NUMERICAL SIMULATION OF TANGENTIAL FLOW FLAMELESS COMBUSTION PROCESS

EHSAN HAMIDI

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Specially dedicated to *my parents and bothers*

I really thank you for your support.

Ehsan

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ABSTRACT

Rapid industrialization and changes in life style cause a teremendous increase in energy consumption. Fossil fuels are the most common energy source in the world. Increasing of fuel consumption cuased more pollutant formation and resources depletion. In this project flameless combustion has been investigated as a reliable solution to this problem. Many studies has been carried out on different setup of flameless burners. In this thesis a new setup has been studied that is tangential fuel-oxidizer arrangement of inlets. This study shows that changing in the arrangement of inlets from co-axial to tangential will increase the efficiency of the lab scale combustor upto 14% and caused reduction of emissions and in particular NOx formation upto 55%. Also it has been concluded that the maximum temperature of flameless combustion in this new setting is higher by about 12%. Additionally this maximum temperature occurs near the wall of the combustor despite of co-axial flow which its highest temperature occurs at the center line. This phenomena helps improving of combustion efficiency. Because the most application of this kind of burners are in the boilers and the pipes which carry water to be heated are installed near the wall of boilers this issue can be considered as a big advantages of tangential flow flameless combustion process rather than co-axial one.

ABSTRAK

Perindustrian yang pesat dan perubahan gaya hidup menyebabkan peningkatan terememdous dalam penggunaan tenaga. Bahan api fosil adalah sumber tenaga yang paling biasa di dunia. Meningkatkan penggunaan bahan api cuased lebih pencemar pembentukan dan sumber mendadak. Dalam projek ini flameless pembakaran telah disiasat sebagai penyelesaian yang boleh dipercayai untuk masalah ini. Banyak kajian telah dijalankan ke atas persediaan yang berlainan pembakar flameless. Dalam tesis ini persediaan baru telah dikaji iaitu tangen susunan bahan api-pengoksida teluk. Kajian ini menunjukkan bahawa perubahan dalam susunan teluk dari bersama-paksi untuk tangen akan meningkatkan kecekapan pembakar skala makmal hamper 14% dan menyebabkan pengurangan pengeluaran dan dalam pembentukan NOx tertentu hamper 55%. Juga ia telah membuat kesimpulan bahawa suhu maksimum flameless pembakaran dalam suasana baru ini adalah lebih tinggi oleh kira-kira 12%. Selain itu suhu maksimum ini berlaku berdekatan dengan Dinding pembakar walaupun aliran bersama-paksi yang suhu tertinggi berlaku pada garis tengah. Fenomena ini membantu bertambah baik kecekapan pembakaran. Oleh kerana aplikasi yang paling seperti ini pembakar berada dalam dandang dan paip yang membawa air ke dipanaskan dipasang berdekatan dengan Dinding dandang isu ini boleh dianggap sebagai satu kelebihan besar tangen proses pembakaran aliran flameless bukannya ko-paksi

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R_i	-	the net rate of production of species i
S_i	-	the rate of creation from dispersed phase
N	-	the total number of fluid phase chemical species
Sc_t	-	the turbulent Schmidt number
μ_t	-	the turbulent viscosity
D_t	-	the turbulent diffusivity
ε	-	the dissipation rate
k	-	the thermal conductivity
$M_{w,i}$	-	the molecular weight of species i
$\hat{R}_{i,r}$	-	the Arrhenius molar rate of creation of species i in reaction r
N	-	number of chemical species in the system
$\nu'_{i,r}$	-	stoichiometric coefficient for reactant i in reaction
$\nu''_{i,r}$	-	stoichiometric coefficient for product i in reaction
$\mathcal{M}_i$	-	symbol denoting species i
$k_{f,r}$	-	forward rate constant for reaction r
$k_{b,r}$	-	backward rate constant for reaction r
$C_{j,r}$	-	molar concentration of species j in reaction r (kmol/m3)
$\eta'_{j,r}$	-	rate exponent for reactant species j in reaction r
$\eta''_{j,r}$	-	rate exponent for product species j in reaction r
$\gamma_{j,r}$	-	the third-body efficiency of the jth species
A_r	-	pre-exponential factor (consistent units)
β_r	-	temperature exponent (dimensionless)

E_r	-	activation energy for the reaction (J/kmol)
R	-	universal gas constant (J/kmol-K)
K_r	-	the equilibrium constant for the *r*th reaction
P_{atm}	-	atmospheric pressure
S_i	-	the entropy of the *i*th species
h_i	-	the enthalpy of the *i*th species
R_n	-	the production rate of species *n*
$J_{n,i}$	-	the diffusion flux of species *n*

CHAPTER 1

INTRODUCTION

1.1 Background

Combustion, mankind's oldest technology, still provides more than 95% of the energy consumed throughout the world [1], and despite the continuous search for alternative energy sources, there is little doubt that combustion will remain important for many years to come. While early combustion research was focused on efficiency of combustion processes, today research on pollutant formation in combustion is becoming increasingly important.

