NOTE TO USERS

This reproduction is the best copy available.

UMI[®]

**DEVELOPMENT OF
AN AUTOMATED FLAMMABILITY BURNER SYSTEM**

by

Fanni Bu

Submitted
in partial fulfillment of the requirements
for the degree of

MASTER OF APPLIED SCIENCE

Major Subject: Chemical Engineering

at

DALHOUSIE UNIVERSITY

Halifax, Nova Scotia

May, 2001

© Copyright by Fanni Bu, 2001

**National Library
of Canada**

**Acquisitions and
Bibliographic Services**

**395 Wellington Street
Ottawa ON K1A 0N4
Canada**

**Bibliothèque nationale
du Canada**

**Acquisitions et
services bibliographiques**

**395, rue Wellington
Ottawa ON K1A 0N4
Canada**

Your file Votre référence

Our file Notre référence

The author has granted a non-exclusive licence allowing the National Library of Canada to reproduce, loan, distribute or sell copies of this thesis in microform, paper or electronic formats.

The author retains ownership of the copyright in this thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without the author's permission.

L'auteur a accordé une licence non exclusive permettant à la Bibliothèque nationale du Canada de reproduire, prêter, distribuer ou vendre des copies de cette thèse sous la forme de microfiche/film, de reproduction sur papier ou sur format électronique.

L'auteur conserve la propriété du droit d'auteur qui protège cette thèse. Ni la thèse ni des extraits substantiels de celle-ci ne doivent être imprimés ou autrement reproduits sans son autorisation.

0-612-63493-0

Canada

TABLE OF CONTENTS

TABLE OF CONTENTS.....	iv
LIST OF FIGURES.....	vi
LIST OF TABLES.....	viii
LIST OF SYMBOLS AND ABBREVIATIONS.....	ix
ACKNOWLEDGMENTS.....	xi
ABSTRACT.....	xii
1. INTRODUCTION.....	1
1.1 Background.....	1
1.2 Objectives of This Work.....	2
2. LITERATURE REVIEW.....	4
2.1 Explosion Vessel Method.....	6
2.1.1 ASTM Standard.....	6
2.1.2 Coward and Jones Method.....	10
2.2 Premixed Flame Burner Method.....	12
2.2.1 Flat Flame Burner Method.....	13
2.2.2 Counterflow Flame Burner Method.....	14
2.3 Tubular Flame Burner Method.....	15
2.3.1 Ishizuka, S.	16
2.3.2 National Research Institute of Fire and Disaster (NRIFD).....	17
2.4 Summary of Different Methods for Determining Flammability Limits.....	20
3. EXPERIMENTAL.....	23
3.1 Ignition System Design.....	23
3.1.1 Ignitor Assembly Design.....	23
3.1.2 Computer Controlled Ignition System.....	25
3.2 Experimental Setup.....	27
3.3 Mass Flow Controller (MFC)	30
3.3.1 MFC Selection.....	30
3.3.2 Operation Principle of MFC (Omega).....	33
3.3.3 MFC Specifications.....	34
3.4 PC-Based DAQ System.....	35
3.5 Experimental Procedures.....	36
3.6 Development of LabVIEW Application.....	39
3.7 Safety Concerns of This Burner System	47
4. RESULTS AND DISCUSSION.....	50
4.1 Triangular Flammability Diagram.....	50
4.2 Development of Data Graphing Package.....	51
4.3 Experimental Results and Discussion.....	54

4.3.1	Investigation of A Time Standard for the Judgement of Flame Extinction.....	54
4.3.2	Results.....	55
4.3.3	Comparison of Results.....	58
4.4	Error Analysis of the Experimental Data.....	61
5.	CONCLUSIONS AND RECOMMENDATIONS.....	64
5.1	Conclusions.....	64
5.2	Recommendations for Future Work.....	65
6.	REFERENCES.....	67
APPENDICES.....		71
Appendix 1:	Drawings of Ignitor Assembly Components.....	71
Appendix 2:	Test Program of the Ignition System.....	79
Appendix 3:	List of Items Purchased for This Work.....	81
Appendix 4:	MFC 15-Pin “D” Connector Configuration.....	82
Appendix 5:	DAQ Board and Accessories.....	87
Appendix 6:	LabVIEW Programming.....	86
A.6.1	VI Hierarchy.....	86
A.6.2	LabVIEW Program.....	87
Appendix 7:	Data Graphing Package (Visual Basic Program).....	115
Appendix 8:	Experimental Data for Methane/Air/Carbon Dioxide.....	120

LIST OF FIGURES

Figure 2.1 Schematic diagram of test apparatus of explosion sphere method (ASTM, E681-98)	7
Figure 2.2 Test apparatus of flammability limits at evaluated temperature and pressure (ASTM, E918-83)	9
Figure 2.3 Apparatus for determining flammability limits of gases and vapors (Coward and Jones, 1952)	11
Figure 2.4 Schematic diagram of flat flame burner (Powling, 1949)	14
Figure 2.5 Sketch of counterflow burner system (Ishizuka, 1991)	15
Figure 2.6 Sketch of tubular flame burner system (Ishizuka, 1991)	16
Figure 2.7 Schematic diagram of tubular flame burner system used by Ishizuka (1991)	17
Figure 2.8 Schematic diagram of tubular flame burner system used by NRIFD (Liao et al., 1996; Satio et al., 1995 and 1997; Ogawa et al., 1998)	18
Figure 3.1 Ignitor assembly design	24
Figure 3.2 Electronic circuitry of the ignition system	26
Figure 3.3 Schematic diagram of tubular flame burner system	28
Figure 3.4 Photograph of tubular burner system	29
Figure 3.5 Illustration of measurement procedure for LFL, UFL and peak concentration	37
Figure 3.6 Module structures for LabVIEW programming	40
Figure 3.7 Working flowchart of module 1 — parameter setting	41
Figure 3.8 Working flowchart of module 2 — initial state	42
Figure 3.9 Working flowchart of module 3 — gas injection and ignition	45
Figure 3.10 Working flowchart of module 4 — determination of flammability limits	47
Figure 4.1 Triangular flammability diagram for CH ₄ /O ₂ /N ₂ mixture (Mashuga, 1998)	51
Figure 4.2 Form structure of the Data Graphing Package	52
Figure 4.3 Algorithm of Data Graphing Package	53
Figure 4.4 Investigation of a time standard for the determination of flammability limits	54
Figure 4.5 Triangular flammability diagram of CH ₄ /air/CO ₂ mixture	56
Figure 4.6 Zoom-in triangular flammability diagram of CH ₄ /air/CO ₂ mixture	56
Figure 4.7 Comparison of flammability limits of CH ₄ /air/CO ₂ system	58
Figure A.1.1 Ignitor assembly component – A	72
Figure A.1.2 Ignitor assembly component – B	73
Figure A.1.3 Ignitor assembly component – C	74
Figure A.1.4 Ignitor assembly component – D	75
Figure A.1.5 Ignitor assembly component – E	76
Figure A.1.6 Ignitor assembly component – F	77
Figure A.1.7 Ignitor assembly component – G	78
Figure A.2.1a Icon/connector, VI description and front panel of ignitor_test.vi	79

Figure A.2.1b Block diagram of ignitor_test.vi	80
Figure A.5.1 I/O connector pin assignment for PCI-6023E (NI, 1999).....	84
Figure A.5.2 I/O connector pin assignment for AI-AO-6 (NI, 1994a)	85
Figure A.6.1 VI hierarchy of LabVIEW program	86
Figure A.6.2a Icon/connector, VI description and front panel of MAIN.vi	87
Figure A.6.2b Block diagram of MAIN.vi	88
Figure A.6.3a Icon/connector, VI description and front panel of Parameter_setting.vi..	89
Figure A.6.3b Block diagram of Parameter_setting.vi	90
Figure A.6.4a Icon/connector, VI description and front panel of initial_state.vi	91
Figure A.6.4b Block diagram of initial_state.vi	92
Figure A.6.5a Icon/connector, VI description and front panel of Injection_Ignition.vi..	93
Figure A.6.5b Block diagram of Injection_Ignition.vi	94
Figure A.6.6a Icon/connector, VI description and front panel of Time.vi	95
Figure A.6.6b Block diagram of Time.vi.....	96
Figure A.6.7a Icon/connector, VI description and front panel of Limits.vi	97
Figure A.6.7b Block diagram of Limits.vi.....	98
Figure A.6.8a Icon/connector, VI description and front panel of Inject_gases.vi	99
Figure A.6.8b Block diagram of Inject_gases.vi	100
Figure A.6.9a Icon/connector, VI description and front panel of control_flowrate.vi ..	101
Figure A.6.9b Block diagram of control_flowrate.vi	101
Figure A.6.10a Icon/connector, VI description and front panel of monitor_flowrate.vi	102
Figure A.6.10b Block diagram of monitor_flowrate.vi.....	102
Figure A.6.11a Icon/connector, VI description and front panel of ignitor.vi	103
Figure A.6.11b Block diagram of ignitor.vi	104
Figure A.6.12a Icon/connector, VI description and front panel of DAQ_board.vi	105
Figure A.6.12b Block diagram of DAQ_board.vi	106
Figure A.6.13a Icon/connector, VI description and front panel of gas.vi	107
Figure A.6.13b Block diagram of gas.vi.....	107
Figure A.6.14a Icon/connector, VI description and front panel of equal.vi	108
Figure A.6.14b Block diagram of equal.vi	109
Figure A.6.15a Icon/connector, VI description and front panel of slm_volt.vi.....	110
Figure A.6.15b Block diagram of slm_volt.vi	110
Figure A.6.16a Icon/connector, VI description and front panel of volt_slm.vi.....	111
Figure A.6.16b Block diagram of volt_slm.vi	111
Figure A.6.17a Icon/connector, VI description and front panel of AO.vi	112
Figure A.6.17b Block diagram of AO.vi	112
Figure A.6.18a Icon/connector, VI description and front panel of DIO.vi.....	113
Figure A.6.18b Block diagram of DIO.vi	113
Figure A.6.19a Icon/connector, VI description and front panel of Air_piston.vi.....	114
Figure A.6.19b Block diagram of Air_piston.vi.....	114

LIST OF TABLES

Table 2.1	Description of effects of different factors on flammability limits.....	5
Table 2.2	A comparison of different methods for the determination of flammability limits	21
Table 2.3	A comparison of flammability limits and peak concentration of methane/air/ carbon dioxide from existing literature.....	22
Table 3.1	Selection process for MFC specification – fuel.....	32
Table 3.2	Selection process for MFC specification – oxidant.....	32
Table 3.3	Selection process for MFC specification – diluent gas.....	32
Table 3.5	Configuration of DAQ system.....	36
Table 3.6	Safety factors involved in the experiments.....	48
Table 4.1	Comparison of flammability limits and peak concentration for CH ₄ /air/CO ₂ mixture.....	59
Table 4.2	Determination of bias error for the measurement of the flammability limits (in the result of 5.3% CH ₄ , 84.7 % air and 10% CO ₂)	63
Table 4.3	List of bias error and relative error for the measurement data.....	63
Table A.3.1	List of items purchased for this work.....	81
Table A.4.1	MFC 15-pin “D” connector configuration.....	82
Table A.5.1	List of DAQ boards and related accessories.....	83
Table A.8.1a	LFL of CH ₄ /air mixture.....	120
Table A.8.1b	UFL of CH ₄ /air mixture.....	120
Table A.8.2a	Dilution LFL of CH ₄ /air/CO ₂ mixture with 5% of CO ₂	121
Table A.8.2b	Dilution UFL of CH ₄ /air/CO ₂ mixture with 5% of CO ₂	121
Table A.8.3a	Dilution LFL of CH ₄ /air/CO ₂ mixture with 10% of CO ₂	122
Table A.8.3b	Dilution UFL of CH ₄ /air/CO ₂ mixture with 10% of CO ₂	122
Table A.8.4a	Dilution LFL of CH ₄ /air/CO ₂ mixture with 15% of CO ₂	122
Table A.8.4b	Dilution UFL of CH ₄ /air/CO ₂ mixture with 15% of CO ₂	122
Table A.8.5a	Dilution LFL of CH ₄ /air/CO ₂ mixture with 20% of CO ₂	123
Table A.8.5b	Dilution UFL of CH ₄ /air/CO ₂ mixture with 20% of CO ₂	123
Table A.8.6a	Dilution LFL of CH ₄ /air/CO ₂ mixture with 22% of CO ₂	124
Table A.8.6b	Dilution UFL of CH ₄ /air/CO ₂ mixture with 22% of CO ₂	124
Table A.8.7a	Dilution LFL of CH ₄ /air/CO ₂ mixture with 23% of CO ₂	125
Table A.8.7b	Dilution UFL of CH ₄ /air/CO ₂ mixture with 23% of CO ₂	125
Table A.8.8	Dilution UFL of CH ₄ /air/CO ₂ mixture with 24% of CO ₂	125
Table A.8.9a	Investigation of peak concentration of CO ₂ in CH ₄ /air/ CO ₂ mixture with 6.6% of CH ₄	126
Table A.8.9b	Investigation of peak concentration of CO ₂ in CH ₄ /air/ CO ₂ mixture with 6.8% of CH ₄	126
Table A.8.9c	Investigation of peak concentration of CO ₂ in CH ₄ /air/ CO ₂ mixture with 7.0% of CH ₄	126

LIST OF SYMBOLS AND ABBREVIATIONS

A	Area of porous cylinder surface of gas injection section
A'	Area of porous cylinder surface of nitrogen injection sections
AI	Analog Input
AO	Analog Output
ASTM	American Society for Testing and Materials
c	Confidence level
D	Diameter of burner
DAQ	Data Acquisition
DI/O	Digital Input/Output
F_{CH_4}	Flowrate of methane
F_{Air}	Flowrate of air
F_{CO_2}	Flowrate of carbon dioxide
G	Graphical programming language
K	Relative correction factor (Gas factor)
L	Length of the gas injection section
L'	Total length of the nitrogen injection sections
LFL	Lower Flammability Limit
MFC	Mass Flow Controller
NI	National Instruments
NRIFD	National Research Institute of Fire and Disaster
psia	Pounds per square inch, absolute
psig	Pounds per square inch, gauge
P_x	Precision uncertainty (repeatability)
r	Radius of burner
slpm	Standard liter per minute
S_x	Standard deviation
UFL	Upper Flammability Limit

$U(F_{CH_4})$	Uncertainty of methane flowrate
$U(F_{Air})$	Uncertainty of air flowrate
$U(F_{CO_2})$	Uncertainty of carbon dioxide flowrate
$U_{(CH_4\%)}$	Uncertainty of the bias error for the flammability limits of methane (systematic error)
U_T	Total error of the measurement data
V	Injection velocity of gas
V_c	Capacitor voltage
VDC	Volts Direct Current
VI	Virtual Instruments
x	Measured data
$\bar{x}$	Mean value of the measured data
ε	Stretch rate
α	Significance level

ACKNOWLEDGEMENTS

I would like to acknowledge the assistance of several people involved in the pursuit of my thesis project.

Dr. P. R. Amyotte and Dr. M. J. Pegg, my present and previous supervisors, who have given me great guidance and encouragement on this project. I have been inspired by their wealth of knowledge and intelligence.

Dr. Y. P. Gupta, my co-supervisor, for his continuous financial and technical support.

Dr. K. I. Wilkie and Dr. P. Thibault for their willingness to serve on the supervisory committee and their contributions of time commenting on my thesis.

Mr. R. Dube and Mr. J. Kozel, who have contributed a lot of time and intelligence in the construction of my experimental system.

Yoshio Ogawa, who works for National Research Institute of Fire and Disaster in Japan, for his valuable discussions and suggestions throughout my whole project.

Finally, special thanks are expressed to my friends and family for their constant support, encouragement and understanding.

ABSTRACT

Knowledge of flammability limits is of great practical importance for the prevention of fire and explosions in the mining, transportation, storage and use of fuels. Several methods exist for the measurement of flammability limits and significant work has been done regarding this fundamental combustion phenomenon. After a critical review of the literature on the measurement of flammability limits, the tubular flame burner method, a newly developed technology, was selected for this work. Its advantages over other traditional methods include easy operating procedure, distinct criteria of flammability, and reasonable and repeatable results.

