



شبكة المعلومات الجامعية  
التوثيق الإلكتروني والميكروفيلم

# بسم الله الرحمن الرحيم



**MONA MAGHRABY**



شبكة المعلومات الجامعية  
التوثيق الإلكتروني والميكروفيلم



# شبكة المعلومات الجامعية التوثيق الإلكتروني والميكروفيلم



**MONA MAGHRABY**



شبكة المعلومات الجامعية  
التوثيق الإلكتروني والميكروفيلم

# جامعة عين شمس

## التوثيق الإلكتروني والميكروفيلم

### قسم

نقسم بالله العظيم أن المادة التي تم توثيقها وتسجيلها  
علي هذه الأقراص المدمجة قد أعدت دون أية تغيرات



### يجب أن

تحفظ هذه الأقراص المدمجة بعيدا عن الغبار



**MONA MAGHRABY**



**A NUMERICAL STUDY OF OPTIMUM NORMALIZED  
PREMIXING LENGTH FOR TURBULENT PARTIALLY  
PREMIXED FLAME IN A CONCENTRIC FLOW  
CONICAL NOZZLE BURNER**

By

**Eng. Ahmed Said Hanafy Mhmoud**

A Thesis Submitted to the  
Faculty of Engineering at Cairo University  
in Partial Fulfillment of the  
Requirements for the Degree of  
**MASTER OF SCIENCE**  
in  
**Mechanical Power Engineering**

FACULTY OF ENGINEERING, CAIRO UNIVERSITY  
GIZA, EGYPT  
2021

**A NUMERICAL STUDY OF OPTIMUM NORMALIZED  
PREMIXING LENGTH FOR TURBULENT PARTIALLY  
PREMIXED FLAME IN A CONCENTRIC FLOW  
CONICAL NOZZLE BURNER**

By  
**Eng. Ahmed Said Hanafy Mhmoud**

A Thesis Submitted to the  
Faculty of Engineering at Cairo University  
in Partial Fulfillment of the  
Requirements for the Degree of  
**MASTER OF SCIENCE**  
in  
**Mechanical Power Engineering**

Under the Supervision of

**Prof. Dr. Hatem Omar Hariedy**

**Dr. Mohamed Fayed Zayed**

.....  
Associate Professor  
Mechanical Power Engineering  
Department  
Faculty of Engineering, Cairo University

.....  
Assistant Professor  
Mechanical Power Engineering  
Department  
Faculty of Engineering, Cairo University

FACULTY OF ENGINEERING, CAIRO UNIVERSITY  
GIZA, EGYPT  
2021

**A NUMERICAL STUDY OF OPTIMUM NORMALIZED  
PREMIXING LENGTH FOR TURBULENT PARTIALLY  
PREMIXED FLAME IN A CONCENTRIC FLOW  
CONICAL NOZZLE BURNER**

By  
**Eng. Ahmed Said Hanafy Mhmoud**

A Thesis Submitted to the  
Faculty of Engineering at Cairo University  
in Partial Fulfillment of the  
Requirements for the Degree of  
**MASTER OF SCIENCE**  
in  
**Mechanical Power Engineering**

Approved by the  
Examining Committee

---

Associate.Prof. **Hatem Omar Hariedy**

Thesis Main Advisor

---

Prof. Dr. **Hindawy Salem Mohamed**

Internal Examiner

---

Prof. Dr. **Mahmoud Abdel-Fatah El Kady**  
Professor, Faculty of Engineering, Al-Azhar University

External Examiner

FACULTY OF ENGINEERING, CAIRO UNIVERSITY  
GIZA, EGYPT  
2021



**Engineer's Name:** Ahmed Said Hanafy Mhmoud  
**Date of Birth:** 26/9/1986  
**Nationality:** Egyptian  
**E-mail:** [En\\_ahmed86@yahoo.com](mailto:En_ahmed86@yahoo.com)  
**Phone:** 01004426355  
**Address:** 13 Ahmed Mukhaimer Street,  
Nozha, Cairo, Egypt  
**Registration Date:** 1/10/2017  
**Awarding Date:** / /2021  
**Degree:** Master of Science  
**Department:** Mechanical Power Engineering



