AIN SHAMS UNIVERSITY

FACULTY OF ENGINEERING

EFFECTS OF CROSS-FLOW AND DOUBLE SWIRL ON VITIATED CO-FLOW JET FLAMES

By

Ghada Abd El Zaher El-Saeed Ali El-Gamal

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Under The Supervision of

Dr. Abd El-Aziz Morgan Abd El-Aziz

Associate Professor at the Mechanical Power Department

Faculty of Engineering

Ain Shams University

Dr. Mahmoud Mohamed Kamal Abd El-Aziz

Associate Professor at the Mechanical Power Department

Faculty of Engineering

Ain Shams University

Cairo

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Name of Researcher : Ghada Abd El Zaher El-Saeed Ali El-Gamal

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Examiners Committee

1. **Prof.Dr. Mahmoud Abd El-Fatah El- Kady**

   Professor at the Mechanical Power Department

   Faculty of Engineering

   Al Azhar University

2. **Prof.Dr. Mahmoud Abd El-Rasheed Nosier**

   Professor at the Mechanical Power Department

   Faculty of Engineering

   Ain Shams University

3. **Dr. Abd El-Aziz Morgan Abd El-Aziz**

   Associate Professor at the Mechanical Power Department

   Faculty of Engineering

   Ain Shams University

4. **Dr. Mahmoud Mohamed Kamal Abd El-Aziz**

   Associate Professor at the Mechanical Power Department

   Faculty of Engineering

   Ain Shams University

AIN SHAMS UNIVERSITY

FACULTY OF ENGINEERING

Curriculum Vitae

Name of Researcher : Ghada Abd El Zaher El-Saeed Ali El-Gamal

Date of Birth : February, 19th , 1985

Place of Birth : Tanta, Al- Gharbeia , Egypt

First University Degree : B.Sc. in Mechanical Engineering

Department : Mechanical Power

University : Ain Shams University

Date of Degree : July, 2007

Current Job : Mechanical Power Engineer

Signature :

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ABSTRACT

Effects of Cross-Flow and Double Swirl on Vitiated Co-Flow Jet Flames

An experimental work was carried out to investigate the influence of the cross-flow and the double swirl on the performance of co-flow jet flames (as vitiated by the confining streams). The cross-flow was employed in the form of opposing jets (to be either air or reactive streams). The double swirl effect on the premixed flames was pronounced with co- and counter-swirl modes. The target was to enhance the flame stability while keeping high values for the combustion efficiency so as to combine the favorable features of reduced NOx emissions and minimized carbon monoxide and unburned hydrocarbons. The momentum flux ratio, the swirl intensity and the relative swirl angle as well as the vitiating stream heat input ratio are correspondingly involved as the working parameters. Inasmuch as the strain rate dramatically affects the flame stability limits, the turbulent kinetic energy was computed to address the flow-straining features. Due to increased power demands in combination with stringent environmental regulation, the combustion designer seeks innovative firing techniques for maximizing the turn down ratio thus controlling the power output flexibly via extending the flame stability limits. A combination between passive and active control techniques is commissioned to achieve these targets.

A test rig (comprising a cylindrical combustor and fitted with a double swirler burner in addition to cross-flow admission holes) was commissioned for the experimental study. While separate valves were utilized to control the flow of the different reactive streams, orifice-flow meters were used to determine the flow rates. The quantification of the effects of the different working parameters on the flame performance was provided by an S-type thermocouple (for the gas temperatures) and an electrochemical gas analyzer (for the exhaust gas concentrations). Flame imaging was also used to qualitatively verify the experimental results. A computational Fortran code was operated for the numerical part of the work.

The characterization of the vitiated jet flames (as surrounded by the hot gases pertaining to another flame) involves either normal or inverse triple flames. The tangential inlet swirl

arrangement was thus employed to provide the swirl for the outer reactive stream. Due to such enhanced flow strain, the combustion efficiency (for the diffusion flame established between the triple flame two wings) was significantly improved.