An automated tubular flammability burner system was successfully designed and constructed for the selected tubular flame burner method. This includes the hardware construction and software development. An ignitor was designed using AutoCAD and constructed for the need of the experiment. A comprehensive LabVIEW program was developed to perform automated data acquisition, control of gas flowrates and the ignition system. The gas mixture of $\text{CH}_4/\text{air}/\text{CO}_2$ has been used to test the efficiency of this system and the results have been compared with related findings. This system proved to be more efficient than other experimental procedures, which is especially useful for unknown gases.

A Data Graphing Package was developed in an interactive Visual Basic environment to draw a triangular flammability diagram, which is the most useful tool for presenting detailed information of a three component system (in this case, fuel, oxidant and diluent gas). The flammability envelope was constructed using the experimental results of $\text{CH}_4/\text{air}/\text{CO}_2$.

1. INTRODUCTION

1.1 Background

Research on flammability limits is of great practical importance for prevention of fire and explosion in the use and storage of fuels. Many experimental investigations have been carried out previously regarding the measurement of flammability limits. The flammability limits refer to Lower Flammability Limit (LFL) (also called the lean limit), and Upper Flammability Limit (UFL) (also called the rich limit). These terms apply to flammable gases, vapor and explosive dust. However, only flammability limits for gases are studied in this work. Flammability limits are also historically referred to as the limits of inflammability and are defined as the lowest and highest concentrations of vapor or gas in air, below and above which flame propagation does not occur (NFPA49, 1994). These limits are obtained when a flame initiated by a sufficiently strong ignition source fails to propagate throughout a gas mixture. They are usually expressed in terms of percent by volume of the gas in air.

The safest method in preventing fires and explosions of flammable gases is to avoid the presence of flammable mixtures in the first place. Sometimes it is necessary to make a flammable gas mixture nonflammable in industrial plants. Nonflammable concentrations can be achieved in the following ways:

(1) Reduce the concentration of the flammable gas until it falls below the LFL.

(2) Increase the concentration of the flammable gas until it exceeds the UFL.

Increasing the amount of flammable gas might be dangerous, but it is technically feasible in certain situations when the flammable gas has a low UFL (Coward and Jones, 1952).

(3) Add a sufficient amount of inert gas, usually referred to as a diluent gas, agent or fire suppressant.

When the amount of diluent gas in the flammable gas mixture increases, the rich and lean limits approach each other and eventually meet at a point, beyond which the mixture is nonflammable. The concentration of the diluent gas at this point is called peak concentration, which is defined as the minimum concentration of diluent gas in a combustible mixture, for which flame propagation will be inhibited for any concentration of fuel (Satio et al., 1995 and 1997).

In recent years, the addition of diluent gas has become a topic with increasing interest. Sometimes it is necessary to make a flammable gas mixture nonflammable due to safety concerns. In addition, some flammable gases containing diluent gases are used in industrial plants and domestic purposes. Examples of these mixture include natural gases, by-product gases from coal gasification and oil sand, landfill gases and the combustion of fossil fuels. Therefore, research on the addition of diluent gas has practical significance. In many studies, an inert gas is added to investigate flammability limits, which are called dilution limits in the literature. In this situation, the dilution limits refer to the concentrations of air and the additional inert gas in the gas mixture.

For a system of fuel, oxidant and fire suppressant (or diluent), it is imperative to obtain a detailed knowledge of the flammability zone as a function of these three component concentrations. A triangular flammability diagram is the most useful method to display the flammability zone, and to determine if a flammable mixture is present during plant operations. Once the flammability envelope is defined, it can be utilized to avoid flammable mixtures for industrial situations.

1.2 Objectives of This Work

There were three main objectives in this work. First, a suitable method for measuring flammability limits was selected. Second, an experimental system was designed and constructed for the selected method. Third, measurements of the flammability limits and

the peak concentration of a diluent gas were undertaken, with the results presented in a triangular flammability diagram.

The following report is comprised of four sections. First, a critical review of the literature concerning different experimental methods for measuring flammability limits is undertaken. Second, design and construction of the automated flammability burner system is described, including the hardware construction and software development. This is followed by a presentation of a triangular flammability diagram, which conveys the experimental results, and leads to a comparative discussion of previous research. Finally, conclusions and recommendations are presented, based on this automated flammability burner system.

2. LITERATURE REVIEW

Armed with the information on the flammability limits of a mixture containing fuel and oxidant with or without diluent gas, fire and explosion hazard could be prevented in industry. Flammability data from recent studies display less variation than the 1950s because the apparatus and experimental techniques are more standardized and more accurate measurement technology is available. At present, there are many methods and experimental apparatus to measure flammability limits. These are normally classified into two main categories: explosion vessel methods and premixed flame burner methods. This chapter will discuss these methods and then summarize their advantages and disadvantages. The tubular flame burner method is presented as a new technology to measure flammability limits. Selection of this technique as the experimental method for this work is discussed in detail in this chapter.

Flammability limits can be used to generally appraise the fire hazard and as elements of fire risk assessment that takes into account all of the factors pertinent to an assessment of the fire hazard of a particular end use (ASTM, E681-98 and E918-83). Therefore, flammability limits should be determined under conditions which can represent a good approximation of the actual situation. For example, it must be ensured that the limits obtained from experiments based on a small amount of gas mixture are a good representation of large volumes of mixture (Egerton, 1953). It is known that flammability limits are affected by many factors, such as pressure, temperature, ignition source, ignition energy, shape and dimension of vessel, criteria of flammability, and addition of diluent gas. Table 2.1 gives a summary of the effects of these factors on flammability limits, as determined by different researchers.

At present, the literature does not offer a clear standard to evaluate the following methods used to determine flammability limits. It is normally accepted that a good method should have simple and easy operation procedures, clear criteria to determine flame extinction, a

good approximation of the actual situation, and the ability to produce reproducible and reliable results.

Table 2.1 Description of effects of different factors on flammability limits

Factor	Description
Temperature	The range of flammability limits narrows with a decrease in initial temperature (Harris, 1990) and widens with an increase in temperature (Ale, 1998).
Pressure	An increase in pressure leads to a larger flammability range in most cases (Ale, 1998; Harris, 1990). A decrease in initial pressure below atmospheric does not change the flammability limits of most gases, but a pressure point can be reached below which a flame cannot propagate (Glassman, 1996; Lewis and Von Elbe, 1987).
Ignition source	Many methods have been used for ignition in flammability experiments, such as spark ignition, hot rods or wires, fused wires, pilot flames and plasma jets. A non-flammable gas mixture for a certain ignition source may become flammable when another ignition source is employed (Ale, 1998).
Diluent	The addition of diluents to a fuel-air mixture usually narrows the range of flammability limits.
Turbulence	Flammability limits are normally unaffected by moderate levels of turbulence, but the flammability range narrows at high levels of turbulence (Coward and Jones, 1952). Lovachev et al. (1973) found that if the size of the ignition source increases with increased turbulence, the range of flammability actually widens as the turbulence levels increase.

2.1 Explosion Vessel Method

This is a traditional method for the measurement of flammability limits, which mainly refers to the ASTM standards and the explosion tube method of Coward and Jones.

2.1.1 ASTM Standard

There are two test standards published by ASTM (American Society for Testing and Materials) regarding the measurement of flammability limits. One is “Standard Test Method for Concentration Limits of Flammability of Chemicals (Vapors and Gases) (E681-98)”, and the second is “Standard Practice for Determining Limits of Flammability of Chemicals at Elevated Temperature and Pressure (E918-83)”.

E681-98: Standard Test Method for Concentration Limits of Flammability of Chemicals (Vapors and Gases)

Scope:

This method is to determine flammability limits of chemicals having sufficient vapor pressure in air at 1 atm at the test temperature. It may be used to determine limits in the presence of inert diluent gas. This method is limited to an initial pressure of 101 kPa (1 atm) or less, with a practical lower pressure limit of approximately 13.3 kPa (100 mm Hg). The maximum practical operating temperature of this equipment is approximately 150 °C (302 °F).

Summary of test method:

A uniform mixture of a gas or vapor with air is ignited in a closed vessel, and the upward and outward propagation of the flame away from the ignition source is noted by visual observation. The concentration of the flammable component is varied between trials until the limits where the gas composition will just sustain flame propagation is reached.

Apparatus:

Figure 2.1 shows the schematic diagram of the test apparatus. The apparatus mainly consists of a 5-liter glass test vessel (i.e. a glass flask), an insulated chamber equipped with a source of controlled-temperature air, an ignition device with appropriate power supply, a magnetic stirrer, and a cover equipped with the necessary operating connections and components.

Figure 2.1 Schematic diagram of test apparatus of explosion sphere method (ASTM, E681-98)

Criteria of flame extinction:

The propagation of flame is defined as the upward and outward movement of the flame front from the ignition source to the vessel walls or at least to within 13 mm (1/2 in.) of

the wall. During an experiment, the operator must watch for ignition and flame propagation away from the ignition source in the darkened viewing area. Obviously the method used to judge the flame propagation is not so reliably accurate.

Significance and use:

Flammability limits may be used to determine guidelines for the safe handling of volatile chemicals. They are used particularly in assessing ventilation requirements for the handling of gases and vapors.

E918-83 (Reapproved 1993): Standard Practice for Determining Limits of Flammability of Chemicals at Elevated Temperature and Pressure

Scope:

This standard covers the determination of flammability limits of combustible vapor-oxidant mixtures at temperatures up to 200 °C and initial pressures up to as much as 1.38 MPa (200 psia).

Summary of practice:

A mixture of gases or vaporized fuels with a gaseous oxidizer is prepared in a steel or other appropriate metal vessel at controlled temperature and pressure. Proportions of the components are determined by the measurement of partial pressures during filling of the vessel. Fuel concentration is varied between trials until flammability limits have been determined.

Apparatus:

See Figure 2.2 for the test apparatus. The apparatus mainly consists of a metal pressure vessel with a minimum volume of 1 L and a minimum inside diameter of 76 mm (3 in.), an insulated chamber, an ignition device, remotely controlled valves, pressure measuring equipment, and a venting system for handling overpressuring.

Figure 2.2 Test apparatus of flammability limits at evaluated temperature and pressure (ASTM, E918-83)

Criteria of flame propagation:

Flame propagation by this method is defined as a combustion reaction that produces at least a 7% rise in initial absolute pressure.

Significance and use:

Knowledge of flammability limits at elevated temperature and pressures is needed for safe and economical operation of some chemical processes. For example, this

information may be needed to start up a reactor without passing through a flammable range, to operate the reactor safely, or to store or ship the product safely.

The flammability limits determined by the above standards are influenced by flame quenching effects of the test vessel walls. Therefore, it is necessary to employ a vessel with sufficient size to eliminate these effects for most materials. Many safety precautions must be considered as well, such as implosion and explosion that may result in equipment rupture. These unsafe factors have to be taken into account during the system construction, and therefore it is complicated to construct the experimental apparatus. The procedures to conduct the experiments are also complicated; these are described in detail in the E681-98 and E918-83 standard. The criterion used for the determination of flame extinction is visual observation in the E681-98 standard. This criterion is susceptible to human errors that may lead to inaccurate results.

Hirst et al. (1981/82) indicated that the peak concentration of diluent gas determined by explosion sphere method is affected by a number of variables, particularly the ignition method. Saito et al. (1997) and Ogawa et al. (1998) reported that the data obtained from using explosion spheres are hard to repeat due to many factors, such as pressure, temperature, and criteria of flammability.

2.1.2 Coward and Jones Method

Coward and Jones (1938) proposed a “standard” procedure to measure flammability limits, commonly referred to as explosion tube method, explosion burette method or Coward and Jones method. This is often cited as the “standard method” in literature. Flammability limits have been studied using this method for many years. Burgoyne and Williams-Leir (1948a and 1948b) and Coward and Jones (1952) determined flammability limits of selected gases using this method. Figure 2.3 shows the experimental apparatus constructed in the Bureau of Mines laboratory and used by Coward and Jones (1952).

This apparatus was specifically designed for determining limits of vapors of liquids, but it can be simplified for gases.

Figure 2.3 Apparatus for determining flammability limits of gases and vapors (Coward and Jones, 1952)

The explosion tube “a” is actually a glass tube in which the mixture is tested. A propagating flame was used in this tube and the mixture was judged to be flammable if the flame could propagate throughout the whole length of the tube. Flammability tests done in a closed tube in the past have since been changed to an open tube to avoid some

unnecessary complication (Harris, 1990). A visual observation is used to judge the flame extinction, and limits need to be determined by trial in this experimental setup.

The ignition source has no effect on the flammability limits, since this experiment is concerned with the capacity of a gas mixture to propagate flame, not the capacity of the source of energy to initiate flame. Therefore the limits are unaffected by the variations in the nature and strength of the ignition source (Coward and Jones, 1952).

Direction of flame propagation affects the flammability limits. The limits obtained from upward propagation of the flame are wider than those for horizontal or downward propagation (Coward and Jones, 1952). Therefore the limits for upward propagation are normally considered more suitable for safety in industrial operation.

The diameter and the length of the tube affect the flammability limits. A tube 50.8 cm in diameter and 120-180 cm in length has been adopted by the US Bureau of Mines and has also been used in many studies (Ale, 1998). Flame propagation depends on energy transfer from the burned to the unburned gas. Anything affecting the available energy will affect the limits. Therefore, increasing the tube diameter or decreasing the tube length will give a wider range of flammability limits (Coward and Jones, 1952; Zabetakis, 1965; Lewis et al., 1987).

Drysdale (1985) reported that this method is not suitable for examining the effects of small quantities of chemical suppressants and heavier-than-air mixtures.

2.2 Premixed Flame Burner Method

Premixed flames are obtained by the ignition of homogeneous premixed flammable gas mixtures. Sufficient ignition energy is needed to initiate the combustion process. This premixed flame burner method is not as mature a method as the Coward and Jones method. Most researchers actually tried to find out if this method can agree with the

results obtained from the traditional explosion vessel method. It is known that the premixed flame burner method gives a wider flammability range than the explosion vessel method (Ogawa et al., 1998), and also gives repeatable and reliable results for determining flammability limits and peak concentrations (Satio et al., 1995). The premixed flame burner method includes flat flame burner, counterflow flame burner and tubular flame burner methods, among which the tubular flame burner method was selected as the experimental method for this work. The evaluation of these three methods is mainly contingent upon the amount of heat loss, which is one of the most important factors in determining the flammability limits. Ishizuka (1991) suggested that limits should be obtained in a system in which external heat loss is eliminated. If the system-dependent heat loss mechanisms are eliminated, the lowest and highest limits determined could be representative of the actual values of flammability limits (Ishizuka et al., 1982).

2.2.1 Flat Flame Burner Method

This method is mainly employed for fundamental studies of flame properties, because the flat flame is established in a one-dimensional flow of flammable mixture corresponding to the one-dimensional flame model in the theoretical analysis. Refer to Figure 2.4 for a schematic of the flat flame burner designed and used by Powling (1949). This burner can stabilize slow burning flames and therefore obtain a flat flame. It was mainly used to determine burning velocities and flammability limits. In the studies of Powling (1949) and Egerton (1952), the lower limits of some flammable gases are considerably lower than those given elsewhere in the literature. For example, methane has a lower limit of 5.1% by the flat flame burner method, compared with 5.3% determined by the explosion tube method. The upper-limit value is lower than that cited in the literature for the tube method (Egerton, 1952). In fact, the flat flame burner method gives a wider flammability range than the explosion tube method (Ishizuka, 1991). The obvious drawback of this method is the occurrence of downstream and upstream heat losses.

Figure 2.4 Schematic diagram of flat flame burner (Powling, 1949)

2.2.2 Counterflow Flame Burner Method

This method causes much less heat loss than the flat flame method. See Figure 2.5 for a sketch of a counterflow system, which consists of two identical and opposing premixed gas streams. Counterflow flame is also referred to as twin flame or binary flame in some literature. Due to symmetry, the stagnation surface in this system can be considered almost adiabatic, which implies a negligible amount of downstream heat loss. This method is expected to give a wider flammability range than Coward and Jones. Indeed the flammability limits determined by Ishizuka et al. (1982) are concurrent with theory. For example, the lower and upper limits for methane are 4.8% and 15.8% respectively, which gives a wider flammability range than the Coward and Jones method (5.3% and 14.0% respectively). The lower-limit value of this method is lower than that obtained by Egerton et al. (1952), which was 5.1% for the flat flame method. This binary flame method is more effective in reducing heat loss than the flat flame method. However, in this kind of experimental design, there exists a radiative loss from the burned gas as well as a conductive heat loss from the peripheral part of the flame into the atmosphere in a

radial direction. Therefore the tubular flame burner method is presented below as a superior method in the elimination of heat loss.

