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Application of Mobile Technology in Waste Collection

Oluleke Bamodu *indomitablejnr@engineer.com*
Faculty of Computing, Engineering and Sciences
Staffordshire University
Stoke-on-Trent, ST4 2DE, United Kingdom

Abstract

One of the stages in waste management is waste collection, and as global waste generation continue to increase year after year, the need for better and more efficient waste disposal, collection and management methods become more evident and urgent. Automated forms of waste collection are very expensive and far from being affordable in many low income communities, especially in the so called developing countries. To solve this dilemma, mobile technologies are considered for use in waste collection as a prospective means of improving waste management.
This paper is an attempt to proffer a generic but yet concrete and efficient solution to the problems associated with waste collection via the application of mobile technologies, firstly, by tackling the problems individually in form of subsystems and then, through integration of the subsystems together.

Keywords: Mobile Technology, Waste Collection, Waste Management, RFID, Tracking.

1. INTRODUCTION

One of the problems that have plagued mankind for a long time is improper waste disposal. Despite many initiatives taken to resolve the problems associated with wastes, waste generation and accumulation has continued to increase yearly.

Municipal Solid Waste (MSW), garbage as it is known in the US or refuse as it is called in the UK, which comprises of all sorts of discarded 'everyday' items like left-over food, containers, papers, faulty and unrepairable electronic appliances from households, institutions and industrial sources. In the US alone, there is documented record of unprecedented waste disposal and accumulation in the last half decade, and this is attributed partly to increase in population and waste per capita generation [1, 2].

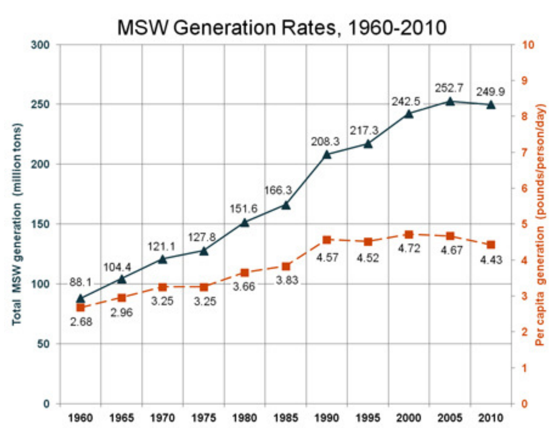

FIGURE 1: MSW Generation Rates, 1960-2010 (Source: Environmental Protection Agency).

The growth rate of waste in China over the last 20 years has exceeded that of other nations, in fact it is projected that China would produce twice as much waste as the USA by 2030, with over 1.5 billion tons of waste generated in urban areas alone yearly [3, 4]. The situation in the UK and EU is not any different too [5].

To reduce the effect of waste production on the environment, health, and quality of life (as they are all interconnected), different forms of waste management are being proposed.

1.1 Definition of Waste Management

As defined in the ‘Waste framework Directive 75/442/EEC’, “Waste management is the collection, transportation, recovering and disposal of waste along with the supervision of such operations and after-care of the disposal sites,” [6].

Although definitions of waste management and the management practices may differ between rural and urban areas, residual and industrial regions, as well as between the so called developing and developed countries, they all include the component of waste collection which is an important part of the management process [7].

Waste collection is the premier phase of waste management, involving the collection and transferring or transporting of waste from the site of generation to the treatment or disposal area. Typically during waste collection, the waste is usually put in the allocated container or bin on the collection day, then the waste workers move from house to house collecting the waste bins and emptying them into their waste collection vehicle or dustcart.

1.2 Waste Collection Problems

The traditional waste collection method had always been sufficient for collecting waste, but with continuous increase in the amount of waste generated and the number of people needing waste collection services this method has lost its efficiency and become rather tedious to manage. Some of the areas where problems have been encountered include report filling, clients and billing management, route scheduling and uncollected waste (possibly because the waste was not ready at the collection time or probably because it was unpicked by the waste workers). These problems and others have inspired other means of collection, such as Automated Vacuum Collection System or Pneumatic Refuse Collection System.

Although the automated vacuum collection system is fully automated, requires less manpower, provides more favorable working condition for the refuse workers and is faster, it requires a very huge capital to procure, install and maintain [8], leaving it out of option for most resource-limited countries, small regions or areas and old communities.

2. OPPORTUNITY

With the almost unaffordable high cost associated with the Pneumatic Refuse Collection System, many communities are unwilling to or just cannot afford to adopt such system, thus, leaving only the option of adapting the traditional method of collection or upgrading it to meet up to the current challenges affecting it.

The present waste-associated situation has led to the application of IT and mobile technologies to help solve some of the problems affecting typical waste management. An example of such applications is ‘Fleetlink’ which is an in-vehicle telemetry-based product used for tracking refuse trucks [9, 10]. Another example is ‘Recycle T’ from a town in Madrid. The ‘Recycle T’ is a mobile technology solution developed by Everis and Orange to solve waste management and collection problems using Near Field Communication (NFC) [11].

Harrow, a Borough in Northwest London also uses mobile technologies in the form of mobile computers with fleet management and route optimization software to improve waste collection services.

3. PROPOSED APPROACH

Looking at the vast number of mobile technologies available, the speed of development and the convenience their application is bringing to many different fields, coupled with the success reports of several solved refuse management problems, the world of possibility and prospective efficacy of the mobile technology will be further explored. This is intended to be achieved in this paper by starting with a comparative analysis of their strengths and weaknesses and concluded by providing a generic solution to waste collection.

The proposed approach entails creating subsystems, with each subsystem solving a particular business process area for each subsystem, the available mobile choices shall be listed out and compared against each other to choose the best suited option, then the subsystems shall be integrated together to present the general waste collection solution.

4. MOBILE TECHNOLOGY

Also referred to as mobile communication technology, mobile technology includes various types of technologies such as GSM, GPRS, wireless LAN, satellite communications and devices such as cellular phones, Global Positioning Systems (GPS), Bluetooth and the list is endless.

When mobile technology is mention, one term that instantly comes to mind is wireless technology. For a system to be mobile, it most probably must be wireless, but wireless systems are not necessarily mobile. For example, a cellular phone (mobile) can handover between different networks when connection is weak (roaming), but the cordless phone (wireless) has to be within a stipulated coverage area to operate. Cordless phones usually are fixed phone with fixed area/region codes, but without the connecting wire, thus offering some restricted form of mobility [12].

In this paper, mobile and wireless technologies shall be used together as part of the subsystems to provide the final integrated system solution to the waste collection problem.

5. SYSTEM DESIGN APPROACH

5.1 Dustcart Tracking/ Fleet Management

A couple of methods can be used in tracking or attaining the positioning of a vehicle (dustcart in our case). Possible methods include satellite tracking system, mobile or cellular based tracking system and Radio Frequency Identification (RFID) tracking system.

5.1.1 Cellular Tracking System: Cellular tracking systems work using triangulation calculation based on Cell of Origin, Time of Arrival method among many criteria, and can be used to track dustcarts, but the accuracy it offers is low (hundreds of meters), which makes it unsuitable for use in this subsystem.

5.1.2 RFID Tracking System: With RFIDs, it is possible to create a tracking system for the dustcarts. To accomplish this, RFID tags can be installed at specific distance from one another, for example, every 200 meters while the dustcart has a reader installed on it. Every time the dustcart passes by the tags, the reader picks up the signal codes and sends it to the monitoring system at the central office. To know where a vehicle is, the last code sent in is checked against the database which contains the position detail of each tag.