Among fossil fuels, natural gas is the cleanest. Natural gas is primarily composed of methane with very low or no nitrogen or sulphur content. During combustion very small amounts of sulphur dioxide and nitrogen oxides and virtually no ash or particulate matter are released. Coal and oil, on the other hand, have much higher nitrogen and sulphur contents and a higher carbon ratio than natural gas. By combustion of natural gas less carbon dioxide will be produced per energy unit burnt compared to coal and oil.

Natural gas is considered as a clean fuel compared to the other fossil fuels, but formation of unwanted pollutants, such as nitrogen oxides, are still taking place while burning this fuel. Research in the field of natural gas combustion to increase combustion efficiency and abate formation of pollutants emitted to the atmosphere are therefore still of importance.

Emissions reduction and efficiency improvement have been long-standing goals for combustion system designers. In the combustion of conventional fuels, emissions of CO_2, unburned hydrocarbons (UHC), CO, CO_2, soot particulates, NOx and SOx have been of particular concern due to their detrimental impact on health and the environment. Greenhouse gases such as CO_2, H_2O, CH_4, N_2O and chloro-flouro carbons have been found to be the major contributors to the global warming problem, and there is an unmistakable consensus that there is an urgent need to curtail the anthropogenic contribution of these gases [2]. As a result of the Kyoto Protocol, many countries are considering emissions trading and imposition of taxes on CO_2 generation. Several countries have taken initiatives to improve energy efficiency and harness pollution-free energy resources and technologies. Renewable energy resources like wind, hydraulic or solar energy are likely to reduce overall emissions; however, these cannot entirely meet the growing energy demand.

Biofuels have been proposed as a short term solution to heightening energy and pollution crisis. Biofuel combustion is considered to reduce CO_2 impact on the environment, since the biomass consumes CO_2 in its production cycle before being used as a fuel. Using CO_2 sequestration and storage is another proposed CO_2 reduction concept. Integrated gasification combined cycle (IGCC) plants fired with biomass, are one example of reduced CO_2 emissions and clean combustion technology that employs gasification of biomass to produce syngas and its subsequent combustion. CO_2 separation can be achieved through installation of additional equipment, as in open or semiclosed combined cycle gas turbine (CCGT) plants, or chemically reformed gas turbine (CRGT) plants, where fuel is treated with steam to increase its hydrogen content and its subsequent oxy-fuel combustion [3]. Thermo-chemical reforming (TCR) may also be employed by mixing fuel with steam and insufficient oxygen, resulting in partial oxidation or mixing with recirculated exhaust gases (containing steam from combustion products). The benefits of this include reduction in combustion irreversibility and recovery of exhaust heat [3]. Other concepts for CO_2 reduction include partial oxidation cycles and burning carbon-free fuels.

NOx (NO and N2O) is another major pollutant from high temperature combustion systems, known for its deleterious effects. It forms acid rain and contributes to global warming (through production of ground level ozone) [2]. The formation of ground-level ozone due to NOx is also known to aggravate respiratory problems [2]. Low NOx systems and ultra-low NOx systems have been proposed with emissions below 10 ppm, and several NOx reduction strategies have been employed. Wünning and Wünning [4] have discussed reduction of NOx through several techniques. Thermal NOx can be reduced through flame cooling techniques, including injection of NH3 or H2O (wet NOx control) or cooling through exhaust gas recirculation (EGR) or cooling rods in burners (dry NOx control) [4].

Multistaging and usage of high velocity inlet streams are employed to cool fresh charge with exhaust products, for dry NOx control Wünning and Wünning [4]. Lean premixed technology [5] uses premixed air and fuel combustion with excess air for flam e temperature suppression. The technology, however, suffers from problems of poor combustion stability and flashback [4]. The GE Rich-Quench-Lean technology [6] uses fuel-rich primary zone combustion, followed by a fuel-lean low temperature combustion, for thermal NOx reduction [7]. For reduction of fuel-bound NOx, reburning strategies are used for reduction of NOx to N2.

Oxyfuel combustion is yet another dry NOx reduction technique, and has been employed in zero emissions semiclosed cycle concepts [3]. However, it suffers from drawbacks of O2 expense, the need for the system to be air-tight, and that nitrogen-bound fuels cannot be used (such as natural gas with up to 14% nitrogen) [4]. Secondary NOx removal strategies include selective catalytic reduction (SCR) and selective non-catalytic reduction (SCNR). These are particularly useful for retrofitting older high emissions technologies, but may be expensive [4]. Staged combustion for NOx reduction may be applied by air or fuel staging (or reburning), air staging being a more effective approach [8]. Xu et al. [8] also suggested that NOx formation in fuel-rich or reburning zones is hindered by the absence of O and the profusion of CHi radicals.