Figure 2.5 Sketch of counterflow burner system (Ishizuka, 1991)

2.3 Tubular Flame Burner Method

The tubular flame burner method is one of the premixed flame burner methods and is employed as a new technology for measuring flammability limits. Figure 2.6 shows a sketch of the tubular flame burner system. The tubular flame is established in a counter flow field with axial symmetry. This flame seems to produce a negligible downstream heat loss, as does the binary flame. It also produces a lateral conductive heat loss which is smaller than that of the binary flame method as a result of a smaller area on the end of the tubular flame. Theoretically this flame can therefore produce a wider flammability range than other methods. Research related to this area has gained considerable attention in recent years, for example, Ishizuka (1991) and a group at the National Research Institute of Fire and Disaster in Japan (Liao et al., 1996; Satio et al., 1995 and 1997; Ogawa et al., 1998).

Figure 2.6 Sketch of the tubular flame burner system (Ishizuka, 1991)

2.3.1 Ishizuka, S.

Ishizuka (1991) proposed the tubular flame burner method which uses a porous cylinder burner to measure flammability limits. Figure 2.7 shows the experimental setup used in his research. The burner is made of a porous bronze cylinder with 5 mm thickness and 5 μm porosity. The gases and air were metered with a battery of capillary meters. He measured the flammability limits of methane-air-nitrogen, propane-air-nitrogen and hydrogen-air-nitrogen mixtures. Ishizuka (1991) concluded that these limits give somewhat wider flammable ranges than the Coward and Jones method and almost coincide with the limits obtained by the binary flame. For example, in his experiment the lower and upper limits determined for methane/air are 4.7% and 15.1% respectively, compared with 4.8% and 15.8% for the binary flame method (Ishizuka et al., 1982) and 5.1% for lower limit by the flat flame (Egerton et al., 1952). The reason for the extension of the flammable range is mainly due to a reduction of downstream heat loss behind the flame in this counter flow system.

Figure 2.7 Schematic diagram of tubular flame burner system used by Ishizuka (1991)

2.3.2 National Research Institute of Fire and Disaster (NRIFD)

Since the tubular burner system is very simple and has the potential to give results which closely resemble an actual situation, NRIFD (Liao et al., 1996; Satio et al., 1995 and 1997; Ogawa et al., 1998) have conducted thorough research on this area since Ishizuka's experiments. Figure 2.8 shows the schematic diagram of the tubular burner system built and used by NRIFD.

The system consists of a tubular flame burner, mass flow controllers, a gas mixing chamber and a buffer tank. The burner is made of a porous bronze cylinder with the same thickness (5 mm) and porosity (5 μm) as Ishizuka's. The flow rates of each gas and compositions of the mixture are adjusted by precision-type mass flow controllers manually. For measurements of flammability limits of a ternary mixture, the concentration of fuel is increased or decreased stepwise until the flame goes out. The criterion of extinction is that a flame in the burner is extinguished within one minute after the mixture component is changed (Saito et al., 1997). This flame extinction was judged

by the naked eye or a video camera. This system, however, is not an automated data acquisition and control system. All operations involved manual intervention.

Figure 2.8 Schematic diagram of tubular flame burner system used by NRIFD (Liao et al., 1996; Satio et al., 1995 and 1997; Ogawa et al., 1998)

Ogawa et al. (1998) experimented with three burners consisting of different diameters (18 mm, 30 mm and 40 mm) to examine the dimensional effect on the flammability limits. They concluded that the flammability limits are independent of burner size when the flame stretch rate is kept constant. This important conclusion will be used later in Chapter 4 to validate the selection of the working range of mass flow controllers. The definition of flame stretch rate is given by the following equation:

$$\varepsilon = \frac{1}{A} \frac{dA}{dt} = \frac{1}{2\pi rL} \frac{d(2\pi rL)}{dt} = \frac{1}{r} \frac{dr}{dt} = \frac{V}{r} = \frac{2V}{D} \quad (2-1)$$

Where:

ε : Stretch rate

A: Area of the gas injection section

r: Radius of burner

V: Injection velocity

D: Diameter of burner

L: Length of the gas injection section

Stretch rate ϵ is defined as $2V/D$. Injection velocity V is obtained by dividing the mixture flowrate by the area of the porous cylinder surface A .

In the case of the tubular burner with the 30-mm diameter, an injection velocity of 5 cm/s was employed as a standard injection velocity in the NRIFD study (Liao et al., 1996; Satio et al., 1995 and 1997; Ogawa et al., 1998). Under this injection velocity, not only was the flame securely stable, but a wide and repeatable flammability range could be obtained (Satio et al., 1995 and 1997). Increasing injection velocity causes the flammability range to narrow due to a larger flame stretch rate (Kobayashi and Kitano, 1989). If the injection velocity is smaller than 5 cm/s, a larger amount of heat loss from the flame to the burner wall may result in narrow ranges, and the unstable flame may lead to unrepeatable results (Liao et al., 1996). Therefore all measurements of the limits were conducted under 5 cm/s injection velocity of the mixtures on the inside surface of the burner cylinder.

Satio et al. (1995) investigated the differing effects of horizontal and vertical burner position on the results of flammability limits. They reported that wider flammability regions and larger peak concentrations were obtained in the horizontal burner position than in the vertical orientation. For example, for the horizontal burner set-up, the lower and upper limits for methane/air are 4.8% and 15.4% and the peak concentration of CO_2 for methane/air mixture is 29.6%. For the vertical burner, the limits are 4.7% and 15.1%, and the peak concentration of CO_2 is approximately 27%. Table 2.3 includes the results of the tubular flame burner method under vertical and horizontal situations.

Saito et al. (1997) at NRIFD also built a 7.9-liter explosion vessel to compare the results obtained from the tubular flame burner system. They concluded that the tubular burner

method is superior to the explosion vessel method because it has the following advantages:

- (1) The flammability region and peak concentration can be measured simply and quickly with reproducible results (Satio et al., 1995; Liao et al., 1996).
- (2) A larger range of flammability limits was obtained because of less heat loss from the flame zone (Liao et al., 1996).

2.4 Summary of Different Methods for Determining Flammability Limits

The current methods for measuring flammability limits have been reviewed. A summary is given in Table 2.2, including the advantages and disadvantages of each method. It is clear that the tubular flame burner method has several advantages over other methods. From the in-depth studies of Ishizuka and NFIRD, the burner method was proven to yield more reproducible results, and was most easily operated. Also results obtained using burner method were in good agreement with those obtained using traditional methods (Ishizuka, 1991; Liao et al., 1996; Satio et al., 1995 and 1997; Ogawa et al., 1998). Therefore, the tubular flame burner method is a good alternative new technique to the mature traditional methods. These are key reasons for the selection of this experimental method for the current work.

Table 2.3 lists available results of flammability limits and peak concentrations of methane/air/carbon dioxide mixtures, depending on different methods and researchers. This ternary gas mixture has been used in this thesis project to investigate the tubular flame burner system. Table 2.3 is therefore helpful in comparing the results obtained from the current work to those from other researches.

Table 2.2 A comparison of different methods for the determination of flammability limits

Method		Advantage		Disadvantage	
ASTM standard	E681-98	♦ Standard test method approved by ASTM	♦ Results can be obtained under different temperatures (max. 150 °C) and pressures (101 kPa or less)	<ul style="list-style-type: none"> ♦ Complicated experimental procedure ♦ Complicated requirements of apparatus construction ♦ Flammability limits affected by flame quenching effects of the test vessel walls ♦ The criteria of flame propagation and extinction are susceptible to human errors ♦ Peak concentration affected by several factors, especially ignition source 	
	E918-83 (Reapproved 1993)		♦ Results can be obtained at temperatures up to 200 °C and initial pressures up to 1.38 MPa (200 psia)		
Explosion tube method (also referred to as the Coward and Jones method and the explosion burette method)		<ul style="list-style-type: none"> ♦ Proposed by Coward and Jones and used as a standard method ♦ Ignition source has no effect on the flammability limits 		<ul style="list-style-type: none"> ♦ Complicated experimental procedure ♦ Several factors affect the flammability limits: diameter and length of the tube; direction of flame propagation ♦ Not suitable for examining the effects of small quantities of chemical suppressants and heavier-than-air mixtures 	
Premixed flame burner method	Flat flame burner	<ul style="list-style-type: none"> ♦ Ignition source and ignition energy have no effect on flammability limits ♦ Wider flammability range ♦ Clear criteria to judge flame extinction ♦ Easily operated ♦ Reliable and repeatable results 	♦ One dimensional flame model, used for studying basic flame properties	♦ Results can only be obtained under room temperature and atmospheric pressure	♦ Downstream and upstream heat loss occur
	Counterflow flame burner		♦ Less heat loss than flat flame due to symmetry		♦ Conductive heat loss occurs, from peripheral part of the flame to ambient in radial direction
	Tubular flame burner		♦ Negligible heat loss and less lateral conductive loss than binary flame due to counter flow with axial symmetry		

Table 2.3 List of flammability limits and peak concentration of methane/air/carbon dioxide from existing literature

Method	Reference	Flammability limits (%)		Peak concentration of CO ₂ (%)
		LFL	UFL	
Tubular flame burner (D=30 mm, vertical)	Saito et al., 1995	4.7	15.1	27
Tubular flame burner (D=30 mm, horizontal)	Saito et al., 1995 and 1997	4.8	15.4	29.6
Tubular flame burner (D=30 mm, vertical)	Ishizuka, 1991	4.7	14.9	--
Tubular flame burner (D=30 mm, horizontal)	Ishizuka, 1991	4.7	15.1	--
Flat flame burner	Egerton et al., 1952	5.1	--	--
Counterflow flame burner (twin flame)	Yamaoka et al., 1979	4.7	15.3	--
Counterflow flame burner (binary flame)	Ishizuka et al., 1982	4.8	15.8	--
Explosion tube	Zabetakis, 1965	5.0	15.0	--
Explosion tube	Coward and Jones, 1952	5.3	14.0	24
Explosion tube	Ale, 1998	4.8	15.1	--
Explosion sphere	Andrews and Bradley, 1973	4.5	15.5	--

3. EXPERIMENTAL

3.1 Ignition System Design

The ignition source has no effect on the flammability limits for the selected tubular flame burner method. The ignition source is only used to initiate the flame. As mentioned in Chapter 2, there are many kinds of ignition sources. Theoretically, any ignition source would be suitable for the burner methods. Spark ignition was selected as the ignition source for this experiment because it was the preferred ignition method for most flammability tests. This section discusses the design and construction of an automated spark ignition system.

3.1.1 Ignitor Assembly Design

Figure 3.1 shows the engineering drawing of the designed ignitor assembly. This ignitor was constructed with the individual component parts, A to G, which were then assembled together. Detailed information on the separate parts is shown in Figures A.1.1 to A.1.7 in Appendix 1. These figures show the precise dimensions, tolerance, material and scale. AutoCAD 14.0 is the graphing tool that was used to draw all these mechanical components.

The key for the construction of this ignitor was to make the positive and negative rods well insulated, otherwise danger could occur during operation. To achieve better insulation, castable ceramic, teflon sleeve, and silver solder were used. In one particular part, the castable ceramic was used to withstand higher temperatures instead of using teflon sleeve. A pencil lead was tightly screwed between the positive and negative pole. As a strong current travels through the lead, a spark will occur causing an ignition of flammable gas mixture. It is necessary to make sure the pencil lead is screwed tightly before ignition and replaced with a new lead regularly, otherwise the ignition energy will be lost.

Figure 3.1 Ignitor assembly design

Title	Ignitor Assembly Design		
Tolerance	$\pm 0.0050''$ unless indicated		
Scale	3 : 1	Designer	Fanni Bu
Location	Chemical Dept., Dalhousie Univ.	Date	Jun. 7, 1999

3.1.2 Computer Controlled Ignition System

To have a more advanced automation system to measure the flammability limits, the ignition system is expected to achieve automatic ignition at a specific condition. According to the experimental requirements, this PC-controlled automated ignition device should possess the following two capacities:

- (1) Monitor the capacitor voltage and satisfy the desired voltage set point.
- (2) Automatic charge, discharge and firing action according to the given conditions.

The electronic circuitry of the ignition system is shown in Figure 3.2, which was designed by Jan Kozel of the Department of Chemical Engineering at Dalhousie University. Protel 98 was used as the graphing tool to draw this circuit. The maximum capacitor voltage was designed to be 250 volts, which corresponds to a 0 to 5 volts signal that can be read by the computer. The behavior of the ignition system during the experiment process is detailed in Section 3.6. This circuit which has four switches is connected to the digital I/O of a DAQ board, which can be easily switched on or off using LabVIEW. These switches are used for controlling the following actions:

- ◆ Charge capacitor voltage,
- ◆ Fire flammable gas mixture,
- ◆ Discharge capacitor voltage, and
- ◆ Air piston up or down position (for moving ignitor up and down).

A detailed description of the DAQ configuration is shown in Section 3.4. This ignition system must be tested regularly to make sure it can work properly and to avoid the failure of the system to ignite during an experiment. Appendix 2 gives a LabVIEW program which displays the change of the capacitor voltage during charging, firing and discharging processes. Therefore, this program performs a check of system functionality prior to the actual experiment.

Figure 3.2 Electronic circuitry of the ignition system

3.2 Experimental Setup

Figure 3.3 and Figure 3.4 show a schematic diagram and a picture of the tubular flame burner system, respectively. This burner system is comprised mainly of a tubular flame burner, Mass Flow Controllers (MFCs), a gas-mixing chamber, gas cylinders, an ignitor, and an air piston system. The MFCs are the main components in this system used to monitor and control the flowrates of each gas automatically. Detailed information regarding MFC is given in Section 3.3.

The tubular flame burner used for this research is similar to the burners used by NRIFD (Liao et al., 1996; Satio et al., 1995 and 1997; Ogawa et al., 1998) and Ishizuka (1991). This burner was designed with a 40-mm inner diameter, 80-mm length and 5-mm thickness. The porous steel cylinder has a 5- μ m porosity, which is different from the porous bronze material used by NRIFD and Ishizuka. The construction of the three different parts of the tubular flame burner is described as follows:

(1) Centre section of the burner

This is the main part of the burner, which is a porous steel cylinder with 5- μ m porosity. This section is for the injection of flammable gas mixture.

(2) Nitrogen barriers on either side of the centre section

The burner is equipped with 25-mm nitrogen barriers made of the same material as the centre section. The purpose of these nitrogen barriers is to suppress the diffusion flames, which may occur when investigating rich flames during experimentation.

(3) Water-cooling ends outside of the nitrogen barriers

The burner is also equipped with 25-mm water-cooling ends outside the nitrogen sections. These are made of solid steel cylinder. The cold water flows into the inlet and out from the outlet of the burner. This is to protect the burner from over-heating from the effluent hot gas.

Figure 3.3 Schematic diagram of tubular flame burner system

Figure 3.4 Photograph of tubular burner system

The gases are mixed in a gas-mixing chamber and then injected into the burner from the centre section. The gas-mixing chamber is composed of an empty cylinder stuffed with steel wool. The air piston is used for moving the ignitor up and down. The ignitor must be taken out immediately after igniting the flammable gas mixture. Fuel, nitrogen and diluent gases are supplied from pressurized cylinders. In this experiment, methane (99.97% purity) and carbon dioxide (99.99% purity) were selected as fuel and diluent gases due to their common usage for the measurement of flammability limits. The oxidant (air) is introduced from the air pipe in the wall of the laboratory. This dry air is supplied from an oil-free compressor with a dryer and has a purity of 99.5%. A mirror can be adjusted angularly and is used to observe the flame condition during an experiment.

