Annotated Confirmation Report

Combustion, Thermal and Emission Characteristics of gas-fired Inverse Diffusion Flames Burning Mixed LPG/Hydrogen Fuel

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Confirmation of Registration

Doctor of Philosophy

Abstract

Abstracts usually follow this pattern:

a. Background b. Aims c. Methods results d. Conclusions (and Future Work)

This project aims to analyze effect of hydrogen addition on LPG inverse diffusion flame (IDF). Inverse diffusion flame has draw attention of researches these years due to its features on safe operation, adjustable flame length and low soot emission. n inverse diffusion flame, fuel and air are delivered separately so that the flame is more stable, and operation is safer than that of Bunsen burner. Usually the inner air jet has higher velocity than that of outer fuel jet. In this way, a premixed zone is form by the mixing of air and fuel due to the velocity difference. Expect of premixed zone, structures of inverse diffusion flame also contain diffusion zone. Fuel, which is not fully mixed with inner air jet, reacts with surrounding air to form diffusion zone. With the special structure, inverse diffusion flame shows the distinctive features.

✓Clearly states aims of research

Include only key details in abstract

Hydrogen is a well-known clean fuel. With the lowest molecular weight, hydrogen has very high burning velocity. The flammability range of hydrogen is also wide. However, there are also some problems exist in burning hydrogen. Hydrogen can easily catch fire. The combustion process should be carefully controlled to prevent accidence. It can be seen that to realize using pure hydrogen in large scale is still in need of further research. To extenuate the drawback of pure hydrogen and adopt the advantage of hydrogen, it may be a practicable way to mix hydrogen with other hydrogen carbon fuels, such as LPG. With large molecular and high density, LPG may slow down the leaking speed of hydrogen

Place this background information at start of the abstract

✓Highlights why this study will add to knowledge in this subject and how study may be done

and reduce hazard possibility. While addition of hydrogen may extend flame stability range of mixtures and may improve the heating performance of the flame.

This is an experiment-based project. Most data will be obtained through tests and experiments. The experiments focus on flame structure, flame length, impinging flame temperature distribution and impinging flame pollution emission of hydrogen enriched LPG inverse diffusion flame. In the experiment, the major variables include

✓Outlines how study was carried out

✓Uses key vocabulary from study

Reynolds number of center air jet, overall equivalence, and hydrogen addition fraction. Reynolds numbers of center air jet are various from 500~7000, which include laminar and turbulent. Range of overall equivalence ration is from 0.5~2.2. Preliminary results show that small amount hydrogen addition can significantly extend stability range of LPG inverse diffusion flames. Heights of LPG inverse diffusion flames under fixed Reynolds number are gradually lengthened with equivalence ratio. 50% hydrogen diluted LPG IDFs also appear similar structure changes under various equivalence ratios as that of LPG IDFs. Height of both LPG IDFs and H_2-LPG IDFs can correlated well with Global Momentum Ratio under Reynolds number=1500 and 3000. And LPG IDFs are seen to be higher then H_2-LPG IDFs in fuel rich situations.

✓Explains results using key findings

Table of Content

Table of contents should also include

a. A List of Figures and Tables

B A List of Abbreviations

Give clearer subheadings, i.e. "Types of Flame" (e.g. Section 2.2)

Special Note:
The page numbers may not exactly match those in the report due to the annotations.

Chapter 1 Introduction

The Introduction is often organised in the following way:

a. Background b. Areas of research and key concepts c. Aims of your research d. Organization of your study. Some writers include an outline of the contents of the chapter, i.e. Section 1.1 defines and classifies the use LPG and Hydrogen, section 1.2 explains the problems caused by their use and section 1.3 outlines the objectives of the research.

1.1 Overview

Give more specific details for background information, i.e. "The study of combustion has been of central importance since fire was first discovered."

During the history of fire usage, the study of combustion science and control has never been stopped. Combustion science can be defined as the science of exothermic chemical reactions in flow with heat and mass transfer.[1]

Usually the combustible substances used to produce heat are called fuels [2]. According to the physical state of fuels, they are divided into three main categories: solid fuels, liquid fuels, and gaseous fuels. Gaseous fuels mainly generated from solid fuels or liquid fuels, contain little ash and sulfur and are the most important energy source for domestic and light industrial applications. Because of its availability, thermal and combustion characteristics, liquefied petroleum gas (LPG) becomes the most widely used gaseous fuel. Therefore, LPG is chosen as the main fuel in the present study.

✓Highlights importance of this subject, e.g. "most important" and "most widely used"

✓Defines key terms

LPG is a mixture gaseous fuel consisting mainly of butane and propane [3]. Since both butane and propane are very light gases, LPG can be easily separated from other hydrocarbons during manufacturing process. [3] According to the general trend that lighter fuels are usually clean due to their lower ash and sulfur contents, LPG is identified to be one of the very clean fuels for users. Another advantage of LPG is that it can be stored in cylinders and then delivered to any location. In fact, LPG is one of the main energy source used for domestic and commercial applications. Even though LPG is a clean fuel because of its low ash and sulfur contents, the emission of carbon dioxide (CO_2) is still causing environmental problem due to its greenhouse gas nature. As the ever increasing demand for clean fuels in the world, the need for research to improve the utilization of LPG especially the reduction of CO_2 emission is significant.

✓Explains importance of research

Do not place full stop before reference number, .i.e. [3]. is better than .[3]

Another very well-known clean fuel is hydrogen (H_2). Containing no carbon, hydrogen is regarded as a perfect fuel regarding to environmental issue, as the main combustion product of hydrogen is water vapor. Also, the mass heating value of hydrogen is very high, which means that hydrogen has high heating performance as a fuel. However, burning hydrogen fuel in domestic and commercial applications still has some major problems not yet been solved. Due to the least weight and extremely fast burning velocity, hydrogen can be rather unstable during operation and cause very high risk. Thus, more considerations are needed to prevent accident and balance the advantages and disadvantages in utilizing hydrogen fuel.

✓Gives topic sentence outlining what paragraph will contain

Put result first then reason, i.e. "Hydrogen can be...due to..."

Although LPG is regarded as a clean fuel, the chemical components of LPG make it inevitable to have carbon monoxide (CO) and carbon dioxide (CO_2) in the combustion products. It was reported by the National Academy of Science [4] that the release of

greenhouse gases including CO_2 is one of the main causes of global warming. Due to the global warming phenomenon, available water resource will decrease, rainfall will contain heavy precipitation, saltwater will intrude into freshwater aquifers, and coral reefs will be bleached as a result of high temperature.

Include only examples and details that are directly linked to current study, i.e. give details of contribution of LPG to global warming rather than details of global warming.

The consequences of global warming are notably serious. The United States Environmental Protection Agency reported that CO_2 accounted for 84% of all greenhouse gas emission due to human activities of US in 2010 [5]. In addition to global warming, CO_2 produced by human activities also influences carbon cycle of the Earth. Nowadays, the CO_2 emission has exceeded the ability of natural sinks of the Earth. Effective strategies are in serious need to relieve the problem. Considering the significant environmental problem and the inevitable CO/CO_2 emissions in LPG, combination of hydrogen with LPG seems to be a promising solution. Therefore, the main focus in the present study is to evaluate the possibility and efficiency in utilizing LPG/H_2 fuel. It should be noted that the extremely high burning velocity and very low ignition point of hydrogen make it a relative dangerous fuel for daily applications. LPG has rather low burning velocity and produces stable flames during the combustion process. The combination of LPG and hydrogen may have very good chance to relieve the risk of using hydrogen fuel and reduce combustion emissions including CO and CO_2 at the same time.

Include background information and motivation for study at start of introduction.

State details of relative dangers of LPG and hydrogen earlier in description of two methods.

In the science of combustion, flame is another key word. Flame can be basically classified into premixed flame and diffusion flame. In premixed flame, fuel and air are mixed before combustion whereas in diffusion flame, fuel is introduced to react with air during the combustion process. Premixed flame has been studied by many scientists and is well-known that application of premixed flame is rather limited by its narrow stability range. The air/fuel ratio should be carefully calculated and applied to prevent the blow-off or flame-lift problem. This problem is significantly serious especially for burners with large diameter [6]. By adding a separate central air jet to create a turbulent entrainment zone, use of the inverse diffusion flame may be a promising alternative and is able to overcome the problem of narrow operational range of the premixed flame.

Do not be vague. Rather than "Flame is another key word", write: "Flame is an important technical term in combustion science that can be..."

✓States problem and importance of problem

✓Then gives a possible solution

✓Evaluates solution using "may" to show uncertainty

In the present study, the inverse diffusion flame will be used by burning LPG enriched with different percentages of hydrogen fuel. With different combinations of LPG and hydrogen fuel mixtures, investigations of stability, appearance, pollution emissions and combustion characteristics of the flame will be performed. The results obtained are expected to provide knowledge about a better and safe utilization of the mixed LPG/H_2 fuel for domestic and commercial applications. In addition, results obtained in the present study can be used in further studies of inverse diffusion flame, and provide very valuable reference for other researchers.

✓Explains how study will contribute to further research and have practical benefits

1.2 Statement of Problems

According to the data provided by the Energy Information Administration [7], energy consumption of the world is increasing year by year. The increasing energy demand especially in hydrocarbon fuels results in severe problems on both economy and environment. The most significant problems occurred at global scale are the greenhouse effect caused by CO_2 emission and the NO_X emission during combustion leads to serious health problems. Emissions of soot particles, CO and unburned hydrocarbons also cause serious regional problems [8]. Therefore the provision of clean energy and the improvement of energy efficiency for sustainable energy development become a major consideration of the worldwide energy research [9]. A noble solution for better heating performance, lower pollution emissions, and totally reliability in utilizing hydrocarbon fuels is in serious need. In the present study, the combustion, thermal and emission characteristics of a specially designed circumferential-Fuel-Jets Inverse Diffusion Flame (CIDF) burner burning the mixed LPG/H_2 fuel will be studied with the aim to provide a better answer for the problems as mentioned above.

Do not repeat general background information here. Greenhouse effect has already been mentioned. Start with the main point, i.e. "There are a number of problems associated with the use of LPG and hydrogen".

Place information on CIDF as topic sentence in paragraph below that describes how it operates.

In the inverse diffusion flame burner, a bigger air jet is delivered to the combustion zone from the burner center whereas several uniformly-spaced smaller fuel jets surrounding the central air jet supply fuel into the combustion zone. Velocity of the central air jet is usually significantly higher than that of the fuel jet. During the combustion process, surrounding fuels are entrained towards the combustion zone by the high momentum of the air jet to form the inverse diffusion flame

✓Clearly explains how CIDF works
✓Explains how CIDF affects key concepts in the study e.g. "velocity" "speed" and "stability".

Do not repeat the problems caused and the importance of the study again.

(IDF). Since air and fuels are delivered separately in IDF, this kind of flame may be safer than the traditional premixed flame and is found to be stable under a larger range of operation conditions [10]. In addition, the velocity differential between the air and fuel jets enhances air/fuel mixing, which will lead to better combustion performance and lower pollution emissions including NO_X and soot particles. Flame length is a very important parameter to identify and affect flame characteristics. Flame length of an IDF can be adjusted by varying velocity and hence Reynolds number of the central air jet and the air/fuel ratio and hence equivalence ratio. If the expected better heating performance, lower pollution emissions, and wider range of reliable operation are achieved, IDF can be widely applied in domestic, commercial and industrial sectors. Thus, it is necessary to fully investigate the characteristics of IDF burner burning the most ideal hydrocarbon fuel, in order to explore the best solution for this global energy problem.

✓Describes process using present tense and passive voice, e.g. "are delivered" and "is found"

Define and explain key terms such as "Reynolds number" when they are first introduced.

LPG is one of the most commonly used gaseous fuels in many international cities including Hong Kong because of its low pollution emissions and user-friendly nature such as easy to deliver, store and burn. Despite of its many advantages, using LPG fuel encounters several drawbacks. As a mixture of essentially butane and propane, LPG has a rather low burning velocity such that flame stability can only be achieved at low Reynolds numbers, as well as a narrow range of equivalence ratio. Improvement can be obtained by using IDF burner instead of premixed burner, but room for improvement is still expected to be significant [11]. Another significant drawback in burning LPG is the emission of CO_2, which is blamed to be the main cause of global warming. This disadvantage cannot be overcome by

Put main point of paragraph first, e.g. "There are a number of drawbacks with the use of LPG fuel. Firstly,..."

✓Links ideas well using the phrase:" Another significant drawback is...".

altering the flame type: premixed or diffusion. However, burning a hydrocarbon fuel with lower carbon content, for example, LPG enriched with H_2 is definitely a solution.

Avoid assertive words that indicate 100% certainty, e.g. definitely, undoubtedly, certainly".

With the lowest molecular weight, hydrogen flame has very high burning velocity. The flammability range of hydrogen fuel is also very wide. Since the only combustion product obtained in burning hydrogen is water vapor, burning hydrogen is sometimes regarded as zero pollution even though water vapor is also a greenhouse gas. However, there are also some problems exist in burning hydrogen fuel. Hydrogen can easily catch fire therefore the combustion process must be carefully controlled to prevent accidence. Although hydrogen has a high mass heating value, the volumetric heating value of hydrogen is very low due to its extremely low density. Comparing with other gaseous fuels, such as LPG, much bigger volume of hydrogen is required to produce the same amount of heat. For a burner used in relative small scale, low airflow rate can reduce operation cost and pollution emissions, but reducing airflow rate can usually be detriment to combustion stability [12]. Thus, burner and flow control system should be redesigned when hydrogen fuel is used.

