O_2	-	Oxygen
N_2	-	Nitrogen
LPG	-	Liquefied Petroleum Gas
NG	-	Natural Gas
CH_4	-	Methane
ppm	-	Part Per Million
CFD	-	Computational Fluid Dynamics
FLOX	-	Flameless Oxidation
HiTAC	-	High Temperature Air Combustion
MILD	-	Moderate or Intense Low Oxygen Dilution
LNI	-	Low NO_X Injection
FODI	-	Fuel/Oxidant Direct Injection
IPFC	-	Internal Preheated Flameless Combustion
COSTAIR	-	Continuous Staged Air Combustion
EGR	-	Exhaust Gas Recirculation
R_{tu}	-	Temperature Uniformity Ratio
LHV	-	Lower Heating Value
HRS	-	High Cycle Regenerative Combustion System
CGRI	-	Canadian Gas Research Institute Burner
IFRF	-	International Flame Research Foundation
SCFH	-	Standard Cubic Feet Per Hour

LIST OF SYMBOLS

T	-	Temperature (K ,° C)
Φ	-	Equivalence ratio
M_F	-	Mass flowrate of fuel
M_A	-	Mass flowrate of air
M_E	-	Mass flowrate of exhaust gas
$\dot{m}$	-	Mass flowrate
T_a	-	Air temperature
$\bar{T}$	-	Average temperature within the combustion chamber
Q_{in}	-	Input power
Q_{out}	-	Output power
$\eta_{(th)}$	-	Thermal efficiency
C_p	-	Higher specific heat
ΔT	-	Difference of temperature between two points
H_F	-	Final enthalpy
H_O	-	Initial enthalpy
A,a	-	Air
F,f	-	Fuel
Ø	-	Diameter
ρ	-	Density
v	-	Volume

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CHAPTER 1

INTRODUCTION

1.1 Research Background

Heat and power, which are integral parts of our daily lives, are generally produced via combustion processes. Excessive heat production and elevated global warming are consequences of the process. Global warming is a topic of great importance. According to the Intergovernmental Panel on Climate Change, averaged over all land and ocean surfaces, temperatures warmed roughly 0.85 degrees Celsius from 1880 to 2012 (IPCC 2013). Due to the gradual increase in the average temperature of the earth, a permanent change of the earth's climate is expected. This change poses a significant threat to human civilization. Combustion of fossil fuels which is the primary cause of global warming. Fossil fuels are hydrocarbons, primarily coal, fuel oil or natural gas, formed from the remains of dead plants and animals. The fossil fuels is the main source of energy production in the world. It is related to the emissions of potential pollutants and green-house gases. Hence, reducing combustion emissions and improving the thermal efficiency of combustion systems are critical challenges in designing thermal energy and power systems. Several combustion techniques were developed to reduce emissions of pollutant gases.

Flameless combustion is one of these techniques. The main feature of flameless combustion is the absence high temperature of flame front. The reaction takes place uniformly throughout the combustion chamber well below the dissociation temperature of N_2, hence minimizing NOx formation. This form of combustion features a low concentration of oxygen around 5% (Lezcano 2013). Therefore, the ignition process of flameless combustion is characterized by slower chemical reaction rates, uniform temperature distribution, wider reaction zones, and invisible flame. The main operation principle for this technique lies in the concept of exhaust gas and heat recirculation. The heat from the exhaust gases is used to raise the temperature of the oxidant stream while, the exhaust gases are used to dilute the oxidant stream and hence, reduce the oxygen concentration to maintain low temperature in the combustion zone. As a result of this technique, less NO is formed (Dally, Riesmeier et al. 2004). The name flameless refers to a negligible visible signature from the flames as compared to conventional ones.

The recirculation of flue gas means that combustion products are recirculated and mixed with fresh fuel and air streams. It is a key parameter in flameless combustion. Recirculation is divided into two categories: internal and external. The former category depends on burner design, while the latter is based upon the returned flue gas to the combustor by an external pipe. In the internal, the flue gases are circulated back to the combustion due to the burner aerodynamics. Recirculation and superior mixing of air and fuel are highly significant in combustion processes. Common procedures are used to create the recirculation and stabilization of the combustion during swirl flow. This plays a critical role to recirculate the section of the hot combustion product back toward the flame origin. Several approaches are used for that process; the generation of swirling combustion by a tangential air entry in a cylindrical combustor is one of them.

Swirling flameless combustion is employed in a direct injection of both air and fuel, without any need for a flame stabilizer. To generate an auto swirling process, the air is injected tangentially and axially to impart swirling without the use of swirlers that are typically used in conventional combustors. Benefits of flameless combustion technology are the ultra-low pollutant emissions, homogeneous temperature inside the combustion chamber, and stable combustion.

Flameless is a promising combustion technology that can achieve the combination of high efficiency and ultra-low emissions. It is based on mixing of fuel and oxidizer and high flue gas recirculation. The separated fuel has high momentum, and air flows entrain the flue gas through internal recirculation. Thus, the oxygen concentration in the combustion zone is diluted. This leads to a more distributed heat release rate of the chemical energy, thus avoiding the high peak temperatures and reducing the pollutant emissions.

