COMPUTATIONAL STUDY OF TURBULENT UNCONFINED SWIRL FLAMES

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To my beloved father and mother
Siblings and the special one
Thank you for your love and moral support

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ABSTRACT

This study investigates the performance of Reynolds Averaged Navier-Stokes technique in predicting the behavior of swirl flames as well as a parametric study on the effects of fuel jet velocity and swirl number on the structure of the swirl flames. Two turbulence models which are realizable k-ε and standard k-ω from RANS technique were chosen and applied as the closure model. Comparison of simulation results were done with the experimental evidence obtained from Sydney University database and it is found that both models show good performance in predicting the turbulent swirl flame near the vicinity of the burner exit plane. However, due to isotropic nature of the two-eddy viscosity model, turbulent swirl flows farther downstream were not accurately captured.

Parametric studies on the effects of fuel jet velocity and swirl number on the swirl flame structure were done. Simulation of turbulent unconfined swirl flames shows that the structure of the swirl flames is consists of outer and inner recirculation zones. The outer recirculation zone occurs due to the bluff-body effect; meanwhile the inner recirculation zone occurs farther downstream due to reversed flow. For fuel jet velocity, an increase in the velocity causes suspension of the occurrence of secondary recirculation zone. In this case, for higher fuel jet velocity, longer time is required for the fuel jet to decay and recirculation zone to form. In addition to that, the flame height increases with increasing fuel jet velocity. On the other hand, an increase in swirl number causes an increase in flame width and flame height. Results from the simulation have also shown that for low swirl number of 0.3, recirculation zones were absent. As swirl number increases, the tangential momentum of air flow increase and therefore greater adverse pressure gradient will be produced. As a result, fuel jet is prohibited to travel farther downstream, and flow is reversed back into the recirculation zone.

ABSTRAK

Kajian ini bertujuan untuk mengkaji prestasi teknik Reynolds Averaged Navier-Stokes (RANS) dalam meramal kelakuan api berpusar. Di samping itu, kajian parametrik untuk mengkaji kesan halaju bahan api dan nombor pusaran ke atas struktur api berpusar juga dilaksanakan. Dua model pergolakan dari teknik RANS dipilih dan digunakan sebagai model penutupan iaitu dua-persamaan Eddy-viscosity Realizable k-ε dan Standard k-ω. Perbandingan antara keputusan dari simulasi dan keputusan eksperimentasi dari pangkalan data Universiti Sydney telah dilakukan dan kedua-dua model pergolakan telah mempamerkan prestasi yang baik dalam meramal api golak berpusar di persekitaran salur keluar pembakar. Walau bagaimanapun, oleh kerana sifat isotropi yang dimiliki dua model tersebut, pergolakan berpusar di hilir pembakaran tidak dapat diramalkan dengan tepat.

Simulasi pergolakan api berpusar terbuka menunjukkan struktur api berpusar adalah terdiri daripada zon edaran semula luaran dan dalaman. Zon edaran luaran terjadi akibat dari kesan “bluff-body” manakala zon edaran dalaman terjadi di hilir aliran akibat dari aliran berpatah balik. Untuk halaju bahan api, peningkatan dalam halaju bahan api menyebabkan kelewatan dalam pembentukan zon edaran semula. Dalam kes ini, semakin tinggi nilai halaju bahan api, semakin banyak masa diperlukan untuk jet dan pembentukan zon edaran semula. Tambahan dari itu, ketinggian api juga meningkat selari dengan peningkatan halaju bahan api. Manakala, peningkatan nombor pusaran akan mengakibatkan peningkatan dalam kelebaran api dan ketinggian api. Keputusan simulasi menunjukkan bahawa untuk simulasi pada nombor pusaran rendah iaitu 0.3,zon edaran semula tidak terbentuk. Apabila nombor pusaran meningkat, momentum tangent aliran udara meningkat dan kecerunan tekanan yang tidak diingini akan terbentuk. Akibatnya, jet bahan api terhalang dari terus mengalir ke hilir, dan aliran di edarkan semula ke dalam zon edaran semula.