It was found that employing double and tertiary swirl arrangements as well as opposing jets pronounced increased burning capacities relative to conventional co-flow normal and inverse triple flames due to the increased strain rates. The subsequent reduction in both the residence time and the peak flame temperatures led to significant reduction in NOx concentrations. Inasmuch as wall quenching was retarded by excess oxygen and hot gas recirculation, swirling a lean mixture (around a double swirled vitiated inverse triple flame) sustained higher stability limits than those of swirling both rich mixture and normal triple flame. Decreasing the tertiary-swirled flame jet diameter relative to those of the vitiated stream enhanced the stability limits. Aided by the thermo-diffusive effects of non-unity Lewis number, increasing the mixture fraction gradient sustained an increase in the flame stability limits. Introducing the outer pilot flame via cross-flow multiple opposing jets was more beneficial than tertiary swirl for steepening the mixture fraction gradient as testified by extending the normalized stability limit (that is aided by the enhanced stagnation effects). By modulating the diameter and separation of the opposing jets (such that the strain rate increases by increasing the mixture flow rate per cross-flow stage), the NOx emissions were minimized.

NOMENCLATURE

A	:	Orifice cross-section area, m^2
A/F	:	Air to Fuel ratio
A_j	:	Junction Surface Cross section area,m^2
a_s	:	Strain rate , s^{-1}
C	:	Sonic velocity, m/s
C_d	:	Coefficient of discharge
C_p	:	Specific heat at constant pressure , J/kg K
CRZ	:	Central Recirculation Zone
CTRZ	:	Central Torroidal Zone
G_x	:	Linear momentum flux , kg/ms^2
G_θ	:	Angular momentum flux, kg/s^2
H	:	Height of working fluid in manometer , m
H_r	:	Heat of Reaction , kJ/kg
K	:	Specific heat ratio
k/ε	:	Eddy mixing time scale, is a model based on model transport equations for the turbulence kinetic energy (k) and its dissipation rate (ε), s
L	:	Characteristic length, m
Le	:	Lewis Number, is a dimensionless number defined as the ratio of thermal diffusivity to mass diffusivity.
M	:	Mach number
m^o_{air}	:	Air mass flow rate , kg/s
m^o_{fuel}	:	Fuel mass flow rate , kg/s
P	:	Pressure, N/m^2
R	:	Swirl radius, m
R	:	Gas constant, J/kgK
RR	:	Reaction Rate , kg/m^3s
Re	:	Reynolds' number
S	:	Swirl number, is a non-dimensional parameter characterizing the swirling flows. It is

the ratio of angular momentum flux, G_θ to the linear momentum flux G_x multiplied by a characteristic length, L

S1	:	Inner Swirl
S2	:	Double Swirl
S3	:	Tertiary Swirl
T	:	Temperature , K
T_f	:	Flame Temperature, K
T_j	:	Junction Temperature, K
T_w	:	Wall Temperature, K
U	:	Axial Velocity, m/s
U_{Conv}	:	Convection Heat Transfer Coefficient, Watt/m^2.K
V	:	Radial Velocity, m/s
W	:	Tangential Velocity , m/s
X	:	Distance, m
Y_f	:	Fuel Mass Fraction
A	:	Burner quarl angle , rad
ε_{jf}	:	Junction/Flame Combined Emissivity.
ε_{jw}	:	Junction/Wall Combined Emissivity.
Y	:	Coefficient of kinematic viscosity, m^3/s
Θ	:	Swirl vane angle , rad
P	:	Density, kg/m^3
Σ	:	Boltzman Constant, Watt/m^2.K^4
Φ	:	Equivalence Ratio

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CHAPTER 1

INTRODUCTION

1.1. General:

There is always a direct impact for turbulence on combustion rates and flame stability limits which can be favorably modulated to increase the thermal loading, minimize pollutants and establish reliable firing techniques.

As mixing between reactive premixed streams are concerned in combustors wherein pilot jet flames support combustion of vitiated streams, the enhanced heat and active species mass transport reflects such couple between the flow turbulence development and chemical kinetics. For sustaining higher combustible flow rates, reverse flow techniques such as swirl are commissioned to stimulate local stagnation and flow prolonged residence times [Liao et al., (2000)]. The series of flow instabilities associated with the vortex breakdown provide strong turbulence. The modulation of the flow/combustion interference is enhanced by involving a double swirl flow [Ghanem,(1996)].

The fundamental aspect of double swirl is thus it has a great variety for having significantly different radial flow distribution and swirl [Gupta et al., (1998)]. In this sense, double swirl flow is aerodynamically controlled via variation in the individual swirl strength, the swirl diameter ratio, the expansion ratio as well as the swirl mode (either co- or counter-swirl).