1.2 Problem Statement

In the nowadays strict emission regulations, environmental issues of power generation play an important role in the economic viability of modern power plants. To reduce harmful emissions, the current trend is to design industrial combustion devices that operate with high efficiency and low emissions. One of these harmful emissions is NOx from combustion processes. One of the most effective method of reducing NOx is the design and implementation of flameless combustion. To achieve flameless combustion, there are two fundamental requirements to be achieved (Wünning and Wünning 1997, Lille, Blasiak et al. 2005).

1. The combustion temperature within the chamber should be greater than the auto ignition temperature of the mixture (E.g., ≈ 800 °C for natural gas/air) (Wünning and Wünning 1997, Cavigiolo, Galbiati et al. 2003).

2. The flue-gas recirculation ratio (Kv) between fuel, oxidizer and diluted gas (flue gas, N_2 or CO_2) should be greater than ‘three’ (>3) (Wünning and Wünning 1997, Flamme 2001).

A key point necessary for efficient design of a flameless combustor is to ensure good mixing between the incoming fresh fuel/air mixture and the re-circulated hot burnt gases. Adequate and fast mixing between the injected air and the internally re-circulated hot reactive gases to form hot and diluted oxidant is critical for flameless combustion, followed by rapid mixing with fuel. Many researchers used diluted gases like CO_2 and/or N_2 that are injected into the combustion chamber to achieve high circulation required for flameless combustion. Swirl is a phenomenon known to help combustion. Many researchers used vanes or tangential entry to generate swirl. Some researcher proposed introduction of swirl with tangential entry using asymmetric vortex combustor. In this study asymmetric vortex combustion (AVC) concept is used as the basic design for the flameless combustion system (Saqr 2011). However the (AVC) by Saqr has some problem regarding the low temperature region near the center. In vortex combustion, where there are no axial air such as in AVC, the process of flame stabilization and mixing in AVC is concentrated near the circumferential wall of the combustor. The temperature at the center of the combustor is to be relatively low compared with wall combustor. This is justified by the presence of CRZ which entrains ambient air into the combustor (Saqr 2011). This situation is not good for flameless combustion. The axial component of the reacting flow within the combustor is essential, and this is normally achieved by introducing a swirl motion generated by the interaction between axial and tangential air velocity components.

This study focuses on a new combustor that solves the problem by achieving a swirling flameless combustion with high recirculation, and without gas dilution. A modified design is proposed for a flameless combustor with a high recirculation for fast mixing. This combustor configuration adopts the previous asymmetric vortex geometry proposed by Saqr (Saqr 2011). The concept of vortex flame provides flame stability by stabilizing the reaction zone on the boundary of a forced vortex field, which allows rapid mixing between air and fuel upstream of the reaction zone. Therefore, the vortex flame demonstrates the visual characteristics of a premixed flame, although it is a non-premixed flame. Therefore, the stability is radically enhanced while avoiding the typical drawbacks of premixed flames.

This involves the investigation of the effects of burner geometry, air preheating and swirling on flameless combustion efficiency as well. Current research focuses also on the development of combustion technology, aiming at reducing NOx emission while increasing combustion efficiency.

1.3 Research Objectives

This study focuses on the newly designed asymmetric swirling flow combustion system. The objectives of this present work are:

1. to analyze experimentally the effects of multiple air-fuel injection configurations on swirling flameless.
2. to evaluate the effect of air preheating on thermal efficiency of swirling flameless combustion.
3. to investigate numerically the gas recirculation and fuel-air mixing characteristics for different flow configuration swirling flameless combustion.

1.4 Significance of Research

In this study a new design of a flameless combustor called the Internally Preheated Swirling Flameless Combustor (IPSFC) has been proposed, developed, fabricated and investigated. This study has practical applications in production industries in general. It also has a significant contribution in solving the problem of global warming and reduction of depletion of ozone layer. It also contributes in supporting the relevant industries such as gas turbines, to obtain more efficient combustion process. A new combustor configuration is designed to achieve a swirling flameless combustion without the addition of gas dilution (e.g N_2, CO_2 etc.). To the best of author's knowledge, the present study is the first study of its kind, in swirling flameless combustion.

1.5 Research Scope

The research scope covers the design and manufacture of a laboratory scale flameless combustor called HiREF Internally Preheated Swirling Flameless Combustor (IPSFC-HiREF). Computational and experimental approaches are used in this research. The experimental component is focused on the characteristics of swirling flameless combustion under different locations of axial air inlets. Three types of hydrocarbon gases are utilized: natural gas, propane, and diluted methane. Nitrogen oxides (NOx), carbon monoxide (CO), carbon dioxide (CO_2) emissions, and oxygen (O_2) concentrations are measured in the exhaust gas during the experiments. The effect of axial to tangential air ratio induction on the swirling flameless combustion performance for natural gas is studied. Effects of the equivalence ratios on the pollutant emissions are determined. These equivalence ratios are in the range between 0.5 and 1.2. The effect of diluted methane (CO_2 diluted) on the swirling flameless combustion process is also investigated. Numerical investigations are performed to calculate the recirculation ratio and swirling number of the combustor in each case study. In the study, swirling flameless combustion was investigated for two cases: with and without tangential air preheating.

1.6 Thesis Outline

This thesis consists of five chapters. Chapter one introduces the present study. Chapter two is a twofold literature review covering: (i) pollutant emissions with an emphasis on nitrogen oxides (NOx), and (ii) a review of past and current studies on flameless combustion. In chapter three, the design criteria for swirling flameless combustion are listed with emphasis on reactive gas recirculation and recirculation enhancement, swirl generation, and mixing fuel and air. Chapter 3 also presents a discussion of the equipment, as well as the methodology employed in all phases in the present study. A thorough discussion of the results then follows in chapter four. The thesis finishes with chapter five, which contains the conclusion that precedes recommendations for future research based on our findings.

