A Review Paper on Experimental and Numerical Investigation of Parametric Study on Liquid Fuel Flow Parameters: Flame Length and Diameter

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Abstract— Combustion phenomena related to Froude number and Stroukal number were investigated in diffusion flames under various gravity levels. The Froude number of the fuel was controlled by gravity level, diameter of the nozzle, and fluid flow rate. Theoretical analysis is presented to laneway flame length model based on dimensional analyses. Analysis results indicate that flame length relates to heat release rate, fire source diameter, combustible matter diffusivity, etc. Based on Similarity principle, the laneway fire experiment plant has been setup. And using a video camera, the data of the experiment is recorded. Experiment results indicate that flame length is directly proportional to heat release rate, fire source diameter and combustible matter diffusivity. And a semi-empirical formula on flame length has been got using the least-square program to fit the experimental data. The results are of importance for flame radiation calculation and fire risk analysis. Flame is an important parameter for any combustion process which is responsible for either the complete or incomplete combustion process. There are certain factors which influence the flame length and diameter such as fire source diameter or nozzle diameter, equivalence ratio, quality of fuel, heat release rate etc. Investigation of flame length and diameter is more relevance in the rational design of combustion chamber, be it for an internal engine or for a furnace. The flame represents the zone of combustion, its length is a measure of the intensity of combustion and therefore of heat release. So, this paper reviews about the flame behavior on the basis of flame length and diameter.

Key words: combustion, flame, equivalent ratio, heat release rate

I. INTRODUCTION

A. *What is combustion?*

Combustion is a subject which is truly interdisciplinary requiring the merging of knowledge in different subject of physics and chemistry, including hydro dynamics, chemical kinematics, thermodynamics, statistical physics, kinetic theory, quantum theory.

Combustion has a wide variety of uses. Chemical combustion is used for energy production in power plants, gas turbines and engines. Similar process of thermonuclear combustion is a heat source in the sun and stars. Combustion is also involved in explosions for both industrial and military purpose.[16]

Combustion is a process of heat release in exothermal reactions, which is accompanied by mass and heat transfer. Combustion can involve all phase of matter – solid, liquid, and gas.[17]

Combustion process elaborated by this equation.

$$C + O2 : CO2 - Q$$

The most distinctive feature of premixed combustion is its ability to forming self-sustained reaction wave propagating with a well-defined speed, which is either large or much less then sound velocity.

Two main regimes of combustion should be distinguished; strongly sub sonic regime, which is known as flame or deflagration, and supersonic regime of the reaction wave propagation known as detonation.

B. *Define the Flame*

A flame comes from the Latin word flame. Flame is the visible, gaseous part of a fire. It is caused by a highly exothermic reaction taking place in a thin zone. The chemical in such flames occurs within a narrow zone several micrometres thick. This combustion zone is usually called the flame front.[16]

If the combustible substances produce vapour burning process, a flame is produced. Flame is a luminous zone of rapid exothermic reaction in combustion of vapour with the formation of light and heat energy.

Flame produced will be at a high temperature within a narrow zone or region flame.

C. *Types of Flame*

Flames may be of different types depending on the extent of mixing of fuel and oxidizer or how the mixture reach the reaction zone. The flow patterns in the reaction vessel, such as well mixed and plug flows are the major tools to classify the flames in different types. The flame may be turbulent in a premixed flame the fuel and the oxidant are molecularly mixed before the combustion process takes place. The flames are mainly classified as: (i) Non -Premixed or Diffusion Flames and (ii) Premixed flames. These flames may be both laminar or turbulent types.

D. *Non –premixed flame*

In many combustion process the fuel and air are often initially not mixed. The fuel and oxidizer are kept on either side of the reaction zone. The resultant flame is termed as diffusion flame.

The diffusion flame occur at the interface of gaseous fuel and air with the progress of time as the flame propagates, the reaction zone increase.

The non premixed flame stoichometric condition optimize the flame temperature with a definite air fuel ratio.