Start sentences with the main subject. Rather than "With the lowest..., Hydrogen..." write "Hydrogen flame with the lowest..." Rather than "Since the only.., burning hydrogen is..." write: "Burning hydrogen flame...since..." Rather than "Comparing with other...much bigger volume..." write: A much bigger volume...compared to other gaseous fuels". Rather than "For a burner...low airflow..." write" "Low airflow rate...for a burner..."

In order to integrate the advantages and overcome the drawbacks of IDF burner and the mixed LPG/H_2 fuel, the present study is aimed to fully investigate the combustion, thermal and pollution emission characteristics of the inverse diffusion flame (IDF) burning the liquefied petroleum gas (LPG) fuel enriched with different percentages of hydrogen fuel (H_2). In

Place this paragraph in next section as this is describing project's objectives rather than problems.

the mixed LPG/H_2 fuel, flame stability of LPG may be enhanced by hydrogen addition, thus, using LPG as the main fuel may reduce the risk in burning hydrogen. Also, this mixture may balance the properties of LPG and H_2 to become a more reliable, lower pollution emissions, and better thermal performance fuel. Using the mixed LPG/H_2 fuel, the IDF burner may be able to fully utilize its advantages and overcome its drawbacks.

Place adverbs, e.g. "also" next to the verb, i.e. "may also balance".

Nowadays, most of the investigations related to IDF are about its flame appearance, soot loading and thermal performance, it is rather few research concerning about the effect on these characteristics by using different fuels. Unlike the premixed flame, the study of inverse diffusion flame is also few. Therefore there is a significant need of information of inverse diffusion flame to help building up a complete understanding of flame and combustion. Base on the literatures obtained, research on LPG/H_2 fired IDF seems to be a new step in scientific research in combustion and flame. To conclude, there is a need to conduct an intensive study to investigate the combustion, thermal and emission characteristics of gas-fired inverse diffusion flame burner burning mixed LPG/H_2 fuel.

Do not use "Nowadays" at the start of a sentence. Use "currently", next to the verb, i.e. "investigations currently related to".

1.3 Project Objectives

There are five integrated tasks planned to achieve the objectives of the present study. Investigations will be performed with a circumferential fuel-jet inverse diffusion flame burner. The characteristics of both open flame and impingement flame will be fully explored. The main fuels used for the investigations are liquefied petroleum gas fuel (LPG) enriched with different percentages of hydrogen fuel (H_2). The five integrated tasks to be carried out are:

✓Clearly introduces five tasks

1. Flame stability range of the inverse diffusion flame (IDF) when they are burning the mixed LPG/H_2 fuel will be fully explored. Effects of the major operation parameters including Reynolds number and equivalence ratio of the air/fuel mixture will be investigated. The effects of percentage of hydrogen added to the mixed fuel on flame stability will also be assessed.

✓States first four numbered points with same grammatical structure. Here nouns are used, e.g. Flame, Effect, Thermal performance, Pollution emissions. Should do same with point five., i.e. "Relationships…will be established based on…"

2. Effects of hydrogen addition, Reynolds number and equivalence ratio on flame structure and combustion characteristics of the IDF will be investigated over the entire range of stable flame.

3. Thermal performance including heat release from flame and flame temperature of the IDF burning mixed LPG/H_2 fuel at different hydrogen contents will be assessed in detail over the same operation range as described by Reynolds number and equivalence ratio of the air/fuel mixture. Both impinging and open flames will be studied. Influence of hydrogen added on the IDF burning mixed LPG/H_2 fuel on its thermal performance especially temperature distribution of the flame will be analyzed and compared. For the impinging flame, configuration of the burner system is also an important parameter and will therefore be studied.

✓Uses wide range of verbs to describe actions done, e.g. compared, analyzed, studied, assessed, investigated, explored

4. Pollution emissions of the IDF burning mixed LPG/H_2 at different percentages of hydrogen enrichment, Reynolds numbers and equivalence ratios will be analyzed. Focus will be made on the emissions of CO, CO_2, NO_X, and particulates. Again,

both open and impinging flames will be investigated. Effects of the configuration of the burner system will also be studied for the impinging flame.

5. Base on results of the previous tasks, relationships among combustion, thermal and pollution emission characteristics of the IDF burning mixed LPG/H_2 fuel will be established.

Better to use passive form "Based on".

The Literature Review chapter should explain the key findings of previous research and how those findings developed understanding of the topic and influenced the design of the current study. It should also contain evaluative comments on the studies, highlighting what was successful in the studies and what was less successful. It should not just be a list of previous studies.

Chapter 2 Literature Review

Avoid overusing "Literature". It can be used as title of chapter, but alternatives in text, e.g. "Research has examined impinging flame" than "Literatures about impinging flame".

2.1 Introduction

This project aims to analyze the heat transfer characteristics of hydrogen enriched LPG inverse diffusion flame. The literature about flame and fuels were comprehensively reviewed for experiment. Since there are different kinds of flames, which show different characters, information about the most related flame, inverse diffusion flame, diffusion flame and premixed flame were studied. In addition, literatures about impinging flame were also studied to support the further research on temperature distribution of impinging inverse diffusion flame. For the fuel part of literature review, the major fuels used in this project are LPG and hydrogen. Information about LPG flame and hydrogen-enriched flame were carefully studied. Literature review part of this report will includes a introduction of flame and flame category, detail description of premix and diffusion flame, information about impinging flame, comprehensive review of inverse diffusion flame, and finally introduction of LPG flame and hydrogen-enriched flame.

✓Outlines content of chapter. Better to use "section" than "part". "The section of the Literature review on fuels"...

Use "section" rather than "part", e.g. "The section of the Literature review on fuels"...

2.2 Flame

Flame is a special kind of combustion reaction, which can propagate subsonically through space. [13] Flame can also be regarded as a kind of flow with reaction. The microstructure of flame depends on the movement of burning reactants relative

✓Defines key terms based on a given reference

Use "type of" rather than "kind of"

to the unburned reactants. [13] Flame first caught people's attention with its luminosity and heating characteristics. Nowadays, various flame types have been achieved with different burner design, and more and more features of flame have been discovered, such as particle emission and combustion reaction. Generally, flame can be classified into premixed flame and diffusion flame according to the fuel and air supply method. For a premixed flame, the fuel and air are mixed before being ignited. While, for a diffusion flame, the fuel and air meet at the ignition time. With different air/fuel supply method, premixed flame and diffusion flame show significantly different features regarding to both appearance and heating characteristics. Despite of air/fuel supply method, flame can also be divided into open flame and impinging flame. Opening flame is a kind of flame burning naturally without disturber. And impinging flame is obtained by impinging a flame to a plate or some kind of disturber. In this way, the flame will change its direction, and characteristics of flame will be changed a lot. In the following sections, features of premixed flame, diffusion flame, impinging flame and inverse diffusion flame will be discussed.

Use "increasing numbers of" rather than "more and more"

✓Classifies "flame"

Do not use key words in definition. Rather than "Impinging flame is obtained by impinging", use "impacting".

Avoid using "And" at start of sentence. Use "In addition" at start ofsentence.

Avoid using "a lot". Here, "greatly changed" or "a large number of changes" could be used.

✓Outlines the following sections

2.2.1 Premixed Flame

✓This section gives clear pattern of a. background b. description c. analysis

As a kind of flame, in which fuels and air are mixed before reaction, flame produced by Bunsen burner is a famous representative of premixed flame. Invented by Bunsen around 1855, Bunsen burner has been used in laboratory for years. Comparing to

Avoid emotional words like "famous" better to use "well-known" or "common".

diffusion flame, Bunsen premixed flame has the advantages that the better air/fuel mixing provide more intense combustion, higher temperature and lower soot emission. However, Bunsen flame also has it shortcoming. The stability range of Bunsen flame highly depends on air/ fuel ratio, and the flame has tendency to flash-back with large diameter burners.[6]

✓Contrasts two types of flame using "however"

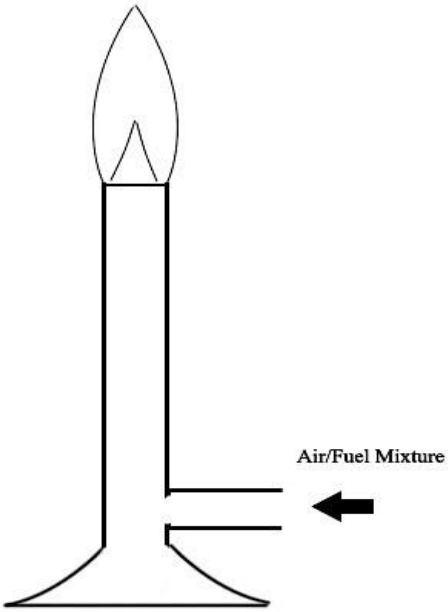

Figure 2---1 Bunsen Burner

The figure above shows a typical Bunsen burner. Fuel and air are mixed before burning. And the carefully calculated air/fuel mixture is delivered to the nozzle with a speed that exceed burning velocity of the mixture.[6] In premixed flame, the fundamental properties of flame have been intensely studied. For example, formula has been built to calculate the burning velocity of premixed flame, which is not yet concluded for diffusion flame. In 1979, Clavin et al. [14] reported a statistical theory about propagation velocity of premixed flame. In the research, Clavin and Williams

✓Refers to figure and explains figure in words

Do not refer to year of publication, e.g. "In 1979" when giving a reference. Start with "Clavin et al [14]...

[14] divided premix flame into convective-diffusive and reactive-diffusive zones.

✓States topic of paragraph in first sentence

There are also numbers of experimental researches about premixed flames. Laser deflection techniques has been used in flame researches for many years. In 1984, Kizirnis et al. [15] used laser deflection techniques to measure hydroxyl (OH) distribution and temperature distribution in a premixed flame. In the research, Kizirnis et al. [15] imaged the flame with both high and low spatial resolutions. With the experiment, Kizirnis et al. [15] proved that Laser deflection technology lead to no significant perturbation on flame performance. Goix et al. examined the effect of Levis Number on premixed flame structures with laser tomography technique. The result of Goxi et al. shown that the flame shape of turbulent premixed flame highly depends on Lewis number.[16] In 1996, Bedat et al. [17] studied the influence of buoyancy on stability of premixed flame. To get the result data, Bedat et al. [17] conducted experiment under both normal gravity and reversed gravity conditions. And finally, Bedat et al. [17] concluded that buoyancy had the most influence on laminar premixed flame stabilization, and the effect was not significant for turbulent flames. In the same year, Buschmann et al. [18] measured the turbulent premixed flame structure with planner laser-induced image and UV-Rayleigh thermometry. Recently, Steinberg et al. [19] used cinema stereoscopic particle image to determine the flame dynamics of a slot turbulent Bunsen flame.

Do not repeat name of authors of study in every sentence. Change name second and third time for reference word, e.g. "they imaged" and "The study proved"

Do not place full stop before reference number, .i.e. [16]. is better than .[16]

Use present perfect tense with recently, i.e. "Steinberg et al. [19] have recently used..."

As it mentioned before, premixed flame is stable only with a very limited range. Scientists worked out several methods to stabilized premixed flames. One way to stabilize premixed flame is to add swirl into the flame. Shepherd et al. [20]

Be specific. Rather than "Scientists" write "Research has calculated..."

Avoid phrase "In the research of" we already know it is research.

use "claimed" only when you don't agree with the writer.

stabilized a methane flame with low-swirl, and studied the flame structure. Similar experiment was done by Luo et al. [21] with a impinging premixed flame. In the research of Luo et al, [21] detail about heat transfer characteristics of impinging swirling premixed flame were recorded. In 2012, Yu et al. [22] used laser-induced plasma (FLIP) to stabilize premixed flames. It was claimed by Yu et al. [22] that the blow-off velocity of premixed flame could be increase 2 times with FLIP.

Nowadays, premixed flames are the most common used flame in domestic applications. With thoroughly researches on fundamental aspects, premixed flame is also a must exist topic in almost all combustion textbooks. In this project, some scientific researches about premixed flame were considered as references for the study of inverse diffusion flame. Also some concepts, which were used in premixed flame before, such as equivalence ratio, flame stability limit, and turbulent flame, were partially introduced in inverse diffusion flame research.

Avoid using "nowadays" at start of sentence. "Premixed flames are currently the most commonly used..." is more appropriate.

Use formal language. Rather than "some scientific researches", use "a large amount of research has examined..."

✓Outlines important features of next section. This links sections well.

Use future tense to refer to content of sections that follow. "Certain concepts... will be introduced /discussed in the section on inverse diffusion flame research".

2.2.2 Diffusion Flame

Similar with premixed flame, diffusion flame is a fundamental flame always being mentioned in combustion textbooks. In diffusion flame, fuel and oxidizer meet during the combustion process. A typical case of diffusion flame is a candle flame. For diffusion flame with gaseous fuel, the fuel is delivered to burner nozzle and is ignited at nozzle with surrounding air. The most notable difference of diffusion flame from premixed flame is that air/fuel ratio inside flame is no longer constant. There is a gradually increasing of oxidizer fraction from center of diffusion flame to the flame boundary. And the varied oxidizer fraction results in variation on pollution rate, heating performance and so on. Also, since in premixed flame, velocities of oxidizer and fuel are the same, flame-burning velocity can be easily defined with formula. In diffusion flame, however, there are complicate relative movement between oxidizer and fuel. Since the combustion rate of diffusion flame is influenced by the diffusion rate and mixing rate of fuel and oxidizer, no burning velocity is defined for diffusion flame.[6] In diffusion flame, combustion leads to the exchange between air molecules and fuel molecules, so that the flow is not one-dimensional. Scientists have concentrate on the detail study of diffusion flame, such as flame height, flame shape, lifted diffusion flame, flame stability and flame pollution emission.