Some of the advantages of this method include, that it can be created cheaply; and it is also easy to track the nearest dustcart to a particular location (for redeploying). The disadvantages of this system however is the difficulty of maintenance and the a requirement that tags must be within the range where they can be read by the scanner on the passing dustcart, it is also possible for the scanner to pick up and send unnecessary codes from other similar tags within range creating error in the database. Another limitation of this system is that of the accuracy of location provided, which is dependent on the amount of tags used and the distance between two tags. The shorter the distance between the tags, the higher the accuracy provided but the more the amount of tags needed. Also to make this system user friendly, good graphical management software would have to be developed.

5.1.3 GPS Tracking System: Tracking system based on GPS can be used in knowing the position of a dustcart at all time. To achieve this, a GPS tracking device is installed on the dustcart, and the information about its location made available to the central office. To transfer this information, it is possible to use satellite transfer method or to transfer through a mobile network. For this subsystem, the mobile network transfer method shall be used because it is less expensive than the satellite transfer method, and mobile network is readily available, without need for installing any expensive components or dealing with complex maintenance problems [13].

5.2 Route Designing

This subsystem is depends on the subsystem above, and as such can be best accomplished together with it. From the tracking systems discussed; based on the information gathered, some parameters can be obtained about the vehicle such as speed, direction and location. With this information, the duration it is going to take the dustcart to arrive at a particular location can be predicted. To be able to make accurate predictions, the parameters need to be fed real-time to a management system (software) that makes calculation (prediction) based on them. This requirement of real-time feeding of parameters and the lack of direction (heading) which is a major parameter for the calculation makes the RFID not a very suitable solution for the two subsystems, so the GPS tracking system shall be used along with graphical software. To design routes, earlier routes pattern can be stored in a database and used to identify area that continually encounter problem which should be avoided when designing and optimizing new routes.

5.3 Communication

As it is sometimes necessary for the dustcart drivers to be contacted for redeployment to some other location for other pickups, a means of communication is needed.

Possible options for such subsystem are Voice (GSM, Satellite) and Data (GPRS, Satellite). Considering driving rules and safety, and the fact that detailed information which should be jotted down might need to be passed across, the voice option is eliminated.

For message or data communication, the pager, GPRS or satellite devices can be used, but since the pager is a one way communication device and cannot allow the drivers to communicate back with the central office to accept or decline new tasks, it is not seen as a suitable option. Comparing the cost for the use of GPRS and Satellite data communication, the GPRS is considered a more suitable option and shall be used in this subsystem.

5.4 Staff Checking

Generally, tracking of staffs can be achieved with the use of RFID tags and GPS devices. Such system is usually used by supermarkets to track workers in the workplace, but has received a lot of privacy related complaint [14]. Going by the amount of related privacy issues with the RFID plus GPS device system and the fact that only the rest of the worker is required, two simple systems are looked into for this subsystem.

The first system uses a smart card which is required to be swipe through a scanner at the beginning of the work (sign-in) and at the end of the day work (sign-off). The time after the sign-off and before the next sign-in is considered as rest period.

The benefit of this system is that it is simple and does not interfere with the workers' privacy, however, with this system, it is impossible to know if a worker actually rested before next sign-in.

The second system, utilizes a motion sensor device, possibly in the form of a wristband, a tag or a pocket device which the workers are required to carry always. The device records the amount of inactive period and transfers this data wirelessly by bluetooth when the worker resumes for work.

For the system to serve its purpose, the workers should be required to honestly carry the device with them at all time and no more information than what is required should be collected to avoid invasion on workers privacy.

5.5 Bin Tracking and Weight Calculation

Tracking of bin and weight calculation: To calculate the weight of the bin, different approaches can be used; one of such is that of using the volume of the known type of waste to calculate the overall weight [15]. This method, would although not need any new equipments, but the process is slow and the efficiency is low as it would require each bin to be opened and the waste types listed out. Another possible option will be to redesign the bin to carry on board electronic scale (weighing equipment), which can allow the weight to be produce whenever required. But this option requires supply of new bin or adjustments to be made to the old ones. Considering associated cost, this option is dropped.

One more option and probably the best with regards to cost and efficiency will be to install an electronic weighing scale or system on the dustcart. This can be used in weighing the bin before it is emptied into the dustcart. To get the waste weight, the empty bin weight (mostly standard weight) is subtracted automatically from the total bin weight (empty bin plus waste).
To track the emptied bin, RFID tags (passive type) can be installed on every bin while the reader or scanner is installed along side with the weighing system (scale) on the dustcart. When the bin is weighed in the earlier stage, it is also scanned and the weight value is recorded along with the tag code. With this information, the amount of refuse collected from each house can be known (and used for billing later), also, whether or not a household bin was collected or not can be known and proved by this subsystem as codes of collected bins would have been recorded.

The limitation of this system is that proof of reason for the missed bin is not available (whether it was left out by the refuse workers or it was not available for collection from the household).

5.6 Real Time Central/ Control Office

Real Time central/control office: For feeding real time data to the central/control office for management reporting, the following options are considered.

5.6.1 Satellite communication: One of the application areas of satellite communication is data transfer. After data have been gathered by the other subsystems, they can be relayed back to control office by satellite data transfer; although the associated cost of this option is high, and the latency period (time delay) is high (more than 500ms for geostationary) and as such may not meet the real time data transfer requirement [16].

5.6.2 Mobile Broadband: Mobile broadband in other words are wireless internet access through cellular phones. The possible network collections that could be used are GPRS, 3G, LTE, WiMax and others. For this subsystem, the GPRS based wireless internet access will be used to transmit data to the back office because of the availability of mobile networks supporting the GPRS.

Although data transmission rate of GPRS is not as good as that of the satellite, 3G or LTE, the amount of data needed to be transmitted to the control office by individual dustcart is not very large, also the charges associated with GPRS is much lower than the other options and the latency time is not as high as that for satellite transmission.

5.7 Overall System
Based on the choices in the subsystems, the general waste collection system is built up of the below components.

Business Process Area	Mobile Technologies	Devices
Dustcart Tracking	Mobile Network Based GPS Tracking	GPS tracking device
Time Prediction and Route Designing	Mobile Network Based GPS Tracking	GPS tracking device and Optimization Software
Communication with Vehicle	GPRS	Messaging Device eg. Smart phone
Worker Monitoring	Bluetooth	Bluetooth enabled Motion Sensor
Bin Tracking and Weighing	RFID	RFID tags, scanner, electronic scale, smart phone
Real Time Data Transmission	Mobile Broadband by GPRS	Smart phone
Back Office Requirement		Computer Systems, Management Software, (Database, Route mapping, prediction and optimization software, GPS tracking viewer, communication and messaging software, monitoring software)

TABLE 1: System Components.

The overall system will make use of the above components with computer systems and management software installed at the control office.

6. FUTURE RESEARCH
This paper has researched into how mobile technologies can be used in solving different aspects of waste collection on a small scale, although it is possible for the system to be commercialized. Aspects that will need attention are the software and also the security issues and are currently been researched. Security measures will have to be taken in the storage of data (possibly having backups and guarding against attacks such as virus etc); also, information sent through wireless internet will need to be encrypted.

Developing countries that would benefit much from such a system might be limited by the reliability of mobile network services in those areas. These related issues are planned to be solved using cloud computing, which should provide a breakthrough in waste collection and find further applications in other waste management areas [17, 18].

7. CONCLUSION
In this paper, mobile technologies have been studies and used in conceptually designing a system solution to waste collection which is an important step in waste management.