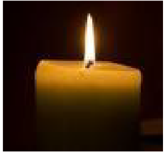

Fig. 1: diffusion flame [16]

E. Premixed Flame

In this type, the fuel and oxidizer gas are mixed together as ambient condition before delivered to flame front. It is heated by conduction and radiation. Gradually the mixture is sufficiently heated at the chemical reaction take place.

The turbulent premixed flame plays important role in the various practical application because it increase with reduce emissions.

Turbulence actually results in reduction flame length.

The turbulence can be increase by recirculation of fuel air mixture.

Fig. 2: premixed flame[16]

F. Flammable (Explosive) Limits

When vapors of a flammable or combustible liquid are mixed with air in the proper proportions in the presence of a source of ignition, rapid combustion or an explosion can occur. The proper proportion is called the flammable range and is also often referred to as the explosive range. The flammable range includes all concentrations of flammable vapor or gas in air, in which a flash will occur or a flame will travel if the mixture is ignited. There is a minimum concentration of vapor or gas in air below which propagation of flame does not occur on contact with a source of ignition. There is also a maximum proportion of vapor in air above which propagation of flame does not occur. These boundary-line mixtures of vapor with air are known as the lower and upper flammable limits (LFL or UFL) respectively, and they are usually expressed in terms of percentage by volume of vapor in air.

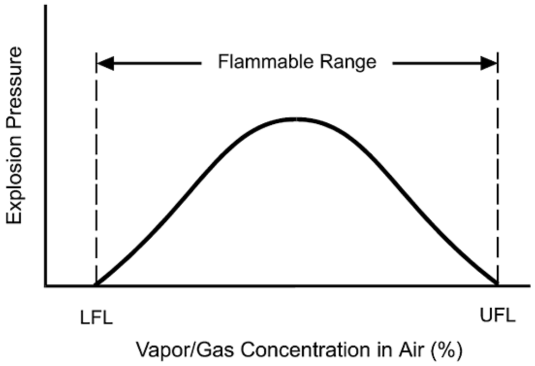

Fig. 3: [17]

G. Lower Explosive Limits

A vapor/air mixture below the lower flammable limit is too "lean" to burn or explode is known as lower explosive limits. It also defined as minimum percentage of fuel by volume in the mixture.

H. Upper Explosive Limits

A vapor/air mixture above the upper flammable limit is too "rich" to burn or explode is known as upper explosive limits. It also defined as maximum percentage of fuel by volume in the mixture.

I. Flammability Range

The flammability range is defernciate by the upper and lower flammability limits.

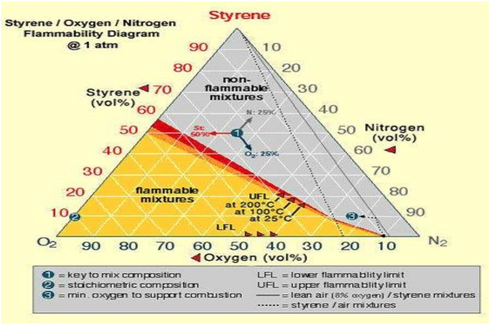

Fig. 4: [17]

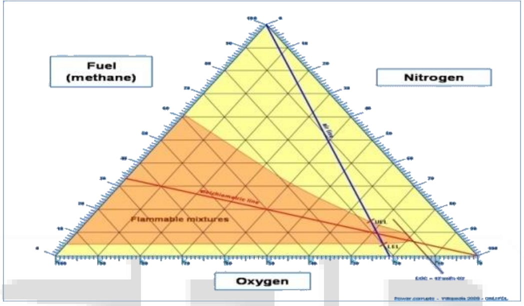

Fig. 5: [17]

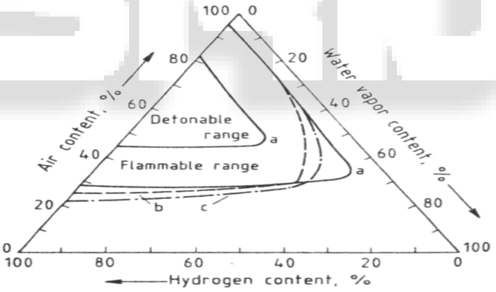

Fig. 6 : [16]