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LIST OF ABBREVIATIONS

CFD	–	Computational Fluid Dynamics
RANS	–	Reynolds Averaged Navier-Stokes
LES	–	Large Eddy Simulation
DNS	–	Direct Numerical Simulation
PVC	–	Precessing Vortex Core
NOx	–	Nitrogen Oxides
PDF	–	Probability Density Function
MILD	–	Moderate and Intense Low Oxygen Dilution

LIST OF SYMBOLS

r – Radial location (mm)

x – Axial location (mm)

R_b – Radius of bluff-body (25 mm)

D – Diameter of air annulus (50 mm)

Re – Reynolds number

Re_{jet} – Reynolds number for fuel jet

Re_S – Reynolds number for swirl flow

S – Swirl number

S_g – Geometric swirl number W_s/U_s

W_s – Tangential velocity of primary air annulus

U_s – Axial velocity of primary air annulus

U_j – Velocity of fuel jet

U_e – Co-flow velocity of air tunnel

ρ – Density of gas (kg m^{-3})

ν – Viscosity of air (1.51 x 10^{-5} m^2s^{-1})

mm – Milimeter

Pa – Pascal

CHAPTER 1

INTRODUCTION

1.1 Introduction

The increasing demand of energy consumption and the concern of fossil fuels depletion motivate the search and discoveries of alternative energy conversion technologies. However, the alternative technologies are not capable of replacing the internal combustion engines in generating the required energy, for example hydrogen fuel cells. Therefore, researches and development of efficient, low polluting combustion systems are still an on-going process. Researchers and engineers have been collaborating to achieve the goal and making sure that the new combustion systems are reliable and acceptable for the industry.

One of the major concerns with combustion system is the emission of pollutants especially nitric oxide. Recent years has shown a progress in the development of combustion system to reduce NOx emissions. Many countries have implemented the law of which every internal combustion engines of automobiles have to be installed with catalytic converters to reduce the emission of pollutants. Another major concern in the field of combustion is the development of efficient combustion systems and the objective is to ensure complete process of combustion.

In combustion field, employing swirl-stabilised turbulent flames offers favourable features which are enhanced flame stability and pollutant emission reduction (Radwan et al., 2014). The reverse flow through swirl kept the reactants inside the combustor for an enhanced residence time, allowing for better mixing and complete reaction (Kempf et al., 2008). Understanding the mechanism of swirl-stabilised turbulent flames will help to enhance the performance of a combustor, ensuring in complete combustion by better mixing, thus reducing the emission of pollutants.

Computational approach is a powerful tool in predicting and analysing complex flow problems. The primary concern of computational approach is to predict flow separation which greatly influences the efficiency of a device. In computational approach, there are several computational methods available in analysing complex flow problems such as Reynolds averaged Navier-Stokes (RANS), Large Eddy Simulation (LES) and the most advanced Direct Numerical Simulation (DNS). The present study focuses on swirl-stabilised turbulent flame by using RANS methodology to investigate the features and mechanisms of swirling flames. The device of interest for current study is the Sydney swirl burner which is described in this study.

1.2 Background and Rationale

Swirling flows are frequently found in nature and are also common in many practical applications. Naturally occurring tornados, dust devils or waterspouts are dominated by swirl flows. Turbulent swirl flows also play a major role in many non-reacting and reacting engineering applications such as internal combustion engines, burners, vortex shedding from aircraft wings, and cyclone separators. In reacting turbulent combustion systems, swirling flows are favourable due to several benefits. In order to take advantage of swirling flow, one has to understand the mechanism and features of swirling flow. The mechanism of swirling flow is that it produces an adverse pressure gradient that can cause flow reversal or vortex breakdown (Shamami and Birouk, 2008). As a result of flow reversal, some of the combustion products return to the flame fronts to mix with the fresh combustible product (Radwan et al., 2014). In combustion systems, the effects of flow reversal are favourable as it enhanced mixing which leads to better combustion efficiency and less pollutant formation. In addition to that, another feature of swirling flow in combustion is that it stabilizes the flame by reducing the flame length (Meester, Naud and Merci, 2009).