In creating the system, a break down method was used; where individual problems were solved using subsystems which are then integrated together. In each subsystem, the strength and weakness of available mobile options were compared, and a suitable option chosen.

This system can be commercialized and could be very helpful in developing countries, though security issues, data collection and processing, and network connections along with signal issues would have to be further considered.

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9. APPENDICES

Case Study: Refuse Collection – Silverdale Waste

Silverdale Waste provides refuse collection services for the North Cumberland Waste Authority (NCWA). Silverdale have a fleet of 20 dustcarts (refuse collection vehicles) and only collect household refuse in the North Cumberland district which represents a 40km geographical area. The district is divided into 5 parts and each part has a dedicated refuse collection day. Two stations are operated with 10 carts each, one in the North of the district and one in the South. On average 8 carts are available for use each week; 2 being serviced or in the repair shop.

All systems are non-mobile at present with the only IT presence being a PC at each station which is used by the station manager for excel spreadsheets, email and a rudimentary database of historical collection records. There is no IT equipment on the dustcarts and the refuse workers use no IT equipment. Every month the station manager has the difficult task of providing performance statistics to the NCWA.

The household bins are typical wheelie bin designs.

Every week a house-holders bin will be collected by the refuse worker, emptied into the dustcart and then returned empty to the household. This is called a route.

The management at Silverdale Waste is conscious that the firm is not IT enabled and they have issues which they would like to see addressed. They have asked Cumberland Business Link to provide a consultant to review their business and how IT can help in the following business process areas:

Business Process Areas:

• Tracking the position of its fleet.

• Predicting how long a route will be and scheduling the use of dustcarts by designing routes.

• Redirect vehicles when necessary by being able to communicate with them.

• Making sure the company complies with the working time directive by enabling a check that each worker has had the statutory amount of rest.

• Calculations of bin weights and tracking of bins emptied.

• How real time data can be fed to back office systems for management reporting.

An Experimental Study of the Effect of Partial Premixing Level on the Interaction between the Flame Kernel and Flow Field

A. M. Elbaz *ayman_alhagrasy@m-eng.helwan.edu.eg*
Faculty of Engineering/Mechanical Power Engineering Department,
Helwan University
Cairo, 11718, Egypt

Mohy Mansour *mansour@niles.edu.eg*
Faculty of Engineering/Mechanical Power Engineering Department,
Cairo University
Cairo, Egypt

Khaled A. Elsayed *kelsayed@niles.edu.eg*
Faculty of Science/Physics Department,
Cairo University
Cairo, Egypt

Diaaeldin Mohamed *diaa.eldin@aucegypt.edu*
Faculty of Engineering/Mechanical Power Engineering Department,
Cairo University
Cairo, Egypt

Abstract

Flame kernels in spark-ignited combustion systems dominate the flame propagation and combustion stability, performance and emissions. The aim of the present work is to investigate the flow field associated with flame kernel propagation history in partial premixing natural gas turbulent flames. The main parameters under investigation are the degree of partial premixing and jet velocity. Three different degrees of partial premixing and five values of jet velocity between10 and 20 m/s have been selected for the present work at an equivalence ratio of 2. The mean flow field and turbulence intensity are measured using two-dimensional Planar Imaging Velocimetry (PIV). A pulsed Nd: YAG laser is used for flame ignition. The turbulent flow field is captured after the ignition at several time intervals between, 150, and 2500 µs after ignition. The results show that the flame kernel does not show any significant effect on the scale of mean flow field. On the other hand, the flame kernel increases the global turbulence intensity in flames in comparison with the isothermal cases. The flame kernel propagation is associated with a steep increase in the centerline turbulence intensity of the jet flow. An increase in the degree of partial premixing and/or the jet velocity increases the centerline turbulence intensity accompanying the flame kernel propagation. This leads to break-up of the degree of partial premixing of the flame structure, and hence, decreased flame stability. Also, the higher the degree of partial premixing or the higher the jet velocity leads to more rapid flame kernel extinction. The results show that the rate of flame kernel propagation is very fast at the early stage of the kernel propagation up to the first 300 µs and then it slows down afterwards.

Keywords: Flame Kernel, Partial Premixed Flame, PIV, Flow Field.

1. INTRODUCTION

The early phase of combustion in spark ignited combustion systems affects the flame propagation and stability, and hence the performance, of the combustion process and the system efficiency. The developing flame kernel represents this phase and is affected by many parameters, such as spark energy, rate of energy release, turbulent flow field and the fuel/ air mixing. Previous studies have shown that variations in the initial growth of the flame kernel contribute significantly to cycle-to-cycle variation in engine performance and emissions [1]. The flame kernel has attracted many experimental research groups [2, 3-5] and DNS research groups [4, 6-9] interested in studying flame kernel evolution in turbulent environmental and the main factors that control its characteristics and propagation. Many parameters have been investigated to study their effects on the flame kernel characteristics and propagation, e.g., flame shape, wrinkling and curvature. In the following section a brief review of these studies and their findings are presented and discussed.

Katta et al. [10] reported an experimental and numerical investigation using a unique counter flow diffusion flame with an embedded vortex generator. This study was to understand the local quenching process associated with the vortex-flame interaction in methane diffusion flames. The results show that, the high increase in CH3 radicals in the strained flame zone depleted the radical pool (such as OH, H, and O) and, hence, the flame is quenched locally. They concluded that this quenching process is different from the quenching observed in steady counter flow flames, where the quenching was due to the gradual reduction in temperature with increasing strain rate. Renard et al. [11] investigated experimentally (using OH PLIF) the flame front of a non-premixed flame interacting with a vortex to study the heat release, extinction and time evolution of the flame surface. They concluded that global intensification or extinction of the flame is characterized by an increase or decrease in flame surface area because of straining.

Arcoumanis et al. [12] showed that using a small quantity of rich mixture injected near the spark gap can yield to formation of a stable and consistent flame kernel after spark ignition. The function of this local variation in equivalence ratio is to support the flame in a mixture with an overall equivalence ration as low as 0.39. They concluded that not only the average flame speed could be increased by local injection at all equivalence ratios [13] but also the fluid dynamic effect alone caused overstretching of the flame for the ultra lean homogeneous conditions, while rich local stratification in the vicinity of the spark allowed the suppression of this effect and a reduction of the drivability limit [14]. Roberts et al. [15-17] investigated the added complexity of flame kernel–vortex interactions compared to some earlier planar flame–vortex configuration. The initial flame kernel–vortex interactions were experimentally observed using OH-PLIF in a lean atmospheric-pressure methane–air flame kernel to determine the degree of flame wrinkling and the ability of vortices of varying size and strength to globally quench combustion [15].The disturbed flame existed in either the flamelet regime (which has a continuous reaction zone) or distributed reaction zone regime (which has a coexistence of reactants and products) and is strongly dependent upon: the vortex size, the vortex strength, and the time of the initial flame–vortex interaction. They investigated the global extinction of the flame kernel with large vortex sizes interacting with small flame kernels. In addition to that, they concluded that the localized flame front extinction occurred for a range of vortex sizes and strengths and a range of flame kernel sizes.

Meanwhile, Thevenin et al. [18] and Renard et al. [19] reported an experimental and numerical work of non-premixed flame interacting with a vortex. They investigated the influences of global mixture ratio and vortex velocity on changes in the flame surface. Their study concluded that straining effects are responsible for the extinction of the non-premixed flame front, and that the degree of mixing actually increases at the end of the extinction process. They were able to observe the fuel pocket formation, evolution and consumption are another important phenomenon during flame-vortex interactions. In addition to that, the causes for local flame quenching were reported by [20] as well. They concluded that these causes happen due to simultaneously high strain and the heat losses in flame-vortex interactions of lean methane/air mixture. Furthermore, they proved that a minimum interaction time is required for quenching.