J. Examples of flammability limits

Gas	Flammability Limits			
	% in air		%in oxygen	
	LEL	UEL	LEL	UEL
Hydrogen	4.1	74.2	4.0	94.0
CO	12.5	74.2	15.5	94.0
Methane	5.3	14.0	5.1	61.0
Ethane	3.2	12.5	3.0	66.0
Propane	2.4	9.5	2.3	55.0
Butane	1.9	8.4	1.8	48.0
Acethylene	2.5	80.0	2.5	89.4
Benzene	1.41	6.75	2.6	30.0
Methanol	6.72	36.5	—	—
Ethanol	3.28	18.95		

II. RESEARCH WORK DONE AREA

A. Introduction

Experimental and Numerical Study of a Water Spray in the wake of an axis symmetric Bluff body, X.Q.Chen reviewed in his work that an experimental and numerical study was made of a water spray issuing into a recirculating flow behind a bluff body disk mounted in a nozzle. A two-component laser-Doppler/phase-Doppler an zoometry system was used to characterize the mean and turbulent dispersed phase. The numerical prediction of the hollow-core spray was based on an Eulerian-Lagrangian stochastic hybrid model. The continuous gas flow field was predicted using a differential Reynolds stress transport model whereas the particulate droplet flow field was predicted using an improved Lagrangian stochastic dispersion model. Comparison of numerical predictions and experimental measurements was carried out for droplet mean and fluctuating velocities, number mean diameters, and mass fluxes. An experimental and numerical study was conducted of a water spray in the near wake of a disk air flow. To better account for normal stress anisotropy, the gas flow field was predicted using the Reynolds stress transport model instead of two-scale turbulence models. It was found that the dispersion of droplets is strongly influenced by the presence of flow recirculation behind the disk. The detailed comparison of the numerical predictions with the experimental measurements also demonstrates the ability of the Eulerian-Lagrangian stochastic model to predict droplet dispersion in strongly recirculating gas flows.

An experimental study of the flame propagation and combustion characteristics of LPG fuel, Kihyung Lee investigates the flame propagation and combustion characteristics of LPG(Liquefied Petroleum Gas) fuel. To clarify the combustion process of the heavy duty LPG engine, the flame propagation and combustion characteristics were investigated using a CVCC(constant volume combustion chamber) and a port injection type heavy duty LPLi (Liquefied Petroleum Liquid injection) engine system. According to the CVCC and heavy duty LPLi engine experimental results, the flame propagation reached a maximum speed at the stoichiometric equivalence ratio, regardless of operating conditions, and the effect of the equivalence ratio on both flame propagation and combustion characteristics was greater than that of ambient conditions. An experimental study has been conducted on the measurement for LPG flame propagation speed by using an optical method and the combustion characteristics of an LPG fuel engine. The influence of the initial conditions on the flame propagation speed and the combustion characteristics were investigated. The results of this investigation have led us to the following conclusions.

- The effect of the equivalence ratio on combustion duration was rapidly increased in the lean mixture region. This result indicates that the combustion worsened in the lean equivalence ratio region.
- The flame propagation speed of LPG fuel is increased as initial unburned mixture temperature increases and as initial unburned mixture pressure decreases.
- Both the combustion duration of a laminar flame in a constant volume combustion chamber and the combustion duration of a turbulent flame in a real LPLi engine are proportional to the initial unburned mixture pressure.

