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BURNING VELOCITY MEASUREMENT OF BIODIESEL FUEL AND ITS BLENDS USING PARTICLE IMAGING PATH TECHNIQUE AND IMAGE PROCESSING

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Abstract: In present investigation an air-blast atomizer was designed and developed for fuel atomization which is used in liquid fuel burner. The burning velocity was measured experimentally. The experiments have been performed for different liquid fuel types, air to liquid mass flow rates (ALR) and equivalence ratio (φ) to study the effects of these parameters on burning velocity (BV). The liquid fuels used during the tests are biodiesel (sunflower fatty acid methyl ester SME) and its blends (biodiesel-diesel Bx and biodiesel-kerosene Bkx) with three values of ALR (0.6, 0.8 and 1.0) for five values of φ (0.6, 0.8, 1.0, 1.2 and 1.4).The flames images were investigated for the region before the flame front by using imaging setup and using particle image path (PIP) with dispersion techniques. The image viewing regions is 366.6 mm^2 for determine the (BV). Matlab cod software has been used for a number of image processing techniques to identify and improve the detection of the path of particles movements. The results showed that the increasing of biodiesel ratio in blending with diesel and kerosene decreases the (BV), and the increasing of ALR increases the (BV) for all experiments fuels. Also the results showed that the agreement is good of this method of (BV) measurement with published studies.

Keywords: *biodiesel, particle image path (PIP), shutter speed, atomizer, image processing.*

قياس سرعة الاحتراق لوقود الديزل الحيوي وخلائطه باستخدام تقنية تصوير مسار الجسيم ومعالجة الصور

الخلاصة: في هذا البحث تم تصنيع مرذذ نوع (air-blast atomizer) وتطويره لغرض ترذيذ الوقود المستخدم في مشعل الوقود السائل. حيث تم قياس سرعة الاحتراق (BV) تجريبيا. واجراء التجارب لمجموعة مختلفة من الوقود السائل، كذلك استخدمت نسب مختلفة لتدفق كتلة هواء الترذيذ الى كتلة الوقود السائل (ALR) ولنسب مكافئة φ مختلفة ، وذلك لدراسة تأثيرات هذه المتغيرات على سرعة الاحتراق (BV). إن أنواع الوقود السائل المستخدمة أثناء الاختبارات هي وقود biodiesel وخلائطـــــــه (biodiesel-diesel Bx, biodiesel-kerosene Bkx) عند ثلاث نسب ترذيذ (ALR=0.6, 0.8 and 1.0) ولنسب تكافؤ (0.6, 0.8, 1.0, 1.2, 1.4) تم اخذ صور اللهبة باستخدام منظومة التصوير عند المنطقة قبل جبهة اللهب بمساحة 366.6 mm^2 وباستخدام صورة مسار الجسيم (PIP) و (dispersion technique) لتحديد سرعة الاحتراق وذلك باستخدام برنامج Matlab لمعالجة الصور وباستخدام تقنيات معالجة الصور لتحديد وتحسين الكشف عن مسارات الجسيمات .أظهرت النتائج أن زيادة نسبة وقود الديزل الحيوي عند مزجه مع الديزل والكيروسين يقلل من (BV)، وزيادةALR يزيد من (BV) لجميع أنواع الوقود المستخدم في التجارب. كما اظهرت النتائج أيضا أن هذه الطريقة تتفق مع نتائج البحوث السابقة وهي طريقة فعالة.

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1. Introduction

The industrial development and the growth of social raise the demand of fossil fuels, and increase the pollutant emissions of petroleum fuels, which effects on environment that led to many investigations on alternative fuel like biodiesel which can be used directly or by blending with hydrocarbon fuel. Burning velocity is one of the important parameters that it give the information of (characteristics) of the mixture. Burning velocity help in the calculation of many combustion properties like flashback, blow off and minimum energy for ignition, predicting explosions and designing burners. It also used to understanding of the process of combustion like the turbulent combustion and system of power generation [1]. Burning velocity is impacts by many parameters which involve (type of fuel, equivalence ratio, the temperature and pressure of mixture and combustion chamber dimensions also ALR and SMD in liquid combustion).Therefore the survey of this work will be concerned with the previous studies performed on the biodiesel burning velocity measurements.

There are a few and weak researches that concern in the burning velocity of liquid fuel especially biodiesel and it's blending, following some of these research.

Alekseev et al., [2] determined experimentally the laminar burning velocity of n-decane & binary kerosene surrogate (liquid hydrocarbon fuel) using heat flux method. The experimental setup is equipped with evaporator to evaporate the liquid fuel to gaseous, which supply the burner. The stabilization of flat adiabatic flames is the balance of heat transfer between the burner and flame. The unburned gas temperature was set 338K & 358K. And the equivalence ratios ranges (0.7 – 1.3). The results showed that, the heat flux method agrees with counter flow method and disagrees the data from spherical method. The increase of burning velocity in the binary fuel is very small. Also the maximum values of burning velocity for both type fuel were at φ=1.1.