✓Links to previous section with phrase "similar with premixed flame". Use "another, i.e. "Another fundamental

✓Defines key terms

✓Gives an example

✓Explains process

Do not start sentences with "And" and "Also". Use "In addition" at the start of a sentence.

Cite your sources when you mention previous studies, i.e.
A number of studies have examined various details of diffusion flame (e.g. [23],[24],[25], [26], [27] and [28]).

2.2.2.1 Stabilization Range

Since the theory of diffusion flame is affected by many flow dynamic interactions, scientists mainly focus on the observation and measurement to study the science of diffusion flame. In 1966, Vanquickenborne et al. [23] measured data of a circular diffusion burner, and they pointed out that the stability of diffusion flame regarding to blow off and drop back was related to the interaction between flow pattern and burning velocity. The idea claimed by Vanquickenborne that a premix zoned on the base of a lifted diffusion flame could determine the stability of flame has been widely accepted in later researches. Takeno et al. [24] did experiment on jet diffusion flame with preheated coflowing air stream, and in the research they observed two kind of stability limits: blow-off and break-off (extinction). In 1993, Chao et al. [25] applied molecular Rayleigh Scattering technique to measure molecule concentration inside diffusion flame. According to the concentration profile, they concluded that mean flow velocity, turbulent fluctuating velocity, length scale of turbulence and jet width were the governing parameter of diffusion stability

Use strong subject and verb when citing previous research. Rather than "The idea claimed by..." use "Verquickenborne found that"

Explain technical words when they are first introduced, i.e. "blow-off" and "break-off".

✓Uses "they" to refer to researchers. This is better than repeating name of authors each time

With the observation and instable phenomenon described in previous works, in the latest decade, scientists tried different methods to extend the stability range of diffusion flame. Kim et al. [26] compared three types of plasma, and they found that plasma produced by asymmetric dielectric-barrier discharge could significantly improve lifted diffusion flame stability. Otakeyama et al. [27] examined flame stability range from another direction. They did experiment on burners with different rim thicknesses, and they reported that thick burner rim could

Do not add an "s" on "work". It changes meaning. Write "previous work"

✓Gives important details of previous reports and explains key finding

extend blowoff limit, but burner rim thickness did not affect lifted flame stability limit.

2.2.2.2 Flame Length

Except of flame stability, flame length measurement is also a topic, which has been intensely studied by researches. Since diffusion flame is more widely applied in industry than premix flame is, flame length of diffusion flame is very important regarding to flame application and pollution control. Modified Burke-Schumann theory used by Roper et al. [28] in predicting diffusion flame length was often used by later researches to analysis flame length data. Except of flame length prediction, flame lengths of diffusion flame are usually measured by visual observation with high-speed camera. Kumar et al. [29], [30] studied the effect of N_2 addition and H_2 addition in LPG fuel on diffusion flame length. Their researches indicated that diffusion flame length increased with N_2 addition and decreased with high percentage of H_2 addition. Also in the research, Kumar et al [29] applied a name called soot free length fraction (SFLF), which was defined as the length of blue flame divided by total flame length. It was claimed by Kumar [29] that SFLF could be used to predict the pollution emission of flame. Similar result was shown in work of Mishra et al. [31] that adding hydrogen into LPG could result in reduction in diffusion flame length. Recently, Mishra et al. [32] measured a LPG jet diffusion flame length with N_2 addition and preheated fuels. Mishra found that with increasing temperature of fuels, flame shown reduction on length. Study of Gan

✓Uses clear topic sentence for the paragraph.

Better not to use "Except of..." when adding extra point, use "in addition to". For contrast, use "In contrast", i.e. "In contrast, flame..."

Do not just list previous research. Try to link ideas and comment on research using evaluative language, i.e. "further developed this idea", using a different method", "importantly", "successfully" "Mishra et al achieved interesting results by ..."
Comment on what is lacking in research, i.e. However they did not examine short tube Bunsen burners."

et al. [33] analyzed influence of burner design and fuel velocity on diffusion flame length. Gan reported that diffusion flame burning on burner with long tube had short length due to increased heat transfer to environment, and there was a linear relationship between Reynolds number of fuel jet and flame length.

Put main point first with topic sentences, i.e. "Diffusion flame has attracted a number of researchers because it is frequently …"

2.2.2.3 Pollution examine in Diffusion flame

Flame pollution analysis mainly focus on the NOx concentration on flame emission gas and instaneous OH profile in flame. Mishra et al. [32] measured NOx emission level of LPG jet diffusion flame with and without N_2 addition. Data achieved by Mishra et al. shown that inert addition could lead to reduction in NOx emission. Kumar et al. [30] did a similar experiment with Bluff-body stabilized LPG jet diffusion flame and found that N_2 addition also reduced NOx emission in that flame. Another experiment done by Kumar et al. [31] in 2008 shown that addition of hydrogen could also attenuate NOx emission level in LPG jet diffusion flame. The mechanism of flame pollution level highly influenced by the chemical reaction rate and temperature of the flame. To investigate the chemical reaction inside flame, researcher did experiment with Laser-induced incandescence to see the soot fraction. Smooke et al. [34] in 2005 reported a detail soot fraction profile of laminar diffusion flame. In Smooke's work, a computational simulation was build to compare with the experiment data.

Do not use "shown" as a past tense verb use "showed", i.e. "Mishra et al's results showed"

✓Links different studies using "similar"

Give details of research. What were Smooke's findings?

2.2.2.4 Conclusion

As a frequently used flame type in industry, diffusion flame attracted numbers of researchers. With a complicated diffusion and mixing of fuel and oxidizer, diffusion flame shows its special characteristics in flame shape, thermal performance and pollution emission. Nowadays, it is a challenge for scientists to figure out and build up a systematic theory to explain complex flow dynamic phenomenon, such as fuel/air mixing and reaction in diffusion flame. Before finalizing the flow dynamic of combustion, collecting comprehensive experimental data on flame are very necessary. Experimental work, similar as theoretical analysis is important in seeking science lies behind the phenomenon. In this project, the research mainly concentrates on experimental analysis of inverse diffusion flame.

Put main point first with topic sentences, i.e. "Diffusion flame has attracted a number of researchers because it is frequently ..."

Do not use informal verbs such as "figure out" and "build up" use "calculate" and "develop".

Do not use "in this project, the research", use a strong subject, i.e. "This research mainly.."

2.2.3 Impinging Flames

Impinging flame is the flame formed by impinging flame to a specific surface. Impinging flames have been widely applied in heat transfer industry. For example, the flame used in domestic stoves is an impinging flame during cooking. Comparing with open flames, impinging flames have significant difference in flame appearance, flame stability, and flame thermal performance.

Do not use key words in definition, i.e. impinging is formed by ~~impinging~~ the flame colliding with a specific surface.."

✓Gives an example
✓Compares and highlights differences

It was described by Zhang and Bray that with different nozzle-to-plate distances, impinging flames shows four flame patterns: ring flame, conical flame, disc flame and envelope flame.[35] It can be seen that nozzle-to-plate

Use strong subject, i.e. "Zhang and Bray described different nozzle..."

Explain which figure you are referring to, i.e. It can be seen in figure 2.2 that..."

distances is a key parameter for impinging flame. Other important parameters include Reynolds Number,

equivalence ratio of flame, nozzle-to-plate distance, and soot loading of flame.

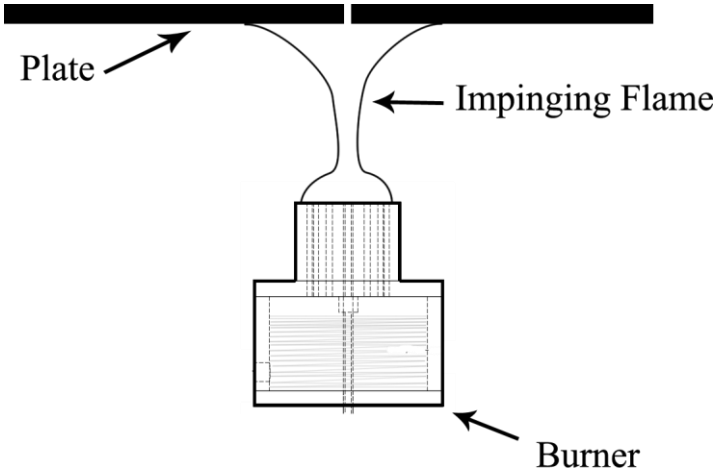

Figure 2---2 Impinging Flame

Previous researches of impinging flames are mainly focus on flame structure, heat flux distribution on impinging plate at different heating height, flame temperature distribution, flame numerical simulation, flame emission and noise, and flame stability, among which lame numerical simulation will be described in simulation part of this chapter.

Do not add "es" to research. It is uncountable, i.e. Previous research..."

✓Outlines content of rest of section

Use a subject, i.e. "These properties will be discussed..."

Addition to the five flame patterns investigated by Zhang et al. [35] mentioned above, Zhen et al. analyzed the relationship between flame structure and local heat transfer behavior. And Zhen found that there existed two stable patterns of impinging premixed flame: V shape flame and M shape.[36] Dong et al. conducted a series experiment to identify favorable impinging flame structure of inverse diffusion flame, which has been proved feasible to be

Be consistent with citations. Zhen et al. is a different research paper to Zhen. Include the reference for Zhen et.al

Explain new concepts. What is an M shaped flame?

used for impingement heating.[37] Effect of burner features on impinging flame structure has also been studied by various researchers. Singh analyzed the impinging flame structure of a nature gas swirling flame.[38]

Explain more about what previous research did, i.e. Singh analyzed...and found that...

Heat Flux distribution on imping plate is one of the key areas in impinging flame research, and it has been intensely studied by different researchers with various methods. Dong et al. reported heat flux distributions of rectangular impinging flames with different nozzle-to-plate distances and different jet-to-jet spacing.[39] In the research, Dong found that jet-to-jet spacing of flame and nozzle-to-plate distances could affect the optimal heat flux of impinging flame. A similar test was done by Zhen et al. with a premixed flame.[36] Ng et al. examined the average local heat flux distribution of an inverse diffusion flame under impinging condition. By comparing the result of inverse diffusion flame with that of premixed flame, Ng found that inverse diffusion flame could achieve better heat transfer efficiency than premix flame.[40] Zhao conducted a further investigation on heat transfer characteristics of imping flame by using a premixed circular flame with swirl. Research done by Zhao et al. shown that flame with swirl could realize better thermal performance than normal flame. Zhao et al. also found that the enhancement of thermal performance could vary with Reynolds number, equivalence ration of flame and nozzle-to-plate distance.[41] To investigate the heat flux distribution of impinging flame, researches have tried different methods. Brubach conducted an experiment to examine surface temperature gradient of impinging flame by coating impinging plate with thermographic phosphors (TP) and exciting the phosphors with laser.[42] In the same year, Chander, considering the

Put action first and then reason, i.e. "Researchers have tried different methods to investigate..."

✓Clearly explains research methods used and findings when discussing previous research by Ng et al

✓Links previous research using "further investigation", "a similar test" and "also found"

problem from another direction, compared the flame heat flux distributions on a cylindrical surface with that on a flat plate. Chander used a brass cylindrical surface and measured flame heat flux under different Reynolds numbers and equivalence ratios. And he found that Reynolds numbers, equivalence ratio and non-dimensional separation distance of burner can work together to affect heat flux.[43]

✓Compares study with previous research
✓Gives details of methods used in Chandler's research
✓Outlines Chandler's key findings

Although testing heat flux distribution is the most direct way to analyze heat transfer characteristic of flame, there are also some other elements, for example, flame emission. As flame impinges to a plate, the flame pollution could stick onto the plate and form a thin layer, which can significantly change heat transfer rate. Also emission gas of flame between flame and the plate can also act as a new heat transfer medium instead of normal air. Several studies have been done on flame emission and noise area. Choy analyze the effect of port diameter and air-to-fuel spacing of burner on pollution emission and noise radiation of impinging flame. In the research, Choy concluded that for fixed airflow rate, burner with smaller port diameter could reduce NOx emission but produce larger noise.[44] In 2010, Li published a paper about the effect of nozzle diameter on CO emission of impinging flame. Li found that reducing nozzle diameter could increase CO emission of flame.[45] Since Li used premixed flame, while Choy used inverse diffusion flame, the information about how nozzle diameter affect impinging flame pollution should be further investigated.

Avoid vague expressions, e.g. "there are also some other elements".

✓Highlights gap in research and what needs to be investigated

Avoid using "can" and "could" in same way, e.g. "could stick" and "can significantly change". Could generally refer to things which are not real. Use "can stick" as it is possible.

Avoid "published a paper on", use single verb, i.e. Li examined..."

For impinging flame stability, Hsieh et al. did a serious test on flame methane premix flame, and he found that a double solution region exist in premix impinging flame. According to Hsieh et al. flame in double solution region was not stable.[46] This result could be taken into consideration in impinging flame application. Durox also found that impinging premixed flame was unstable in a range of burner-to-plate distance. Furthermore Durox believed that the instabilities was partially due to the interaction between flames and sold boundaries.[47]

Avoid informal expressions, e.g. "did a serious", use, "conducted a well-designed test..."