Experimental Investigation of noise generated by large Turbulent Diffusion Flames, C. Bertarand shown in his work that experimental studies on noise generation processes in flames have, to date, been performed mainly on premixed flames and small size burners. For such systems theoretical laws have been derived to account for the fundamental parameters governing the combustion noise. The following conclusions may be drawn from this study:

- It is valid to use a monopole source theory to describe the emission of combustion noise from large turbulent diffusion flames.
- The results indicate a variation of the, sound power with the burner throat diameter to the 5.6 power and the average gas flow velocity to the 2.8 power.
- Existing scaling laws do not account for the effect of preheat on combustion noise, unless the turbulent characteristics of the flame are strongly dependent on this parameter.
- The peak frequency of the combustion noise appears to depend mainly on the turbulent
- mixing characteristics of the flame.

Equivalence ratio gradient effects on flame front topology in a stratified iso-octane/air turbulent V Flame, P.C.Vena is reviewed from his work that the effect of partial premixing on the local topology of globally stoichiometric flames was considered using a novel burner that permits controlled transverse variation of equivalence ratio along a continuous stratified flame front. The effects of large-scale gradients in equivalence ratio on locally stoichiometric turbulent iso-octane/air V-flames were studied using a novel stratified burner capable of producing transverse variations in mixture strength. PLIF images of OH, CH2O, and 3-pentanone were acquired for five flame conditions to evaluate variations in flame front topology and to quantify these differences through flame surface density and curvature measurements.

Critical to interpreting the data was the technique of using variable width interrogation windows to fix the range of equivalence ratios being considered when comparing flames subjected to different mixture gradients. Gradients in equivalence ratio had a dramatic effect on flame wrinkling, leading to enhanced corrugation of the flame front for the strongest gradients. However, the effect of increased flame surface density was more modest, balanced in part by an increase in flame brush thickness, and ultimately by a decrease in flame length. Perhaps surprisingly, variations in curvature distribution were nearly negligible and not nearly as prominent as those reported in the literature for lean methane/ air V-flames. This suggests that although gradients in mixture strength may alter the overall structure and instantaneous behavior of globally stoichiometric combustion systems, their effect on the topology of locally stoichiometric flames may be limited, suggesting that premixed models for turbulent combustion should be adequate for simulating near stoichiometric, stratified flames.

A study of Turbulent Diffusion Flames Formed by Planar Fuel Injection in to the wake formation region of slender square cylinder, P.Koutmos**,** The present work describes the experimental and numerical investigation of turbulent reacting wake flows formed by planar fuel-jet injection into the wake formation region of a confined two-dimensional square cylinder Comparisons between simulations and measurements indicated the ability of the model to reproduce the experimentally observed variations in the mean and the turbulent fields for a range of FAVR values and two Reynolds numbers. The method resolved important large-scale features of the isothermal and reacting flows, thus allowing a more effective exploitation of the combustion model and clearly out performed. Measurements of turbulent velocities, temperatures, and statistics have been obtained to document diffusion flames formed by two-dimensional fuel injection into the wake of a square cylinder. Comparisons between the model and measurements underlined its ability to reproduce most measured trends. The present method proved superior to standard *k-e* procedures and coped well under conditions of high- or low-level unsteadiness. With improvements to the combustion model, it may provide a good basis for the characterization of burner stability. This procedure may also be necessary to recover large-scale structure effects in bluff body flames.

Experimental investigation of the nonlinear response of turbulent premixed flames to imposed inlet velocity oscillations, R. Balachandran review in his article this paper describes an experimental investigation of acoustically forced lean premixed turbulent bluff-body stabilized flames in an enclosure short enough so that no coupling of the combustor downstream acoustics occurred for the frequencies studied here, which allows an unambiguous examination of the flame response to inlet velocity.

Fluctuations. The theoretical description of combustion-induced oscillations, a problem of significant theoretical and practical importance, necessitates a quantification of the response of the flame to the unsteady inlet velocity and/or equivalence ratio caused by the pressure waves that may be set up in the combustor Detailed.

Experimental investigations were performed

To measure the response of lean premixed turbulent bluff-body stabilized flames to imposed inlet velocity perturbations through transfer function measurements. Special attention was given to the amplitude dependence of the transfer function, since the flame response to high amplitudes is relevant to the emergence of limit-cycle combustion-induced oscillations.