3.3 Mass Flow Controller (MFC)

3.3.1 MFC Selection

The MFC specification has a great effect on the measurement accuracy. To obtain the suitable MFC working range for each gas, some results and conclusions obtained by NRIFD were used. As discussed in Chapter 2, the flammability limit is independent of the burner diameter when stretch rate is kept constant (Ogawa et al., 1998). An injection velocity of 5 cm/s was employed as a standard injection velocity for the 30-mm diameter burner in the NRIFD study due to its many advantages (previously discussed in Section 2.3.2). These advantages, such as the stable flame and largest and repeatable results, were also desired in the current work. Accordingly, the following calculation was conducted to obtain the injection velocity (V) based on the stretch rate (ϵ) obtained by NRIFD. The total gas flowrate calculated is used later to deduce the working range of MFCs.

NRIFD study:

$$\epsilon = 2V/D = 2 \times 5 \text{ cm s}^{-1} / 3 \text{ cm} = 3.3 \text{ s}^{-1} \quad (3-1)$$

This work:

Using $\varepsilon = 3.3 \text{ s}^{-1}$ and then calculating the injection velocity (V) for the burner of this work:

$$V = \varepsilon D / 2 = 3.3 \text{ s}^{-1} \times 4 \text{ cm} / 2 = 6.7 \text{ cm s}^{-1} \quad (3-2)$$

Total gas mixture flowrate is then determined by:

$$V \times A = V \times \pi D L = 6.7 \text{ cm s}^{-1} \times \pi \times 4 \text{ cm} \times 8 \text{ cm} \approx 40 \text{ slpm} \quad (3-3)$$

The injection velocity for the gas mixture is also used for nitrogen injection. The nitrogen flowrate is then calculated by:

$$V \times A' = V \times \pi D L' = 6.7 \text{ cm s}^{-1} \times 3.14 \times 4 \text{ cm} \times 5 \text{ cm} \approx 25 \text{ slpm} \quad (3-4)$$

Where:

ε : Stretch rate

V: Injection velocity

D: Diameter of burner

A: Area of the gas injection section

A': Area of the nitrogen injection sections

L: Length of the gas injection section

L': Total length of the nitrogen injection sections

slpm: standard liter per minute

Tables 3.1, 3.2 and 3.3 show the factors used to determine the MFC working ranges for fuel, oxidant and diluent gases. Several commonly used fuels, oxidants and inert gases were used for this selection process. Normally MFCs are calibrated by nitrogen, so the working range for the actual gas must be converted into the working range of nitrogen, based on the correction factor K, which is discussed in Section 3.3.3.

Table 3.1 Selection process for MFC specification – fuel

Fuel	Methane	Propane	Ethane	Butane
Formula	CH ₄	C ₃ H ₈	C ₂ H ₆	C ₄ H ₁₀
Flammability Range (NFPA 49)	5 - 15%	2.1 - 9.5%	3.0 - 12.5%	1.9 – 8.5%
Working Range for Fuel (slpm)	2 - 6	0.8 - 3.8	1.2 - 5.0	0.8 - 3.4
Correction Factor K	0.72	0.35	0.50	0.26
Working Range of N₂ (slpm)	2.8 - 8.3	2.3 - 10.9	2.4 - 10.0	2.9 – 13.1
MFC Specification	15 slpm			

Table 3.2 Selection process for MFC specification – oxidant

Oxidant / Nitrogen	Air	Nitrogen	Oxygen
Formula	--	N ₂	O ₂
Maximum Concentration	98.1%	77.5%	20.6%
Maximum Flowrate (slpm)	39.2	31.0	8.2
Correction Factor K	1.00	1.00	1.00
Maximum flowrate of N₂ (slpm)	39.2	31.0	8.2
MFC Specification	50 slpm		10 slpm

Table 3.3 Selection process for MFC specification – diluent gas

Diluent gas	Carbon Dioxide	Nitrogen	Argon
Formula	CO ₂	N ₂	Ar
Maximum peak concentration	39.7%	51.6%	63.1%
Maximum flowrate (slpm)	15.9	20.6	25.2
Correction Factor K	0.74	1.00	1.45
Maximum flowrate of N₂ (slpm)	21.5	20.6	17.4
MFC Specification	30 slpm		

From Tables 3.1, 3.2 and 3.3, 10 slpm, 15 slpm, 30 slpm and 50 slpm MFCs (calibrated by N₂) were selected. The Omega Company was chosen as the supplier of these MFCs. A

Rotameter FL-2042 (3-30 slpm) was selected for monitoring the flowrate of the nitrogen barriers, which are used to suppress the diffusion flames. Appendix 3 shows all components purchased for this work with prices and other details.

In fact, each MFC is not strictly used for fuel, oxidant, oxygen and diluent respectively based on the above tables. As long as the working range is satisfied, these four MFCs are interchangeable in order to obtain better accuracy. This depends on the different gas mixtures. For example, methane, air and carbon dioxide are used in this application. The 10 slpm MFC is used for methane instead of 15 slpm; The 15 slpm MFC is used for carbon dioxide instead of 30 slpm.

3.3.2 Operation Principle of MFC (Omega)

The operation principle of the MFCs is based on the fundamentals of fluid dynamics, i.e., the flow rates of a gas in the two laminar flow conduits are proportional to one another. Gas entering the mass flow transducer is divided into two portions: a small flow portion travels through a capillary stainless steel sensor tube, while the remainder flows through the primary flow conduit. The sensor tube and the primary conduit are designed to achieve laminar flow in each branch. Therefore, the flow rates measured in the sensor tube are proportional to the total flow through the mass flow controller.

The key is to determine the gas flow rates through the sensor tube. A heat flux is introduced at two sections of the sensor tube by means of precision wound heater-sensor coils. The heat is carried by the gas stream from the upstream coil to the downstream coil. The resultant temperature dependent resistance differential is detected by the electronic control circuit. The gradient is linearly proportional to the instantaneous rate of flow taking place. The output signal is therefore the function of the amount of heat carried by the gases, and is proportional to the mass flow rates.

MFC also incorporates a proportional solenoid valve. The closed loop control circuit compares the mass flow output with the selected flowrate, and compensates for deviations from the setpoint by adjusting the solenoid valve.

3.3.3 MFC Specifications

(1) Relative correction factor K

An MFC is usually calibrated by dry nitrogen gas. The calibration can then be adjusted for the desired gas based on the relative correction factor K. For example, the MFC used for methane, which is calibrated with nitrogen, is 15 slpm, and the K factor for methane is 0.72. The actual flowrate of methane therefore is: $15 \times 0.72 = 10.76$ slpm

The OMEGA Company performs their calibrations at standard conditions, i.e. 14.7 psia and 21.1 °C.

(2) Accuracy

The accuracy is $\pm 1.5\%$ of the full working range, including linearity for gas temperatures ranging from 15 °C to 25 °C and pressures of 5 to 60 psig. Normally the gas pressure is kept at 20 psig, which, as mentioned below, is the optimum working pressure of an MFC.

(3) Response time

For units up to 15 slpm, the time constant is 300 ms. It takes approximately 1 second to achieve a set flowrate between 25% - 100% of full-scale flow, within $\pm 2\%$ accuracy.

For units from 20 slpm to 100 slpm, the time constant is 600 ms. It takes approximately 2 seconds to achieve a set flowrate between 25% - 100% of full-scale flow within $\pm 2\%$ accuracy.

(4) Gas pressure

The maximum pressure at which the MFC can operate is 500 psig and the optimum pressure is 20 psig. This optimum pressure of 20 psig is the working pressure in this work.

(5) Output signals

The output signal is linearized from 0 - 5 VDC (Volts Direct Current) which corresponds to 0% - 100% of the full range flowrate, and is used to monitor the flowrate.

(5) Command signal

The command signal is actually the control signal, which is analog 0 - 5 VDC signal that is a linear representation of 0% - 100% of the full-scale flowrate. This signal is used to control the flowrate.

It is recommended that MFCs be warmed up for a minimum of 15 minutes before conducting gas injection in order to avoid inaccurate data acquisition. For the electrical connection, the meaning of each pin in the 15-pin “D” connector must be clearly understood before wiring it to the DAQ board. See Appendix 4 for the 15-pin “D” connector configuration.

3.4 PC-Based DAQ System

Hardware requirements are major factors considered in the selection of the DAQ boards. Table 3.5 gives a brief description of the system configuration. Clearly, this DAQ system needs five analog inputs (AI), four analog outputs (AO) and four digital input/output (DI/O). The PCI-6023E and AI-AO-6 boards were selected for this application. Table A.5.1 in Appendix 5 shows the detailed description of the selected DAQ boards and related accessories. Also Figure A.5.1 and Figure A.5.2 give the I/O connector pin assignments for PCI-6023E and AI-AO-6 respectively. A VI was designed using LabVIEW to specify the channel configurations for these DAQ boards. This VI named DAQ_board.vi is shown in Figures A.6.12a and A.6.12b in Appendix 6. It is very easy to change the configuration of each channel if the hardware wiring is altered.

Table 3.5 Configuration of DAQ system

Channel	DAQ Board		Description
	PCI – 6023E	AI-AO-6	
MFC (0-10 slpm)	AI	AO	Monitor & control the flowrate of CH ₄ in this work
MFC (0-15 slpm)	AI	AO	Monitor & control the flowrate of CO ₂ in this work
MFC (0-50 slpm)	AI	AO	Monitor & control the flowrate of air in this work
MFC (0-30 slpm)	AI	AO	For future usage
Capacitor Voltage	AI		Monitor capacitor voltage of ignition system
Switch 1: Charging	DI/O		Control charging action of ignition system
Switch 2: Firing	DI/O		Control firing action of ignition system
Switch 3: Discharging	DI/O		Control discharging action of ignition system
Switch 4: Air piston	DI/O		Control air piston up and down

3.5 Experimental Procedures

Figure 3.5 illustrates the measurement procedure used to determine the LFL, UFL and peak concentration. The solid circles are the points of flame extinction and the open circles, triangles and diamonds are the flammable points.

Figure 3.5 Illustration of the measurement procedure for the LFL, UFL and peak concentration

For the measurement of LFL and UFL, the methodology used in this work involved keeping the diluent concentration constant, while decreasing or increasing the fuel concentration. An initial flammable fuel-air mixture, with or without a small amount of diluent gas, was injected into the burner and then ignited. The desired amount of diluent was gradually added to the mixture. The fuel concentration was increased or decreased incrementally until the flame went out. It was found that the initial concentration of diluent which was no more than 10% was easily ignited.

The introduction of diluent after ignition has nothing to do with measured flammability limits provided this addition is finished before flame extinction. Therefore, the initial

diluent is normally set at 5% when investigating the dilution limits. For example, the dilution UFL with 15% carbon dioxide is to be determined. As shown in Figure 3.5, the initial concentrations are 9.0% methane and 5.0% carbon dioxide. After the initial gas mixture is ignited, the addition of CO₂ is introduced stepwise until it reaches the desired 15%. The methane concentration keeps increasing during the addition of CO₂. The 15% CO₂ must be completely added before the limit is reached, which is normally several steps before flame extinction. In this study the adjustment amplitude of methane was 0.1%, which can be easily changed based on the precision requirement. The same method is used to determine the dilution LFL.

For the measurement of peak concentration of diluent gas, the diluent concentration was increased step by step while the fuel concentration remains unchanged. As shown in Figure 3.5, the amount of CO₂ added was larger for the first several steps, and then decreased when the CO₂ concentration neared the peak concentration. In this case the adjustment amplitude was 0.1% when CO₂ concentration is over 24%. Several trials were needed to discover the peak concentration of CO₂.

Theoretically, each concentration condition of the gas mixture was kept constant for one minute to observe whether the flame disappeared or not before the next concentration condition was applied. This one-minute criterion is described in Section 4.1. This process would take a long time, especially for the unknown gas mixtures. To speed up the process and avoid the waste of gases, a much shorter time such as five seconds, was set to investigate the gas concentrations at flame extinction. A small range could then be estimated for the real flammability limit. By investigating this range using the one-minute standard, the flammability limit was obtained very quickly. The observation time can be adjustable in real time during a measurement. Each experimental run was usually kept to within five minutes to avoid overheating the burner and water condensation from the combustion gases.

During an experiment, the injection velocity was kept at 6.7 cm/s, i.e. total gas flowrate was 40 slpm for this burner system. All measurements were conducted at atmospheric pressure and room temperature of 25 °C. The burner needed to cool down for three to five minutes between experiments. A diffusion flame occurred when investigating rich mixtures, so the nitrogen barriers are necessary in this case. The mirror could be turned away from the diffusion flame to avoid overheating. In this situation, the hot exhaust gases could still be seen easily from the outside of the burner. Water must be kept running in the water-cooling sections during all measurements to cool down the burner.

3.6 Development of LabVIEW Application

To make this system work properly and efficiently, software development plays the same important role as the hardware construction. In this application, LabVIEW was used as the development tool to operate the burner system automatically. LabVIEW is a product of National Instrument (NI) and is known for its powerful function in the industrial automation of processes. “LabVIEW programs are called Virtual Instruments (VIs) because their appearance and operation imitate actual instruments (NI, 1994b)”. Basically a LabVIEW program has three sections:

- ◆ Front panel: i.e. the interactive user interface, which simulates a physical instrument.
- ◆ Block diagram: i.e. the source code for the VI. This is constructed in G (Graphical programming language).
- ◆ Icon and connector: VIs are hierarchical and modular. A VI within another VI is called a subVI. The icon and connector of a VI are a graphical parameter list so that other VIs can pass data to a subVI.

This comprehensive LabVIEW program is shown in Appendix 6 and consists of many layers of subVI. The organization of the VI hierarchy is shown in Figure A.6.1 in Appendix 6. The Hierarchy window of LabVIEW can display a graphical representation of the calling hierarchy for all VIs. Normally an application is created from the top-level VI and then many branches of subVIs might be constructed to perform the necessary

operations. If a block diagram has a large number of icons, it is better to group them into a lower-level VI to maintain the simplicity of the block diagram. This modular approach makes applications easy to debug, understand, and maintain. Figure A.6.2a to A.6.19b display all VIs developed for this application. Each VI (or subVI) comes with an icon and connector, a front panel, block diagram and VI description.

In this work four main modules were developed using LabVIEW to implement different functions, as shown in Figure 3.6.

Figure 3.6 Module structures for LabVIEW programming

It is seen from Figure 3.6 that there are four steps needed to fulfill the entire measurement process and data recording. The following section displays the working flowchart and a brief description of each module.

(1) Module 1: parameter setting

The working flowchart of module 1 is shown in Figure 3.7. All parameters are set at this stage, which are needed in the following modules, such as the correction factor K and working ranges of each MFC calibrated by nitrogen. Also certain parameters might need updating for each experimental run, such as the initial fuel concentration, initial diluent concentration, total gas flowrate, set point of capacitor voltage, file path for data recording and names of gases for experiments. According to different experimental requirements, all these parameters can be easily changed. This is a very efficient way to maintain and enhance the program, especially for a complicated program such as the one involved in this study.

Figure 3.7 Working flowchart of module 1 — parameter setting

(2) Module 2: initial state

The working flowchart of module 2 is shown in Figure 3.8.

Figure 3.8 Working flowchart of module 2 — initial state

The initial gas concentrations and gas nomenclatures are displayed in the front panel of LabVIEW, which are obtained from the settings of module 1. It is important to ensure that the initial concentrations of the gas mixture are correctly selected (i.e. can be ignited). Accordingly, it is possible to increase or decrease the fuel concentration to determine UFL or LFL when the flame goes out. The working ranges of the MFCs for the actual gases, which are calculated from the correction factor K , are displayed as well. One of the selection buttons for the UFL and LFL must be activated at this stage.

(3) Module 3: gas injection and ignition

The working flowchart of module 3 is shown in Figure 3.9. After the initial gas concentrations are determined and the selection of UFL and LFL is completed, the gas mixtures are injected into the burner. As soon as the monitored flowrate is equal to the controlled flowrate for fuel and air within set error tolerances, the system begins capacitor charging. When the capacitor voltage reaches the setpoint, the ignitor fires the gas mixture and then discharges the capacitor in order to avoid personal harm due to residual voltage. It has been determined that the time period from charging to firing is enough to allow the gases to travel through the tube and mixing chamber to the burner.