Marshall, et al., [3] measured the laminar burning velocity of some liquid hydrocarbon fuels, the experiments carried out using constant volume vessel (Bomb method) with initial range of pressure (50, 100, 200, …, 400kPa), temperature (310, 380 and 450K) and φ (0.7-1.4). The test rig equipped with mixing loop to supply the vessel with air fuel mixture after evaporate the liquid fuel to gas phase. They used a schlieren photography system and an image processing algorithm using Matlab code to find the radius of flame with time from schileren images. Also they derived the burning velocity at any pressure and temperature with r_i of flame. The result showed that, the burning velocity decrease with pressure increase and the maximum burning velocity for all cases at φ=1.16.

Myers and Lefebvre [4] conducted an experimental study on the influence of fuel chemistry on the burning velocity of liquid hydrocarbon fuel in air at atmosphere pressure. The test rig include a 10cm^2 test section contain two opening to let optical access to the flame, sixty-four air-blast atomizer to provide uniform distribution of mixture in combustion chamber . To measure the burning velocity, Schlieren flame images which helps to using the angle method. The experiments carried out on a conventional No.2 fuel and its blends. The results of all fuels showed that, the burning velocity is inversely proportional to SMD. The fuels contain multi-ring aromatics exhibiting the highest burning velocity.

Richards & Lefebvre [5] conducted an experimental study on the effect of equivalence ratio and mean drop size on the burning velocity of kerosene, toluene and decalin fuel-air mixture. The test rig units including main air, atomization, fuel line etc. also the combustion chamber fitted with quarts windows which let optical access to the flame. Thirty six air-blast atomizers were used to ensure a uniform distribution of fuel-air mixture inside the combustion chamber. Burning velocity measured from the data of schlieren pictures, using the angle method. The experiments carried out at atmospheric pressure with equivalence ratio from 0.37 to 1.84. From the results SMD values from 20 to 110µm and the burning velocity increase with SMD decrease at φ less than 1.1.

Abed Al-khadim [6] conducted an experimental study of the effect of equivalence ratio and droplet size on burning velocity of gasoil and kerosene and with LPG additions. He used the angle method with sixteen air blast atomizer and schileren photography to determine the burning velocity also derived empirical formula for burning velocity calculation at any conditions. The results showed that, the optimum burning velocities are 2.4m/s and 2.2m/s at equivalence ratio 0.94 and 0.92 of kerosene and gasoil respectively where SMD equal 50 µm in the range.

Wirawar et al. [7] measured the laminar burning velocity of bio-oil fuel (kapok seed oil) experimentally using Bunsen burner method with open tip, cellular and triple flame Fig.The range of premixed equivalence ratio of liquid fuel vapor and air varied from 0.3 to 1.07. The results showed, the combustion of (kapok seed oil) requires a big amount of air to complete the combustion process, therefore the maximum laminar burning velocity value at very lean mixture with equivalence ratio (φ) = 0.36.

Christensen [8] investigated the laminar burning velocity of oxygenated fuels (biofuel) and intermediates experimentally using the heat flux method to support the database of these fuels and compared with kinetic mechanisms, also investigated numerically and experimentally the expressed formula between temperature and laminar burning velocity $S_L=S_{L0}(T/T_0)^{\alpha}$. The results showed, the kinetic mechanism were predict the experimental laminar burning velocity that display agreement with experimentally temperature dependence.

Cheng [9] measured the burning velocity of biodiesel, palm methyl ester (PME) and It's blending with jet-A1 and diesel fuel, using jet-wall stagnation flame coupled with PIV system and laser pulses generator equipped with CCD camera to record the images of particles moving during the nanosecond pulse. The liquid fuel enters the vaporizer after atomized by an external atomizer. The burning velocities were determined from velocity flow field.

The results showed that, the burning velocity of biodiesel is less than jet-A1 at φ=(0.7-1.5), the 10% PME blend is same flame speed of jet-A1 and the peak flame speed of 20% PME blend is 88.3 cm/s at φ=1.08, is lower than the peak of jet-A1 about 3.5 cm/s. but the burning velocity of diesel fuel is lower than biodiesel fuel. The 20% PME blend with diesel at lean side showed lower burning velocity but at rich side is higher than diesel fuel.

The previous studies have been conducted to investigate the burning velocity of conventional liquid fuels, biodiesel and some blends. Different methods were used to measure the burning velocity. It can be seen from the available literatures that there are a shortage in dealing with burning velocity of biodiesel and its blending for two types of blending.

The objective of this work to fill part of this research gap by study the effect of fuel type (diesel, kerosene, biodiesel, and their blending) and ALR on burning velocity by using particle path imaging (PIP) technique and image processing. The results of this study are expected to provide some insights into understanding the relation between biodiesel blends (Bx and Bkx), equivalence ratio, ALR and burning velocity.

2. Experimental setup and procedure

In this research fabricated liquid fuel air-blast burner for experiments were performed equipped with imaging system is used for measuring the burning velocity of the liquid fuel fig 1.