Diffusion Flames and Their Flickering Motions Related with Froude Numbers under Various Gravity Levels, H.Sato reviewed the behavior of gas-jet diffusion flames has been studied theoretically and experimentally by many researchers. He predicted the concentration profiles of fuel in a flame and the flame shape by solving a diffusion equation for a coaxial laminar fuel jet. The length of a laminar flame by using a simple model, in which the diffusion rate and flow rate of fuel were equated. Showed that the calculated flame length was in qualitatively good agreement with experimental data, and confirmed that the experimental results were consistent with the theoretical model. He conclude that For jet diffusion flames, flame length and flickering phenomena were investigated experimentally by controlling the gravity level. The following results were obtained: For laminar diffusion flames, flame length decreased and the blue flame height increased with an increase in gravity level. The gravity effect on flame length was independent of the fuel density even for gravity levels ranging from *G* 5 1 to 14.

Lift-off of jet diffusion flame in sub-atmospheric pressures: An experimental investigation and interpretation based on laminar flame speed, Qiang Wang introduced this paper reports an experimental investigation of lift-off behavior of turbulent jet diffusion flames in sub-atmospheric pressures. The dependency of lift-off height on pressure is interpreted based on laminar flame speed. Major findings are:

- The flame lift-off height is higher in the sub-atmospheric pressures than that in normal pressure.
- The variation of lift-off height with fuel velocity in sub atmospheric pressures can be still well characterized by the Kalghatgi model based on the premixed flame turbulence intensity theory. However, the lift-off height increases linearly faster with fuel velocity when the ambient pressure is lower.

Initiation and formation of the corrugated structure leading to the self-turbulization of downward propagating flames in a combustion tube with external laser absorption, Yoshikazu Taniyama reviewed in his paper investigates the process of the transition from the convex disturbed flame structure to a corrugated flame, which has not been observed in detail previously. The experiments employed a CO2 laser irradiation method with a downward propagating flame in a tube. This method successfully controlled the deformation scale by changing the laser power or the exposure time. Increasing the initial disturbance to some extent with increases in these laser parameters made it possible to observe the flame behavior in the transition to turbulence via the clearly corrugated flame. Experiments with low laminar flame speed mixtures(mixture B) allowed to observe the process of the transition in great detail. From the precise observations, it was established that the concave structure appears just before the appearance of the corrugated flame in conditions where the flame results in turbulent motion. A physical mechanism of the transition is proposed by taking into account the interaction between acoustic wave and deformed flame. The pulsating Froude number, which is defined in this paper, can characterize the transition domain of the corrugated flame followed by self-turbulization and has a critical value around 175.

The burning rate's effect on the flame length of weak fire whirls, Kazunori Kuwana reviewed in this paper This paper aims at establishing the relationship between the visible flame length of weak fire whirls and the burning rate based on our previous study for dependence of the burning rate on flow circulation. The effect of the burning rate on the visibly determined flame length was studied for methane burner flames and ethanol pool fires with and without weak spin (which we call weak fire whirl). CFD simulations were conducted to successfully explain the experimentally observed effect of fuel evaporation rate on the flame length. Based on experimental observations and CFD calculations, two different analytical models were developed to predict the flame height of weak fire whirl.

Predictive analysis of combined burner parameter effects on oxy-fuel flames, T. Boushaki evlauted The combined effect of burner parameters on the studied flame characteristics suggests the following correlations:

- Lift-off height of flame is dependent on all burner parameter interactions in the sense that larger heights.
- The horizontal position of the flame lift-off is dependent on a unique burner parameter interaction. If we exclude the former interaction term, a simple linear correlation is sufficient to represent truly the correlations.
- The flame length is predicted to depend positively on all parameters.

Simultaneous instantaneous measurements of soot volume fraction, primary particle diameter, and aggregate size in turbulent buoyant diffusion flames. Brian M. Crosland present this paper All measured parameters were shown to have self-similar behavior when axial location was normalized by Lf, with two restrictions: (1) the two cases that are closest to becoming laminar flames exhibit significantly higher fv and lower intermittency than the remaining flames, and (2) the cases where the laminar-to-turbulent transition occurs due to shear exhibit lower fv on centerline and reach peak fv later in the flame.