Recently, experimental work on the flame kernel structure and propagation in a high turbulent premixed methane flow was performed using combined two-dimensional Rayleigh and LIPF-OH techniques by Mansour et al. [21]. The spark of ignition was generated using pulsed Nd: YAG laser. Four flames have been investigated at two equivalence ratio of 0.8, and 1, and jet velocity of 6, and 12 m/s. They showed that the flame kernel structure starts with spherical shape, and then changes gradually to peanut-like, then changes to mushroom-like and finally the turbulence effectively distributes the kernel. They concluded that the trends of the flame propagation, flame radius, flame cross section area, and mean flame temperature are correlated to the jet velocity and equivalence ratio, also lean flames propagate faster. In addition to that, Elbaz et al. [22] studied the effect of the mixture equivalence ratio and turbulence intensity on the flame kernel and flow field interlinks in partially premixed natural gas flames. Three jet equivalence ratios of 1, 1.5, and 2 were considered at values of jet velocities in range from 10 to 20 m/s. They concluded that jet equivalence ratio of one enhances the flame kernel propagation and gives the highest rate of kernel propagation. Increasing the jet equivalence ratio to 1.5 and 2 reduces the intensity of chemical reaction and hence the effect of turbulence becomes the dominant factor effecting the propagation of the flame kernel.

Based on this review of previous research, it is notable that the interaction between the flow field and flame kernel propagation hasn't been experimentally investigated in a highly turbulent, partially premixed flow field. Thus, the aim of the present work is to investigate the flow field associated with flame kernel propagation history in partial premixing turbulent flames. The experimental program is devoted to study the effect of the degree of partial premixing and jet velocity on the flow field-flame kernel interaction, while the jet equivalence ratio is kept constant. The mean flow field and turbulence intensity are measured using two-dimensional Planar Imaging Velocimetry (PIV), in terms of mean axial velocity and rms. The flow field is first captured for the isothermal field without ignition accompanied to be as a reference flow field to those flow fields with ignition. The flow field with ignition is recorded after the start of ignition at different delay times. Therefore, the flame kernel-turbulent flow field interaction could be interpreted by the comparison of flow fields of the isothermal and ignited cases.

2. EXPERIMENTAL TECHNIQUE

The kernel propagation/flow field interaction of partial premixed natural gas mixture is investigated, where flow is issued from a vertical burner in stagnant surrounding while the ignition plasma and subsequent flame kernel propagation is generated using Nd: YAG laser pulse. The burner consists of two vertical concentric stainless steel tubes of 6 and 10 mm inner diameters, while the thickness is 1mm, as shown in Fig. (1-a), see [22]. The partial premixing between the fuel and air is obtained by letting a mixing distance L, which is the distance between the inner tube exit and the outer tube exit. L can be varied to generate different degree of partial premixing. Air flows through the inner tube while the fuel (natural gas, 95% by volume CH_4) flows through the annular passage between the inner and outer tubes. Mixing starts at the exit of the inner tube and continues downstream along the premixing distance L. To generate a highly turbulent flow, the burner is sitting at the top of conical turbulence generator, see Fig. (1-a). The turbulence is generated using the notion of Videto and Santavicca [23]. Similar to [23], air flow in the current work passes through a narrow slit at a diameter, d_s, of 45 mm and a slit thickness, of 0.8 mm, followed by an inverted cone with a base diameter of 62 mm. The base cone angle is 52^o.The flow issuing from the slit provides a ring-like cylinder flow. This flow is opposed by the cone and broken at the inner cone wall to generate a wide range of eddies, which leads to higher turbulence intensity. The turbulence intensity due to this configuration concept can be as high as 25% [23]. Care is taken into consideration to enable most of jet flow passing through the turbulence generator, so about 90% of the total air is passed through the annular slit without seeding particle needed for the PIV system measurements. The rest of the air carrying the seeding particles (Titanium dioxide of 0.5 µm in diameter) from a fluidized bed seeder is passed directly through concentric central tube fitted to the turbulence generator disk.

The interactions between the flame kernel and flow field is investigated at several delay time intervals from ignition, under different degree of partial premixing and jet velocity. This is based on capturing the turbulent flow field after the ignition at different delay time, namely 150, 300, 500, 1000, 1500, and 2500 µs [22]. These flow fields are compared with flow field without ignition (henceforth to be termed isothermal flow) to identify the effects of the evolving flame kernel. A pulsed Nd:YAG laser (Continuum Surelite II) is used for flame ignition, see Fig. (1-b). Laser ignition provides more stable measurable pulse energy, and overcome the problems of the effects of spark electrodes on the flame structure, as well as heat loss to the electrodes. The laser provides a beam of 6 mm diameter at 1064 nm with 230 mJ and is focused to a beam of waist radius of 5.6 µm using spherical lens of 50 mm focal length.

The flow field is measured using two-dimensional Planar Imaging Velocimetry (PIV) technique, where the flow field can be well described in two-dimensional. Two head Nd:YAG laser with pulse energy of 50 mJ at the second harmonic of 532 nm. The cameras are HiSense MkII PIV CCD cameras (model C8484-5205CP) with 1280 x 1024 CCD light sensitive array and equal number of storage cells. The objective of the camera is covered with interference filters at 532 nm with a bandwidth of 10 nm. The laser pulse duration is 6 ns and the inter-pulse delay between the two laser heads is controlled according to the flow velocity with a minimum of 0.2 µs for supersonic flow. The laser sheet is created by sheet forming optics that produces expanding laser sheet. Timing between the laser ignition, the PIV laser sheet forming and the camera capturing was controlled by 4 channel Stanford Research DG535 pulse delay generator and monitored with a Tektronix 4 channel 200 MHz oscilloscope, see Fig.(1-b).The PIV images were processed using an adaptive window offset cross-correlation algorithm implemented in a commercial analysis package (Dantec Dynamic Studio V 2.30). The final interrogation window was 32×32 pixels with a 50% window overlap, resulting in a spatial resolution 1 mm and vector spacing of 0.5 mm.

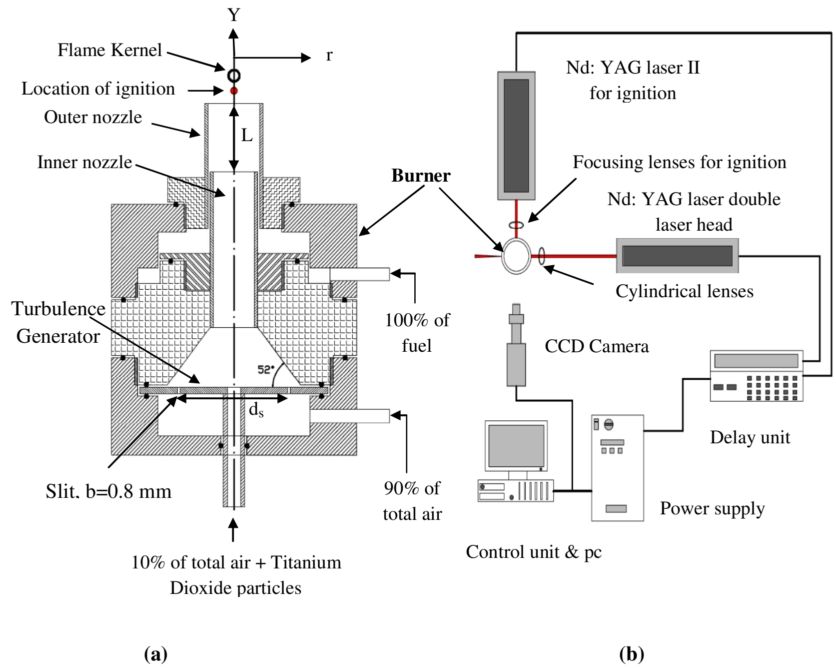

FIGURE 1: a) The Burner, b) The Experimental Set up.