SCR is a wet NOx removal strategy and involves ammonia injection for reduction of NOx to N2. The reactions [9] for NOx removal are given below:

$$4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O \tag{1.1}$$

$$2NO_2 + 4NH_3 + O_2 \rightarrow 3N_2 + 6H_2O \tag{1.2}$$

Particulate matter (PM) consist of very small condensed phase particles including aerosols, dust, etc. dispersed in the atmosphere, and they impact the lungs (aggravate asthma, bronchial diseases) and the heart [2]. Particulate matter less than 10 microns and fine particles of size less than 2.5 microns are of particular concern due to the problems associated with decreased visibility [2]. The soot particulates are typically of the order of 0.5 to 50 nm, and are a result of combustion under local fuel-rich conditions. These are predominantly composed of carbon in the form of polyaromatic hydrocarbons (PAH), known to be carcinogenic. Small sized particulates are easily ingested in the human pulmonary system, and are significant contributors to bronchial disorders and lung cancer. The traditional approach for reduction of soot emissions was that of providing adequate time, temperature and turbulence [7] for combustion. Using hydrogen fuel combustion has been proposed as one of the means of curtailing soot and UHC emissions.

Carbon monoxide is extremely dangerous when respirated in excessive quantities, since it binds with hemoglobin and prevents oxygen supply in the blood. It is known to have detrimental effects on the heart and the nervous system [2]. The reduction of CO, UHC and soot emissions in combustion systems, is typically achieved by increasing the residence time inside the combustion chamber, and avoiding cold-spots through efficient design. The CO, UHC and soot emissions are typically lower for fuel-lean combustion, for a range of equivalence ratios. The key problem in optimization of emissions is that, simultaneous reduction of CO, UHC, soot emissions and NOx, imposes severe constraints on the system variables, and may be extremely challenging in conventional combustion systems [7].

However, semiclosed cycles can achieve substantially lower carbon (CO_2, CO, UHC and soot emissions) as well as NOx emissions, and are a key motivation behind this work.

1.2 Motivation

Flameless combustion is a recent technology developed for control of nitrogen oxides in the field of combustion engineering. Various names and acronyms have been used to describe this technology including Fuel/Oxidant Direct Injection (FODI) [10], flameless oxidation-FLOX [4], MILD or diluted combustion [11] and High Temperature Air Combustion (HiTAC) [12]. The nitrogen oxides, or NOx, of interest in this subject include NO and NO_2. N_2O is placed in the category of a Greenhouse Gas and isn't usually categorized as NOx. Flameless combustion provides lower NOx emissions based on in-furnace control of the mixing and reaction mechanisms rather than post treatment methods such as Selective Catalytic Reduction (SCR) [13] or Selective Non-Catalytic Reduction (SNCR) [14] in combustion facilities. Side benefits of flameless combustion include lower peak gas temperatures, uniform heat transfer to furnace loads and compatibility with energy saving strategies such as air preheat and oxy-fuel combustion.

Combustion-generated NOx is formed by three mechanisms [15]: thermal-NOx, prompt-NOx, and fuel-NOx. Thermal-NOx, normally produced from the reaction of oxygen and nitrogen in the combustion air, is considered the dominant mechanism and is closely related to the reaction temperature in the combustion environment. Methods to reduce thermal-NOx formation include lowering the peak combustion temperature, shortening the residence time of combustion air within the high peak temperature region, and lowering the concentration of nitrogen in the combustion air. With flameless combustion, the reaction product gases are mixed with the fuel and oxidant reactants producing a very diffuse reaction zone – the combustion products (e.g. CO_2, H_2O, CO) are entrained into the reactant feed streams before the main combustion reaction occurs.

The diluted reactants cause a small amount of heat release (small temperature variance) and relatively slow combustion reaction (fast energy diffusion). Accordingly, there is a relatively low and uniform gas temperature profile in the furnace environment with a significant reduction in thermal-NOx production.

The High Speed Reacting Flow Lab (HiREF) of UTM initially developed an ultra-low NOx burner (non-premixed, natural gas-fired, multiple-jet burner, see Figure 1.1), by adopting the flameless combustion technology. This burner was further studied and improved by some of students. A key configuration of the geometry of the this burner, called the 'Strong-Jet/Weak-Jet' (SJ/WJ) configuration, was also studied to understand fundamental characteristics of flameless combustion in the burner [16]. The burner system includes a fuel inlet and four oxidant feed streams. The inlets have a similar diameter leading to a higher momentum (the Strong Jet) for the oxidant feed and a lower momentum (the Weak Jet) for the fuel feed. The jet feed streams are separated by a specified distance and angle as shown in Figure 1.2.