✓Clearly links ideas in paragraph using range of expressions e.g. "This research", "also found" and "furthermore"

Impinging flame is a very common flame used in domestic, commercial and industry applications. Scientists have done numbers of researches on impinging flame with both premixed and diffusion flames. The results show that burner geometry, nozzleto-plate distance, air-fuel ratio, and Reynolds number are all important parameters in impinging flame research. It is necessary to analyze the impinging flame structure, thermal characteristic and flame emission in order to evaluate the performance of a flame.

Use more formal language when describing previous research. "A large amount of research has examined the role of impinging flame...".

2.2.4 Inverse Diffusion Flame

Inverse diffusion flame (IDF) is a kind of flame, of which air and fuel are supplied separately. Different from normal diffusion flame, in IDF air jet is supplied in center of flame, and fuel is supplied surrounding the air jet. With the central air jet, IDFs have special flame structure and heat characteristics. And the special characteristics make IDFs a potential choice for several newly industries, such

Better not to use "a kind of". Use "a type of "

✓Defines key terms
✓Gives examples of their possible applications.

as Nano carbon tube production and soot precursors generation. In the recent decade, there are scientists draw attentions on IDFs. Most of the studies focus on flame stability, flame appearance, flame thermal performance, and flame pollution emission.

Do not use vague language such as "In recent decade", "scientists", use: "A number of recent studies into IDFs have focused on..."

2.2.4.1 Flame Stability of IDF

Stability range of a flame is one of the key information, which scientists should know before doing other experiments on the flame. A flame is considered stable if it maintains stable ignition without blow off or lifted. Different combination of fuels and burner can have different stability range. Wu et al. examined three IDFs with methane, propane, and acetylene respectively, and they concluded the flame stability range of IDFs regarding to air jet velocity and fuel jet velocity. Research of Wu et al shown that IDFs were stable with different flame appearances under a specific range of Reynolds number and equivalence ratio.[48] Mahesh et al. also studied the flame stability and structure of IDFs. In the research of Mahesh et al., comparison between IDFs produced by backsteps burner and coaxial burner were examined.[49] It can be concluded that the previous researches on IDFs stability mainly focused on the effect of fuel, burner parameter, Reynolds number and overall equivalence ratio.

Do not use "information", use more exact language such as "characteristics".

Use "summarised" rather than "concluded" here. Conclusion is a logic result. This is just summing up.

Try and include key numbers from previous research. State relevant Reynold's number and ranges.

2.2.4.2 Flame Appearance of IDF

In research done by Wu et al. IDFs were divided into six flame types and features of each type were described with detail.[48] Currently, most of the experiments were done with the Type 1, Type 2 and Type 3 IDFs described by Wu [48] for the best stability and heating performance. The Type 3 IDF has the typical structure of IDFs, which consisted an enclosed blue zone, an orange-yellow cap and a center dark zoon.

Do not use past tense with activities that are still done, i.e. Currently, most...are done with..."

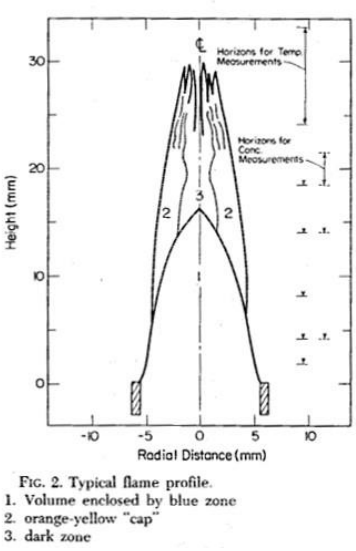

FIG. 2. Typical flame profile.
1. Volume enclosed by blue zone
2. orange-yellow "cap"
3. dark zone

Figure 2.3 Typical Inverse Diffusion Flame [48]

Figure 2.4 Typical Inverse Circumferential Inverse Diffusion Flame

Dong et al. further investigated IDFs structures and classified IDFs into seven typical flame shapes under different Reynolds numbers and overall equivalence ratios. The seven flame shapes were mainly divided into buoyancy-driven diffusion flames and momentum controlled flames. Dong et al reported that when Reynolds number was low, IDFs shown buoyancy-driven diffusion flame structures, while when Reynolds number was above 500, IDFs changed to momentum-controlled flames.[37] In IDFs only air jet velocity is considered in Reynolds number calculation. Under low Reynolds number condition, the velocity of air jet is low,

✓Clearly explains Dong et al's,. research
✓Gives scope of research and methods used
✓Explains findings giving key details

Include also evaluative comments, i.e. "successfully demonstrated".

and the structures of IDFs are mainly controlled by buoyance force. However, under high Reynolds number condition, high velocity air jet will force the surrounding fuel jet to be entrained into the center. In this way, the momentum of air jet acts as a key controller in flame structures.

Figure 2.5 Buoyance Force IDF

Figure 2.6 Moment Force IDF

Explain the figures in writing, i.e. Figure 2.3 shows…"

In addition to flame structure, flame height of IDFs also attracted scientists' attention. In application of IDFs, flame height acts an important role especially in impinging application, in which length of flame determines the heating area size. Dong et al. measured the IDFs length of three IDFs burners with different air jet diameters. Data analyzed by Dong et al shown that with fixed burner parameter, outer layer length of IDFs increased with overall equivalence ration (Φ) in the range of Φ =0.8-2.8.[50] Similar result has been concluded by Zhen et al. and Sze et al. Zhen et al. did experiment with IDFs and swirling IDFs

✓Links and comments on different research at same time e.g. "Zhen et al and Sze et al"

under equivalence ratio of 1 to 5, and their data shown that flame lengths of both IDFs and swirling IDFs increased with equivalence ratio.[51] Sze at al. compare the flame length of circumferentially arrange port IDF and co-axial jet IDF. Although two kinds of IDFs shown variation on flame appearance, both of them share the features that under Re=2500, flame length climbed with equivalence ratio.[11] Considering the flame length was also related to burner parameter, Mahesh et al. used a no dimensional parameter the Global Momentum.

Ratio (GMR) to correlate with the flame length under different equivalence ratios and Reynolds number. In the research, Mahesh et al. found that GMR shown good correlate with flame length in the range of air jet velocity from 5.65 to 10.32 m/s.[49] Flame length, especially the visible outer flame length was usually measured by vision. Nowadays, scientists also use laser measurement to determine the soot distribution inside flame and compare the result with visible flame length. Detail about the research will be discussed in flame pollution emission section.

✓Summarises key findings in research paper and gives key numbers

✓Refers to what will appear later in the paper

Flame color highly depends on the fuel used. Hydrogen flame and LPG flame can have different color due to soot emission and flame temperature. In research about IDFs color, Dong et al., Zhen et al. and Sze et al. observed IDFs color with butane or LPG as fuels. All of them regarded flame luminosity as a signal of soot distribution. Sunderland et al. examined the IDFs with enhanced oxygen, and they conclude that oxygen-enhanced condition lead to increase luminosity.[52] Not so much

Use topic sentence to link to previous paragraphs, i.e. "Another important characteristic of flame appearance is colour".

Do not use "Not much". Better to use Few studies", i.e. "Few studies have examined IDF colour..."

literature about IDFs color, however, in most of the case, color description is in aid of descripting pollution emission.

2.2.4.3 Flame Thermal Performance of IDF

For a flame, the thermal performance directly affects flame application in various fields. Flame temperature also influence soot production and flame luminosity.

Do not use structures like "For a flame" at start of paragraph. Use "The thermal performance of a flame..."

Mahesh et al. measured the centerline temperature distribution of a LPG-air inverse diffusion flame. In research of Mahesh et al., temperature of IDFs was in the range from 600K to 1850K, and they reported tat in premixed zone, temperature rose with position, while in luminous zone, temperature dropped gradually as position increased.[49] Ng et al. [40] , Zhen et al. [53-55] and Dong et al. [50] investigated the heat flux distribution of impinging IDFs with different burners. It can be conclude from the previous research that the heat flux distribution on impinging IDFs have two features: first, as low nozzle-to-plate distance increases, heat flux increase dramatically, after reaching the maximum point, heat flux drops a little and keep unchanged; second, with fixed nozzle-to-plate distance, the peak radial heat flux located on a distance from centerline. More impinging flame detail was discussed in imping flame part. Scientists also investigated radiation heat transfer of IDFs. Hwang et al. [56] used infrared radiation heat flux gauge to measured radiation of oxygen enhanced inverse diffusion flame. In the work of Hwang et al., [56] they mentioned that oxygen enhanced IDF shown to be more effective in radiant heat flux generation than oxygen enhance normal diffusion flame did. Another test done by

✓Clearly structures summary, e.g. ...two features..., first..., second..."

Do not use double subjects. e.g. "Hwang et al., they..." se "Huang et al. [56] found...

Do not use "mentioned" as it means idea referred to is not main point.

Kwak et al. [57] with double inverse diffusion flame and double normal diffusion flame shown that the radiation heat produced by double inverse diffusion flame was greater than that produced by normal diffusion flame. It may conclude that inverse diffusion flame can somehow enhance the radiation heat production.

2.2.4.4 Flame Emission of IDF

Do not use "Scientists studied". "A number of studies have examined" is more appropriate.

Flame emission is the most intensely reported data in IDFs research. Scientists studied the emission of IDFs from several different directions including pollution gas collection, pollutant particle gathering and laser-induced analysis. Dong et al. [50], Zhen et al [54], [55], [58], [59], and Mahesh et al.[60] were used pollution gas collection method to investigate the EICO, EINOx and EIHC of different IDFs. Santamaria et al. [61], [62] studied the soot and soot precursors particles in ethylene IDFs with the help of FT-IR ,^{1}H NMR and TEM. Blevins et al. [63] also investigated the precursor particles produced by ethylene IDFs with TEM image. In the research, Blevins et al. [64] pointed out that IDFs were special in producing large quantity of early soot, which was usually produced by invading the flame with other kinds of flames. Scientists also want to know what is going on inside inverse diffusion flames. Recently laser-induced incandescence technology has been widely used in analysis chemical particles distribution inside flame. Shaddix et al. [65] used OH and PAH laser-in-duce florescence (LIF) and laser-induced incandescence (LII) to analyze the hydroxyl radicle (OH), polycyclic aromatic hydrocarbons (PAH) and soot distribution in a slot IDFs. These methods can capture the instant image of particles distribution inside flame. Shaddix et al. [65] reported signal of PAH and soot concentration in slot

Do not use "going on". It is better to write "occurs" or "happens".

Do not use "somehow", use "in some way"

✓Clearly describes how Shaddix et al. carried out their study
✓Explains methods used
✓Outlines their findings

IDF were smaller than in the normal flames. Mikofski et al. [66] compared the OH distribution results of ethylene-air and methane-air IDFs with planar laser-induced fluorescence (PLIF) method. Lee et al. [67] also used LIF method to studied OH and PAH distribution inside IDF of diluted ethane. Laser can also used to identify nitric oxide in flame. Partridge et al. [68] measured nitric oxide concentration inside IDF with laser-saturated fluorescence, and they found majority of nitric oxide were formed in the flame tip.

- Clearly state cause and effect using linking words, i.e. "Unrau et al [69] mentioned...carbon nanotubes because using flames as a...electric field, so it is not the metal used for carbon..."
- Avoid using 'mentioned' when reporting research. It suggests author referred to did not study topic adequately.

2.2.4.5 IDF application in Nano technology

Unrau et al. [69] mentioned that inversed diffusion flame with high stoichiometric mixture fraction can be used for synthesis of single-walled carbon nanotubes. Using flame as heating source will not create electric field, which may affect the metal used for carbon nanotube synthesis. Xu et al. [70] reported that inverse diffusion flame could also be used to produce multi-walled carbon nanotubes with uniform diameters. Lee et al. [71] pointed out that carbon nanotubes formed under gas temperature varied from 900K to 1400K, and if the gas temperature was below 900K or above 1400K nanorods or nanofibers would be formed. Lee et al.[72] also mentioned that the typical temperature for carbon nanotube formation was outside the

Use article or plural form with word "method" i.e. "the LIF method" and, "These methods"

State "...they found nitric oxide was predominantly formed in the flame tip".

✓Describes key figures from Lee et al

sooting zone of inverse diffusion flame. In this way, inverse diffusion flame would be an approach to carbon nanotubes mass production.

✓Uses "In this way" to introduce summary sentence of paragraph

Different from normal diffusion flames, there are not very much researches about inverse diffusion flames. However, the special features of invers diffusion flames draw scientists' attention these years. With wide range of stability, low NOx emission, higher radiation heat flux, and medium temperature distribution, inverse diffusion flame would act an important role on heat transfer application. After reviewing literature about inverse diffusion flame, it is clear that there are few researches about using fuels mixture with inverse diffusion flame. Using different combination of fuels can adjust the temperature, soot distribution and stability range of IDFs. Without making complex change on burner dimension or flame Reynolds number, changing fuels mixture percentage could realize flame adjustability. Considering the future application of inverse diffusion flame in both daily life and scientific research, it is necessary to investigate heat transfer characteristics of inverse diffusion flame with different combination of fuels mixture. In this project combination of LPG and hydrogen were studied as the first step to realizing the IDFs optimization.

Link to previous paragraph with "In contrast to the number of studies into normal diffusion flames..."

Do not use "not very much", use "a limited number" or "little", i.e "Little research has examined inverse..."

Better to use an article or plural form with the word "combination" i.e. "different combinations" and "a combination of LPG and hydrogen"

✓Explains what has not been studied, 'the research gap'

✓Explains how research can be done

✓Explains how it might be useful

2.3 Fuels

In this project, a mixture of fuels was applied to analyze inverse diffusion flame. The fuels include commercial LPG fuel and hydrogen fuel. LPG fuel with various hydrogen percentages was used in the experiment. Basic information and previous researches on LPG and hydrogen will be introduced in this part.