3. FLAME STABILITY AND SELECTED CONDITIONS

The flame stability is studied for three different degrees of partial premixing. This is achieved by changing the mixing length L, namely three different values of L/D =2, 4, and 6, are used (where D is the inner diameter of the outer burner tube) [22]. The stability results are presented as the relation between the bulk jet velocity (Uj) at the burner exit, and the jet equivalence ratio (Φj). The stability point is achieved via gradual decrease of the fuel admitted to the burner until the blow off is achieved; while the air jet flow rate is kept constant. Figure (2) illustrates the stability limits for the three mixing lengths. The results indicate a correlation between the jet velocity and the jet equivalence ratio, where, the increase in the jet velocity requires an increase of the jet equivalence ratio. L/D = 2, provides the most stable flames as compared to those flames of L/D = 4 and 6. This result doesn't agree with the results of [24], where in this investigation, L/D = 5 provides the optimum mixing length from the flame stability perspective. This is believed to be due to the turbulence generator disk used in our study, which increases the turbulence intensity (this will be confirmed by the flow field measurements), therefore, increase the degree of partial premixing for the same mixing length L. This in turn, means a lower mixing length to get the optimum flame stability conditions.

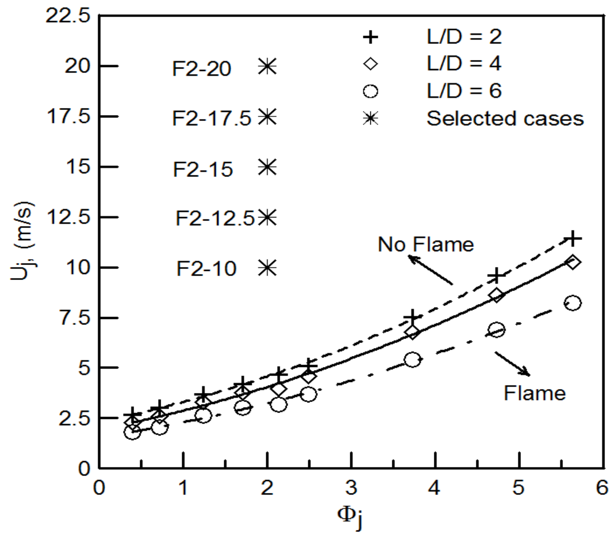

FIGURE 2: Stability Limit and the Selected Flame Conditions.

Based on the stability results, the interactions between the flame kernel and the flow fields are investigated at five conditions relative to this stability limit and for the three different mixing lengths. This leads to fifteen cases for the current flame kernels. The flames' positions relative to the stability limit are illustrated in Fig. (2). While their flow conditions are listed in Table 1 below. Five jet velocities of 10, 12.5, 15, 17.5, and 20 m/s at constant jet equivalence ratio of 2 are selected. The selected flames lie in the unstable region of the stability curve, and no stability factors are used for this burner. This leads to the result that each laser pulse is followed by the generation of one flame kernel that propagates and is advected downstream by the flow. Thus, the resulting configuration and flow conditions provide the ability to capture the flow fields at several time intervals during the flame kernel propagation. The flow fields of the previous flames are also examined for the isothermal cases to be used as references for those flow fields with ignition.

4. RESULTS AND DISCUSSION

The contours of constant mean velocity U/Uj and the local axial turbulence intensity Urms/U of isothermal and ignited case of $F2\text{-}10_{L=2}$ are illustrated in Figs. (3-a) and (3-b), respectively. The contours of mean velocity U/Uj for isothermal case $F2\text{-}10^{iso}_{L=2}$ shows that, the mixture emerging from the burner nozzle interacts with the surrounding quiescent environment to form a jet flow. Immediately downstream of the nozzle exit lies a central core of fluid with a nearly constant velocity ratio of U/Uj =1.2 which extends to an axial distance of nearly twice the burner diameter (D). Outside this region, a free boundary layer (mixing layer) develops perpendicular to the direction of the flow. Downstream of the core region, the mixing layers start to merge. The turbulence intensity associated with the core region shows a relatively low level and this level increases at the outer mixing layers, as shown in Fig. (3-b). Further downstream, the centerline turbulence intensity decreases to nearly Urms/Uj = 0.08 at axial distance Y/D = 5 (see figure 4-c). The mean velocity contour of the corresponding ignited case $F2\text{-}10_{L=2}$, at several delay times relative to the ignition event is illustrated in Fig. (3-a) at the right of the isothermal flow field. The data shows qualitatively and quantitatively similar results to those previously examined in the isothermal case. This proves that the flame kernel does not exhibit any significance influence on the scale of mean flow field.

TABLE 1: The Selected Flames Conditions.

Flames*	Φj	Uj (m/s)	L/D = 2	L/D = 4	L/D = 6
F2-10	2	10	√	√	√
F2-12.5	2	12.5	√	√	√
F2-15	2	15	√	√	√
F2-17.5	2	17.5	√	√	√
F2-20	2	20	√	√	√

*A subscript L is added to the flames designation to indicate the partial premixing length. For example, $F2\text{-}10_{L=4}$ it means the premixing length of L/D=4. Also the isothermal case is indicated by superscript iso like $F2\text{-}10^{iso}_{L=4}$, it means the premixing length of L/D =4 but in the isothermal case.

Regarding to the turbulence scale, the turbulence intensity of the ignited case shows a remarkable change in comparison with the corresponding isothermal case (the left contour of Figure 3-b). This can be seen from the higher turbulence intensity at the centerline of the jet flow, which continued for some axial distance, which is then followed by a sudden decay in the centerline turbulence intensity, as shown in Fig. (3-b).This increase in the turbulence intensity propagates with the increase in time up to 1500 μs. The turbulence intensity field at 2500 μs eventually becomes identical to the turbulence intensity field of the isothermal case, as shown by the first and seventh Contours of Fig. (3-b). This means that a total extinction of the flame kernel has happened between 1500 μs and 2500 μs. Consequently, the centerline turbulence intensity profile can be taken as a marker of flame kernel propagation.

The flame kernel propagation could be traced by examining the centerline turbulence intensity. Figure 4 shows the turbulence intensity contours for both isothermal and flame conditions with$F2\text{-}10_{L=2}$, as well as the centerline turbulence intensity at 300 μs after ignition Fig. (4-a, b) and Fig. (4-c), respectively. The centerline turbulence intensity is first seen to increase up to Urms/U = 0.28 at an axial distance Y/D = 0.25 in comparison with a value 0.12 for the isothermal case. Further downstream, the turbulence intensity is suddenly decreases to nearly 0.13 at an axial distance of Y/D =1. This steep decline to turbulence intensity to slightly higher than the corresponding values for the isothermal case. Moreover, at higher axial distances, both the centerline turbulence intensities of the ignited and isothermal case show the same rate of decay in the turbulence level, since they have parallel centerline decay profiles.