REFERENCES

Abuelnuor, A. (2014). *Thermal Characteristics and Emississions of Gaseous Fuel Flameless Combustion with Tangential Air Inlet*. Doctor Philosophy, Universiti Teknologi Malaysia, Skudai.

Abuelnuor, A., M. A Wahid and M. Osman (2014). Characterization of a Low NOx Flameless Combustion Burner Using Natural Gas. *Jurnal Teknologi,* 66 (2) : pp. 121-125.

Abuelnuor, A., M. Wahid, H. Mohammed and A. Saat (2014). Flameless Combustion Role in the Mitigation of NOx Emission: A Review. *International Journal of Energy Research*, 38(7): pp. 827-846.

Abuelnuor, A. A. A. and A. W. Mazlan (2013). Flameless Combustion and the Effect of Air Preheat on the Combustion Performance: A Review. *International Journal on Heat and Mass Transfer Theory and Applications,* 1(1): pp. 121-130.

Alwan, R. A., M. A. Wahid, M. F. Mohd Yasin, A. AlTaie and A. A. Abuelnuor (2015). Effects of Equivalence Ratio on Asymmetric Vortex Combustion in a Low NOx Burner. *International Review of Mechanical Engineering (IREME),* 9(5) : pp. 476-483.

Arghode, V. K. (2011). *Development of Colorless Distributed Combustion for Gas Turbine Application*. Doctor Philosophy, University of Maryland, College Park.

Arghode, V. K. and A. K. Gupta (2010). Effect of Flow Field for Colorless Distributed Combustion (CDC) for Gas Turbine Combustion. *Applied Energy*, **87**(5): 1631-1640.

Ayoub, M., C. Rottier, S. Carpentier, C. Villermaux, A. Boukhalfa and D. Honoré (2012). An Experimental Study of Mild Flameless Combustion of Methane/Hydrogen Mixtures. *International Journal of Hydrogen Energy,* **37**(8): 6912-6921.

Burggraaf, B.T., P.D.J. Hoppesteyn, N. Fricker+, S. Santos and B.K. Slim. (2009). Towards Industrial Application of High Efficiency Combustion. *IFRF Combustion Journal,* 1562-479X.

Battaglia, V., F. Crippa, E. Malfa and M. Fantuzzi (2008). CFD for Flameless Burners Development. *31st Combustion Meeting Sezione italiana del Combustion Institute*. June 2008. At Torino, Italy.

Baukal, C. (2005). Everything you need to know about NOx: Controlling and Minimizing Pollutant Emissions is Critical for Meeting Air Quality Regulations. *Metal Finishing* , 103(11): p. 18-24.

Beer, J. and N. Chigier (1972). *Combustion Aerodynamics (Fuel and energy science series)* . London. Elsevier Science Ltd.

Beer, J. M. (1994). Minimizing NOx Emissions from Stationary Combustion; Reaction Engineering Methodology. *Chemical Engineering Science*, 49(24): 4067-4083.

Beer, J. M. (1996). Low NOx Burners for Boilers, Furnaces and Gas Turbines; Drive Towards the Lower Bounds of NOx Emissions. *Combustion Science and Technology*, 121(1-6): 169-191.

Beér, J. M. (2000). Combustion Technology Developments in Power Generation in Response to Environmental Challenges. *Progress in Energy and Combustion Science,* 26(4–6): 301-327.

Blasiak, W., W. H. Yang, K. Narayanan and J. von Scheele (2007). Flameless Oxyfuel Combustion for Fuel Consumption and Nitrogen Oxides Emissions Reductions and Productivity Increase. *Journal of the Energy Institute*, 80(1): 3-11.

Bowman, C. T. (1992). Control of Combustion Generated Nitrogen Oxide Emissions: Technology Driven by Regulation. *Symposium (International) on Combustion*, 24(1): 859-878. Elsevier.

Cain, B., T. Robertson and J. Newby (2000). The Development and Application of Direct Fuel Injection Techniques for Emissions Reduction in High Temperature Furnaces. *2nd International Seminar on High Temperature Combustion in Industrial Furnaces*. January 2000. Stockholm, Sweden.

Castela, M., A. Veríssimo, A. Rocha and M. Costa (2012). Experimental Study of the Combustion Regimes Occurring in a Laboratory Combustor. *Combustion Science and Technology,* 184(2): 243-258.

Cavaliere, A. and M. de Joannon (2004). Mild Combustion. *Progress in Energy and Combustion Science,* 30(4): 329-366.

Cavigiolo, A., M. A. Galbiati, A. Effuggi, D. Gelosa and R. Rota (2003). Mild Combustion in a Laboratory-Scale Apparatus. *Combustion Science and Technology*, 175(8): 1347-1367.

Chin, J. and A. Lefebvre (1990). Influence of Fuel Chemical Properties on Soot Emissions from Gas Turbine Combustors. *Combustion Science and Technology*, 73(1-3): 479-486.

Cho, E. S. and S. H. Chung (2004). Characteristics of NOx Emission with Flue Gas Dilution in Air and Fuel Sides. *Journal of Mechanical Science and Technology*, 18(12): 2303-2309.