Be accurate with word choice. Rather than vague phrases such as" basic information" and "In this part", use: "Section 2.3 describes the use and properties of LPG and hydrogen fuels and outlines previous studies into their use".

2.3.1 LPG Fuel

Start new paragraph for new idea, i.e. one paragraph on what LPG is and another on its production and uses.

As one of the key energy resource of domestic and commercial application in Hong Kong, LPG consists of butane and propane. The percentages of butane and propane are various in different regions. For example, in the Unite States, the volumetric percentage of propane in LPG should be at least 85%. While in France, the percentage of C3 hydrocarbon (propylene and propane) should be between 19% and 50%.[73] In this project, LPG used in experiment contains 30% (vol) propane and 70% (vol) butane, which are satisfied to the regulation of Hong Kong. Production of LPG is very easy. In the past, LPG is a byproduct of petrol and was usually regarded as waste.

Ensure there is a logical connection with the use of "as". Here LPG is not a key resource because it contains butane and propane. Better to use, "LPG, which consists of butane and propane, is one of ..."

Nowadays, people extract LPG by purifying natural gas or refining crude oil.[73] LPG can be easily compressed and stored in a can. The properties of LPG make it a convenient heating resource for people no matter where they are living. Also as a gas fuel with several process of extraction, LPG is one of the cleanest hydrocarbon fuels.

Thanks to the manufacturing process, sulfur contain is very low in LPG. Considering the high volumetric heating value of LPG, it could be said that LPG is a very suitable fuel for domestic, commercial and industrial application regarding to availability, heating performance, and pollution emission.

Ensure there is logical and clear connection by using "because" or "since" to link ideas, i.e., "It could be said that...and pollution emission because of the high volumetric heating value".

Since contains of LPG is various, most of researches on LPG flames are about the application improvement of LPG. Scientists focus on how to improve LPG flame heating performance, reduce pollution emission and extend flame stability range.

Point out if a study has been previously discussed, i.e. "Flame structure of...reported by Mahesh et al [49], discussed earlier in section 2.2..4.

Flame structure of LPG inverse diffusion flame was reported by Mahesh et al. [49] in 2010. Kiran et al. [74] studied on flame stability and emission of LPG diffusion flame. In the work, Kiran measured lift-off heights and flame length of LPG diffusion flame with various fuel exit velocities. Charoensuk et al. [75] investigated temperature distribution of LPG flame using a porous combustor burning partially premixed LPG. Ng et al. [40] examined temperature of impinging LPG inverse diffusion flames. Sze et al. [11] also studied temperature distribution of a LPG inverse diffusion flame under different air jet velocities and equivalence ratios.

Do not just list previous studies. Describe what each of studies found, i.e. "Ng et al. [40] examined temperature of impinging LPG inverse diffusion flames and found..."

Do not use "In the work, Kiran measured" use "This study measured..."

Some scientists diluted LPG with other gas fuels to change the performance of LPG flame. Mishra et al. [31], [32] and Kumar et al. [29], [30], [76], [77] tried to add N_2 and hydrogen into LPG flame to see the change in flame length and pollution volume. Zhen et al. [78] used oxygen enriched air in LPG inverse diffusion flame to analyze the effect of increasing oxidization level on the flame heat transfer characteristic. Data obtained by Zhen et al. [78] shown that adding oxygen in air jet of LPG inverse diffusion flame could reduce overall CO emission and increase flame temperature under low overall equivalence condition.

✓Links previous studies that used ame methodology

Do not use "Data obtained by Zhen et al. [78] shown" use "Zhen et al's [78] findings show..."

Comparison between LPG and gasoline fuel regarding to flame propagation and combustion characteristics were done by Lee et al. [79] The experiment was done with help of a combustion chamber. Data shown that flame propagation speeds of both LPG and gasoline fuels were significantly affected by equivalence ration.

2.3.2 Hydrogen Enriched Fuel

Make subheadings clearly show content of section, i.e. "Advantages of Using Hydrogen".

2.3.2.1 Attraction

Nowadays, it is well known that clean energy is one the major areas of researches worldwide. With the simplest chemical structure, hydrogen is regarded as the cleanest fuel and future fuel.

Include clear topic sentence stating content of section, i.e. "There are a number of advantages in using Hydrogen". Then introduce each advantage with clear linking expression, i.e. "One important advantage is...".

Burning of hydrocarbon fossil fuels creates carbon dioxide and results in air pollutant and toxic chemicals.[80] However, the only product produced during hydrogen combustion is water. It means that CO, SOx, or VOCs emission in hydrogen combustion will not be a problem, although NOx will form in hydrogen/air combustion system. Hydrogen is also safer compared to common fuels. With a lightweight, hydrogen can disperse upward if it leaks instead of stacking in a pool and then ignites. Also leaking of hydrogen will not lead to water contamination or ground contamination as oil does.[80] Storage and distribution of hydrogen is very convenient. Hydrogen can be stored in forms of both gas and liquid, and it can also be stored in the molecular structure of solid media. People can distribute hydrogen through various methods, such as pipelines, truck, and ship.[81] Another attraction of hydrogen is that it can be produced from water or from any hydrocarbon fuels. Nowadays, production of hydrogen is a growing industry. It is reported that in 2004 50 million tons of hydrogen were produced in global.[82] Developed countries, such as United State and Japan have implemented regulation to promote the hydrogen usage in daily life. It could be said that research on hydrogen production and application is and will be an attractive direction regarding to both energy supply and environmental protection.

✓Links point with clear linking phrase e.g. "Another attraction of hydrogen

Better to finish by linking the advantages of hydrogen to the points made in the paragraph, i.e. "As a result of these benefits, hydrogen is…".

2.3.2.2 Drawback

Better to make subheadings clearly show the content of the section," Disadvantages of using Hydrogen."

There are also some disadvantages of hydrogen fuel. Instead of being an energy source, hydrogen fuel is usually regarded as an energy media. Production of hydrogen consumes energy. It is necessary to find a low energy consumption way to produce hydrogen.[8] Besides since the density of hydrogen is very low, hydrogen can easily escape from container. And with the smallest molecular, hydrogen can penetrate into the wall of tube or container and ages the material. Considering the physical properties of hydrogen, complicate system is required to ensure the operation safe.[8] Burning of pure hydrogen can produce non-luminous flame, which cannot be easily observed. Flame color can also be a source danger, although flame color can also be affected by burner material. Another problem is that flammability limit of hydrogen is very low, which means that it can catch fire even with very low hydrogen percentage.

✓Uses a clear topic sentence

✓Develops point using phrase "which means"

Leakage of hydrogen can cause serious result.

Link last sentence to paragraph using linking word, i.e. "As a result of these properties of hydrogen, leakage is an important consideration".

2.3.2.3 Hydrogen Enriched Fuel

It can be seen that to realize using pure hydrogen in large scale is still in need of further research. To extenuate the drawback of pure hydrogen and adopt the advantage of hydrogen, it may be a practicable way to mix hydrogen with other hydrogen carbon fuels. Hydrogen carbon fuels with large molecular and high density can slow down the leaking speed of hydrogen and reduce hazard possibility. While addition of hydrogen can extend flame stability range of mixtures and may improve the heating performance of the fuels. There are several research works about burning hydrogen-enriched fuels.

✓Describes possible solution

✓Evaluates possible solution, e.g. "may improve the heating..."

2.3.2.4 Literature

Use "Previous Studies in Hydrogen-enriched fuels" as subheading.

In 1986, Yu et al. [83] added hydrogen in methane and propane fuels, and they found that hydrogen addition could substantially increase flame speed. In 1997, Fotache et al. [84] mixed hydrogen with methane and did the ignition experiment with preheated air. The result indicated that adding hydrogen in methane could obviously improve ignition; while the addition of methane in hydrogen could hinder ignition at low and moderate pressure. A oxygen/hydrogen mixture was used by Lee et al. [85] as fuel to analyze affect of CO_2 on flame temperature distribution. Recently, Miao et al. [86-88] measured heat transfer characteristics of hydrogen enriched nature gas. The experiments were done with combustion chamber. And data showed that hydrogen addition could influence burning velocity and flame stability. A series of experiments were done by Chen et al. [89] to research the effect on hydrogen addition in biogas MILD combustion. Kumar et al. and Mishra et al. [29], [31], [77] examined the influence of hydrogen in LPG fuel on flame length, temperature and pollution emission of diffusion flame. They claimed that hydrogen could shorten flame length and reduce NOx emission of diffusion flames.

Avoid using "indicated" and "obviously" in same sentence. Obviously = 100% certain. Indicate means less than 100%

Use "effect" as noun, i.e. The effect was..." and use affect as verb, i.e. "Speed affects the temperature".

✓Groups studies that used same methodology
✓Explains methods used
✓Explains findings of studies

2.4 Numerical simulation

Use "studies" as a countable noun, i.e. "A large number of studies" and use "research" as an uncountable noun, i.e. "A large amount of research..."

Large numbers of researches have been done on flame simulation. Usually, scientists compared simulation results with experimental data, and tested the reliability of the model. In this project, literature about numerical simulation of inverse diffusion flame, premixed flame and diffusion flame are included.

Use "research" than "literature" and "discussed" instead of "included".

In inverse diffusion flame simulation, researches mainly focus on methane flame. In 1984, Wu et al. [48] used numerical method to simulate methane IDF with 6 flame types. And around a decade later, Takagi et al. [90] examined the effect of preferential diffusion on temperature in IDF of methane. Kaplan et al. did research about flowfield effect on soot formation of IDF methane flame. And they pointed out that normal diffusion flames have both higher peak soot volume and total soot volume than inverse diffusion flame.[91] Recently, Johnson et al. [92] simulated methane IDF with co-flowing air.

- Do not link sentences with "And the results/research..." better to use "These results" or "This research". "And" has been repeatedly used in this paragraph. Use other liking words that show addition, such as "in addition" or "also".
- Use "researchers" instead of "scientist".

Use present perfect tense with "Recently, i.e. "Johnson et al. [92] have recently simulated...".

Comparing with inverse diffusion flame, premixed flame has been much more simulated.

Avoid using unclear subjects, e.g. "Scientists" better to use passive voice, i.e. "Premixed flame was studied with...".

Scientist studied premixed flame with different fuels and under different conditions. Xiao et al. analyzed hydrogen/air premixed flame propagation. The predicted pressure of Xiao's work shown good agreement with experimental data.[93] Boushaki et al. simulated methane-air premixed flame with hydrogen addition. And they found that after adding hydrogen, flame burning velocity increased.[94] Hu et al. also researched methane/hydrogen/air premixed flame. And the result obtained by Hu showed that laminar burning velocity is due to the competition between the reactions of the main chin branching and chain recombination.[95] Hawkes et al. simulated hydrogen enriched premixed methane flame using direct numerical simulation method. And the research done by Hawkes et al. indicated that flame burning velocity is increased by hydrogen addition, and blow-off stability limit of hydrogen enriched flame were also extended.[96] Sarli et al., however, studied premixed flame from another direction. They simulated large eddy of unsteady premixed flame during propagating around obstacles.[97]

- Do not link sentences with "And the results/research…" better to use "These results" or "This research". "And" has been repeatedly used in this paragraph. Use other liking words that show addition, such as "in addition" or "also".
- Use "researchers" instead of "scientist".

There are also vast researches about diffusion flame simulation. Chen et al. analyzed counter flow diffusion of hydrogen/biogas in 2011.[89] Li et al. studied lift off and stabilization phenomena of diffusion flame with numerical simulation method.[98] Hu et al. also studied hydrogen related topic in diffusion flame simulation. They investigated the laminar burning characteristics of hydrogen-methane flame with numerical method.[99] Guo et al., however, analyzed effect of hydrogen addition on flame temperature and NO emission

Better not to use "vast". Better to use "numerous" i.e. "There are also numerous studies on…".

Better to further explain the findings of these studies and point out how they inform the experiments performed in this study.

✓Highlights differences between the two studies using "however".

of diffusion flame with numerical simulation.[100] Khelil et al. predicted the NOx emission and concentration of O and OH in a natural gas diffusion flame with high swirl.[101] Diffusion flame on microgravity condition was also simulated.[102] Jiang et al. used 3 dimensional spatial direct numerical simulations to study structure of buoyant jet diffusion flame.[103] Stability limits of diffusion flames were studied by Yamashita et al. in 1996. And they found that flame structure of diffusion flame included instantaneous local premixed, diffusion and partially premixed flames.[104]. Ghosal et al. in 2001 [105] plotted stability diagram for laminar diffusion flame using numerical simulation.

Better to spell number between one and ten. i.e "three" rather than "3".

✓Explains important findings that are relevant to this study.

Do not state the year of publication when using the IEEE referencing system. "Ghosal et al. [105] plotted..." is more accurate.

Nowadays numerical simulation has become a widely used method in predicting of different kinds of reaction flows. Inverse diffusion flame, as a special kind of flames, which has not been intensely studied yet, is in serious need of numerical prediction. The data provide by simulation can act as a reference for experiment and future theory development.

Avoid using "nowadays" at start of sentence. "numerical simulation has currently become ..." is a more accurate alternative.

Avoid informal phrases such as in "serious need of" better to use "This field of study would greatly benefit from ..."