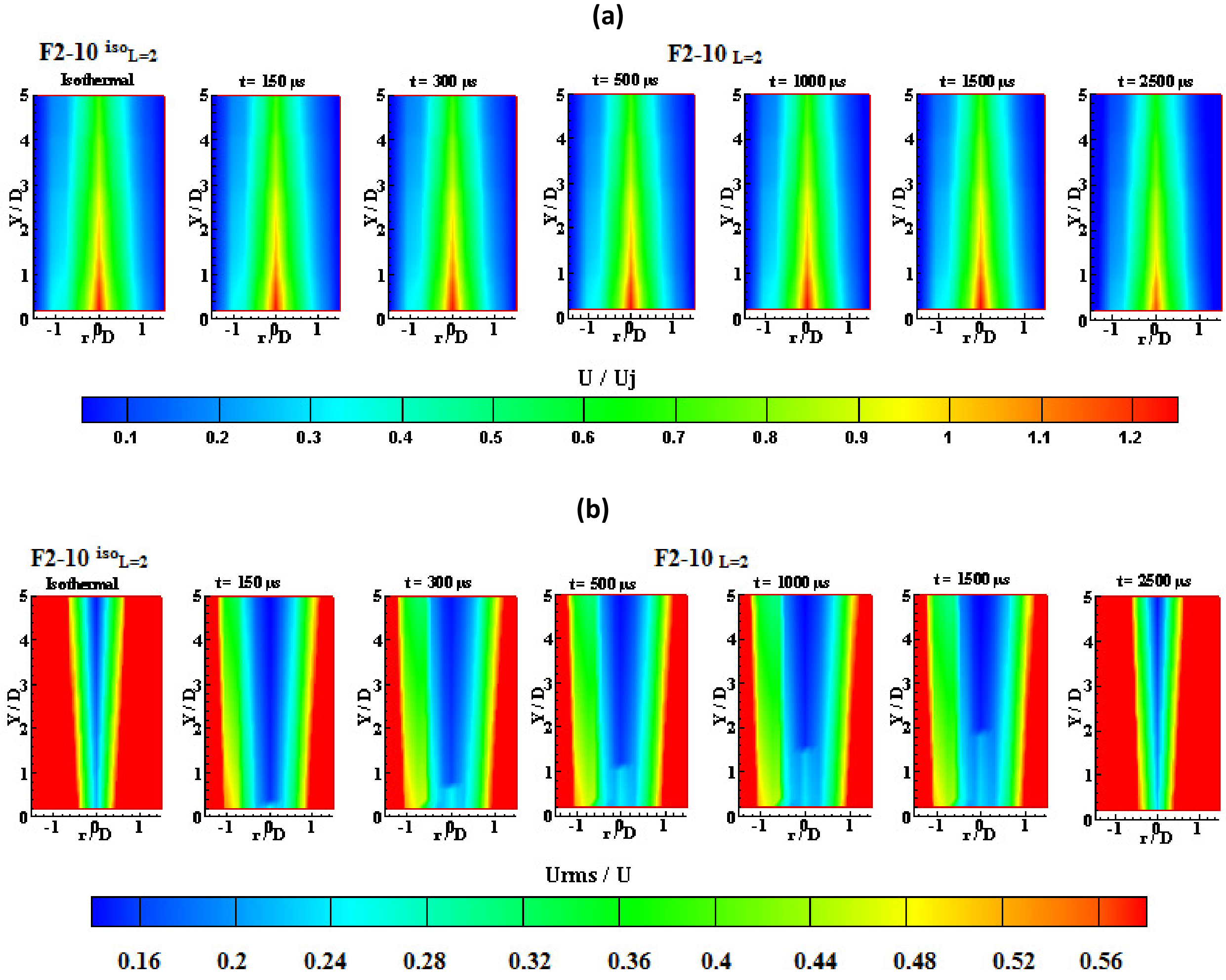

FIGURE 3: a) Contours of the normalized mean axial velocity, b) Contours of the axial turbulence intensity Urms/U of F2-10$_{L=2}$, flame and isothermal cases.

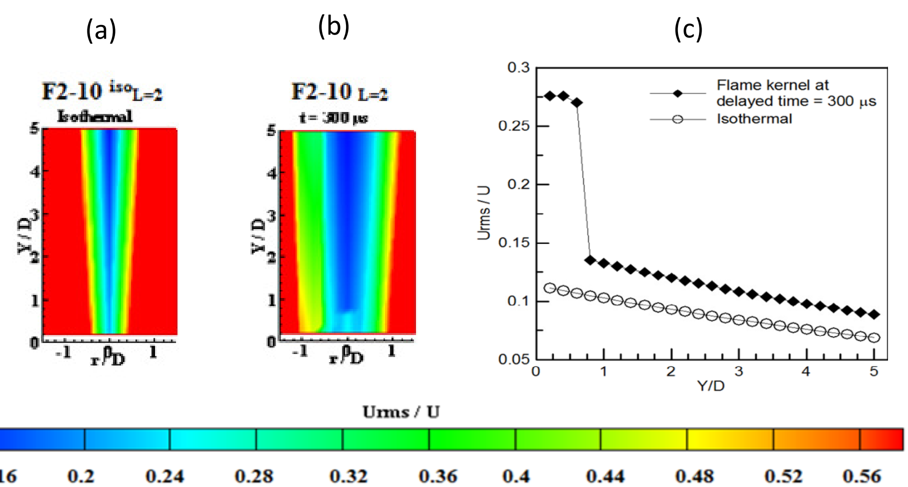

FIGURE 4: a) Contours of the normalized mean axial velocity for isothermal case, b) Contours of the normalized mean axial velocity for flame with kernel at time 300 µs for F2-10$_{L=2}$, c) Centerline turbulence intensity and the corresponding isothermal case.

In order to study the variations of the turbulence intensity across the flame kernel, the radial profiles of Urms/Uj for the F2-$10_{L=2}$, at time delay of 500 µs for three axial locations, are presented in Fig. (5). The first location is at the point of maximum centerline turbulence intensity, denoted as X, the second location, X-2, is at an axial position 2 mm before X, while the third location, X+2, is at an axial location 2 mm after X. The profiles show that at the position X, a peak turbulence intensity of 0.257 is measured at the jet centerline due to the flame kernel propagation. Further radially outward from the jet centerline, the level of turbulence gradually decreases up to radial distance r/R of 0.3, and then starts to increase again due to the outer mixing shear layer. At X-2, the peak Urms/Uj has a slightly lower value as compared to the peak at X. In contrast, at X+2 the centerline Urms/Uj shows a minimum point and increases radially. All the radial profiles (X, X+2, X-2) show the same level of the turbulence intensity starting at radial location of r/D = 0.3, where the effect of flame kernel and the diffusion of the turbulent kinetic energy from the jet centerline becomes very week, on the other hand the higher turbulence intensity of outer shear layer is more pounced the flow field at this point of reflection.

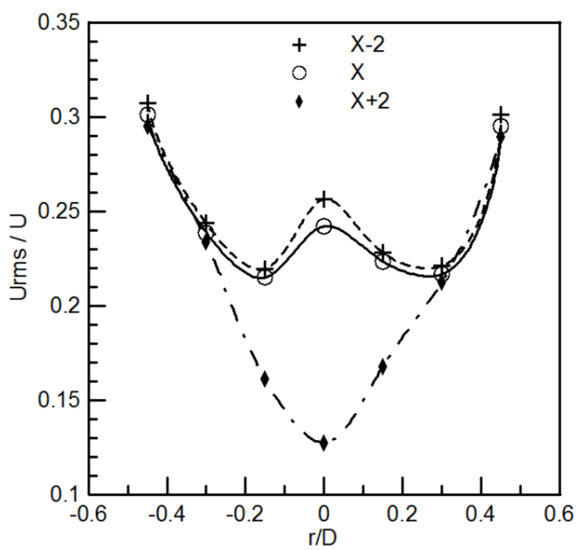

FIGURE 5: Radial Profiles of Turbulence Intensity Urms/U of Flame F2-$10_{L=2}$ at Time 500 µs.