Choi, G. M. and M. Katsuki (2001). Advanced Low NOx Combustion Using Highly Preheated Air. *Energy Conversion and Management*, 42(5): 639-652.

Christo, F. C. and B. B. Dally (2005). Modeling Turbulent Reacting Jets Issuing into a Hot and Diluted Coflow. *Combustion and Flame*, 142(1–2): 117-129.

Coelho, P. and N. Peters (2001). Numerical Simulation of a Mild Combustion Burner. *Combustion and Flame*, 124(3): 503-518.

Colorado, A. F., B. A. Herrera and A. A. Amell (2010). Performance of a Flameless Combustion Furnace Using Biogas and Natural Gas. *Bioresource Technology,* 101(7): 2443-2449.

Correa, S. M. (1992). A Review of NOx Formation Under Gas Turbine Combustion Conditions. *Combustion Science and Technology,* 87: 329-362.

Dally, B., E. Riesmeier and N. Peters (2004). Effect of Fuel Mixture on Moderate and Intense Low Oxygen Dilution Combustion. *Combustion and Flame,* 137(4): 418-431.

Danon, B. (2011). Furnaces with Multiple Flameless Combustion Burners. *Energy Technology*, 164.

Derudi, M., A. Villani and R. Rota (2007). Sustainability of Mild Combustion of Hydrogen-Containing Hybrid Fuels. *Proceedings of the Combustion Institute,* 31(2): 3393-3400.

Driscoll, J. F. and J. Temme (2011). Role of Swirl in Flame Stabilization. *49th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition*. January 2011. Oriando, Florda.

Eldrainy, Y. A., K. M. Saqr, H. S. Aly and M. N. M. Jaafar (2009). CFD Insight of the Flow Dynamics in a Novel Swirler for Gas Turbine Combustors. *International Communications in Heat and Mass Transfer,* 36(9): 936-941.

Fenimore, C. P. (1971). Formation of Nitric Oxide in Premixed Hydrocarbon Flames. *Symposium (International) on Combustion,* 13(1): 373-380.

Fielenbach, C., T. Holfeld, C. von Petery, U. Renz and J. Wünning (2003). NOx Reduction in a Pressurized Pulverized Coal Flame by Flue Gas Recirculation. *Twentieth Annual International Pittsburgh Coal Conference* . September 15 - 19, 2003. Pittsburgh, Pennsylvania, USA.

Fiskum, A. (2008). *Calculation of NOx Formation in a Swirl Burner*. Master Degree, Norwegian University of Science and Technology.

Flamme, M. (2001). Low NOx Combustion Technologies for High Temperature Applications. *Energy Conversion and Management*, 42(15–17): 1919-1935.

Fujimori, T., D. Riechelmann and J. Sato (1998). Effect of Liftoff on NOx Emission of Turbulent Jet Flame in High-Temperature Coflowing Air. *Symposium (International) on Combustion*, 27(1): 1149-1155. Elsevier.

Furukawa, J., H. Hashimoto, S. Mochida and T. Hasegawa (2007). Local Reaction Zone Structure of Non-premixed Flames of Propane with Highly Preheated Low-oxygen Air. *Combustion Science and Technology*, 179 (4): 723-745.

Fuse, R., H. Kobayashi, Y. Ju, K. Maruta and T. Niioka (2002). NOx Emission from High-temperature Air/Methane Counterflow Diffusion Flame. *International Journal of Thermal Sciences,* 41(7): 693-698.

Gabler, H. C. (1998). *An Experimental and Numerical Investigation of Asymmetrically-Fueled Whirl Flames*. Doctor Philosophy. Princeton University. USA.

Galletti, C., A. Parente and L. Tognotti (2007). Numerical and Experimental Investigation of a Mild Combustion Burner. *Combustion and flame*, 151(4): 649-664.

Giles, D. E., S. Som and S. K. Aggarwal (2006). NOx Emission Characteristics of Counterflow Syngas Diffusion Flames with Airstream Dilution. *Fuel,* 85(12-13): 1729-1742.

Guillou, E. (2008). *Flame Characteristics and Application of Flameless Combustion*. Master Degree. University of Cincinnati. Columbus, Ohio

Gupta, A. (2004). Clean Energy Conversion from Waste Fuels Using High Temperature Air Combustion Technology. *Asian J. Energy Environ*, 5(4): 223-266.

Gupta, A., T. Hasegawa and S. Bolz (1999). Effect of Air Preheat Temperature and Oxygen Concentration on Flame Structure and Emission. J*ournal of Energy Resources Technology,* 121(3): 209-216.

Gupta, A. K. (2000). Flame Characteristics and Challenges with High Temperature Air Combustion. *Proceedings of the International Joint Power Generation Conference*. January 17-18 2000. Stockholm, Sweden.

Gupta, A. K. (2004). Thermal Characteristics of Gaseous Fuel Flames Using High Temperature Air. *Journal of Engineering for Gas Turbines and Power-Transactions of the Asme,* 126(1): 9-19.

Gupta, A. K., D. G. Lilley and N. Syred (1984). *Swirl Flows*. Tunbridge Wells, Kent, England, Abacus Press, 1984, 488 p. 1.

Hardesty, D. and F. Weinberg (1973). Burners Producing Large Excess Enthalpies. *Combustion Science and Technology,* 8(5-6): 201-214.

Hasan, A. E. (2013). *Investigation of Colorless Distributed Combustion (CDC) with Swirl for Gas Turbine Application*. Doctor Philosophy, University of Maryland.