**Supervisors:**

Associate Prof. Hatem Omar Hariedy  
Dr. Mohamed Fayed Zayed

**Examiners:**

Prof. Hatem Omar Hariedy (Thesis main advisor)  
Prof. Dr. Hindawy Salem Mohamed (Internal examiner)  
Prof. Dr. Mahmoud Abdel-Fatah El Kady (External examiner)  
Professor, Faculty of Engineering, Al-Azhar University

**Title of Thesis:**

A numerical study of optimum normalized premixing length for the turbulent partially premixed flame in a concentric flow conical nozzle burner

**Key Words:**

Partially premixed; Conical nozzle burner; Mixing field; Stability; Turbulent flame

**Summary:**

The current work involves a numerical study to validate the numerical models to investigate the effects of the normalized premixing length ( $L/D$ ) at a certain overall jet equivalence ratio ( $\Phi$ ) and a certain Reynolds number ( $Re$ ) on the mixing field structure in a concentric flow burner. Also, involves finding the best normalized premixing length,  $L/D$ , in a concentric flow burner using validated numerical models.

Finally, a numerical study of the partially premixed flame structure in a Concentric Flow Conical Nozzle (CFCN) burner by using numerical models, which included calculating the flame curvature and discussing the influence of equivalence ratio on the structure of the flame and finding the lowest value of the equivalence ratio at which the flame be sustainable.

All numerical studies were carried out for air-natural gas mixture using ANSYS 2020 R2 Package.

## **Disclaimer**

I hereby declare that this thesis is my own original work and that no part of it has been submitted for a degree qualification at any other university or institute.

I further declare that I have appropriately acknowledged all sources used and have cited them in the references section.

Name: Ahmed Said Hanafy Mhmoud

Date: .././2021

Signature:



## **Acknowledgments**

All praises and thanks due to Allah, the most gracious, the most merciful, for providing me with the patience to complete this work.

I am grateful to my supervisors, Associate prof. Dr. Hatem Omar Hariedy and Dr. Mohamed Fayed Zayed to their guidance, advice, and encouragement toward the successful completion of this work. They were helpful, reading and correcting me all the way.

I would also like to send my thanks and gratitude to my father, my mother, my wife, and my family for their care and encouragement for me to finish this work in a suitable form and time.

I would like to express my sincere gratitude to all the people who have been associated with this work, helped me in it, and made it a worthwhile experience.

# Table of Contents

<b>DISCLAIMER .....</b>	<b>I</b>
<b>ACKNOWLEDGMENTS.....</b>	<b>II</b>
<b>LIST OF TABLES.....</b>	<b>V</b>
<b>LIST OF FIGURES.....</b>	<b>VI</b>
<b>NOMENCLATURE .....</b>	<b>VIII</b>
<b>ABSTRACT .....</b>	<b>IX</b>
<b>CHAPTER 1 : INTRODUCTION .....</b>	<b>1</b>
1.1. OVERVIEW .....	1
1.2. FLAME CLASSIFICATION .....	2
1.3. MODELS OF TURBULENT COMBUSTION .....	3
1.4. STABILITY OF FLAME.....	3
1.5. OBJECTIVE .....	3
1.6. THESIS OUTLINE .....	4
<b>CHAPTER 2 : LITERATURE REVIEW .....</b>	<b>5</b>
2.1. INTRODUCTION.....	5
2.2. LABORATORY AND NUMERICAL STUDIES OF A CONCENTRIC FLOW CONICAL NOZZLE (CFCN) BURNERS.....	5
2.3. CONCLUSIONS AND SCOPE OF THE PRESENT WORK .....	16
<b>CHAPTER 3 : MODELING OF CONCENTRIC FLOW AND CONCENTRIC FLOW CONICAL NOZZLE BURNERS .....</b>	<b>18</b>
3.1. PHYSICAL MODEL .....	18
3.2. SYSTEM MODELLING .....	18
3.3. GOVERNING EQUATIONS AND MODELS USED IN THE PRESENT STUDY .....	19
3.3.1. Mass conservation equation .....	19
3.3.2. Momentum conservation equation .....	19
3.3.3. Energy conservation equation .....	20
3.3.4. The discrete ordinates radiation model .....	20
3.3.5. Turbulence model.....	21
3.3.5.1. Reynolds stress models.....	21
3.3.5.2. Large-eddy simulation.....	23
3.3.6. Species transport model .....	24
3.3.7. The partially premixed combustion model.....	24
3.4. DEVELOPMENT OF THE NUMERICAL MODEL .....	27
3.4.1 The non-reacting mixture model .....	27
3.4.2 The reacting mixture model. ....	29
<b>CHAPTER 4 : VALIDATION OF THE DEVELOPED MATHEMATICAL MODEL.....</b>	<b>30</b>
4.1. INTRODUCTION.....	30