In the following sections, the effects of both degree of partial premixing and jet velocity on the flame kernel propagation and flow field are discussed. The contours of the turbulence intensity for flames F2-$10_{L=6}$ and F2-$20_{L=2}$, are shown in Figs.6 and 7, respectively. Both sets of contours show qualitative similarities with those previously examined for flame F2-$10_{L=2}$, as shown in Fig. (3-b). However, increasing the mixing length to L/D =6, leads to an increase in the turbulence intensity and a shorter time required for flame kernel extinction, where the flame kernel extinction occurs between 500 µs and 1000 µs, as shown in Fig. (6). Similar effects are recorded by increasing the jet velocity for flame F2-$20_{L=2}$, in comparison with flame F2-$10_{L=2}$, as shown in Fig. (7).

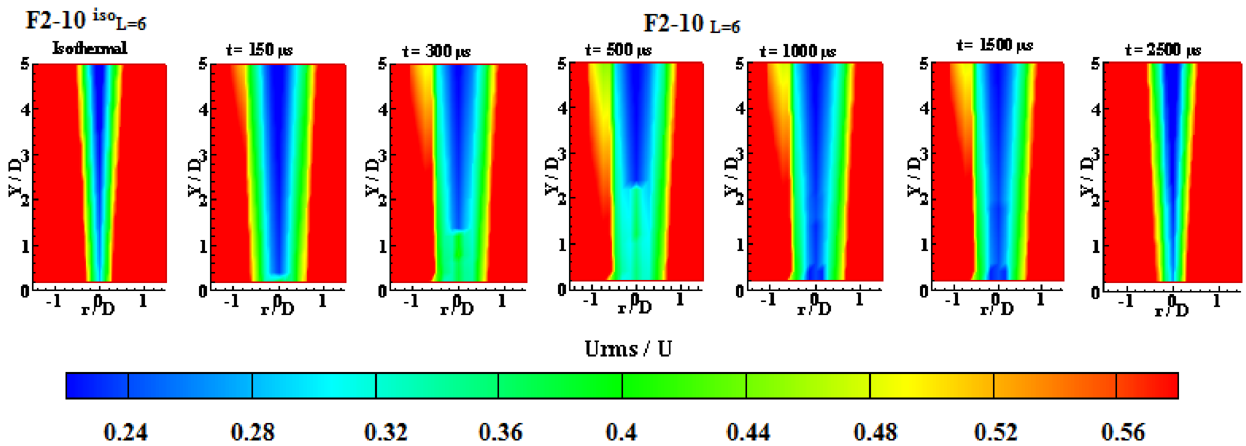

FIGURE 6: The Turbulence Intensity Contours of F2-10$_{L=6}$ with the Reference Isothermal Case.

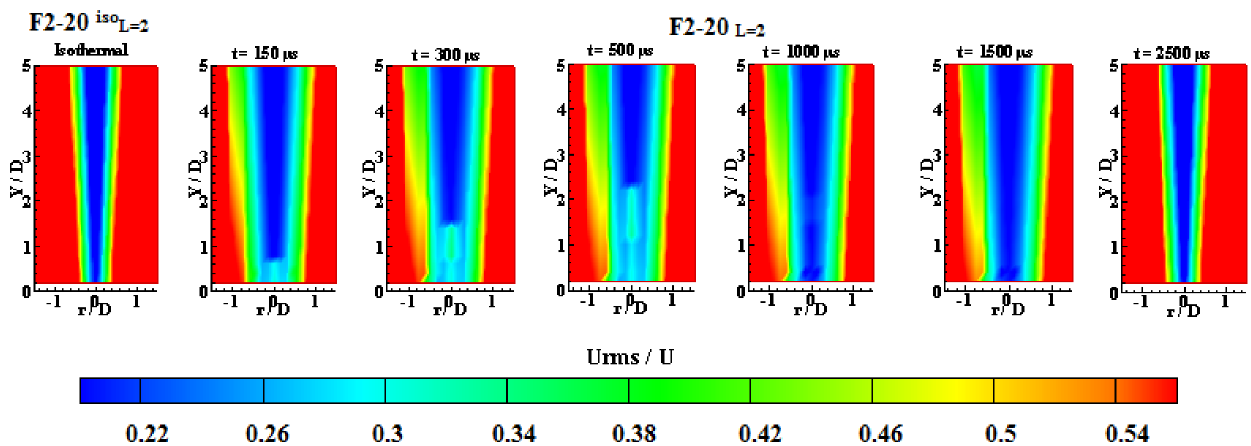

FIGURE 7: The Turbulence Intensity Contours of F2-20$_{L=2}$ with the Reference Isothermal Case.

As previously stated, increasing the mixing length L results in global increasing in the turbulence intensity for the isothermal cases. This is confirmed by the noticeably higher center line turbulence intensity in F2-10$^{iso}_{L=6}$, at delay time of 300 μs, as shown in Fig. (8) than those of L/D=4, and 2 for the isothermal cases. The longer shear layer accompanied by the longer outer pipe of F2-10$^{iso}_{L=6}$ leads to higher turbulence intensity. This higher turbulence intensity for L/D=6 enhances the mixing between the fuel and air, thus resulting in a flame that is closer to the conditions of a fully premixed flame.

Consequently, two reasons can be considered as the causes of the low stability limit of the case of L/D =6, see Fig. (2); the first is the higher turbulence intensity, while the second is the more complete mixing between the fuel and air which breaks up the triple point structure of partially premixed flame, which improve the flame stability, see [24]. At the same time, increasing the degree of partial premixing results in higher centerline turbulence intensity, see Fig. (8) with the flame kernel. This is attributed to the higher turbulence intensity accompanying the isothermal case of L/D =6, as shown in Fig. (8). However, in all cases of L/D a nearly constant centerline turbulence level up to an axial distance of Y/D = 0.75 is observed. Further downstream, there is a steep increase in turbulence intensity reaching a maximum point at the same axial distance of Y/D = 0.95; this is attributed to the dominating effect of the plasma associated with the laser ignition. Beyond the point of maximum turbulence at L/D = 6, the centerline turbulence level indicates a very slow decline up to axial distances of Y/D=1.5, and then is followed by very steep decline to a low turbulence level. Decreasing the mixing length leads to a shorter axial distance of the very low decline regions reaching to a point at L/D =2. This indicates that the shorter the mixing length, the sooner flame kernel extinction occurs (i.e., at shorter axial distances). A higher mixing rate leads to more uniform mixture and, hence, a higher speed of flame kernel propagation.

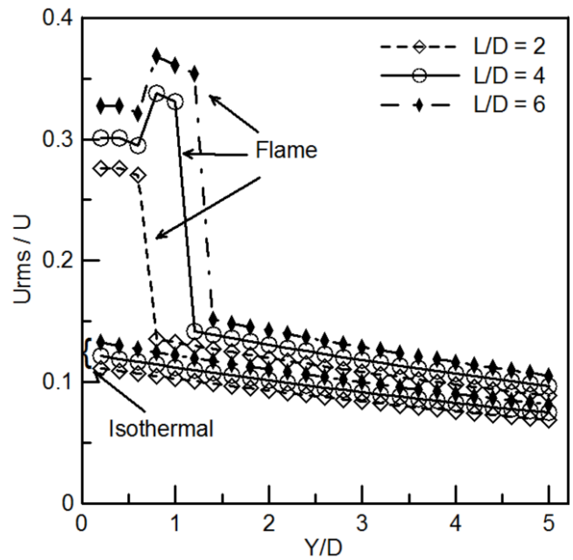

FIGURE 8: Centerline Axial Turbulence Intensity at Uj =10 m/s, L/D=2, L/D=4 and L/D=6.