He, Y. (2008). *Flameless Combustion of Natural Gas in the SJ/WJ Furnace*. Doctor Philosophy. Queen's University. Kingston, Ontario, Canada.

Heng, Q. P., A. K. Jasuja and A. H. Lefebvre (1996). Influence of Air and Fuel Flows on Gas Turbine Sprays at High Pressures. *Symposium (International) on Combustion*, 26(2): 2757-2762.

Hsieh, T. C. A., W. J. A. Dahm and J. F. Driscoll (1998). Scaling Laws for NOx Emission Performance of Burners and Furnaces from 30 kW to 12 MW. *Combustion and Flame*, 114(1-2): 54-80.

IPCC (2013). *Summary for Policymakers. In: Climate Change 2013*. T. P. S. B. C. o. W. G. I. t. t. F. A. R. o. t. I. P. o. C. Change.

Ishiguro, T., S. Tsuge, T. Furuhata, K. Kitagawa, N. Arai, T. Hasegawa, R. Tanaka and A. K. Gupta (1998). Homogenization and Stabilization During Combustion of Hydrocarbons with Preheated Air. *Symposium (International) on Combustion*, 27(2): 3205-3213.

Katsuki, G. M. C. a. M. (Mar 2001). Advanced Low NOx Combustion Using Highly Preheated Air. *Energy Conversion and Management*, (42) :639-652.

Katsuki, M. and T. Hasegawa (1998). The Science and Technology of Combustion in Highly Preheated Air. *Symposium (International) on combustion*, 27(2): 3135-3146. Elsevier.

Khaleghi, M. (2015). *Experimental and Computational Thermal Analysis of Vortex Flame in Meso-scale Combustor*. Doctor Philosophy, Universiti Teknologi Malaysia. Skudai.

Khaleghi, M., S. Hosseini, M. Wahid and H. Mohammed (2015). The Effects of Air Preheating and Fuel/Air Inlet Diameter on the Characteristics of Vortex Flame. *Journal of Energy*, 2015.

Khaleghi, M., S. E. Hosseini and M. Abdul Wahid (2015). Investigations of Asymmetric Non-premixed Meso-scale Vortex Combustion. *Applied Thermal Engineering*, 81: 140-153.

Khaleghi, M., S. E. Hosseini and M. A. Wahid (2015). Experimental and Numerical Investigations of Biogas Vortex Combustion. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy* 229(6): 662-676.

Khaleghi, M., S. E. Hosseini and M. A. Wahid (2015). Vortex Combustion and Heat Transfer in Meso-scale with Thermal Recuperation. *International Communications in Heat and Mass Transfer*, 66: 250-258.

Khalil, A. E., K. M. Bryden, S. C. Lee and A. K. Gupta (2012). Mixture Preparation Effects on Distributed Combustion for Gas Turbine Applications. J*ournal of Energy Resources Technology*, 134(3): 032201.

Khalil, A. E. and A. K. Gupta (2011). Swirling Distributed Combustion for Clean Energy Conversion in Gas Turbine Applications. *Applied Energy,* 88(11): 3685-3693.

Khalil, A. E. E. and A. K. Gupta (2011). Distributed Swirl Combustion for Gas Turbine Application. *Applied Energy,* 88(12): 4898-4907.

Khalil, A. E. E. and A. K. Gupta (2014). Swirling Flowfield for Colorless Distributed Combustion. *Applied Energy*, 113: 208-218.

Khoshhal, A., M. Rahimi and A. A. Alsairafi (2011). CFD Study on Influence of Fuel Temperature on NOx Emission in a HiTAC Furnace. *International Communications in Heat and Mass Transfer*, 38(10): 1421-1427.

Kim, J. P., U. Schnell and G. Scheffknecht (2008). Comparison of Different Global Reaction Mechanisms for Mild Combustion of Natural Gas. *Combustion Science and Technology,* 180(4): 565-592.

Krishnamurthy, N., W. Blasiak and A. Lugnet (2004). Development of High Temperature Air-and Oxyfuel Combustion Technologies for Minimized CO2 and NOx Emission in Industrial Heating. *Sustainable Energy and Environment (SEE)*. December 1-3, 2004, Hua Hin, Thailand.

Kumar, S., P. Paul and H. Mukunda (2002). Studies on a New High-intensity Low-Emission Burner. *Proceedings of the combustion institute,* 29(1): 1131-1137.

Kumar, V., B. Faizee, M. Mridha and K. D. P. Nigam (2008). Numerical studies of a Tube-in-tube Helically Coiled Heat Exchanger. *Chemical Engineering and Processing: Process Intensification,* 47(12): 2287-2295.

Leclaire, B. and D. Sipp (2010). A Sensitivity Study of Vortex Breakdown Onset to Upstream Boundary Conditions. *Journal of Fluid Mechanics,* 645: 81-119.

Lee, C.-E., B. Yu and S. Lee (2015). An Analysis of the Thermodynamic Efficiency for Exhaust Gas Recirculation-condensed Water Recirculation-waste Heat Recovery Condensing Boilers (EGR-CWR-WHR CB). *Energy*, 86: 267-275.

Lefebvre, A. H. (1995). The Role of Fuel Preparation in Low-Emission Combustion. *Journal of Engineering for Gas Turbines and Power,* 117(4): 617-654.