4.1.1	Validation of the mixing field structure for $\Phi = 7$ and $Re = 10000$ .....	30
4.1.2	Validation of the mixing field structure for $\Phi = 2$ and $Re = 10000$ based on the quantitative analysis.....	34
<b>CHAPTER 5 : RESULTS AND DISCUSSION.....</b>		<b>37</b>
5.1.	INTRODUCTION.....	37
5.2.	THE BEST VALUE OF THE NORMALIZED PREMIXING LENGTH (L/D).....	37
5.3.	FLAME STRUCTURE .....	38
5.3.1	Calculating of flame curvature.....	39
5.3.2	Effect of equivalence ratio on flame structure .....	41
5.3.3	Finding the lowest value of the equivalence ratio at which the flame be sustainable.....	47
<b>CHAPTER 6 : CONCLUSIONS AND FUTURE WORK RECOMMENDATIONS</b> .....		<b>49</b>
6.1.	INTRODUCTION.....	49
6.2.	CONCLUSIONS .....	49
6.3.	RECOMMENDATIONS FOR FUTURE WORK .....	50
<b>REFERENCES .....</b>		<b>51</b>

# List of Tables

Table 2. 1: Regime diagram limits [20].....	12
Table 3. 1 Laminar flame speeds of CH <sub>4</sub> /air flames, as a function of mixture fraction, Z.....	26
Table 3. 2 Representative mesh report .....	29
Table 4. 1: The main parameters of $\Phi = 7$ and $Re = 10000$ . ....	30
Table 4. 2: The main parameters of $\Phi = 2$ and $Re = 10000$ . ....	34
Table 4. 3 values of $R\Delta$ and $RZ$ for $\Phi = 2$ and $Re = 10000$ at $L/D=2$ , $L/D=3$ , $L/D=4.5$ , $L/D=6$ , $L/D=10$ and theoretical fully premixed. ....	35
Table 5. 1 : Values of $R\Delta$ , $RZ$ for $\Phi = 2$ and $Re = 10000$ at $L/D=6.5$ , $L/D=3$ and $L/D=8$ .....	38
Table 5. 2 : The main parameters of $\Phi = 1.5$ and $Re = 7500$ .....	39
Table 5. 3: The main parameters of stoichiometric and fuel-rich conditions $L/D = 6.5$ and $Re = 10000$ . ....	41
Table 5. 4 : The main parameters of fuel-lean conditions $L/D = 6.5$ and $Re = 10000$ ...	45
Table 5. 5 : The main parameters of $\Phi = 0.65$ at $L/D = 6.5$ and $Re = 10000$ .....	47