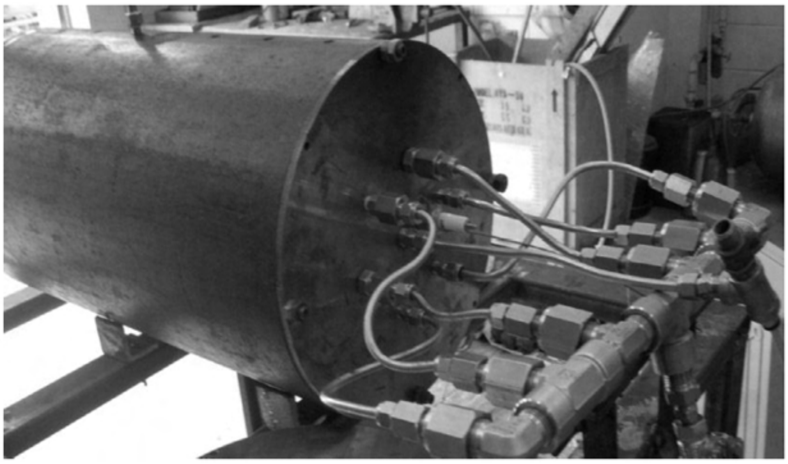

Figure 1.1 The installed flameless combustion system in The High Speed Reacting Flow

Several subjects such as the aerodynamic interaction [16], chemical kinetics and reduction of reaction mechanisms for flameless combustion [17], and Computational Fluid Dynamics (CFD) simulation of the flameless combustion in the furnace [18] were previously studied. Although these previous work made significant contributions in many respects, they have several limitations. This study was, therefore, motivated to improve previous studies and to understand the flameless combustion in the context of different configuration.

1.3 Research Objectives

The objectives of this present study consist of three parts: (a) a development of 3-D physical model for an isothermal, tangential system, (b) a simplification of a detailed chemical reaction mechanism for flameless combustion, and (c) Reynolds-Averaged Navier-Stokes (RANS) simulation of the turbulent, flameless combustion combined with the simplified chemical kinetics in the furnace.

A 3-D integral model [19] was previously developed to predict the co-axial system behavior and showed good agreement with experimental data. But, besides some advantages such as uniformity, the co-axial model has a number of limitations: as one of the major disadvantages of that, it can be said that in this model fuel and oxidizer do not mix as well as tangential one. Although in tangential model lowering the peak combustion temperature cannot be achieved as co-axial one, shortening the residence time of combustion air within the high peak temperature region can be produced well, so it can be predicted that, as the main goal, lower NOx emissions will be produced in this model. Hence, a 3-D physical model of tangential flow was developed in the present work to overcome the limitations. In addition, important design/operation factors were identified from the 3-D physical model.

The chemical reaction kinetics of flameless combustion is considered to be different from that of typical conventional combustion because of distinct differences in the reaction rates. Accordingly the current reduced chemical kinetic models or those based on few reaction steps, while useful in CFD simulation, have limitations for flameless combustion because they are normally suitable only for typical, conventional combustion systems. Gokulakrishnan [20] attempted to reduce a detailed chemical reaction mechanism for flameless combustion by using Principal Component Analysis (PCA) and sensitivity analysis, but the resulting reduced mechanism contains too many species and reactions to be used in CFD simulation.

In this study a significant simplification of a detailed chemical reaction mechanism was made for flameless combustion.

For simplicity many researchers have conducted CFD simulation of flameless combustion with a fast-chemistry assumption [21-24] and global multi-step reaction mechanisms [4, 22-27]. However, some researchers have considered the effects of the detailed chemical kinetics on flameless combustion through the flamelet model [28-31], the Eddy Dissipation Concept (EDC) [30] and the Conditional Moment Closure (CMC) method [32]. In this work, steady-state simulation of the turbulent flameless combustion in the furnace was conducted using the Finite Rate, Eddy Dissipation and Eddy Dissipation Concept methods to examine the effects of detailed chemical kinetics and comparing them with non-premixed method.

In this project, the flameless combustion system includes furnace and refractory, burner and control system has been modelled. Also, installation of the system is one of the objectives of this project. At the end the system was run in conventional and flameless combustion mode and the performance of this system evaluated in fuel consumption and NOx formation aspects.

The objectives of this research are:

1. To Simulate the Flameless Combustion Process Using FLUENT Software

2. To Investigate the Aerodynamic and Pollutant Formation in the Flameless Combustor

3. To study and compare the combustion efficiency, pollutant emissions generation (in terms of CO and NOx) of tangential Fuel-Oxidizer injection, with respect to co-axial flow

4. To investigate the performance (emissions, combustion efficiency and stability) of different solving methods of CFD (e.g., Finite Rate, Eddy Dissipation and Eddy Dissipation Concept), and present a comparison with Non-Premixed solution method.

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