Lefebvre, A. H. (1999). *Gas Turbine Combustion*.Taylor and Francis.

Lefebvre, A. H. (2010). *Gas turbine combustion*. CRC press.

Leuckel W, F. N. (1976). The Characteristics of Swirl-stabilized Natural Gas Flames. *Journal of the Institute of Fuel,* 49-103.

Levy, Y., V. Sherbaum and P. Arfi (2004). Basic thermodynamics of FLOXCOM, the low-NOx Gas Turbines Adiabatic Combustor. *Applied Thermal Engineering,* 24(11-12): 1593-1605.

Lezcano, C. (2013). Numerical Calculation of the Recirculation Factor in Flameless Furnaces. *Universidad Nacional de Colombia*, 80(180): 144-151.

Lille, S., W. Blasiak and M. Jewartowski (2005). Experimental Study of the Fuel Jet Combustion in High Temperature and Low Oxygen Content Exhaust Gases. *Energy*, 30(2-4): 373-384.

Liu, Y. and J.-M. Most (2009). Effects of Diluents on the Behavior of the Diluted Combustion Regime. *Proceeding of the European Combustion Meeting (EMC)*.2009. France.

Lucca-Negro, O. and T. O'doherty (2001). Vortex Breakdown: a Review. *Progress in Energy and Combustion Science*, 27(4): 431-481.

Lückerath, R., W. Meier and M. Aigner (2008). FLOX® Combustion at High Pressure with Different Fuel Compositions. *Journal of Engineering for Gas Turbines and Power*, 130(1): 011505.

Lueckerath, R., W. Meier and M. Aigner (2008). FLOX (R) Combustion at High Pressure with Different Fuel Compositions. J*ournal of Engineering for Gas Turbines and Power-Transactions of the Asme* 130(1).

Lupant, D., B. Pesenti, P. Evrard and P. Lybaert (2007). Numerical and Experimental Characterization of a Self-regenerative Flameless Oxidation Burner Operation in a Pilot-scale Furnace. *Combustion Science and Technology* 179(1-2): 437-453.

Mancini, M., P. Schwöppe, R. Weber and S. Orsino (2007). On Mathematical Modelling of Flameless Combustion. *Combustion and Flame*, 150(1–2): 54-59.

Mancini, M., R. Weber and U. Bollettini (2002). Predicting NOx Emissions of a Burner Operated in Flameless Oxidation Mode. *Proceedings of the Combustion Institute*, 29(1): 1155-1163.

Matvienko, O. (2004). Analysis of Turbulence Models and Investigation of the Structure of the Flow in a Hydrocyclone. *Journal of Engineering Physics and Thermophysics*, 77(2): 316-323.

Mazlan A. Wahid , N. M. J. a. F. N. A. (2006). Studies on the Effect of Swirl Intensity and Fuel Mixtures on Combustion and Flame Characteristics of Swirl Burner. *Project Final Report*, VOT 75181, UTM.

Mickelsen, J., C. Yarrington, J. Bons and D. Snyder (2006). The Effect of Core Flow Turbulence on Planar Lobed-mixer Nozzle Effectiveness. *44th AIAA Aerospace Sciences Meeting and Exhibit*. January 2006. Nevada.

Milani, A. and A. Saponaro (2001). Diluted combustion technologies. *IFRF Combustion Journal*, 1: 1-32.

Mohamed, H., B. Hmaeid and S. Mohamed. Fundamentals and Simulation of MILD Combustion. *Thermal Power Plants,* ISBN 978-953-307-952-3.

Mungal, S. H. S. a. M. G. (1998.). Mixing Structure and Scaling of the Jet in Crossflow. *Journal of Fluid Mechanis,* 357: 83-122.

Nakamachi, I., K. Yasuzawa, T. Miyahara and T. Nagata (1990). Apparatus or Method for Carrying out Combustion in a Furnace, Google Patents.

Nishimura, M., T. Suzuki, R. Nakanishi and R. Kitamura (1997). "Low-NOx Combustion under High Preheated Air Temperature Condition in an Industrial Furnace. *Energy conversion and management,* 38(10): 1353-1363.

Lammel, O., H. S., G. Schmitz, R. Luckerath, M. Stohr, B. Noll, M. Aigner, M. Hase and W. Krebs (2010). FLOX Combustion at High Power Density and High Flame Temperature. *Journal of Engineering for Gas Turbine and Power*, 132: 121503.

Ogawa, A. (1993). *Vortex Flow*. Boca Raton, Fla., CRC Press.

Parente, A., C. Galletti and L. Tognotti (2008). Effect of the Combustion Model and Kinetic Mechanism on the MILD Combustion in an Industrial Burner Fed with Hydrogen Enriched Fuels. *International Journal of Hydrogen Energy,* 33(24): 7553-7564.

Plessing, T., N. Peters and J. G. Wünning (1998). Laseroptical Investigation of Highly Preheated Combustion with Strong Exhaust Gas Recirculation. *Symposium (International) on Combustion,* 27(2): 3197-3204, Elsevier.

Rafidi, N., M. Wasiak and A. K. Gupta (2008). High-temperature Air Combustion Phenomena and its Thermodynamics. *Journal of Engineering for Gas Turbines and Power-Transactions of the Asme*, 130(2).

Ricou, F. P. and D. Spalding (1961). Measurements of Entrainment by Axisymmetrical Turbulent Jets. *Journal of Fluid Mechanics*, 11(01): 21-32.