# List of Figures

Figure 1. 1: World energy consumption,[1],2018. ....	1
Figure 1. 2: Pollutants from the combustion process and their impacts [2]. ....	2
Figure 2. 1: A schematic diagram of the CFCN burner design of (a) Versions I and 2. and (h) Version 3 [9]. ....	5
Figure 2. 2: A schematic diagram of the modified Mansour burner [10]. ....	6
Figure 2. 3: A schematic diagram of the modified EL-Mahallawy et.al. burner [11]. ....	7
Figure 2. 4: A modification CFCN burner with a BK7 glass cone [12]. ....	7
Figure 2. 5: Cut out in Darmstadt piloted burner [15]. ....	8
Figure 2. 6: Stability curve for partially premixed flames [16]. ....	9
Figure 2. 7 : (a) A diagram of the piloted burner model and (b) Section in the piloted burner model [18]. ....	10
Figure 2. 8: Stability curve to the FA and FJ configurations [18]. ....	10
Figure 2. 9: Stability curves [19] of a) CFCN burners and .....	11
Figure 2. 10: The introduced regimen diagram of partially premixed [20]. ....	11
Figure 2. 11: CFCN burner schematic illustration [21]. ....	12
Figure 2. 12: The CFCN flames' stability boundaries with and without co-flow at $\Phi_j = 2$ [21]. ....	13
Figure 2. 13: Stability graphs to Concentric Flow burner at $\Phi = 1.5, \Phi = 2, \Phi = 3$ and $\Phi = 4$ . The relationship between Reynolds number and (a) $L / D$ , (b) $\Delta Z$ , and (c) $R\Delta$ are illustrated [21]. ....	13
Figure 2. 14 : Scatter plot of $R_Z$ versus $R_\Delta$ for $L/D = 2, L/D = 4.5$ and $L/D = 8$ at $\Phi = 2$ and Reynolds number of 10000 [21] ....	14
Figure 2. 15 : Scatter plot of $R_Z$ versus $R_\Delta$ for $L/D = 3.5, L/D = 4.5$ and $L/D = 5.5$ at $\Phi = 2$ and Reynolds number of 20000 [22]. ....	14
Figure 2. 16: Limits of flame stability curves, the relationship between Reynolds number and (a) $L / D$ , (b) $\Delta \xi$ , and (c) $R_\Delta$ are illustrated[22]. ....	15
Figure 2. 17: CFCN swirl burner assembly [24]. ....	15
Figure 2. 18: Stability curve to CFCN swirl burner [24]. ....	16
Figure 3. 1: Schematic drawing of concentric flow conical nozzle burner .....	18
Figure 3. 2: Laminar Flame Speed of CH <sub>4</sub> /air flames, as a function of $\Phi$ [31]. ....	26
Figure 3. 3 : Representative mesh of the burner within the domain. ....	27
Figure 3. 4: Representative mesh of half section of the model. ....	28
Figure 3. 5 : Representative mesh of burner and inlets. ....	28
Figure 3. 6: Representative mesh of the CFCN burner within the 2D domain .....	29
Figure 4. 1: The CH <sub>4</sub> mass fractions contours at different values of $L/D$ for an equivalence ratio of 7 and Reynolds number of 10000, where the first row, simulation results, and second row, experimental result [21]. ....	31
Figure 4. 2: Simulation and Experimental results of pdfs of $Z_{CH_4}$ at $L/D = 0$ for equivalence ratio of 7 and Reynolds number of 10000 [21]. ....	31
Figure 4. 3 : Simulation and Experimental results of pdfs of $Z_{CH_4}$ at $L/D = 2$ for equivalence ratio of 7 and Reynolds number of 10000 [21]. ....	32
Figure 4. 4 : Simulation and Experimental results of pdfs of $Z_{CH_4}$ at $L/D = 5$ for equivalence ratio of 7 and Reynolds number of 10000 [21]. ....	32