Figure 3.9 Working flowchart of module 3 — gas injection and ignition

(4) Module 4: determination of flammability limits

The working flowchart of module 4 is shown in Figure 3.10. If measurement of the LFL is selected in module 2, the program automatically decreases the fuel concentration step by step until the flame disappears. At the point of flame extinction, the fuel concentration is the LFL. Pressing the “Stop” button at this point means that gas injection is terminated. The same method is used to measure the UFL, except the fuel concentration is increased step by step. The observation time for the adjustment of flame extinction can be changed as desired in real time. Also, the diluent gas can be introduced into the burner dynamically and the concentrations of each gas updated continuously. For each run, the

concentration changes for each gas were recorded into a unique data file, which was named in module 1. The limits obtained from the experiments are used in the construction of the flammability envelope.

Figure 3.10 Working flowchart of module 4 — determination of flammability limits

Besides the four main procedures regarding this LabVIEW programming, there is much detailed information inside this program. For example, the emergency buttons must be given in module 3 and 4 in case an unexpected situation occurs during an experiment. When the emergency button is activated, the program immediately shuts down all MFCs; i.e., gas injection is terminated. Sometimes discharging the capacitor voltage is also necessary when the emergency button is pressed during the charging process.

3.7 Safety Concerns of this Burner System

Since this project experiments with flammable gas, safety precautions must be taken into account when dealing with these materials. Table 3.6 gives a list of possible problems and solutions.

Table 3.6 Safety factors involved in the experiments

Possible Problem	Solution	Recommendation
Fire or emergency	<ol style="list-style-type: none"> 1. Emergency button in the computer program to shut off gas injection to burner; 2. Run test panel of AI-AO-6 to initialize MFCs, which can shut off the gas injection; 3. Unplug the power supply of MFCs to stop gas injection to burner; 4. One fire extinguisher, one fire blanket, and two exits are available in the lab; 5. Close cylinder valves individually according to the sequence of CH₄, air, CO₂, and N₂. 	<ol style="list-style-type: none"> 1. Add another fire extinguisher and fire blanket on the other side of the lab in case route to first one is blocked; 2. Install a smoke detector and a fire alarm; 3. Make sure there is a clear route to the exits.
Gas leakage	<ol style="list-style-type: none"> 1. Leak detection solution: leaks are indicated by bubbling; 2. Pressure drop: individually check if pressure drop occurs in the high pressure gauge and delivery pressure gage. 	Check the system regularly.
Gas cylinder empty	The cylinder should be regarded as empty when the cylinder pressure has dropped to twice the delivery pressure or less.	Replace old gas cylinder.
Capacitor voltage	<ol style="list-style-type: none"> 1. Place the ignition circuit in an area that can not be easily accessed; 2. The computer program will automatically discharge the residual capacitor voltage. 	The safest way is to make a water proof and non-conductive casing for the ignition circuit.

Table 3.6 Safety factors involved in the experiments (continued)

Exhaust gases	Fume hood can extract exhaust gases.	Make sure fume hood is on and can satisfy the safety criteria.
Air piston failure after ignition	The ignitor must be removed immediately after ignition because it cannot withstand high temperature. Follow the above solutions for #1 or #2 in “fire or emergency” to stop gas injection to burner.	Confirm the air piston works properly before beginning experiment.
Power failure	The MFCs shut down automatically, and the gas injection is terminated.	Close gas cylinders and air manually.
Ignitor failure	This situation can be detected by the mirror. The gas injection should be stopped immediately by following the above solutions #1 or #2 in “fire or emergency”.	Make sure the pencil lead is tightly screwed between the positive and negative parts; Test the ignition system regularly; Change the pencil lead if necessary.

4. RESULTS AND DISCUSSION

4.1 Triangular Flammability Diagram

A triangular flammability diagram can be used to represent all possible mixtures of a three component system. As mentioned in Chapter 1, a triangular flammability diagram can be used to display the flammability region, and then used to determine if a flammable gas mixture is present during plant operations. Therefore this method has a very practical usage for many industrial plants which operate with hazardous materials. Once the flammability envelope is defined, it can be utilized to prevent flammable mixtures in actual settings.

A typical triangular flammability diagram is shown in Figure 4.1, which was published by Mashuga (1998). This is a kind of special triangular coordinate with three axes. The three concentrations are present on the graph at one time. Any point inside this triangle represents a total 100% concentration. This diagram displays methane, nitrogen and oxygen as the three components. All experimental data are plotted in these triangular coordinates. Each leg of the triangle has markings that run in a specific direction indicating a constant concentration of a given component. The straight line from the apex of the triangle to the 79% nitrogen axis is normally referred to as the air line, which indicates all possible mixtures of fuel and air.

There is a boundary between the solid circles and open circles, usually called the flammability envelope. Inside the envelope lies the flammability zone or flammability region, in which all mixtures are flammable. Those mixtures outside the envelope are non-flammable gas mixtures.

At present, there is no easy and ready-made software that can draw this special triangular graph. Mashuga (1998 and 1999) utilized an indirect way of drawing this graph. He mainly used DesignCad to draw this triangular flammability diagram. This program converts the ASCII data file into points and then layers these on top of a pre-drawn

triangular plot. The plot is then loaded into Corel Draw for final vector projection and property information display.

Figure 4.1 Triangular flammability diagram for $\text{CH}_4/\text{O}_2/\text{N}_2$ mixture (Mashuga, 1998)

To avoid the inconvenient process regarding the drawing of this special triangular diagram, a Data Graphing Package was designed in Visual Basic to simplify the drawing process.

4.2 Development of Data Graphing Package

The Data Graphing Package which was designed to graph the experimental data was developed using Microsoft Visual Basic 6.0 (professional edition). This developmental tool is noted for its extensive Windows development environment.

All data obtained from the experiment correlate to the triangular coordinates, which can represent all possible gas compositions of a three component system. The most difficult task for this program is the conversion of these triangular data points into data in rectangular coordinates, which can then be recognized by Visual Basic. Some mathematics and geometry skills were implemented in this conversion. Also, graphic skills were used to scale the coordinates, draw the triangle, and label the coordinate axes. Figure 4.2 displays the form structure and Figure 4.3 displays the algorithm of this Visual Basic program. The detailed code and information of this Data Graphing Package are shown in Appendix 7.

Figure 4.2 Form structure of the Data Graphing Package

Figure 4.3 Algorithm of Data Graphing Package

After experimental data are obtained, the Visual Basic program can draw the triangular coordinates and plot all data immediately. This program is designed to show all data in one graph from different file paths, which is clearly seen from Figure 4.2. The program is also capable of displaying individual results based on a selection. This program is much more convenient than the traditional method of drawing triangular diagram. It can be utilized for any three-component systems, rather than solely for combustion analysis. Relevant additional functions can be added to this program according to future requirements.

4.3 Experimental Results and Discussion

4.3.1 Investigation of A Time Standard for the Judgement of Flame Extinction

The first experiments conducted were to investigate the time constant for observing flame extinction. This group of experiments measured the LFL of methane in air. See Figure 4.4 for the results of LFL versus time.

Figure 4.4 Investigation of a time standard for the determination of flammability limits

From Figure 4.4, it is obvious that the flammability limit is independent of time when the observed time exceeds 50 seconds. This result is similar to the conclusion drawn by NRIFD (Liao et al., 1996), who utilized one minute as the observation time. In this work, one minute was also selected to determine flame extinction, in order to have more accurate data.

4.3.2 Results

The experimental data are saved in different predefined files automatically. Each file records the individual experiment, which displays the whole process of concentration changes, from initial concentrations at ignition to the final concentrations at flame extinction. This information is important for analyzing the experimental data and process. Tables A.8.1a to A.8.8 in Appendix 8 list each measurement process respectively, which are classified according to the concentration of CO₂. Figures A.8.9a, A.8.9b and A.8.9c give the process to investigate the peak concentration of CO₂. It is clearly seen from these three tables that peak concentration of CO₂ (24.7%) occurs at 6.8% of methane in the CH₄/Air/CO₂ mixture. All final concentrations at extinction (i.e. flammability limits) and peak concentration of CO₂ are utilized to construct the flammability envelope.

The results of flammability limits were loaded into the Data Graphing Package to draw the triangular flammability diagram which is shown in Figure 4.5. It is obvious the flammability zone only occupies a small part of the whole triangle and is not easily seen. To overcome this drawback for many applications like this, the graphing package was also designed with a zoom-in function. It requires the change of several constant parameters in the program to have different zoom-in effects as desired. Figure 4.6 gives the zoom-in triangular graph, which indicates the flammable and nonflammable regions (the text “flammable” and “nonflammable” were easily added using Microsoft Paint).

Figure 4.5 Triangular flammability diagram of $\text{CH}_4/\text{air}/\text{CO}_2$ mixture

Figure 4.6 Zoom-in triangular flammability diagram of $\text{CH}_4/\text{air}/\text{CO}_2$ mixture

From Figure 4.6 and the experimental process, the following phenomena and observations are summarized:

- (1) With increasing concentration of CO₂, the dilution LFL increases slightly while the dilution UFL decrease significantly. It is obvious to see that the addition of diluent gas narrows the flammability range; the more diluent gas added, the narrower the flammability range. This conclusion is in agreement with many other studies.
- (2) The upper and lower limits have converged at a carbon dioxide concentration of 24.7%, i.e., the peak concentration of carbon dioxide is 24.7% for the methane/air mixture in this work.
- (3) The minimum and maximum concentrations at extinction are 5.0% and 14.1% respectively. These are the LFL and UFL for the methane/air system as measured by this apparatus.
- (4) A tubular flame with a light blue color was observed inside the burner, which appears in the circular cross section.
- (5) The nitrogen barriers are indispensable when investigating the rich flame or diminishing the effect of the fume hood system.
- (6) When the injection velocity is small enough, i.e. the total gas flowrate is small, the flame fluctuates unstably and the flammability range narrows, which is not desired for the burner system. Therefore the injection velocity of 6.7 cm/s (i.e. 40-slp_m flowrate) was kept constant during the measurements.

4.3.3 Comparison of Results

Figure 4.7 shows the flammability limits of $\text{CH}_4/\text{air}/\text{CO}_2$ mixture measured in this study, as well as a comparison with the literature data reported by NRIFD (Saito et al., 1995) and Coward and Jones (1952).

Figure 4.7 Comparison of flammability limits of $\text{CH}_4/\text{air}/\text{CO}_2$ system

Table 4.1 lists the flammability limits and peak concentration for $\text{CH}_4/\text{air}/\text{CO}_2$ mixtures as determined by several related studies.

Table 4.1 Comparison of flammability limits and peak concentration for CH₄/Air/CO₂ mixture

Reference	Method	LFL (%)	UFL (%)	Peak concentration of CO ₂ (%)
This work	Tubular flame burner (vertical)	5.0	14.1	24.7
Ishizuka (1991)	Tubular flame burner (vertical)	4.7	14.9	--
NRIFD (Saito et al., 1995)	Tubular flame burner (vertical)	4.7	15.1	27
Coward and Jones (1952)	Explosion tube	5.3	14.0	24

From Figure 4.7 and Table 4.1, the following points are summarized:

- (1) It is apparent that the flammability curve from this work lies between the NRIFD (Saito et al., 1995) curve and that of Coward and Jones (1952). The current flammability range was wider than that obtained by the traditional Coward and Jones method, which was a predicted result. The lean side from this work is lower than Coward and Jones's while the rich side is almost overlapping. The extension of the flammable range is mainly due to a reduction of downstream heat loss in this counterflow system. This means that the tubular burner method can provide safer limits.
- (2) There is a smaller flammability range obtained from this work compared to the result of NRIFD (Saito et al., 1995), as observed from Figure 4.7. The discrepancy may come from the following factors:

- ◆ **Difference of the burners:** the diameter of the current burner is 40 mm compared to 30 mm used by NRIFD. Because the flame is established in a circular section around the burner wall, the larger inner surface area in the current burner leads to more heat loss than that of NRIFD burner. This helps to explain the narrower flammability range obtained in this work. Also the current burner is made of porous stainless steel instead of bronze material as used by NRIFD. This may also affect the results, although the nature of the effect is not known now.
- ◆ **Difference of the experimental methods:** the current burner system is an automated DAQ system compared to the manually controlled system used by NRIFD. An automated system can be reasonably expected to provide slightly different results due to no manual intervention.
- ◆ **Experimental accuracy:** the average relative error determined from the current system is about $\pm 4\%$, which is discussed in Section 4.4. As mentioned by NRIFD (Ogawa et al., 1998), their total error is about $\pm 3\%$. These two errors may contribute to the difference in results.

At present, there is no standard to evaluate the results obtained using tubular flame burners. In fact, many current new methods tend to agree with the Coward and Jones method. The results from Coward and Jones are considered as the standard in many studies. These new alternative methods are normally easier and faster to use in the measurement of flammability limits than the traditional Coward and Jones method. It has been proven from the current work, NRIFD (Liao et al., 1996; Satio et al., 1995 and 1997; Ogawa et al., 1998) and Ishizuka (1991) that the tubular flame burner technique is a good alternative to the traditional method.

- (3) The LFL and UFL were found at 5.0% and 14.1% respectively in this work. Referring to Table 2.3 in Section 2.4, it can be seen that the values of LFL and UFL from this study are in close agreement with other studies.
- (4) The peak concentration of carbon dioxide is 24.7% from this work, compared with 24% Coward and Jones (1952) and 27% NRIFD (Saito et al., 1995). Beyond this peak concentration, the flame propagation is inhibited for any concentration of flammable gas mixture.

4.4 Error Analysis of the Experimental Data

To evaluate the accuracy of the experimental results, error analysis is important for any measurement system. It is known that there are two types of errors in the measurement: bias error and precision error, among which bias error is detailed in this section. It is recommended that future studies using larger sample sizes and smaller measurement intervals be conducted to determine precision error.

Bias error is also referred to as systematic error or bias uncertainty. It occurs in the same fashion for each measurement. The bias errors in this work come from the accuracy of each MFC. The MFCs used in this work have the accuracy of $\pm 1.5\%$ of the full range, according to the Omega manual. Theory of the error propagation is utilized to determine the bias error of the flammability data. It is known that the flammability limits are calculated from the flowrates of fuel, air and diluent gases, which is given by the formula:

$$\text{CH}_4 \% = F_{\text{CH}_4} / (F_{\text{CH}_4} + F_{\text{Air}} + F_{\text{CO}_2}) \quad (4-1)$$

Where:

F_{CH_4} -- Flowrate of methane

F_{Air} -- Flowrate of air

F_{CO_2} -- Flowrate of carbon dioxide

The bias uncertainty is expressed as:

$$U_{(CH_4\%)} = \sqrt{\left[\frac{\partial(CH_4\%)}{\partial F_{CH_4}} U(F_{CH_4}) \right]^2 + \left[\frac{\partial(CH_4\%)}{\partial F_{Air}} U(F_{Air}) \right]^2 + \left[\frac{\partial(CH_4\%)}{\partial F_{CO_2}} U(F_{CO_2}) \right]^2} \quad (4-2)$$

Where:

$U(F_{CH_4})$ -- Uncertainty of methane flowrate

$U(F_{Air})$ -- Uncertainty of air flowrate

$U(F_{CO_2})$ -- Uncertainty of carbon dioxide flowrate

In this application:

$$\frac{\partial(CH_4\%)}{\partial F_{CH_4}} = \frac{1}{(F_{CH_4} + F_{Air} + F_{CO_2})} - \frac{F_{CH_4}}{(F_{CH_4} + F_{Air} + F_{CO_2})^2} \quad (4-3)$$

$$\frac{\partial(CH_4\%)}{\partial F_{Air}} = - \frac{F_{CH_4}}{(F_{CH_4} + F_{Air} + F_{CO_2})^2} \quad (4-4)$$

$$\frac{\partial(CH_4\%)}{\partial F_{CO_2}} = - \frac{F_{CH_4}}{(F_{CH_4} + F_{Air} + F_{CO_2})^2} \quad (4-5)$$

According to the above equations, the bias errors can be determined for the different measurement results. Table 4.2 gives the calculation procedure to obtain the bias error for the result of 5.3% CH_4 , 84.7 % Air and 10% CO_2 . Table 4.3 lists the bias errors and relative errors for the all the measurement results. The average relative error is about $\pm 4\%$, which is calculated from the last column of Table 4.3.