✓Explains future benefit present study will provide

2.5 Summary

From the above literature review, it can be concluded that inverse diffusion flame, as a special kind of diffusion flame still needs

Use a strong subject in the topic sentence, i.e. "The studies discussed above show that inverse diffusion flame still..."

further investigation. Heat transfer characteristics such as flame structure, temperature distribution and pollution emission volume are essential information in researches of flames. Just as diffusion flame, inverse diffusion flame contains many unknown reasons behind the characteristics. Vast numbers of experimental studies are required in the progression of flame science.

In this project, experiments will be done to analyze effect of hydrogen addition on

Use colon ":" at end of sentence that introduces lists i.e. ...addition on:

1. LPG IDF stability range
2. LPG IDF temperature distribution
3. LPG IDF heat flux distribution under impinging condition
4. LPG IDF pollution emission index

Flame with various hydrogen percentages will be tested. And detail experiment setup will be explained in following chapter.

Avoid linking with "and". There is no connection between the last two sentences so no linking word is needed.

Chapter 3 Research Methodology

Use passive voice with "base", i.e. "Research is mainly based on..."

In this project, researches mainly base on experimental data analysis. A small-scale inverse diffusion flame burner is used. And experiments focus on measuring heat transfer characteristics of the flame under open and impinging conditions.

There are five main tasks:

1. Exam the flame stability of pure LPG and LPG enriched with Hydrogen fuel with a CIDF burner. To see the stability range of LPG fuel and effect of hydrogen in flame stability.

✓Uses same word form for first word in each point on list, here verbs are used, e.g. "examine, test"

2. Capture flame image of LPG fuel mixed with various percentages of Hydrogen to see the affect of hydrogen on flame structure, shape, and color.
   Also record the flame height data for further study.

3. Test the flame emission of LPG fuel with different percentages of hydrogen under a range of Reynolds number and equivalence ratio. Mainly focus on the CO, CO2 and NOx emission of flame.

Use full sentences in list, using subject i.e. "It mainly focuses on...". the...".

4. Measure temperature distribution of the flame. For both open flame and impinging flame, to measure the centerline temperature of flame.

5. Conduct experiment with both open flame and imping flame to draw up a complete data record about hydrogen enriched LPG IDFs.

3.1 Assumption and Method

To simplify the problem the following assumptions are made:

1. Air and fuel Exists of burner are perfect circles and 12 fuel exists have the same diameter.
2. Impinging flame stretches on the impinging plate evenly in all directions.
3. Hydrogen and LPG are fully mixed.
4. All gases are considered as ideal gases.

In this study, several parameters of flames were considered, including Reynolds Number (Re), equivalence ratio, volumetric hydrogen percentage, flame length and air/fuel jets velocities.

✓Clearly states mathematical formula used at start of methodology section

Since the velocity of air jet is much higher than that of fuel jet, the flame performance is dominated by air jet velocity. Only Reynolds number of air jet was considered in calculation. The calculation of air jet Reynolds number was evaluated as:

Number equations using correct format.

$$\mathrm{Re} = \frac{\rho_{air} v_{air} d}{\mu_{air}}$$

Equation 1 Calculation of Reynolds Number

Equivalence ratio of fuel and air jet indicating fuel lean, fuel rich and stoichiometric condition was attempted in this study to evaluate flame stability and flame length. Equivalence ratio was calculated as:

$$\Phi = \frac{(V_{air} / V_{fuel})_{\text{stoichiometric}}}{(V_{air} / V_{fuel})_{actual}}$$

Equation 2 Equation of Equivalence Ratio

LPG fuel enriched with various hydrogen percentages is the main supplied fuel in this study. The percentage of hydrogen fuel was calculated as:

$$H_2\% = \frac{V_{H_2}}{V_{H_2} + V_{LPG}} \times 100\%$$

Equation 3 Calculation of Hydrogen Percentage

A no dimensional parameter call Global Momentum Ratio (GMR) was adopted to correlate with flame length. Mahesh and Mishra [106] introduced GMR to relate airfuel jets momentum transfer and flame length in LPG IDF. In this project, correlation between GMR and flame lengths of LPG and 50% hydrogen enrich LPG were test under Re=1500 and Re=3000. GMR is defined as:

Use passive form with verb call, i.e. "A no dimensional parameter called Global..."

$$GMR = \Phi(v_{fuel} / v_{air})$$

Equation 4 Equation of Global Momentum Ratio

3.2 Experiment Setup

✓Clearly describes experimental setup and refers to figure, e.g. "As is shown...".

A special designed IDF burner was utilized in this project. The burner consists of two main parts: a burner head and a burner chamber. As it shown in Figure 3-1, the brass burner head has a center channel, which is 5.5 mm in diameter for air supply. And the twelve smaller channels surrounding the center channel are 2 mm in diameter, and were designed for fuel supply. The smaller channels were arranged 12 mm from the center channel. The burner chamber is in cylinder shape, and has the function of fuels mixing. Several layers of wire net were placed inside burner chamber to insure the uniform mixing of fuels. A tube connected with the center channel of burner head penetrates through the bottom of burner chamber for air supply. Fuels were supplied through the opening on the lower part of burner chamber. With the help of wire net, fuels mixture evenly jet out from the twelve channels, and was surrounded by the ambience air. At the same time, high velocity air jets from center channel and exert drag force on fuel jets to form an inverse diffusion flame.

✓Describes methodology using past tense and passive voice, e.g. "was designed, was surrounded".

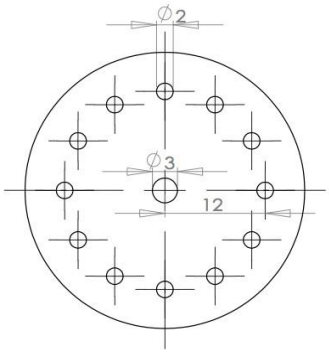

Figure 3.1 Top View of Burner Head

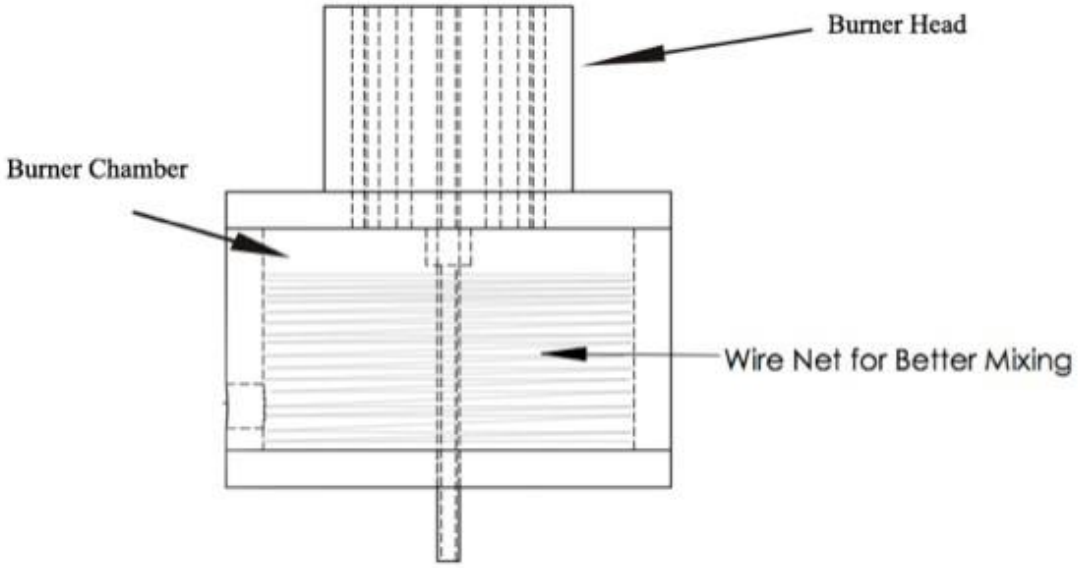

Figure 3.2 Side View of Burner

Refer to figure 3.2 in text, i.e. Figure 3.2 shows..."

Two fuels were involved in this study: liquefied petroleum gas (LPG) and hydrogen (H_2). Commercial grad LPG was used, which contains 30% (vol) propane, and 70% (vol) butane while the hydrogen has purity of 98%. LPG and hydrogen were controlled by regulars and traditional flow meters, and were delivered into the burner chamber to form uniform mixture naturally.

✓Compares different constituents of fuels using "while" to show contrast

Open flame structures were measured by vision. A ruler with 1mm accuracy was placed on left side of burner. Ten photographs were taken for each flame, and average reading of flame heights in photographs was recorded as final result. A high resolution digital camera was used. To ensure clear flame outline and data accuracy, the camera was operated at light sensitivity (ISO)=200, f-number-1/2.8 and exposure time=1s.

Ensure articles such as "a", "an" and "the" are used. i.e. "the left side", "a final result".

To protect flame from outside air current interference, a net screen was designed to surround the burner. The net screen protect burner from 3 sides, with an opening for operation. And a 100 liter/s air extractor was placed 1 meter away from the system to purify indoor air. All the data were collected under standard condition.

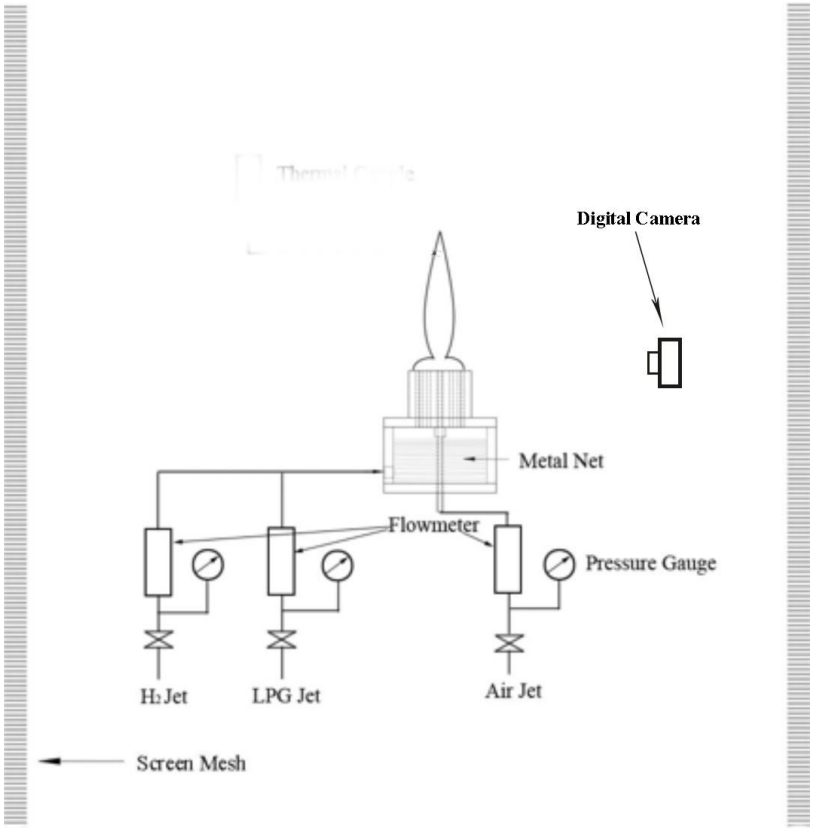

Figure 3.3 Experiment System

Continue to use past tense to describe methods. Present tense refers to experiments that are generally done not ones specific to this study. Use a definite article to refer to a specific item i.e. "The burner was placed".

For the flame temperature distribution under impinging condition, a copper plate with heat flux sensor was utilized to collect data. Burner is placed on a positioner, which can be adjusted in two dimensions. Various nozzle-to-plate distances can be achieved. A heat flux sensor is installed in center of impinging plate, and a small hole is drilled in the plate for emission analyzer. Data of

heat flux are collected and analyzed with computer to figure out instantaneous temperature distribution in side impinging flame.

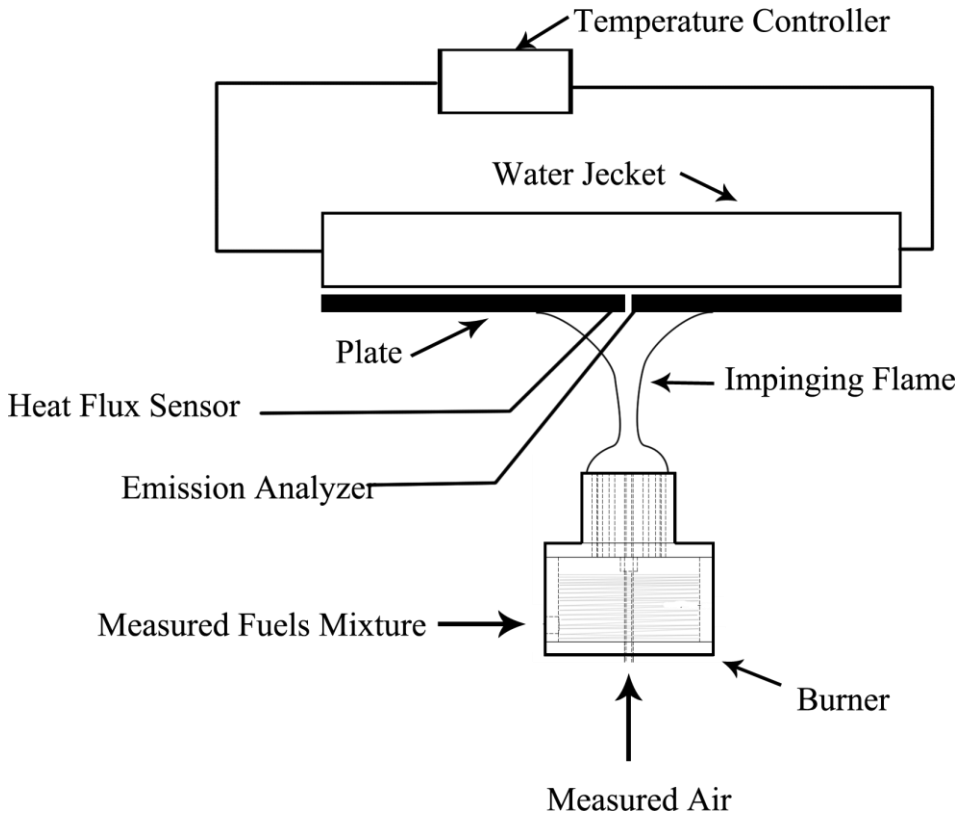

Figure 3.4 Experimental Setup of Impinging IDF

3.3 Experimental Procedures

3.3.1 Flame stability

Use more formal language. Rather than "necessary to grasp", use "It is necessary to establish the stability limit".