Ristic, D. (2010). On the Potential of Flameless Oxidation to Reduce NOx Emissions from Pulverized Coal Combustion. *Journal of the International Flame Research Foundation*: 16.

Ristic, D., M. Schneider, A. Schuster, G. Scheffknecht and J. Wünning (2008). Investigation of NOx Formation for Flameless Coal Combustion. *7th High Temperature Air Combustion and Gasification International Symposium.* 13-16 January 2008, Phuket, Thailand.

Rottier, C., C. Lacour, G. Godard, B. Taupin, A. Boukhalfa, D. Honoré, L. Porcheron and R. Hauguel (2007). An Aerodynamic way to Reach Mild Combustion Regime in a Laboratory-scale Furnace. *Third European Combustion Meeting*. 2007. France.

Salimian, R. K. H. a. S. (1984). Survey of Rate Constants in H/N/O Systems. *Combustion Chemistry*, Springer-Verlag, New York, 361-376(1984).

Saqr, K., M. Sies and M. Wahid (2009). Numerical Investigation of the Turbulence-Combustion Interaction in Nonpremixed CH4/air Flames. *International Journal of Applied Mathematics and Mechanics* 5(8): 69-79.

Saqr, K. M. (2011). *Aerodynamics and Thermochemistry of Turbulent Confined Asymmetric Vortex Flames.* Doctor Philosophy, Universiti Teknologi Malaysia, Skudai.

Saqr, K. M., H. S. Aly, M. M. Sies and M. A. Wahid (2011). Computational and Experimental Investigations of Turbulent Asymmetric Vortex Flames. *International Communications in Heat and Mass Transfer*, 38(3): 353-362.

Saqr, K. M., M. A. Wahid and M. M. Sies (2012). Highly-resolved Large Eddy Simulation of the Nonreacting flow in an Asymmetric Vortex Combustor. *4th International Meeting of Advances in Thermofluids*. IMAT 2011, Melaka.

Sarofim, A. F. and R. C. Flagan (1976). NOx Control for Stationary Combustion Sources. *Progress in Energy and Combustion Science*, 2(1): 1-25.

Sarpkaya, T. (1971). Vortex Breakdown in Swirling Conical Flows. *AIAA Journal*, 9(9): 1792-1799.

Sarpkaya, T. (1974). Effect of the Adverse Pressure Gradient on Vortex Breakdown. *AIAA Journal*, 12(5): 602-607.

Schaffel-Mancini, N. (2011). *Ecological Evaluation of the Pulverized Coal Combustion in HTAC Technology*. Doctor Philosophy. Univ.-Bbibliothek.

Schaffel-Mancini, N., M. Mancini, A. Szlek and R. Weber (2010). Novel Conceptual Design of a Supercritical Pulverized Coal Boiler Utilizing High Temperature Air Combustion (HTAC) Technology. *Energy*, 35(7): 2752-2760.

Schaffel, N. and A. Szlek (2007). Preliminary Studies of HTAC Technology Applications in Boiler Fired with Pulverized Coal. *Archivum Combustionis*, 27(1/2): 55.

Schütz, H., R. Lückerath, T. Kretschmer, B. Noll and M. Aigner (2008). Analysis of the Pollutant Formation in the FLOX® Combustion. *Journal of Engineering for Gas Turbines and Power*, 130: 011503.

Sezgin, E., B. Pesenti, D. Lupant and P. Lybaert (2009). Development of Stability Diagrams of Flame in Diluted Combustion. *European Combustion Meeting ECM*. 2009. Vienna, Austria.

Shimo, N. (2000). Fundamental Research of Oil Combustion with Highly Preheated Air. *2nd International Seminar on High Temperature Combustion in Industrial Furnaces*. Jan 17-18, 2000, Stockholm, Sweden.

Sloan, D. G., P. J. Smith and L. D. Smoot (1986). Modeling of Swirl in Turbulent Flow Systems. *Energy and Combustion Science***,** 12(3): 163-250.

Sobiesiak, A., S. Rahbar and H. A. Becker (1998). Performance Characteristics of the Novel Low-NOx CGRI Burner For Use with High Air Preheat. *Combustion and flame*, 115(1): 93-125.

Stadler, H. A. (2010). Experimental and Numerical Investigation of Flameless Pulverised Coal Combustion. Doctor Philosophy. Universitätsbibliothek. Germany.

Suda, T., M. Takafuji, T. Hirata, M. Yoshino and J. Sato (2002). A Study of Combustion Behavior of Pulverized Coal in High-temperature Air. *combustion Institute*, 29(1): 503-509.

Suvarnakuta, P., S. Patumsawad and S. Kerdsuwan (2010). Experimental Study on Preheated Air and Flue Gas Recirculation in Solid Waste Incineration. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 32(14): 1362-1377.

Syred, N. a. J. M. B. (1972). The Damping of Precessing Vortex Cores by Combustion in Swirl Generators. *Astronautica Acta*, 17(4-5): 783-801.

Szego, G. G. (2010). *Experimental and Numerical Investigation of a Parallel jet MILD Combustion Burner System in a Laboratory-scale Furnace*. Doctor Philosophy. University of Adelaide

Szego, G. G., B. B. Dally and G. J. Nathan (2009). Operational Characteristics of a Parallel Jet MILD Combustion Burner System. *Combustion and Flame*, 156(2): 429-438.