Swirl-stabilised turbulent flames are appealing and relevant for a lot of industrial applications. The aforementioned benefits of swirl-stabilised flames motivate researchers around the world to study the mechanism of swirling flows especially in combustion systems which involve interaction between the flowfield and chemistry. Despite vast amount of study regarding swirling flows, it is yet to be fully understood. Issues concerning complex mechanism of vortex breakdown and precessing vortex core (PVC) are still not fully understood. Vortex breakdown is one of the complex phenomena involved in swirl flames which leads to flow instability such as precessing vortex core (PVC) and periodically expanding or shrinking of recirculation zone (Meester, Naud and Merci, 2009). Therefore, it is in need to further investigate the mechanism and behaviour of swirling flow in order to achieve optimum performance in any swirl-stabilised combustion systems.

The present study focuses on swirl in combustion systems using computational approach. The structures of swirling flows such as the vortex breakdown, recirculation zone, and precessing vortex core are to be studied. Swirling flow is characterised by swirl number which represent the degree of swirl. This study will investigate the effect of fuel jet velocity and swirl number on the structure of swirl flames by observing the mean axial velocity, velocity contours, streamlines, and temperature distribution of the swirling flame. RANS methodology is adopted in analysing complex turbulent swirl-stabilised flame considering the computational cost and time. Evaluation of different RANS turbulence models will be done by comparing the accuracy of the simulation results with experimental data.

1.3 Problem Statement

Efficient combustion means complete combustion of reactants and minimal amount of pollutants released. This is achievable by better mixing of fuel and oxidants during combustion process and by recirculation of combustible products back into combustion process to reduce emission of pollution. The most common method to achieve efficient combustion process is by introducing swirling flow in the combustion system. However, the precession, recirculation, vortex breakdown, and instabilities of swirling flows are the major concerns and have received much attention. In addition, the effects of swirl number from low swirl number to high swirl number on non-premixed combustion is still not fully understood. Therefore, understanding the features and behaviour of swirling flame and investigating factors that could affects the structure are urgently needed to cater these problems.

1.4 Significance of the Study

The purpose of this study is to gain in-depth understanding of the behaviour of turbulent unconfined swirl flames. For confined swirling flow, the boundary conditions are complicated and such flows are extremely difficult to predict computationally (Al-Abdeli and Masri, 2003). Furthermore, sudden expansion and confinement are known to aggravate jet precessing and acoustic instabilities (Al-Abdeli and Masri, 2003). In this study, computational work is made tractable by employing unconfined swirl flames with simplifications to the boundary conditions.

Numerical investigation is essential for such complex swirl flames as experimental works are extremely expensive and time consuming. Therefore, using computational approaches in predicting and analysing swirling flow features is an outstanding effort. This study focuses on predicting flow of unconfined swirl flame using RANS methodology and evaluating different RANS turbulence models. Computational work is done using ANSYS FLUENT software.

1.5 Objectives of the Study

i. To develop and validate a 3D time-averaged CFD model for unconfined swirl flames.

ii. To conduct parametric study using the CFD model to study various features of swirl flames.

iii. To investigate the effect of fuel jet velocity and swirl number on flame structure and temperature.

1.6 Scope of the Study

The research scope focuses on the modelling of unconfined swirl flames. The general-purpose software ANSYS Fluent will be used to develop the CFD model. Experimental measurements of Sydney burner will be used to validate the model. The scope of the parametric study includes the effect of fuel jet velocity and swirl number on the flame structure and temperature.

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