Before measuring other characteristics of flames, it is necessary to grasp the stability limit of flame. The aim of stability test is to ensure later experiment will be done within stable range. Also some preliminary tests and literature showed that addition of hydrogen could

significantly extend flame stability range. To simplify the problem, only flame stability boundary of LPG IDF were examined.

In this project, stability of flame was measured by fixing the airflow rate and then gradually reducing fuel flow rate. Data of Re_{air} from 500-7000 were measured. For each airflow rate, the flame-extinction fuel flow rates were recorded for three times. Average of the data were used as final value

Avoid "In this project", It is unnecessary.

3.3.2 Flame structure and Flame height.

IDF shows different flame structures under different Re_{air}. In this project, structures of IDF with LPG and hydrogen as fuels under Re_{air} =500-7000 were observed and analyzed. Pictures were taken for flame under different Re_{air}. Flame height of IDF under different Re_{air} and hydrogen percentages were also measured. To ensure accuracy, ten pictures were taken for each point. And the average values were recorded for each point.

Use "Then" rather than "And" when describing actions by time, i.e. "The average values were then recorded."

3.3.3 Impinging Flame Temperature Distribution

Special designed impinging plate was used for measuring temperature. A heat flux transducer was placed in the middling of plate. In the first stage of experiment, temperature along centerline of flame will be measured. The process will be done by align center of flame with the transducer, and adjust nozzle-to-plate distance to measure temperature distributed along flame centerline. Different

Continue to use past tense to describe methods. "Will be" refers to things which have not been done yet.

hydrogen percentages LPG IDF under Re_{air} =500-7000 will be examined. After achieving temperature data of IDF centerline, the nozzle-to-plate distance, with which the highest temperature occurs will be set as the best heating distance. Radial temperature distribution on the best heating distance of each combination of Re_{air} and hydrogen percentage will be measured.

✓Describes a process and uses "After achieving" to show ordering of actions. Other ways to do this include using words such as "then" and "after that"

3.3.4 Pollution Emission of Impinging Flame

A hole is drilled on the plate to collect flame pollution emission. The hole is connected with emission analyzers of CO, CO_2 and NOx. Data of flame with various hydrogen percentages and nozzle-to-plate distances can be obtained with the emission analyzers.

Outline contents of chapter 4. Either at end of chapter three or start of chapter four, i.e. This chapter describes..."

Chapter 4 Preliminary Results

4.1 Flame Stability

Include short introduction to chapter rather than starting with detailed findings.

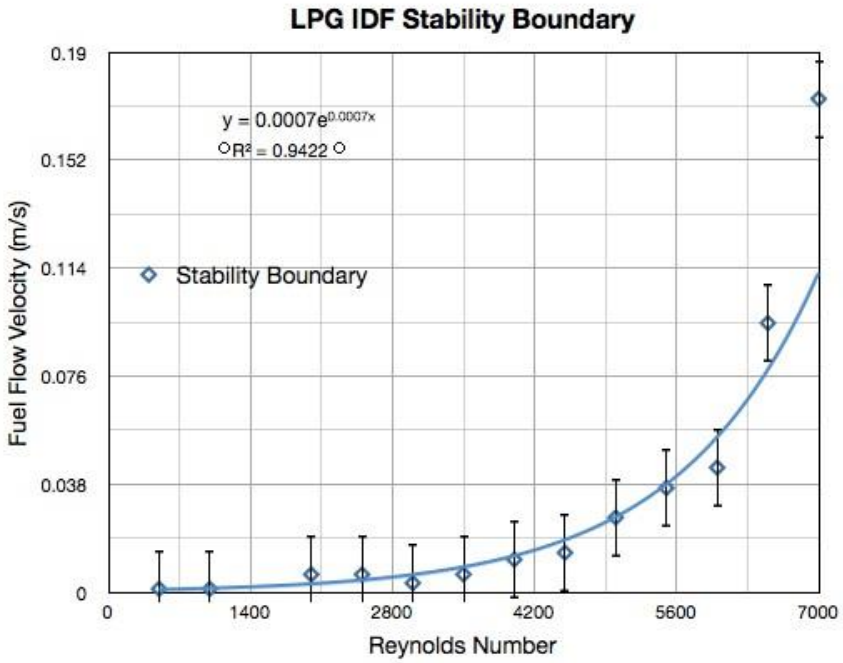

Figure 4.1 LPG IDFs Stable Boundary Regarding Re and Fuel Flow Velocity

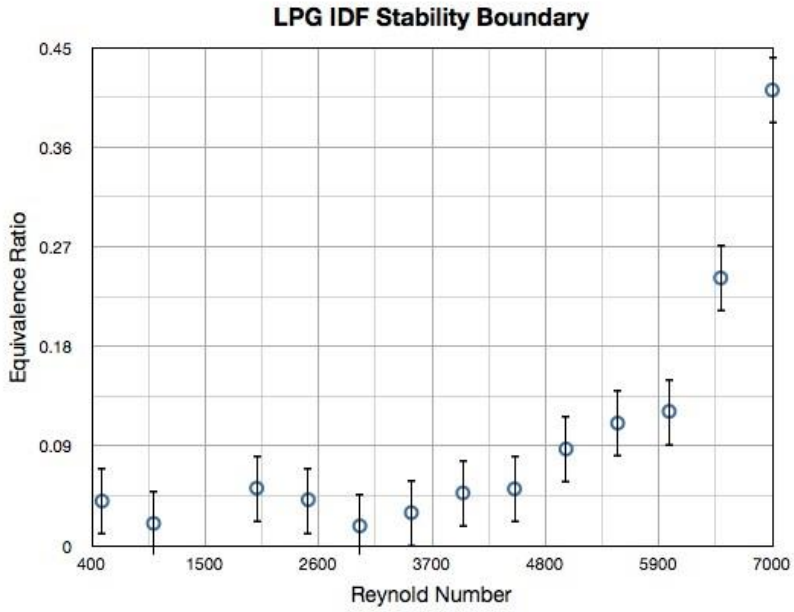

Figure 4.2 LPG IDF Stable Boundary Regarding Re and Equivalence Ratio

Since IDF do not have burning velocity, flame stability range of IDF is a very important character in IDF application and simulation. 12 sets of experiment have been done under

Use "characteristic" to describe single feature.

Re varied from 500 to 7000 to investigate the lowest LPG required for stable flame. During the experiment, air jet flow rate was fixed, and then LPG flow rate was slowly reduced until the flame blow off. The operation was repeated to ensure data accuracy.

Figure 4.1 shows the LPG IDF stability range regarding to Re and fuel flow velocity. The lower limit of fuel jet velocity exponentially ascends with Re. The required of flow velocity grows steeply when Re was larger than 5000. Since the airflow rate was used in this study for Re calculation, the result can be translated as the relationship between air jet velocity and lower limit of flue jet velocity.

Place figure referred to closer to text that refers to it.

Do not mix tenses. When describing findings of particular study use past tense, i.e. "velocity grew..."

When air jet velocity is relative low, such as Re=500-2000, stable flame can be seen even with low fuel velocity. This phenomenon may because when the interference of air jet on fuel jet is low, the flame is mainly affected by buoyance force, and the flame is blue and quiet.[37] When Re rises, large pressure caused by the velocity difference entrains fuel jets to the center air jet and forms a flame neck, which is the mixer and holder for flame torch.[50] An entrainment zoon [107] is formed at the root of flame, and this zoon is usually called flame bass. The entrainment results in better air-fuel mixing [106] and longer residence time for soot. The fuel jet velocity should be high enough to catch up entrainment force and flame speed to form stable flame. Under high Re, center air jet also exerts shear-lifting force onto fuel jets. Higher velocity is required for fuel jet to cover the significantly increment shear lifting force.

✓Discusses possible causes and reasons for findings. This is often done in separate chapter called "Discussion"
✓Give references for definitions and sources cited
✓ Uses tentative language to show lack of certainty, e.g. "mainly" "may"

Figure 4.2 indicates that similar with jet velocity, the lower limit of equivalent ratio also climbs with Re. Stable flame can be achieved under fuel lean condition when Re is from 500~7000. Even when Re was as large as 7000, flame can be stable with Φ =0.41. Fluctuation occurred between Re=1000 and Re=2500, which may be because of flame structure transformation.

Do not use "indicate" to describe results, use "shows".

use linking word to show contrast when results differ depending on variables, i.e. "However, fluctuation occurred..."

Stability range of hydrogen enriched LPG IDFs were also tested. Very low percentage of hydrogen can significantly enlarge stable range of LPG IDFs. The result may be due to the low density of hydrogen, which speeds up the fuel mixture release rate.

4.2 Flame Structure

Figure 4.3 LPG IDF Re=1500

Figure 4.4 LPG with 50% Hydrogen IDF Re=1500

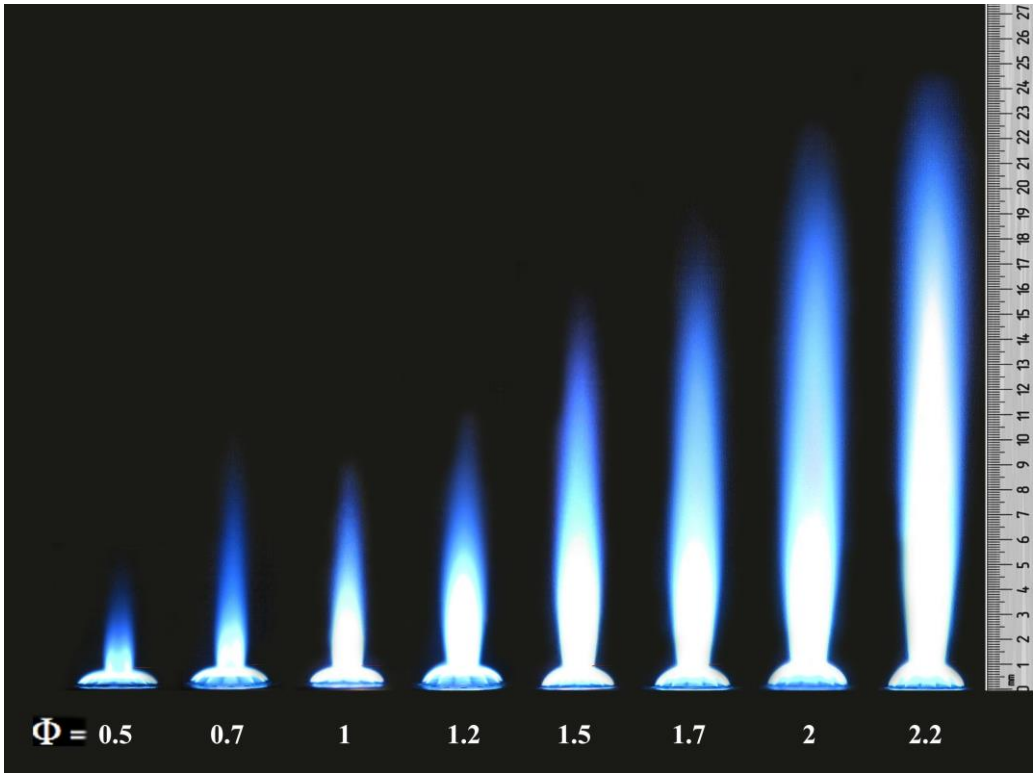

Figure 4.5 LPG IDF Re=3000

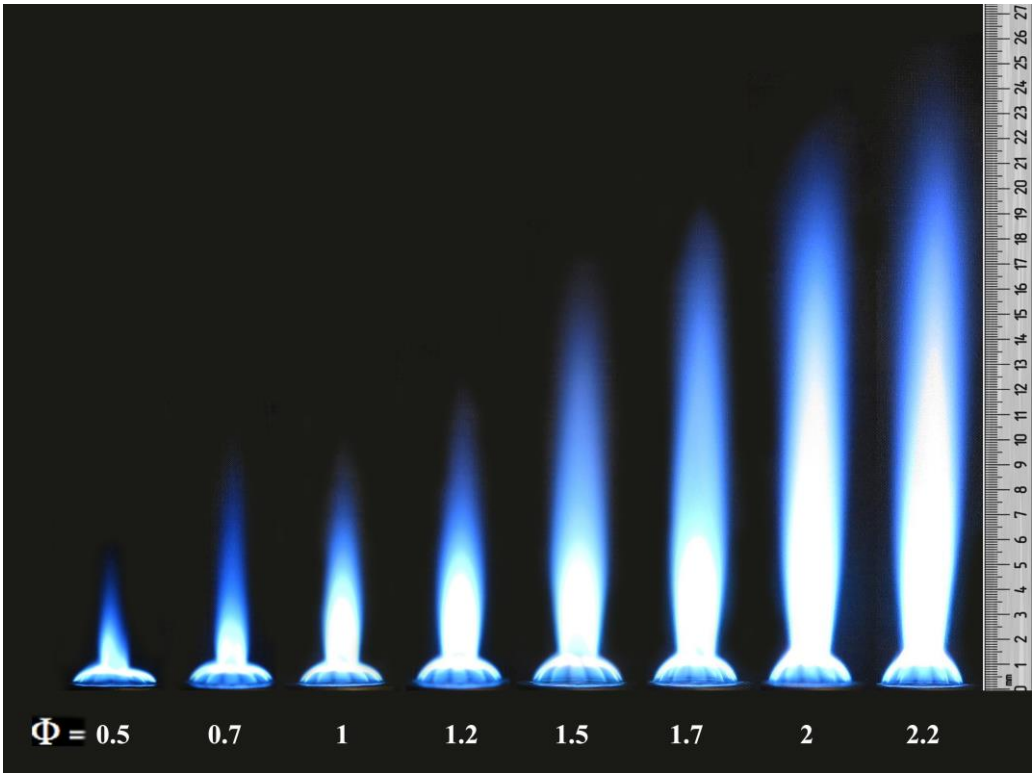

Figure 4.6 LPG with 50% Hydrogen IDF Re=3000

Wu [48] classified IDF into six types according to the flame shapes. Flame shape of IDFs highly depends on equivalence ratio and Reynolds Number. Flames of LPG and H_2-LPG mixture appeared in different flame types under different Re. To simplified the problem, experiments have been done for flame with Φ =0.5, 0.7, 1, 1.2, 1.5, 1.7, 2, 2.2 under Re=1500 and Re=3000 respectively. The flames are all with clear flame torch, flame neck and flame base. For Re=1500 the flames have thinner flame torch with narrow and sharp tip. For Re=3000, the flames show wider inner cores, and shapes of flame torches are more close to ellipse.