Table 4.2 Determination of bias error for the measurement of the flammability limits (in the result of 5.3% CH₄, 84.7 % air and 10% CO₂)

Gas name	CH ₄	Air	CO ₂
Correction factor K	0.72	1.00	0.74
MFC range (slpm)	10 × 0.72 = 7.18	50 × 1.00 = 50.00	15 × 0.74 = 11.07
Bias error (± 1.5% of full range) (slpm)	0.11	0.75	0.17
Measured value	5.3%	84.7%	10.0%
Flowrate (slpm)	2.12	33.88	4.00
$\partial(\text{CH}_4\%)/\partial F$	0.027	-0.0013	-0.0013
$UF \times \partial(\text{CH}_4\%)/\partial F$	0.0026	-0.00099	-0.00022
U (CH ₄ %)	±0.0027		

Table 4.3 List of bias error and relative error for the measurement data

Limit	CO ₂	CH ₄	Bias error	Relative error (%)
LFL	0%	5.0%	±0.27%	±5.46
	5%	5.1%	±0.27%	±5.36
	10%	5.3%	±0.27%	±5.18
	15%	5.4%	±0.28%	±5.09
	20%	5.6%	±0.28%	±4.93
	22%	5.8%	±0.28%	±4.77
	23%	5.9%	±0.28%	±4.70
	24.4%	6.6%	±0.28%	±4.27
Peak concentration	24.7%	6.8%	±0.28%	±4.16
UFL	24.6%	7.0%	±0.28%	±4.06
	24%	7.6%	±0.29%	±3.79
	23%	8.0%	±0.29%	±3.64
	22%	8.4%	±0.30%	±3.51
	20%	9.0%	±0.30%	±3.33
	15%	10.2%	±0.31%	±3.05
	10%	11.4%	±0.32%	±2.84
	5%	12.8%	±0.34%	±2.65
	0%	14.1%	±0.36%	±2.52

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

An automated flammability burner system has been successfully developed, based on the tubular flame burner method. The gas mixture of methane/air/carbon dioxide has been used to investigate the efficiency of this burner system. A series of data obtained from the experiments have been compared with related literature. Based on the work done and results obtained, the following conclusions are given:

- (1) This tubular flame burner system is a fully automated data acquisition and control system and is relatively easy to use. This system has a high degree of automation than many other methods in the measurement of flammability limits and the peak concentration of diluent gas. Using this system, it takes about 10 minutes to obtain a data point of UFL or LFL. Accordingly, it is especially efficient to obtain the flammability limits for unknown gases, which is important for many industrial plants.
- (2) A Data Graphing Package was successfully developed by Microsoft Visual Basic 6.0. This package can plot the triangular flammability diagram in a very simple and expedient way, compared with the traditional drawing method. The flammability envelope can be constructed whenever it is decided to deal with the experimental data. The flammability zone has been experimentally determined for the mixture of methane, air and carbon dioxide and plotted in the triangular flammability diagram. A zoom-in effect can also be implemented if necessary.
- (3) The ignitor assembly was professionally designed using AutoCAD 14.0. This ignition system can implement automatic ignition and charging and discharging action at specific conditions. It can also monitor the change of capacitor voltage. The automatic ignition system makes the automation system more advanced for measuring flammability limits.

- (4) The mixture of methane/air/carbon dioxide was used to investigate the system efficiency. The flammability envelope determined from this work lies between NRIFD (Saito et al., 1995) and Coward and Jones' (1952). A wider flammable region and higher peak concentration were obtained in comparison to the Coward and Jones method, which is an expected result. A smaller flammability range was obtained in this work compared to the NRIFD study. This discrepancy comes from the experimental accuracy and the difference of the experimental methods and the burners (diameter and material). It is proven from this research that the tubular flame burner method is a good alternative to the traditional method, which is in agreement with the findings of NRIFD.
- (5) The average relative bias error of this system was estimated as $\pm 4\%$.
- (6) A one-minute standard was used to judge the flame extinction. It is found that the time period the mixture concentration is kept has no effect on the results when this period is over 50 seconds.
- (7) The presence of diluent gas (carbon dioxide) was found to narrow the flammability range, which agrees with the conclusions from many other studies. The peak concentration of CO_2 determined by this system was 24.7%, which is consistent with the results from NRIFD (27%) and Coward and Jones (24%).

5.2 Recommendations for Future Work

This system was mainly designed for future research work. The mixture of methane/air/carbon dioxide was only used to test the functionality of the system in this work. Many related studies can be conducted using this burner system, which are discussed as follows:

- (1) There are several kinds of applications regarding the measurement of UFL and LFL.

- ◆ Fuel / Air*
- ◆ Fuel / Air / Diluent*
- ◆ Fuel / Nitrogen / Oxygen
- ◆ Fuel / Nitrogen / Oxygen / Diluent

* These two kinds of gas mixtures are investigated in this work.

It is relatively simple to modify the gas tubing connection to the selected MFCs for the other two applications. It is recommended to conduct more experiments on this automated system to obtain the results of some other fuels with different diluent gases.

- (2) It was reported by NRIFD that slightly wider data on the flammability region might be obtained in the horizontal setup (Liao et al., 1996). Ishizuka (1991) reported that the shape of the tubular flame is deformed significantly in the horizontal setup. In this study, only the vertical orientation of tubular burner was investigated. Therefore, it is recommended further studies be done to include measurement of flammability limits using the burner placed in a horizontal position.
- (3) It is recommended that the future studies use larger sample sizes and smaller measurement intervals to determine precision error.
- (4) It is recommended to investigate the profile of flame temperature by mounting an R-thermocouple in the center of the burner.
- (5) With the tubular burner system used in this study, results can be obtained quicker than all other systems. It is also easier to operate and therefore can be used by new users. Therefore, it is recommended that this automated burner system be used for undergraduate studies in combustion phenomena.

6. References

Ale, B. B., Flammability Limits of Gaseous Fuels and their Mixtures in Air at Elevated Temperature, Unpublished Ph.D. Thesis, The University of Calgary, Canada, (1998)

Andrew, G. E. and Bradley, B, "Limits of Flammability and Natural Convection for Methane-Air Mixtures", Fourteen Symposium (International) on Combustion, The Combustion Institute, (1973), pp. 1119-1128

ASTM, "Standard Test Method for Concentration Limits of Flammability of Chemicals (Vapors and Gases)", Designation E681-98, (1998)

ASTM, "Standard Practice for Determining Limits of Flammability of Chemicals at Elevated Temperature and Pressure", Designation E918-83 (Reapproved 1993)

Burgoyne, J. H. and Williams-Leir, G., "Limits of Inflammability of Gases in The Presence of Diluents. A Critical Review of Data", J. Fuel, **27**, (1948a), pp. 118-125

Burgoyne, J. H. and Williams-Leir, G., "The Influence of Incombustible Vapours on The Limits of Inflammability of Gases and Vapours in Air", Proc. Roy. Soc., **193A**, (1948b) pp.525-539

Coward, H. F. and Jones, G. W., Limits of Inflammability of Gases and Vapors, U. S. Dept. of The Interior, Bulletin **279** (Revised), Bureau of Mines, (1938)

Coward, H. F. and Jones, G. W., "Determination of Limits" in Limits of Flammability of Gases and Vapors, U. S. Dept. of The Interior, Bulletin **503**, Bureau of Mines, (1952)
Drysedale, D. D., "An introduction to Fire Dynamics", Jon Wiley and Sons Ltd. (1985)

Egerton, A. C., F. R. S. and Thabet S. K., "Flame Propagation: The Measurement of Burning Velocities of Slow Flames And The Determination of Limits of Combustion", Proc. Roy. Soc. A, **211**, (1952), pp.445-471

Egerton A. C., "Limits of Inflammability", Survey Paper, Proceedings of Fourth Symposium (International) on Combustion, Baltimore, (1953), pp. 4-13

Glassman, I., Combustion, 3rd edition, Academic Press, Inc., San Diego, California 92101-4495, USA, (1996)

Harris, K. P., The Effect of Low Temperature on The Flammability Limits of Some Gaseous Fuels and their Mixtures in Air, Unpublished Master Thesis, The University of Calgary, Canada, (1990)

Hirst, R., Savage, N., and Booth, K., "Measurement of Inerting Concentration", *Fire Safety Journal*, 4, (1981/82), pp.147-158

Ishizuka S. and Chung K. Law, "An Experimental Study on Extinction and Stability of Stretched Premixed Flames", Nineteenth Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, PA, (1982), pp. 327-335

Ishizuka, S., "Determination of Flammability Limits Using A Tubular Flame Geometry", *J. Loss Process Industry*, Vol. 4, April, (1991), pp.185-193

Kobayashi, H. and Kitano, M., "Extinction Characteristics of A Stretched Cylindrical Premixed Flame", *Combustion Flame*, 76, (1989) pp.285-295

Lewis, B. and von Elbe, G., "Combustion Waves in Laminar Flow" in Combustion, Flames and Explosions of Gases, 3rd Edition, Academic Press, Inc., Orlando, Florida 32887, (1987)

Liao, C., Satio, N., Saso, Y., and Ogawa, Y., "Flammability Limits of Combustible Gases and Vapors Measured by Tubular Flame Method", *Fire Safety Journal* 27 (1996), pp. 49-68

Lovachev, L. A., Babkin, V. S., Bunev, V. A., V'yun, A. V., Kirvulin, V. N. And Baratov, A. N., "Flammability Limits--An Invited Review, *Combustion And Flames*, vol. 20, (1973), pp.209-224

Mashuga, C. V. and Crowl D. A., "Application of The Flammability Diagram for Evaluation of Fire and Explosion Hazards of Flammable Vapors", American Institute of Chemical Engineers, 32nd Loss Prevention Symposium, New Orleans, LA, (1998)

Mashuga, C. V., "Flammability Zone" in Determination of The Combustion Behavior for Pure Component and Mixtures Using A 20-Liter Sphere, unpublished Ph.D. thesis, Michigan Technological University, USA, (1999)

NI, AT-AO-6/10 User Manual, Part Number 320379-01, September 1994 Edition, Texas 78730-5039, USA, (1994a)

NI, LabVIEW User Manual for Windows, Part Number 320534B-01, September 1994 edition, Texas 78730-5039, USA, (1994b)

NI, 6023E/6024E/6025E User Manual, Part Number 322072B-01, January 1999 Edition, Texas 78730-5039, USA, (1999)

"NFPA49: Hazardous Chemicals Data" in Fire Protection Guide to Hazardous Materials, National Fire Protection Association, Massachusetts 02269-9010, (1994)

OMEGA Company, User's Guide: FMA 5400/5500 Mass Flow Controllers, <http://www.omega.com>

Ogawa, Y., Satio, N. and Liao, C., "Burner Diameter and Flammability Limit Measured By Tubular Flame Burner", Presentation at 27th Symposium (international) on Combustion, August 2-7, (1998), University of Colorado at Boulder, USA

Powling, J., "A New Burner Method for The Determination of Low Burning Velocities and Limits of Inflammability", J. Fuel **28**, (1949), pp.25-28

Satio, N., Saso, Y., Liao, C., Ogawa, Y., and Inoue, Y., "Flammability Peak Concentration of Halon Replacements and Their Function as Fire Suppressants", American Chemical Society, Chapter 20, (1995)

Satio, N., Liao, C., Ogawa, Y., Saso, Y., Hikiba, K., and Sato, K., "Flammability Limits and Peak Concentrations: The Use of New Technique and Results", Second international

Symposium on Fire-and-Explosion Hazard of Substances and Venting of Deflagrations, 11-15 Aug., Moscow, Russia, (1997)

Zabetakis, M. G., Flammability Characteristics of Combustible Gases and Vapor, U. S. Dept. of The Interior, Bulletin 627, Bureau of Mines, (1965)

APPENDICES

Appendix 1: Drawings of Ignitor Assembly Components

Figure A.1.1 Ignitor assembly component – A

Title	Ignitor Assembly Design (A)		
Tolerance	$\pm 0.0050''$ unless indicated		
Material	316 Stainless Steel		
Scale	3 : 1	Designer	Fanni Bu
Location	Chemical Dept., Dalhousie Univ.	Date	Jun. 7, 1999

Figure A.1.2 Ignitor assembly component – B

Title	Ignitor Assembly Design (B)		
Tolerance	±0.0050" unless indicated		
Material	316 Stainless Steel		
Scale	3 : 1	Designer	Fanni Bu
Location	Chemical Dept., Dalhousie Univ.	Date	Jun. 7, 1999

3-off columns

Figure A.1.3 Ignitor assembly component – C

Title	Ignitor Assembly Design (C)		
Tolerance	$\pm 0.0050''$ unless indicated		
Material	316 Stainless Steel		
Scale	3 : 1	Designer	Fanni Bu
Location	Chemical Dept., Dalhousie Univ.	Date	Jun. 7, 1999

Figure A.1.4 Ignitor assembly component – D

Title	Ignitor Assembly Design (D)		
Tolerance	±0.0050" unless indicated		
Material	Pencil Lead		
Scale	4 : 1	Designer	Fanni Bu
Location	Chemical Dept., Dalhousie Univ.	Date	Jun. 7, 1999

Figure A.1.5 Ignitor assembly component – E

Title	Ignitor Assembly Design (E)		
Tolerance	±0.0050" unless indicated		
Material	316 Stainless Steel		
Scale	3 : 1	Designer	Fanni Bu
Location	Chemical Dept., Dalhousie Univ.	Date	Jun. 7, 1999

Figure A.1.6 Ignitor assembly component – F

Title	Ignitor Assembly Design (F)		
Tolerance	±0.0050" unless indicated		
Material	316 Stainless Steel		
Scale	6: 1	Designer	Fanni Bu
Location	Chemical Dept., Dalhousie Univ.	Date	Jun. 7, 1999

Figure A.1.7 Ignitor assembly component – G

Title	Ignitor Assembly Design (G)		
Tolerance	$\pm 0.0050''$ unless indicated		
Material	316 Stainless Steel		
Scale	3 : 1	Designer	Fanni Bu
Location	Chemical Dept., Dalhousie Univ.	Date	Jun. 7, 1999

Appendix 2: Test Program of the Ignition System

ignitor_test.vi

This VI is used to test the functionality of the ignition system.

Figure A.2.1a Icon/connector, VI description and front panel of ignitor_test.vi

Figure A.2.1b Block diagram of ignitor_test.vi

Appendix 3: List of Items Purchased for This Work

Table A.3.1 List of items purchased for this work

Specification	Part No.	Brief Description	Price (Can\$)	Supplier
FMA5420	N/A	MFC 0-10slpm N ₂	\$1036	Omega Inc.
FMA5422	N/A	MFC 0-15slpm N ₂	\$1036	Omega Inc.
FMA5426	N/A	MFC 0-30slpm N ₂	\$1281	Omega Inc.
FMA5428	N/A	MFC 0-50slpm N ₂	\$1281	Omega Inc.
FMA545C	N/A	Female 15-Pin D-Connector Shielded Cable	4*\$67	Omega Inc.
FMA545PW	N/A	Switching AC adapter 100~240V / 12 VDC	4*\$89	Omega Inc.
FL-2042	N/A	3-30lpm Acrylic Meter	\$69	Omega Inc.
PCI- 6023E	777742-01	Multifunction I/O Board; 16AI & 8DIO	\$572	National Instrument
R6868	182482-01	68-Pin Flat Ribbon Cable	\$95	National Instrument
CB-68LP	777145-01	I/O Connector Block with 68 Screw Terminal	\$131	National Instrument
AT-AO-6	776541-01	6AI & 8(5V/TTL)line	\$1292	National Instrument
NB1	180524-10	1 m 50-Pin Ribbon Cable	\$45	National Instrument
CB-50	776164-90	I/O Connector Block with Din Rail Mounting	\$162	National Instrument

Appendix 4: MFC 15-Pin “D” Connector Configuration

Table A.4.1 MFC 15-pin “D” connector configuration

Pin #	Function	Wire color in cable
1*	Flow signal common	Black / white stripe
2*	0 to 5 VDC flow signal output	Orange
3	Common	Red / white stripe
4	Purge	Blue / white stripe
5**	Common, power supply	Blue
6	(unassigned)	White / black stripe
7**	+12 VDC (+24 VDC) power supply	Red / black stripe
8***	Remote setpoint	White
9	4 to 20 mA return (common)	Green / white stripe
10***	Common, setpoint signal	Blue / black stripe
11	- 5 VDC reference for the remote setpoint	Orange / black stripe
12	Valve off control (open collector)	Green / black stripe
13	+ 12 VDC (+24 VDC) power supply	Black
14	4 to 20 mA flow signal output	Green
15	Chassis ground	Red

***Pin #2 and #1** are the output signal and corresponding common ground respectively, used for monitoring flowrate.

****Pin #7 and #5** are power supply and corresponding common ground respectively. +12 VDC is used in this work, obtained from the 100~240 V / 12 VDC adapter.