Tabacco, D., C. Innarella and C. Bruno (2002). Theoretical and Numerical Investigation on Flameless Combustion. *Combustion Science and Technology*, 174(7): 1-35.

Tsuji, H. (2003). *High Temperature Air Combustion*. Energy Conservation to Pollution Reduction, CRC.

Tsuji, H., A. K. Gupta, T. Hasegawa, M. Katsuki, K. Kishimoto and M. Morita (2002). *High Temperature Air Combustion*. Energy Conservation to Pollution Reduction, CRC press.

Turns, S. R. (2006). *An Introduction Combustion*. Concepts and Application. Boston McGraw-Hill.

Verrissimo, A. S., A. M. R. and. M. C. (2011). Operational Combustion and Emission Characteristics of a Small Scale Combustor. *Energy and Fuels*, 25: 2469-2480.

Wahid, M. A. (2003). *Rotating Flame Characteristics*. Doctor Philosophy. State University of New York at Buffalo.

Wang, A. h., J. J. Cai and G.W. Xie (2009). Numerical Simulation of Combustion Characteristics in high temperature air combustion furnace. Journal of Iron and Steel Research, International 16(2): 6-10.

Wang, Y., Y. Huang, D. McIlveen-Wright, J. McMullan, N. Hewitt, P. Eames and S. Rezvani (2006). A Techno-economic Analysis of the Application of Continuous Staged-combustion and Flameless Oxidation to the Combustor Design in Gas Turbines. *Fuel processing technology*, 87(8): 727-736.

Wang, Y. D., D. McIlveen-Wright, Y. Huang, N. Hewitt, P. Eames, S. Rezvani, J. McMullan and A. P. Roskilly (2007). The application of FLOX/COSTAIR Technologies to Reduce NOx Emissions from Coal/biomass Fired Power Plant: A Technical Assessment Based on Computational Simulation. *Fuel*, 86(14): 2101-2108.

Weber, R. (1996). Scaling Characteristics of Aerodynamics, Heat Transfer, and Pollutant Emissions in Industrial Flames, *Symposium (International) on Combustion,* 26(2): 3343-3354, Elsevier.

Weber, R., S. Orsino, N. Lallemant and A. Verlaan (2000). Combustion of Natural Gas with High-temperature Air and Large Quantities of Flue Gas. *Proceedings of the Combustion Institute*, 28(1): 1315-1321.

Weber, R., J. P. Smart and W. v. Kamp (2005). On the (MILD) Combustion of Gaseous, Liquid, and Solid Fuels in High Temperature Preheated Air. *Proceedings of the Combustion Institute,* 30(2): 2623-2629.

Wunning, J. (1992). Method for Apparatus for Combusting Fuel in a Combustion Chamber, Google Patents.

Wunning, J. A. and J. G. Wunning (1997). Flameless Oxidation to Reduce Thermal NO-formation. *Progress in Energy and Combustion Science,* 23(1): 81-94.

Xia, J. L., G. Yadigaroglu, Y. S. Liu, J. Schmidli and B. L. Smith (1998). Numerical and Experimental Study of Swirling Flow in a Model Combustor. *International Journal of Heat and Mass Transfer,* 41(11): 1485-1496.

Xiaolin, W. and S. Mingxian (2003). Visualization of the Precessing Vortex Core in a Cyclone Separator by PIV. *Chinese J. Chem. Eng, 11(*6): 633-637.

Xing, X., B. Wang and Q. Lin (2007). Structure of Reaction Zone of Normal Temperature Air Flameless Combustion in a 2 ton/h Coal-fired Boiler Furnace. *Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy***,** 221(4): 473-480.

Yang, W. (2008). *Experimental and Mathematical Modeling Study under the High Temperature and Oxygen Deficient Oxidzers*. Doctor Philosophy. *Politechnika Gdanska Wydzial Mechnniczny Katedra Techniki Cieplnej Gdańsk*. Poland .

Yang, W. and W. Blasiak (2005). Numerical Simulation of Properties of a LPG Flame with High-temperature Air. *International Journal of Thermal Sciences*, 44(10): 973-985.

Yang, W. and W. Blasiak (2005). Numerical Study of Fuel Temperature Influence on Single Gas Jet Combustion in Highly Preheated and Oxygen Deficient Air. *Energy, 30(2): 385-398.*

Yang, W. a. W. B. (2006). CFD as Applied to High Temperature Air Combustion in Industries Furnaces. *IRFR Combustion Journal*, 1562-479X

Yu, B., S.-M. Kum, C.-E. Lee and S. Lee (2013). Effects of Exhaust Gas Recirculation on the Thermal Efficiency and Combustion Characteristics for Premixed Combustion system. *Energy,* 49: 375-383.

Yu, B., S.-M. Kum, C.-E. Lee and S. Lee (2013). Study on the Combustion Characteristics of a Premixed Combustion System with Exhaust Gas Recirculation. *Energy*, 61: 345-353.

Yuan, J. and I. Naruse (1998). Modeling of Combustion Characteristics and NOx Emission in Highly Preheated and Diluted air Combustion. *International journal of energy research*, 22(14): 1217-1234.

Zhenjun, C., Z. Tong and J. Chaohua (2010). Thermal and Emission Characteristics of High Temperature Air Combustion: A Technical Review. *Mechanic Automation and Control Engineering (MACE), 2010 International Conference, IEEE*. 26-28 June.Wuhan, China..