Figure (9-a) illustrates the flame kernel propagation at different premixing lengths, while Fig. (9-b) shows the corresponding flame propagation rates. At jet velocity of 10 m/s, the flame propagation is the same for the three mixing lengths up to 150 μs, which indicates the effect of laser plasma is still pronounced. After a delay time of 150 μs increasing the mixing length L, leads to a higher flame propagation rate. This is may be attributed to higher mixture uniformity and higher turbulence intensity at a longer mixing length L. This higher L leads to faster extinction of the flame kernel, since higher mixing rates overcome the energy associated with the flame kernel leading to the early kernel quenching. Increasing the jet velocity results in a faster flame kernel propagation (see Uj=20 m/s). The higher the jet velocity, the larger the axial distance the flame kernel convected, as well as the higher the turbulence intensity, the higher the flame kernel penetration. As indicated in Fig. (9-b), for all the jet velocities, the flame kernel propagation rates are high up to delay time of 300 μs, which is followed by attenuated propagation rates. These attenuated propagation rates are due to the dissipated energy from the flame kernel to the surrounding mixture. Increasing the jet velocity leads to an increase of the flame kernel propagation rates and a shorter time for flame kernel extinction. These are attributed to the higher turbulence levels associated with higher jet velocities and the higher straining of the flame kernel associated with the higher jet velocity.

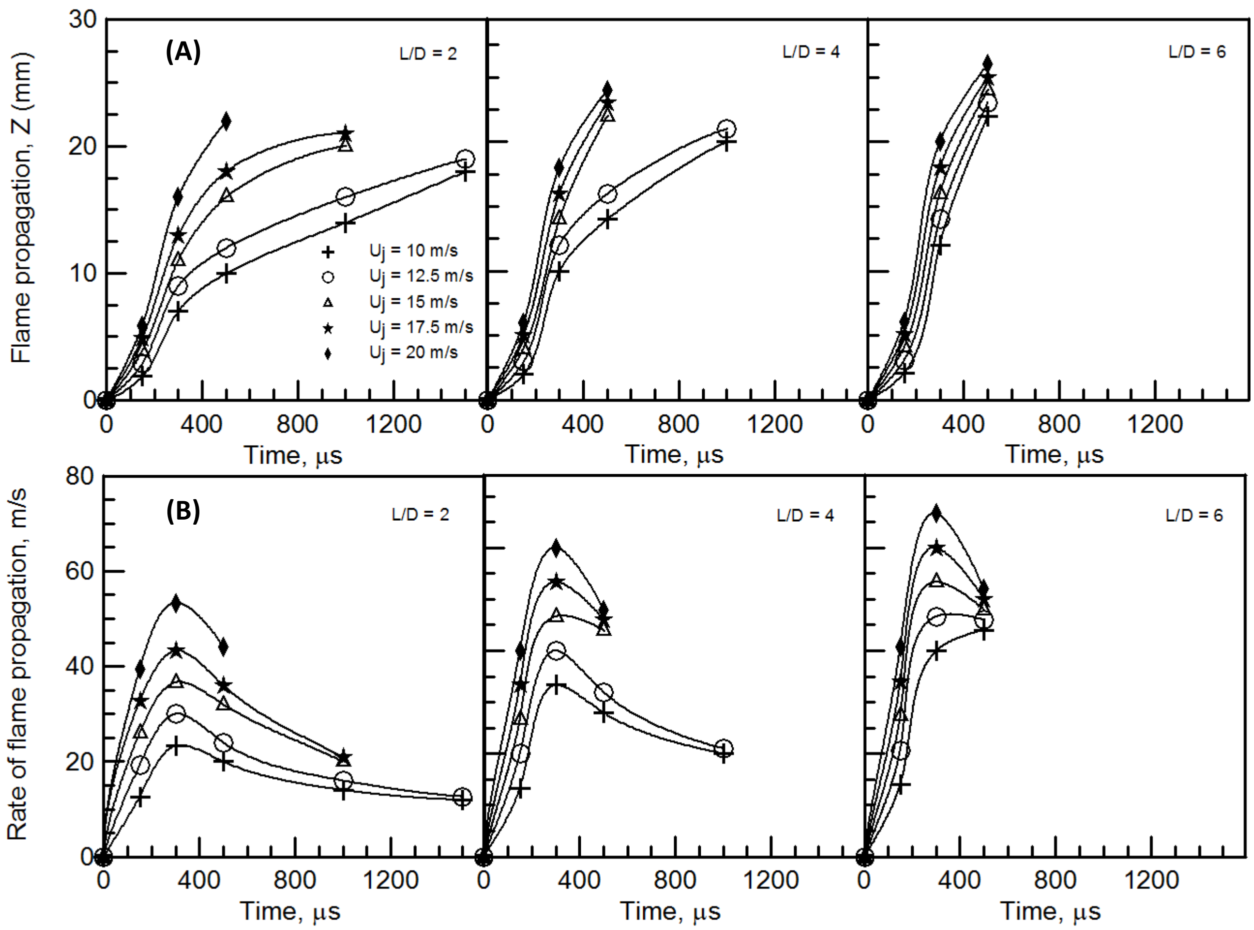

FIGURE 9: a) Flame Kernel Propagation, b) Rate of Flame Kernel Propagation.

5. CONCLUSIONS

An experimental investigation is conducted on the interaction between the flow field and flame kernel propagation of partial premixed natural gas turbulent flames. The investigation is oriented to study the effect of the degree of partial premixing and jet velocity on the flow field-flame kernel interaction, while the jet equivalence ratio is kept constant. The mean flow field and turbulence intensity are measured using two-dimensional Planar Imaging Velocimetry (PIV). The flow field is captured for the isothermal field without ignition, and thus to be a reference flow field to those flow fields with ignition. The flow field with ignition is recorded after the start of ignition at different delay times. The mean flow field doesn't change for the ignited cases as compared to the isothermal flow. The flame kernel propagation is associated with an increase in turbulence intensity, and show a sudden increase in the centerline turbulence level. The higher degree of partial premixing leads to higher turbulence intensities accompanying the flame kernel propagation and faster flame kernel propagation. Increasing the jet velocity increases the global turbulence intensity and leads to faster flame kernel propagation. The rate of flame kernel propagation is very fast at the early stage of the kernel propagation up to the first 300 μs and then it slows down. Moreover, increasing the jet velocity and/or increasing the degree of partial premixing, leads to break out the partial premixing structure and hence a reduction inflame stability and a more rapid flame kernel extinction, attributed to the higher strain rates.

6. ACKNOWLEDGEMENTS
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CONTACT INFORMATION

Computer Science Journals Sdn BhD
B-5-8 Plaza Mont Kiara, Mont Kiara
50480, Kuala Lumpur, MALAYSIA
Phone: 006 03 6207 1607
006 03 2782 6991

Fax: 006 03 6207 1697

Email: cscpress@cscjournals.org

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MALAYSIA

PHONE: 006 03 6207 1607
006 03 2782 6991

FAX: 006 03 6207 1697
EMAIL: cscpress@cscjournals.org