*****Pin #8 and #10** are control signal and corresponded common ground respectively, used for controlling gas flowrate.

Other Pins are not used for this work.

Appendix 5: DAQ Boards and Accessories

Table A.5.1 List of DAQ boards and related accessories

Specification	Description
PCI- 6023E	low-cost multifunction I/O board for PCI; 16SE/8DI analog inputs and 8DIO; 200KS/s sampling rate; 12-bit resolution.
R6868	68-pin flat ribbon cable terminated with two 68-pin connectors. Cable is used to connect a 68-pin E-series to 68-pin accessories.
CB-68LP I/O Connector Block	low-cost termination accessory with 68 screw terminals for easy connection of field I/O singles to 68-pin DAQ products.
AT-AO-6	high performance analog input for IBM PC AT compatibles; 6 analog input and 8(5V/TTL)line; 300 KS/s maximum update rate; 12-bit resolution.
NB1	1 m 50-pin ribbon cable used to connect 50-pin DAQ board to 50-pin accessory like CB-50.
CB-50 I/O Connector Block with Din Rail Mounting	termination accessory with 50 screw terminals for easy connection of field I/O signals; includes an 50-pin header for direct connection to 50-pin cable;

ACH8	34	68	ACH0
ACH1	33	67	AIGND
AIGND	32	66	ACH9
ACH10	31	65	ACH2
ACH3	30	64	AIGND
AIGND	29	63	ACH11
ACH4	28	62	AISENSE
AIGND	27	61	ACH12
ACH13	26	60	ACH5
ACH6	25	59	AIGND
AIGND	24	58	ACH14
ACH15	23	57	ACH7
DAC0OUT ¹	22	56	AIGND
DAC1OUT ¹	21	55	AOGND
RESERVED	20	54	AOGND
DIO4	19	53	DGND
DGND	18	52	DIO0
DIO1	17	51	DIO5
DIO6	16	50	DGND
DGND	15	49	DIO2
+5 V	14	48	DIO7
DGND	13	47	DIO3
DGND	12	46	SCANCLK
PFI0/TRIG1	11	45	EXTSTROBE*
PFI1/TRIG2	10	44	DGND
DGND	9	43	PFI2/CONVERT*
+5 V	8	42	PFI3/GPCTR1_SOURCE
DGND	7	41	PFI4/GPCTR1_GATE
PFI5/UPDATE*	6	40	GPCTR1_OUT
PFI6/WFTRIG	5	39	DGND
DGND	4	38	PFI7/STARTSCAN
PFI9/GPCTR0_GATE	3	37	PFI8/GPCTR0_SOURCE
GPCTR0_OUT	2	36	DGND
FREQ_OUT	1	35	DGND

¹ Not available on the 6023E

Figure A.5.1 I/O connector pin assignment for PCI-6023E (NI, 1999)

Figure A.5.2 I/O connector pin assignment for AI-AO-6 (NI, 1994a)

Appendix 6: LabVIEW programming

A.6.1 VI Hierarchy

Figure A.6.1 VI hierarchy of LabVIEW program

A.6.2 LabVIEW program

This is the main VI which consists of four modules.
(1) Parameter Setting
(2) Initial State
(3) Gas Injection and Ignition
(4) Determination of Flammability Limits

Fuel name Lower Limit %	
CH4	5.30
Oxidant name Oxidant %	
Air	84.70
Diluent name Diluent %	
CO2	10.00

Figure A.6.2a Icon/connector, VI description and front panel of MAIN.vi

Figure A.6.2b Block diagram of MAIN.vi

All parameters needed for this experiment are set in this VI. They can be updated for each experiment run.

Gas Names Fuel: CH ₄ Oxidant: Air Diluent: CO ₂	Correction Factor K K-Fuel: 0.7175 K-Oxidant: 1.0000 K-Diluent: 0.7382	Error Tolerance (slpm) ET for Fuel: 0.02 ET for Oxidant: 0.03
Total Gas Flowrate 40.00 Vc Setpoint(v) 130 Fuel Adjust Amplitude 0.10 Time (flame extinction) 5	Initial Gas composition Initial Fuel%: 6.50 Initial Oxidant%: 88.50 Initial Diluent%: 5.00	N₂ Range for MEC MFC_Fuel: 10.00 MFC_Diluent: 15.00 MFC_Oxidant: 50.00
Save data: d:\bu\LabVIEW\Thesis Data\C10\Mar10\LFL		
<div style="text-align: right;"> Done </div>		

Figure A.6.3a Icon/connector, VI description and front panel of Parameter_setting.vi

Figure A.6.3b Block diagram of `Parameter_setting.vi`

One of the buttons (upper or lower) must be activated, and then this VI can finish.

The gas names and initial concentrations are saved in a unique file which is named by parameter_setting.vi.

Gas mixture	Composition	MFC for Gas Range
Fuel name: <input type="text" value="CH4"/>	Fuel %: <input type="text" value="6.50"/>	<input type="text" value="7.1750"/>
Oxidizer name: <input type="text" value="Air"/>	Oxidant %: <input type="text" value="88.50"/>	<input type="text" value="50.00"/>
Agent name: <input type="text" value="CO2"/>	Diluent %: <input type="text" value="5.00"/>	<input type="text" value="11.0730"/>

Upper limit ☐

Lower limit ☐

User Guide

Want to measure LFL or UFL?

Choose the button now.

Figure A.6.4a Icon/connector, VI description and front panel of initial_state.vi

Figure A.6.4b Block diagram of initial_state.vi

This SubVI is to control each MFC to give the correct flowrate according to the initial gas concentrations.

Controlling and monitoring flowrate are executed at the same time. When each of the flowrates, fuel and air, reaches the desired values within error tolerances, the capacitor starts charging and then firing the gas mixture.

Figure A.6.5a Icon/connector, VI description and front panel of Injection_Ignition.vi

Figure A.6.5b Block diagram of Injection_Ignition.vi

This SubVI shows the concentration changes in real time.

The time for the judgement of flame extinction can be changed dynamically. More diluent should be added at this stage, if needed. Simply change the diluent concentration in real time.

When the flame goes off, press the "Stop" button to terminate the gas injections.

Figure A.6.6a Icon/connector, VI description and front panel of Time.vi

Figure A.6.6b Block diagram of Time.vi

This VI is for the determination of UFL or LFL, with or without diluent added.

Controlled Flowrate		Lower Limit %	
Fuel flowrate(C)	0.00	0.00	
Oxidant flowrate(C)	0.00	0.00	
Diluent flowrate(C)	0.00	0.00	

Monitored Flowrate		
Fuel flowrate	Oxidant flowrate	Diluent flowrate
10.8 8.0 6.0 4.0 2.0 0.0	50.0 40.0 30.0 20.0 10.0 0.0	22.2 15.0 10.0 5.0 0.0
0.00	0.00	0.00

STOP

[Esc]

Figure A.6.7a Icon/connector, VI description and front panel of limits.vi

Figure A.6.7b Block diagram of limits.vi

This VI is to Inject gases based on gas concentration.

Injected Gas Concentration

Fuel %

Diluent%

Controlled Flowrate

Fuel flowrate(C)

Oxidant flowrate(C)

Diluent flowrate(C)

Monitored Flowrate

Fuel Flowrate

Oxidant Flowrate

Diluent Flowrate

Figure A.6.8a Icon/connector, VI description and front panel of Inject_gases.vi

Figure A.6.8b Block diagram of Inject_gases.vi

This SubVI is to control the flowrate for each gas according to the given concentrations.

Figure A.6.9a Icon/connector, VI description and front panel of `control_flowrate.vi`

Figure A.6.9b Block diagram of `control_flowrate.vi`

This SubVI is to monitor the flowrate of each gas.

Figure A.6.10a Icon/connector, VI description and front panel of monitor_flowrate.vi

Figure A.6.10b Block diagram of monitor_flowrate.vi

This SubVI is to control the behavior of the ignition system.

Figure A.6.11a Icon/connector, VI description and front panel of ignitor.vi

Figure A.6.11b Block diagram of `ignitor.vi`

This SubVI is for the channel configurations, which need to be changed when the hardware wirings are changed.

Channel Configuration			
Device		Device	
PCI-6023E		AT-AO-6	
1		2	
Analog Input		Analog Output	
Capacitor Voltage	7	AO for Fuel	1
AI for Fuel	1	AO for Oxidant	2
AI for Oxidant	2	AO for Diluent	3
AI for Diluent	3		
Digital Output			
Charge	SW1		
Fire	SW2		
Discharge	SW3		
Air Piston	SW4		

Figure A.6.12a Icon/connector, VI description and front panel of DAQ_board.vi

Figure A.6.12b Block diagram of DAQ_board.vi

This SubVI decides fuel%, oxidant% and diluent% depending on fuel% and diluent%.

Figure A.6.13a Icon/connector, VI description and front panel of `gas.vi`

Figure A.6.13b Block diagram of `gas.vi`

This SubVI is to check if the monitored flowrate is equal to the controlled flowrate for fuel and oxidant within error tolerances. If no, keep waiting. If yes, this VI is finished.

Figure A.6.14a Icon/connector, VI description and front panel of `equal.vi`

Figure A.6.14b Block diagram of equal.vi

This SubVI converts the flowrate into the corresponding voltage.

Figure A.6.15a Icon/connector, VI description and front panel of `slm_volt.vi`

Figure A.6.15b Block diagram of `slm_volt.vi`

This SubVI converts the voltage value into the corresponding flowrate.

Figure A.6.16a Icon/connector, VI description and front panel of volt_slm.vi

Figure A.6.16b Block diagram of volt_slm.vi

This SubVI is to control the analog output for MFC according to the given voltage for the individual channel.

Figure A.6.17a Icon/connector, VI description and front panel of AO.vi

Figure A.6.17b Block diagram of AO.vi

This SubVI is to control the Digital I/O of the ignition system, such as charging, firing and discharging action.

Figure A.6.18a Icon/connector, VI description and front panel of DIO.vi

Figure A.6.18b Block diagram of DIO.vi

This SubVI is to control the position of the air piston (up or down).

Figure A.6.19a Icon/connector, VI description and front panel of Air_piston.vi

Figure A.6.19b Block diagram of Air_piston.vi

Appendix 7: Data Graphing Package (Visual Basic Program)

Option Explicit

'Declare variables

Dim dblDataRight As Double, dblDataBottom As Double, dblDataLeft As Double

Dim intX0 As Integer, intY0 As Integer

Dim intSideLength As Integer

Dim intXPeak As Integer, intYPeak As Integer

Dim intXRight As Integer, intYRight As Integer

Dim strDataFile1 As String, strDataFile2 As String

Dim strDataFile3 As String

Dim intColor As Integer

'Declare constant parameter

Private Const intScaleX = 6000

Private Const intScaleY = 6000

Private Const intGrid = 10 'This parameter needs changing when zoom-in is needed

Private Const intSubGrid = 5

Private Const dblPAI = 3.141592654

'Define the start and end points of each coordinate.

'These constants need to be modified based on different purposes (with/without zoom-in).

'L-Left, B-Bottom, R-Right.

Private Const intLStart = 0

Private Const intLEnd = 100

Private Const intBStart = 0

Private Const intBEnd = 100

Private Const intRStart = 0

Private Const intREnd = 100

Private Sub Form_Load()

'Set default file paths

txtPathName1.Text = "d:\bu\Thesis\Data\NRIFD.txt"

txtPathName2.Text = "d:\bu\Thesis\Data\Coward.txt"

txtPathName3.Text = "d:\bu\Thesis\Data\My work.txt"

End Sub

Private Sub cmdClear_Click()

Picture1.Cls

lblCO2.Visible = False

lblFuel.Visible = False

lblAir.Visible = False

End Sub

Private Sub cmdDrawData1_Click()

'Obtain path and file name string from the textbox 1 and save it a string variable

strDataFile1 = txtPathName1.Text

'Call drawTriangle subroutine

drawTriangle

'Open data file 1 and read the data

Open strDataFile1 For Input As #1


```

Do While Not EOF(1)
    Input #1, dblDataBottom, dblDataRight, dblDataLeft
    'Define a color
    intColor = 12
    'Call drawPoint function
    drawPoint dblDataRight, dblDataBottom, dblDataLeft, intColor
Loop
Close #1
End Sub

Private Sub cmdDrawData2_Click()
'Obtain path and file name string from the textbox 2 and save it a string variable
strDataFile2 = txtPathName2.Text
'Call drawTriangle subroutine
drawTriangle

'Open data file 2 and read the data
Open strDataFile2 For Input As #2
Do While Not EOF(2)
    Input #2, dblDataBottom, dblDataRight, dblDataLeft
    'Define a color
    intColor = 0
    'Call drawPoint function
    drawPoint dblDataRight, dblDataBottom, dblDataLeft, intColor
Loop
Close #2
End Sub

Private Sub cmdDrawData3_Click()
'Obtain path and file name string from the textbox 1 and save it a string variable
strDataFile3 = txtPathName3.Text
'Call drawTriangle subroutine
drawTriangle

'Open data file 3 and read the data
Open strDataFile3 For Input As #3
Do While Not EOF(3)
    Input #3, dblDataBottom, dblDataRight, dblDataLeft
    'Define a color
    intColor = 13
    'Call drawPoint function
    drawPoint dblDataRight, dblDataBottom, dblDataLeft, intColor
Loop
Close #3
End Sub

'This function is to convert the triangular data, which correlate to the triangular coordinates,
'into the rectangular data, and then plot them
Private Function drawPoint(dblDataRight, dblDataBottom, dblDataLeft, intColor)
Dim intDataX As Long, intDataY As Long
Dim sngZoom As Single
' Calculate zoom size
sngZoom = 100 / intBEnd

```

```

intDataX = intX0 + intSideLength * dblDataBottom * sngZoom / 100 _
+ intSideLength * dblDataRight * sngZoom / 100 * 0.5
intDataY = intY0 - intSideLength * dblDataRight * sngZoom / 100 * 0.866
Picture1.Circle (intDataX, intDataY), 15, QBColor(intColor)
End Function

```

```

Private Sub drawTriangle()
'Set scale
Picture1.Scale (0, 0)-(intScaleX, intScaleY)
'Calculate the side length of the triangle
intSideLength = intGrid / (intGrid + 2) * intScaleX
'Left conner of triangle is (intX0, intY0) which is defined as:
intX0 = 1 / (intGrid + 2) * intScaleX
intY0 = intScaleY - 1 / (intGrid + 2) * intScaleY
'Peak of triangle is (intXPeak, intYPeak) which is defined as:
intXPeak = intX0 + intSideLength / 2
intYPeak = intY0 - intSideLength * 0.866
'Right conner of triangle is (intXRight, intYRight) which is defined as:
intXRight = intX0 + intSideLength
intYRight = intY0

```

```

'Draw bottom line of triangle,
Picture1.Line (intX0, intY0)-(intXRight, intYRight)
'Number the start and end points of the bottom line
Picture1.PSet (intX0 - 110, intY0)
Picture1.Print intBStart
Picture1.PSet (intXRight - 110, intYRight)
Picture1.Print intBEnd
'Name the bottom line
lblCO2.Caption = "Carbon Dioxide "
lblCO2.FontSize = 12
lblCO2.FontBold = True
lblCO2.Visible = True

```

```

'Draw left line of triangle
Picture1.Line (intX0, intY0)-(intXPeak, intYPeak)
'Number the start and end points of the left line
Picture1.PSet (intX0 - 250, intY0 - 140)
Picture1.Print intLEnd
Picture1.PSet (intXPeak - 160, intYPeak - 100)
Picture1.Print intLStart
'Name the left line
lblAir.Caption = "Air"
lblAir.FontSize = 12
lblAir.FontBold = True
lblAir.Visible = True

```

```

'Draw right line of triangle
Picture1.Line (intXRight, intYRight)-(intXPeak, intYPeak)
'Number the start and end points on the right line
Picture1.PSet (intXRight, intYRight - 140)
Picture1.Print intRStart
Picture1.PSet (intXPeak, intYPeak - 100)