Figure 4. 5 : Simulation and Experimental results of pdfs of $Z_{CH_4}$ at $L/D = 10$ for equivalence ratio of 7 and Reynolds number of 10000 [5] .....	33
Figure 4. 6: The probability density functions of the mixture fraction at different values of $L/D$ for an equivalence ratio of 7 and Reynolds number of 10000, where (a) Experimental results [21].and (b) Simulation results. ....	33
Figure 4. 7 Simulation results of the probability density functions of $CH_4$ mass fractions at different values of $L/D$ for an equivalence ratio of 2 and Reynolds number of 10000. ....	35
Figure 4. 8 The numerical and experimental results [21]for $\Phi = 2$ and $Re = 10000$ at $L/D=2$ , $L/D=3$ , $L/D=4.5$ , $L/D=6$ , $L/D=10$ and theoretical fully premixed within the mixing field regime diagram [20].....	36
Figure 5. 1: The curves of stability at equivalence ratios of 1.5,2 and 4. The Reynolds number is shown to (a) the normalized premixing length, $L/D$ , and (b) the normalized ratio of the mixture fraction range, $R_\Delta$ [21].....	37
Figure 5. 2: The numerical and experimental results[21] for $\Phi = 2$ and $Re = 10000$ at $L/D=2$ , $L/D=2.5$ , $L/D=3$ , $L/D=4.5$ , $L/D=6$ , $L/D=6.5$ , $L/D=7$ , $L/D=8$ and $L/D=10$ within the mixing field regime diagram [20]. ....	38
Figure 5. 3: The simulation boundaries within the 2D domain.....	39
Figure 5. 4 OH Contour at the symmetric plane (XZ) for $\Phi = 1.5$ , $Re = 7500$ , $L/D = 7$ . ....	40
Figure 5. 5 : OH Contours line at the symmetric plane (XZ) for $\Phi = 1.5$ , $Re = 7500$ , $L/D = 7$ . ....	40
Figure 5. 6: PDFs of 2D curvatures $K_{xz}$ .....	41
Figure 5. 7 : Velocity contours at symmetric plane for $\Phi = 1,2,3,4$ and $Re = 10000$ , for $L/D=6.5$ . ....	42
Figure 5. 8 : Temperature contours at symmetric plane for $\Phi = 1,2,3,4$ and $Re = 10000$ , for $L/D=6.5$ .....	43
Figure 5. 9 : OH contours at symmetric plane for $\Phi = 1,2,3,4$ and $Re = 10000$ , for $L/D=6.5$ . ....	44
Figure 5. 10 : Velocity contours at symmetric plane for $\Phi = 0.9,0.8,0.7$ and $Re = 10000$ , for $L/D=6.5$ .....	45
Figure 5. 11: Temperature contours at symmetric plane for $\Phi = 0.9,0.8,0.7$ and $Re = 10000$ , for $L/D=6.5$ .....	46
Figure 5. 12 : OH contours at symmetric plane for $\Phi = 0.9,0.8,0.7$ and $Re = 10000$ , for $L/D=6.5$ . ....	47
Figure 5. 13 : Velocity contours at symmetric plane for $\Phi = 0.65$ and $Re = 10000$ , for $L/D=6.5$ . ....	48
Figure 5. 14: Temperature contours at symmetric plane for $\Phi = 0.65$ and $Re = 10000$ , for $L/D=6.5$ .....	48
Figure 5. 15 : OH Contours at symmetric plane for $\Phi = 0.65$ and $Re = 10000$ , for $L/D=6.5$ .....	48

# Nomenclature

$(A/F)$	Actual air-to-fuel ratio
$(A/F)_{st}$	Stoichiometric air-to-fuel ratio
$D$	The inner diameter of the outer tube of the burner nozzle, mm
$L/D$	The normalized premixing length
$pdf$	Probability density function
$Re$	Reynolds number
$R_{\Delta}$	The normalized ratio of the mixture fraction
$R_Z$	The normalized ratio of the mean mixture fraction
$Z$	Mixture fraction
$Z_L$	Lean flammability limit mixture fraction
$Z_R$	Rich flammability limit mixture fraction
$Z_{min}$	The minimum value of the mixture fraction
$Z_{max}$	The maximum value of mixture fraction
$Z_{mm}$	Mean of $Z_{min}$ and $Z_{max}$
$Z_{LR}$	Mean of $Z_L$ and $Z_R$
$\Delta Z$	Range of mixture fraction within the mixing field, $= Z_{max} - Z_{min}$
$v_a$	Airstream velocity, m/sec
$v_f$	Fuel stream velocity, m/sec
$\Phi$	Equivalence ratio

## Acronyms

CFCN	Concentric Flow Conical Nozzle
CFD	Computational Fluid Dynamics
DO	Discrete Ordinates
FGM	Flamelet-Generated Manifold
LES	Large Eddy Simulation
PIV	Particle image velocimetry
PLIF	Laser-Induced Fluorescence
POD	Proper Orthogonal Decomposition
RMS	Reynolds Stress Model