Representing a unique arrangement for interacting premixed flames at different stoichiometry levels, triple flames have recently been highlighted for use in industrial burners rather than as model flames to study flame stability, lift off and turbulence characteristics. While a triple flame structure model evolving downstream of lifted turbulent jet diffusion flame ports is receiving a great attention [Patwardhan, et. al.,(2009)],Stated that there is a potential merit for those triple flames of originally premixed streams [Kamal, (2001)]. As testified to have extended flame stability limits by the preferential diffusion effects for Lewis number less than unity [Echekki and Chen, (1998)], such triple flames were found to be more compact in comparison to non-premixed and partially premixed flames at the same firing rate [Kamal, (2001)]. In order for these originally-fed triple flames to sustain much higher advection velocities of reactive streams, different aerodynamic techniques may further support diffusion of heat and species from the non-premixed flame kernel into the premixed streams. In this sense, the present work is commissioned to reveal an aerodynamic development in the performance of such triple flames by employing the swirl technique which enhances the entrainment by involving different velocity streams.

On the other hand, vitiated co-flow flames have been studied for the purpose of characterizing the heat recirculation from exhaust gases into the reaction zone. While in practical combustion systems the hot gases are often re-circulated to enhance flame stability, their associated turbulence prediction in complex recirculating flow fields is a significant challenge for current models [Cabra et al.,(2005)]. In this regard, the vitiated co-flow flame is a turbulent reacting flow model within a hot environment but with a simplified geometry as it consists of a fuel jet issuing into a co-flow of hot combustion products from a lean premixed flame. The lift-off height, which nominally corresponds to an average stabilization position of the flame, is sensitive to several flow and flame parameters, especially the co-flow temperature [Zhijun et al.,(2005)]. For further characterization, the present work involves the strengthening of such vitiated flow heat recirculation by the swirl and its effective entrainment. This will be highlighted for triple flames currently introduced in two stages in order to achieve the goal of their innovative use in industrial burners. Herein, hot gases issuing from the earlier flame act as the vitiating co-flow or the pilot flame for the other one allocated downstream as a vitiated flow.

Similar to partially premixed flames which exploit the advantages of enhanced flame stability and higher combustion efficiency, triple flames are regarded beneficial in the same sense that they have much higher stability limits than their counter-part pure premixed flames. In the same time, they still pronounce higher combustion efficiencies than their respective diffusion flames since both reactant streams are premixed. However, as reported in the recent work by [Kamal,(2001)], the simple jet configuration does not ensure an efficiency of 100% for triple flames since the extreme jet close to the combustor wall is either a rich fuel/air stream that starves for oxygen or a lean mixture that has weakened reaction zones. The optimum way to effectively set triple flames into practical application is to apply aerodynamic methods in conjunction with a vitiated co-flow. In addition to entrainment across co-axial jets, severe strain rates may be introduced via cross impinging-flow configurations. Furthermore, both double and triple swirl may be currently employed for much better mixing effects to let the overall stoichiometry (for the violently mixed excess reactant streams from rich and lean fuel sides) liable for efficient combustion. In this case, if the non-premixed flame zone separating the rich and lean premixed jets is stretched by a strong aerodynamic field (such as that associated with impinging jets or multiple swirling fields), higher strain rates are enforced into reactants in a hot environment. With more sustainable reaction zones provided, extended stability limits and better performance are thus expected.

1.2. Present Work Objective:

The current work is thus commissioned to investigate the triple flame stability in conjunction with swirl and its associated entrainment into the flame zone to keep the triple flame practically stable and simultaneously efficient. For such target, the stable triple flame burning capacity (in terms of the mixture velocity) is recorded against the heat input ratio between the pilot and vitiated streams under different parametric conditions. It follows that the favorable effects of different parameters, such as the inner swirl strength, on the stability limits could be highlighted. Combined effects of double and tertiary swirl (via a tangential peripheral entry) are enforced to enrich the heat recirculation into the triple flames (for either a normal or an inverse triple flame configuration). According to [ZhiHua et al., (2007)], with the recirculation of hot combustion products in either case the fuel jets will be auto-ignited and stabilized. Therefore, the different residence times introduced by the different swirl combinations favorably extend the stability limits of those triple flames currently investigated. This is because the different contact times between reactants affect the temperature history of the reactants.

Up to the present study, no work has been reported for application of swirl in triple flames (to highlight the swirl favorable role). It may be convenient to apply triple swirl on triple flames here, since the three concentric jets (comprising both normal and inverse triple