```

```

Picture1.Print intREnd
'Name the right line
lblFuel.Caption = "Methane"
lblFuel.FontSize = 12
lblFuel.FontBold = True
lblFuel.Visible = True

Dim i As Integer, intTotalGrid As Integer
Dim intXStart As Integer, intYStart As Integer
Dim intXEnd As Integer, intYEnd As Integer
Dim intSubLength As Integer, intGridLength As Integer

intTotalGrid = intGrid * intSubGrid
intGridLength = intSideLength / intGrid
intSubLength = intSideLength / intTotalGrid

'Draw grid line along bottom line
For i = 1 To intGrid - 1
    intXStart = intX0 + i * intGridLength
    intYStart = intY0
    intXEnd = intX0 + intSideLength / 2 _
    + i * intGridLength * 0.5
    intYEnd = intY0 - intSideLength * 0.866 _
    + i * intGridLength * 0.866
    Picture1.Line (intXStart, intYStart)-(intXEnd, intYEnd), QBColor(10)
    'Number the bottom line
    Picture1.PSet (intXStart - 110, intYStart)
    Picture1.Print i * 10 + intBStart
Next i
'Draw tick mark along bottom line
For i = 1 To intTotalGrid - 1
    intXStart = intX0 + i * intSubLength
    intYStart = intY0
    intXEnd = intX0 + i * intSubLength + intSubLength * 0.5
    intYEnd = intY0 - intSubLength * 0.866
    Picture1.Line (intXEnd, intYEnd)-(intXStart, intYStart), QBColor(10)
Next i

'Draw grid line along left line
For i = 1 To intGrid - 1
    intXStart = intX0 + i * intGridLength * 0.5
    intYStart = intY0 - i * intGridLength * 0.866
    intXEnd = intX0 + i * intGridLength
    intYEnd = intY0
    Picture1.Line (intXStart, intYStart)-(intXEnd, intYEnd), QBColor(10)
    'Number the left line
    Picture1.PSet (intXStart - 210, intYStart - 100)
    Picture1.Print (intGrid - i) * 10 + intLStart
Next i
'Draw tick mark along left line
For i = 1 To intTotalGrid - 1
    intXStart = intX0 + i * intSubLength * 0.5
    intYStart = intY0 - i * intSubLength * 0.866

```

```

    intXEnd = intXStart + intSubLength * 0.5
    intYEnd = intYStart + intSubLength * 0.866
    Picture1.Line (intXStart, intYStart)-(intXEnd, intYEnd), QBColor(10)
Next i

'Draw grid line along right line
For i = 1 To intGrid - 1
    intXStart = intScaleX - intX0 - i * intGridLength * 0.5
    intYStart = intY0 - i * intGridLength * 0.866
    intXEnd = intX0 + i * intGridLength * 0.5
    intYEnd = intYStart
    Picture1.Line (intXStart, intYStart)-(intXEnd, intYEnd), QBColor(10)
    'Number the right line
    Picture1.PSet (intXStart, intYStart - 100)
    Picture1.Print i * 10 + intRStart
Next i

'Draw tick mark along right line
For i = 1 To intTotalGrid - 1
    intXStart = intScaleX - intX0 - i * intSubLength * 0.5
    intYStart = intY0 - i * intSubLength * 0.866
    intXEnd = intXStart - intSubLength
    intYEnd = intYStart
    Picture1.Line (intXStart, intYStart)-(intXEnd, intYEnd), QBColor(10)
Next i

End Sub

```

Appendix 8: Experimental Data for Methane/Air/Carbon Dioxide

In each table, the first entry represents the initial gas concentrations at ignition, and the last entry represents the final gas concentrations at flame extinction. In other words, the final entry in each table represents the LFL, UFL and peak concentration conditions (depending on the particular table).

Table A.8.1a LFL of CH₄/air mixture

CH ₄ %	Air%	CO ₂ %
6.5	93.5	0.0
6.4	93.6	0.0
6.3	93.7	0.0
6.2	93.8	0.0
6.1	93.9	0.0
6.0	94.0	0.0
5.9	94.1	0.0
5.8	94.2	0.0
5.7	94.3	0.0
5.6	94.4	0.0
5.5	94.5	0.0
5.4	94.6	0.0
5.3	94.7	0.0
5.2	94.8	0.0
5.1	94.9	0.0
5.0	95.0	0.0

Table A.8.1b UFL of CH₄/air mixture

CH ₄ %	Air%	CO ₂ %
11.0	89.0	0.0
11.1	88.9	0.0
11.2	88.8	0.0
11.3	88.7	0.0
11.4	88.6	0.0
11.5	88.5	0.0
11.6	88.4	0.0
11.7	88.3	0.0
11.8	88.2	0.0
11.9	88.1	0.0
12.0	88.0	0.0
12.1	87.9	0.0
12.2	87.8	0.0
12.3	87.7	0.0
12.4	87.6	0.0
12.5	87.5	0.0
12.6	87.4	0.0
12.7	87.3	0.0
12.8	87.2	0.0
12.9	87.1	0.0
13.0	87.0	0.0
13.1	86.9	0.0
13.2	86.8	0.0
13.3	86.7	0.0
13.4	86.6	0.0
13.5	86.5	0.0
13.6	86.4	0.0
13.7	86.3	0.0
13.8	86.2	0.0
13.9	86.1	0.0
14.0	86.0	0.0
14.1	85.9	0.0

Table A.8.2a Dilution LFL of
CH₄/air/CO₂ mixture with 5% of CO₂

CH ₄ %	Air%	CO ₂ %
6.5	88.5	5.0
6.4	88.6	5.0
6.3	88.7	5.0
6.2	88.8	5.0
6.1	88.9	5.0
6.0	89.0	5.0
5.9	89.1	5.0
5.8	89.2	5.0
5.7	89.3	5.0
5.6	89.4	5.0
5.5	89.5	5.0
5.4	89.6	5.0
5.3	89.7	5.0
5.2	89.8	5.0
5.1	89.9	5.0

Table A.8.2b Dilution UFL of
CH₄/air/CO₂ mixture with 5% of CO₂

CH ₄ %	Air%	CO ₂ %
10.0	85.0	5.0
10.1	84.9	5.0
10.2	84.8	5.0
10.3	84.7	5.0
10.4	84.6	5.0
10.5	84.5	5.0
10.6	84.4	5.0
10.7	84.3	5.0
10.8	84.2	5.0
10.9	84.1	5.0
11.0	84.0	5.0
11.1	83.9	5.0
11.2	83.8	5.0
11.3	83.7	5.0
11.4	83.6	5.0
11.5	83.5	5.0
11.6	83.4	5.0
11.7	83.3	5.0
11.8	83.2	5.0
11.9	83.1	5.0
12.0	83.0	5.0
12.1	82.9	5.0
12.2	82.8	5.0
12.3	82.7	5.0
12.4	82.6	5.0
12.5	82.5	5.0
12.6	82.4	5.0
12.7	82.3	5.0
12.8	82.2	5.0

Table A.8.3a Dilution LFL of
CH₄/air/CO₂ mixture with 10% of CO₂

CH ₄ %	Air%	CO ₂ %
6.5	88.5	5.0
6.4	86.6	7.0
6.3	84.7	9.0
6.2	83.8	10.0
6.1	83.9	10.0
6.0	84.0	10.0
5.9	84.1	10.0
5.8	84.2	10.0
5.7	84.3	10.0
5.6	84.4	10.0
5.5	84.5	10.0
5.4	84.6	10.0
5.3	84.7	10.0

Table A.8.3b Dilution UFL of
CH₄/air/CO₂ mixture with 10% of CO₂

CH ₄ %	Air%	CO ₂ %
10.0	85.0	5.0
10.1	84.9	5.0
10.2	84.8	5.0
10.3	84.7	5.0
10.4	84.6	5.0
10.5	84.5	5.0
10.6	84.4	5.0
10.7	84.3	5.0
10.8	84.2	5.0
10.9	84.1	5.0
11.0	79.0	10.0
11.1	78.9	10.0
11.2	78.8	10.0
11.3	78.7	10.0
11.4	78.6	10.0

Table A.8.4a Dilution LFL of
CH₄/air/CO₂ mixture with 15% of CO₂

CH ₄ %	Air%	CO ₂ %
7.0	88.0	5.0
6.9	88.1	5.0
6.8	85.2	8.0
6.7	83.3	10.0
6.6	81.4	12.0
6.5	78.5	15.0
6.4	76.6	15.0
6.3	78.7	15.0
6.2	78.8	15.0
6.1	78.9	15.0
6.0	79.0	15.0
5.9	79.1	15.0
5.8	79.2	15.0
5.7	79.3	15.0
5.6	79.4	15.0
5.5	79.5	15.0
5.4	79.6	15.0

Table A.8.4b Dilution UFL of
CH₄/air/CO₂ mixture with 15% of CO₂

CH ₄ %	Air%	CO ₂ %
9.0	86.0	5.0
9.1	83.9	7.0
9.2	83.8	7.0
9.3	81.7	9.0
9.4	79.6	11.0
9.5	79.5	11.0
9.6	77.4	13.0
9.7	77.3	13.0
9.8	75.2	15.0
9.9	75.1	15.0
10.0	75.0	15.0
10.1	74.9	15.0
10.2	74.8	15.0

Table A.8.5a Dilution LFL of
CH₄/air/CO₂ mixture with 20% of CO₂

CH ₄ %	Air%	CO ₂ %
8.0	86.0	6.0
7.9	82.1	10.0
7.8	79.2	13.0
7.7	77.3	15.0
7.6	76.4	16.0
7.5	74.5	18.0
7.4	72.6	20.0
7.3	72.7	20.0
7.2	72.8	20.0
7.1	72.9	20.0
7.0	73.0	20.0
6.9	73.1	20.0
6.8	73.2	20.0
6.7	73.3	20.0
6.6	73.4	20.0
6.5	73.5	20.0
6.4	73.6	20.0
6.3	73.7	20.0
6.2	73.8	20.0
6.1	73.9	20.0
6.0	74.0	20.0
5.9	74.1	20.0
5.8	74.2	20.0
5.7	74.3	20.0
5.6	74.4	20.0

Table A.8.5b Dilution UFL of
CH₄/air/CO₂ mixture with 20% of CO₂

CH ₄ %	Air%	CO ₂ %
7.0	88.0	5.0
7.1	86.9	6.0
7.2	84.8	8.0
7.3	82.7	10.0
7.4	80.6	12.0
7.5	77.5	15.0
7.6	75.4	17.0
7.7	73.3	19.0
7.8	72.2	20.0
7.9	72.1	20.0
8.0	72.0	20.0
8.1	71.9	20.0
8.2	71.8	20.0
8.3	71.7	20.0
8.4	71.6	20.0
8.5	71.5	20.0
8.6	71.4	20.0
8.7	71.3	20.0
8.8	71.2	20.0
8.9	71.1	20.0
9.0	71.0	20.0

Table A.8.6a Dilution LFL of
CH₄/air/CO₂ mixture with 22% of CO₂

CH ₄ %	Air%	CO ₂ %
8.0	87.0	5.0
7.9	87.1	5.0
7.8	82.2	10.0
7.7	82.3	10.0
7.6	82.4	10.0
7.5	79.5	13.0
7.4	76.6	16.0
7.3	75.7	17.0
7.2	72.8	20.0
7.1	70.9	22.0
7.0	71.0	22.0
6.9	71.1	22.0
6.8	71.2	22.0
6.7	71.3	22.0
6.6	71.4	22.0
6.5	71.5	22.0
6.4	71.6	22.0
6.3	71.7	22.0
6.2	71.8	22.0
6.1	71.9	22.0
6.0	72.0	22.0
5.9	72.1	22.0
5.8	72.2	22.0

Table A.8.6b Dilution UFL of
CH₄/air/CO₂ mixture with 22% of CO₂

CH ₄ %	Air%	CO ₂ %
6.5	85.5	8.0
6.6	81.4	12.0
6.7	78.3	15.0
6.8	75.2	18.0
6.9	73.1	20.0
7.0	71.0	22.0
7.1	70.9	22.0
7.2	70.8	22.0
7.3	70.7	22.0
7.4	70.6	22.0
7.5	70.5	22.0
7.6	70.4	22.0
7.7	70.3	22.0
7.8	70.2	22.0
7.9	70.1	22.0
8.0	70.0	22.0
8.1	69.9	22.0
8.2	69.8	22.0
8.3	69.7	22.0
8.4	69.6	22.0

Table A.8.7a Dilution LFL of
CH₄/air/CO₂ mixture with 23% of CO₂

CH ₄ %	Air%	CO ₂ %
8.0	84.0	8.0
7.9	82.1	10.0
7.8	82.2	10.0
7.7	80.3	12.0
7.6	77.4	15.0
7.5	75.5	17.0
7.4	73.6	19.0
7.3	73.7	19.0
7.2	71.8	21.0
7.1	69.9	23.0
7.0	70.0	23.0
6.9	70.1	23.0
6.8	70.2	23.0
6.7	70.3	23.0
6.6	70.4	23.0
6.5	70.5	23.0
6.4	70.6	23.0
6.3	70.7	23.0
6.2	70.8	23.0
6.1	70.9	23.0
6.0	71.0	23.0
5.9	71.1	23.0

Table A.8.7b Dilution UFL of
CH₄/air/CO₂ mixture with 23% of CO₂

CH ₄ %	Air%	CO ₂ %
6.0	89.0	5.0
6.1	88.9	5.0
6.2	87.8	6.0
6.3	85.7	8.0
6.4	84.6	9.0
6.5	82.5	11.0
6.6	81.4	12.0
6.7	80.3	13.0
6.8	79.2	14.0
6.9	78.1	15.0
7.0	76.0	17.0
7.1	74.9	18.0
7.2	72.8	20.0
7.3	71.7	21.0
7.4	70.6	22.0
7.5	69.5	23.0
7.6	69.4	23.0
7.7	69.3	23.0
7.8	69.2	23.0
7.9	69.1	23.0
8.0	69.0	23.0

Table A.8.8 Dilution UFL of CH₄/air/CO₂ mixture with 24% of CO₂

CH ₄ %	Air%	CO ₂ %
6.0	87.0	7.0
6.1	86.9	7.0
6.2	83.8	10.0
6.3	79.7	14.0
6.4	76.6	17.0
6.5	74.5	19.0
6.6	72.4	21.0
6.7	71.3	22.0
6.8	70.2	23.0
6.9	69.1	24.0
7.0	69.0	24.0
7.1	68.9	24.0
7.2	68.8	24.0
7.3	68.7	24.0
7.4	68.6	24.0
7.5	68.5	24.0
7.6	68.4	24.0

Peak Concentration:**Table A.8.9a** Investigation of peak concentration of CO₂ in CH₄/air/ CO₂ mixture with 6.6% of CH₄

CH ₄ %	Air%	CO ₂ %
6.6	88.4	5.0
6.6	83.4	10.0
6.6	78.4	15.0
6.6	73.4	20.0
6.6	71.4	22.0
6.6	70.4	23.0
6.6	69.4	24.0
6.6	69.3	24.1
6.6	69.2	24.2
6.6	69.1	24.3
6.6	69.0	24.4

Table A.8.9b Investigation of peak concentration of CO₂ in CH₄/air/ CO₂ mixture with 6.8% of CH₄

CH ₄ %	Air%	CO ₂ %
6.8	88.2	5.0
6.8	83.2	10.0
6.8	78.2	15.0
6.8	73.2	20.0
6.8	71.2	22.0
6.8	69.2	24.0
6.8	69.1	24.1
6.8	69.0	24.2
6.8	68.9	24.3
6.8	68.8	24.4
6.8	68.7	24.5
6.8	68.6	24.6
6.8	68.5	24.7

Table A.8.9c Investigation of peak concentration of CO₂ in CH₄/air/ CO₂ mixture with 7.0% of CH₄

CH ₄ %	Air%	CO ₂ %
7.0	88.0	5.0
7.0	83.0	10.0
7.0	78.0	15.0
7.0	73.0	20.0
7.0	71.0	22.0
7.0	69.0	24.0
7.0	68.9	24.1
7.0	68.8	24.2
7.0	68.7	24.3
7.0	68.6	24.4
7.0	68.5	24.5
7.0	68.4	24.6