Experiment Research on Flame Length Model of Laneway Fire, CHU Yan-yan present and conclude that Research on the impact of some factors such as fire source, velocity, etc. to flame length has been developed. Through theoretical analysis and experiment study, it is shown that average flame length is always proportionate to heat release rate of fire source, velocity and fire source diameter but it is independent in velocity and fire source diameter when the fire develops rapidly. And a semi-empirical formula on flame length has been got using the least square program to fit the experimental data. It can help us to calculate radiation intensity of fire in actual fire disaster and risk assess of fire disaster.

B. *New technology and development*

Design and experimental investigation of 60 degree pressure swirl for penetration length and cone angel at different pressure, Kamlesh Chaudhari reviewed in his paper and conclude The design of pressure swirl nozzle is carried out at injection pressure of 18 bar. The experiments of penetration length and spray cone angle are carried out with the injection pressure from 3 bar to 18 bar with the step of 3 bar. Experiments suggest that at 3 bar, the penetration length and spray cone angle are minimum and also that at 3 bar liquid film is not breaking into small droplets. From 3 bar to 18 bar as injection pressure increases the cone angle also increases and penetration length decreases but except from 6 bar to 12 bar penetration length increases due to liquid film starts breaking in small droplets. So the maximum angle achieved is nearly 60. and minimum penetration length is achieved nearly 62mm at designed injection pressure of 18 bars. It can be concluded that the designed pressure swirl atomizer operating at 18 bar pressure can be used for Annular Type Gas Turbine Combustion Chamber using Kerosene Type Fuel. As the part of future work the same pressure swirl atomizer experimental investigation will be carried out for effect of injection pressure on flame length with different liquid fuels.

Experimental approach in measuring flame spread rate, Nehal Kamlesh Dalal concluded in his thesis The goal of this project was to improve the flame tracker apparatus and verify the flame spread rate results. Three different methods of flame spread rate were compared.

- First method was the flame tracker method. This method was used to obtain the flame spread rate for both spreading as well as stationary flame.
- Second method was the Spotlight method. Both the stationary as well as spreading flame spread rate were determined using this method.
- Third method was the flame tracker method with two thermocouples. The stationary flame spread rate data was obtained using this method.

So far the results obtained from all the above methods were repeatable and consistent. While the flame spread rate obtained from the Spotlight method was lower than the thermocouple method. The reason for this variation could be the region selected for the Spotlight method was the leading edge of the flame, while the thermocouple tracks the center of the flame. The stationary flame spread data obtained from the flame tracker method with two thermocouples was smooth and consistent compared to the single thermocouple flame tracker method. The limitations of this experiment recommend for future work. A new flame tracker apparatus will be built at the computational thermodynamics laboratory. This flame tracker apparatus will be longer compare to the existing setup. Further, the flame spread rate experiment will be repeated using the above mentioned methods.

III. CONCLUSION

From the review of literature it analyzed that by experimentally and theoretically investigated the behavior of the flame length, flame lift off height, flame velocity etc., it can be increased or decreased by varying the different size of nozzle diameter or fire source diameter, different quality of fuel, different equivalence ratio etc. and different findings are concluded. Flame length is always proportionate to heat release rate of fire source, velocity and fire source diameter but it is independent in velocity and fire source diameter when the fire develops rapidly. The flame length increases with fuel jet velocity and remains almost invariant at higher Froude number which happens to be towards the flame blow-off. The flame length does not depend on fluid dynamics but only on fuel characteristics such as fuel type, pool diameter and burning rate. The flame length generally decreased with increasing primary air-fuel mass flow rate ratio, axial distance between combustor exit, burner tube diameter and entrance of burner tube, fuel-air pressure ratio and degree of swirling represented by air tangential angular speed.

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