Explain why six types of flame are relevant to your study, i.e. "These six types were used in this study to categorize flames".

✓uses "to simplify..." to express purpose of action

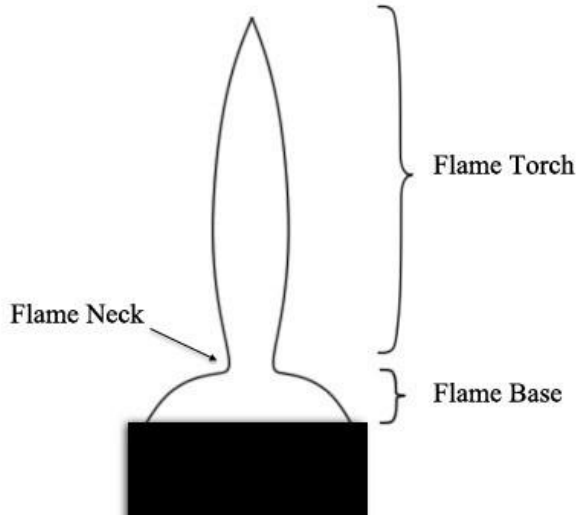

Figure 4.7 Flame Structure

It can be observed from Figure 4-3, Figure 4-4, Figure 4-5, Figure 4-6 that the height of flame lengthens steady with Φ when Re is fixed. No obvious height changes were observed in flame base. For LPG IDF with Re=1500, the flames were elongated from 36 mm to 202 mm during the Φ range. After augment Re to 3000, LPG IDF shows a height change from 46 mm to 250 mm within similar Φ range. The data for 50% Hydrogen diluted LPG IDF are 38 mm to 174 mm and 48 mm to 237 mm respectively. The increment of Re leads to significant growth in flame height for both LPG IDF and H_2-LPG IDF. 50% addition of hydrogen contributes about 5%~14% reduction to flame length. Zhen, Mishra, and Kumar also found hydrogen addition in LPG fuel can shorten flame length.[31], [108] With the increase of Φ , accelerated fuel jet can catch up with high-speed air jet to form higher flame. The air jet drag fuel into centerline of flame, and severely mixing of air and fuel cause the bright blue flame appearance. When the fuel supply rate is high, there is not enough time for all the fuel to be burned completely in entrainment zoon, yellow

Explain where figures can be seen, i.e. "on page 59 and 60".

✓Describes findings and states key numbers

✓ Refers to previous findings by other researchers to add credibility to findings in paper, e.g. "also found"

flame formed by increased amount of soot formation can be noticed. Also the reduced difference between air/fuel velocity leads to wider flame neck under high Φ value.

4.3 Flame Height

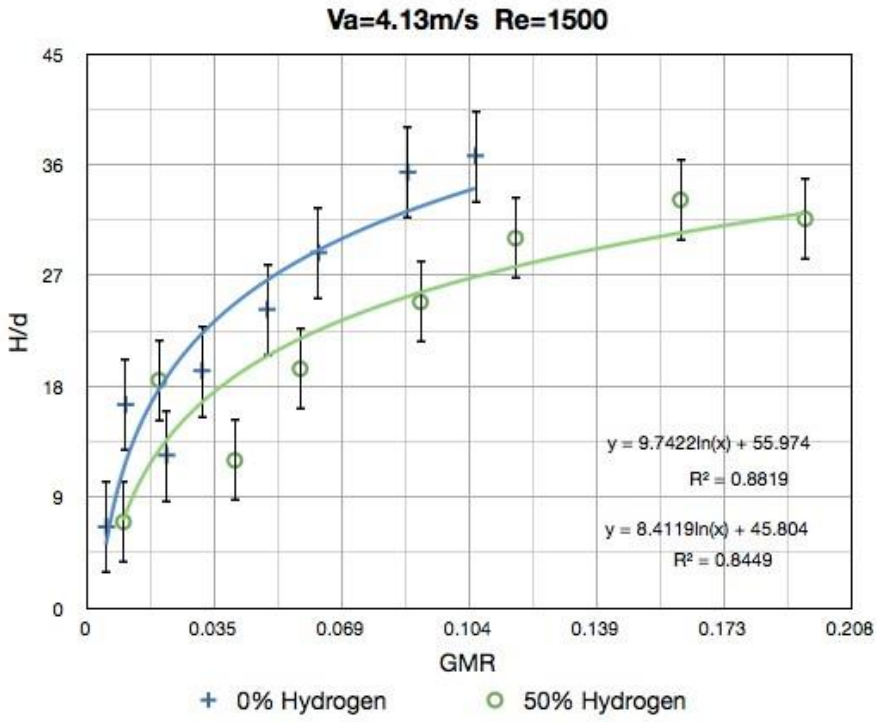

Figure 4-8 Correlation between GMR and H/d, Re=1500

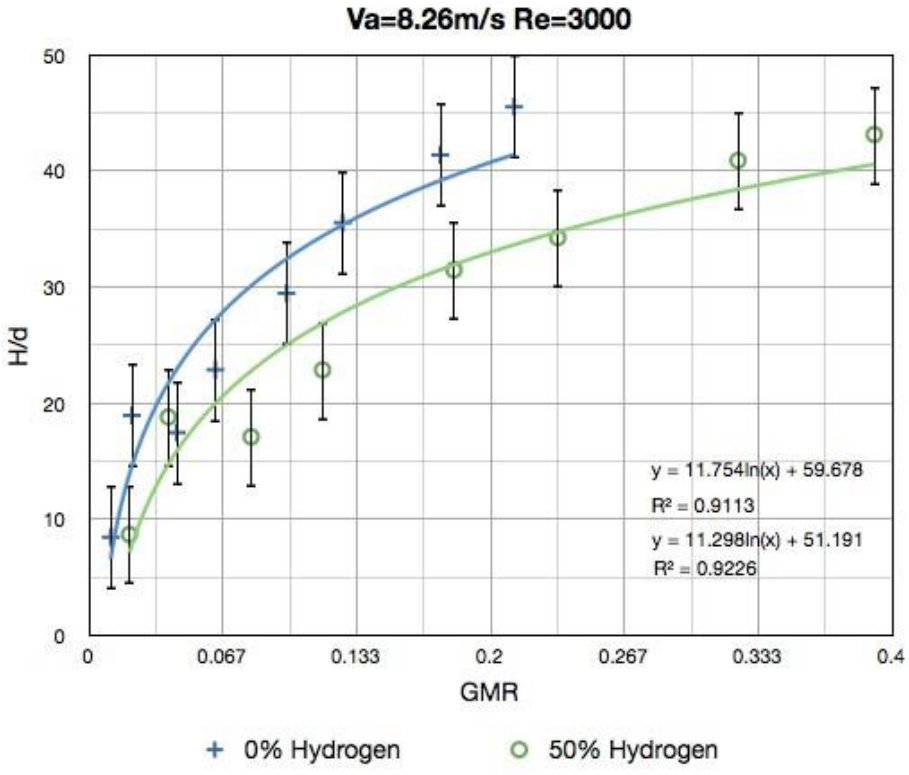

Figure 4-9 Correlation between GMR and H/d, Re=3000

Detailed flame height data were presented in Figure 4-8 and Figure 4-9. The length of flame is also called luminous flame height were defined as the distance between burner exit and the point where flame is no longer visible to human eye.[66] Flame length can provide information about the burning condition. Mahesh found that the Global momentum ratio (GMR) could correlate well with the visible flame length of turbulent LPG IDF.[106] In this study, flame length data under Re=1500 and Re=3000 were collected. Figure 4-8, Figure 4-9imply that the normalized flame height H/d also shows acceptable correlation with GMR for both LPG IDF

Use present tense when referring to tables and figures, i.e. "are presented".

✓Defines key term "luminous flame height"

Better to use present tense and a relative clause in the definition, i.e. "luminous flame height which is defined as ..."

✓Refers to table.
✓Highlights key facts on the table.
✓Explains why, e.g. "This is because..."

and H_2 LPG IDF. Table 1 demonstrates that GMR value is higher for LPG IDF than H_2 LPG IDF. It is because H_2 -LPG fuel has higher fuel velocity for the same equivalence ratio than LPG fuel. The graphs indicate that in fuel lean and stoichiometric conditions (the first 3 points in graph), flame heights of LPG IDF and H_2 -LPG IDF are very close. While for fuel rich conditions, H_2 -LPG IDFs are shorter than LPG IDFs. And the difference between flame height increases with the equivalence ratio. This phenomenon is coincident in both Re=1500 and Re=3000 situation. Correlation between GMR and flame height for four conditions are listed as:

Table 1. Correlation between GMR and Flame Height

Re=1500 LPG IDF	$\frac{H}{d} = 9.74\ln(GMR)+55.97 \quad (R^2=0.8819)$
Re=1500 H_2 -LPG IDF	$\frac{H}{d} = 8.41\ln(GMR)+45.8 \quad (R^2=0.8449)$
Re=3000 LPG IDF	$\frac{H}{d} = 11.75\ln(GMR)+59.68 \quad (R^2=0.9113)$
Re=3000 H_2 -LPG IDF	$\frac{H}{d} = 11.30\ln(GMR)+51.19 \quad (R^2=0.9226)$

Better correlations are achieved for Re=3000. Further experiment should be done to collect enough data for flame height prediction and simulation.

Give explanation why more data is required and to explain what data is required, i.e. "predictions for correlations between flame heights and GMR when Re=2500".

4.4 Conclusion

In the present study, flame stability, flame structure and flame length of LPG IDFs and 50% H_2-LPG IDFs had been studied. The following results were obtained.

1. The LPG IDFs are stable in a wide range regarding to Re =500~7000 even under fuel lean condition. Small percentage addition of hydrogen can give significantly enlargement on LPG IDFs stable range.

✓Gives clear summary of main findings in conclusion.
✓Uses bullet points to present main findings

2. Heights of LPG IDFs under fixed Reynolds number are gradually lengthened with equivalence ratio. 50% diluted LPG IDFs also appears similar structure changes under various equivalence ratio as that of LPG IDFs.

3. Heights of both LPG IDFs and H_2-LPG IDFs can correlated well with GMR under Re=1500 and Re=3000.

4. LPG IDFs are seen to be higher than H_2-LPG IDFs in fuel rich situations.

Highlight any areas study was unable to address.
Finish conclusion chapter by stating why these results/findings are interesting.

Chapter 5 Future Plan and Schedule

It can be seen from preliminary results that addition of hydrogen in LPG inverse diffusion flame significantly influence flame height. With known flame height, in the future, impinging flame temperature distribution and impinging flame pollution emission will be measured. The following tasks will be done in this project:

1. To examine flame height deviation of IDF burner burning LPG/H_2 fuel with various hydrogen percentages under a constant Equivalence Ratio. To study the flame behavior with detail under a specific equivalence ratio, under which flame height data shown special variation in preliminary result.

2. To analyze effects of hydrogen addition on centerline temperature distribution of LPG IDF under constant equivalence ration and Reynolds number to find the best heating distance of each point regarding to each hydrogen percentage.

3. To analyze effects of Reynolds number on centerline temperature distribution of LPG IDF with a fixed hydrogen addition. Temperature of points in flame centerline with a constant distance will be measured and analyzed.

4. To analyze radial temperature distribution of LPG IDF impinging to a plate with various H/D ratios. To study the effect of hydrogen addition in radial temperature distribution of LPG IDF under a constant H/D ratios.

5. To analyze effects of hydrogen addition in LPG IDF on pollution emission. Pollution emission of both open flame and impinging flame with various hydrogen percentages will be examined to see the influence of hydrogen.

✓Gives outline of research still to be done
✓Uses point form with same grammatical structures to start each point

State also limitations of the future work.