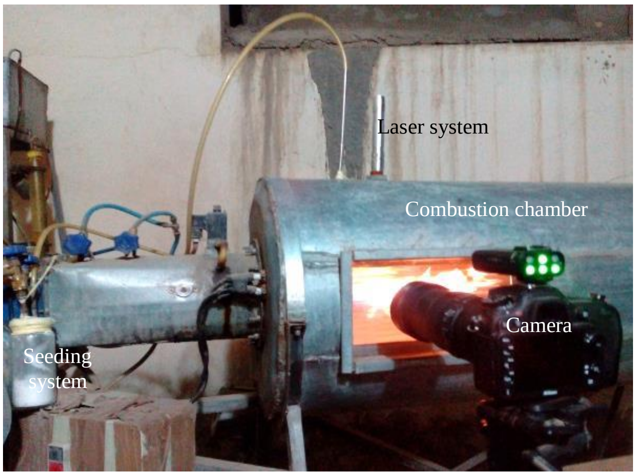


Fig.1: The photo of burner with imaging system

2.1. *Burning velocity measurement system*

The burning velocity is determined by imaging the particles path in a limited zone of flame field, located before the flame front. The system consists of high shutter speed camera Nikon 7100 with 1/8000s shutter speed, 24Mpixel equipped with macro lens sigma 105mm, to enlarge the view of the image, a seeding partials system, which supplies the flame with titanium dioxide (TiO_2) 1µm as seeding particles.

The seeder designed by Mendes-Lopez (1984) [10]. Fig.2, laser source (laser diode 532nm wave length) equipped with optics setup (cylindrical lens) to expend the laser beam into a plane (laser sheet) with 2mm thickness. Also the system equipped with optical green band pass filter (532nm) to reduce the effect of flame luminosity and circular polarizer (DSL) filter to reduce the effects of reflections during the imaging and flexible slide holder.

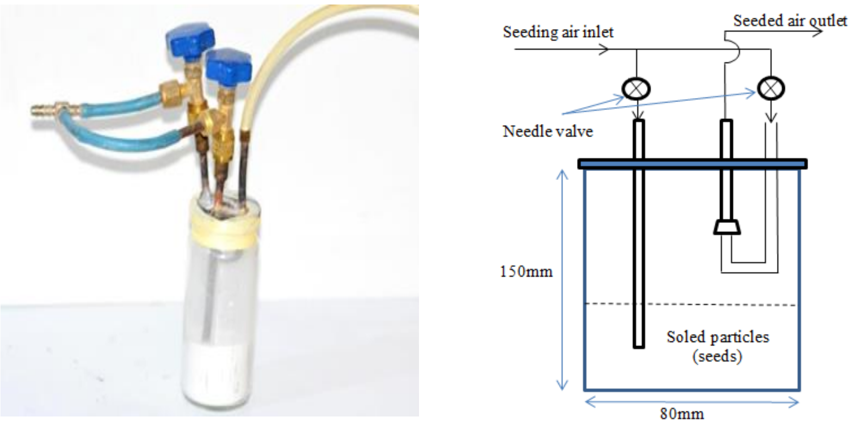
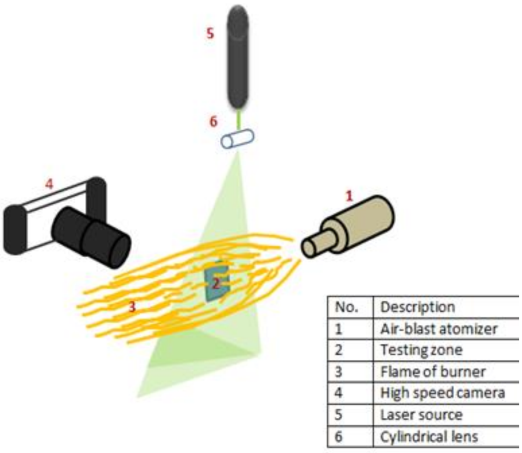


Fig. 2: Photo and schematic of the solid particle seeder

To determine the burning velocity, (Matlab code) software has been used as image processing program. Referring to Fig.3, laser sheet focusing on the test section to appear the illumination of the particles during the imaging, using high shutter speed. The image of particles path is passes normally through the DSL filter to the camera lens; the images are transfer to the PC to determine the burning velocity of fuel by image processing program.



No.	Description
1	Air-blast atomizer
2	Testing zone
3	Flame of burner
4	High speed camera
5	Laser source
6	Cylindrical lens

Fig.3: 3D Schematic of PIP unit for burning velocity measuring

2.2 Air blast atomizer

A reacting atomization facility is utilized to investigate biodiesel and its blending with kerosene and diesel combustion. Sprays established via modified an external mix air blast atomizer. The air and fuel orifice diameter are (da=2.5mm) and (df =1.5mm) respectively, the details of the atomizer geometry shown in Fig. 4.

To determine ALR through the airblast atomizer, using calibrated air and fuel flow meters Fig. 5.

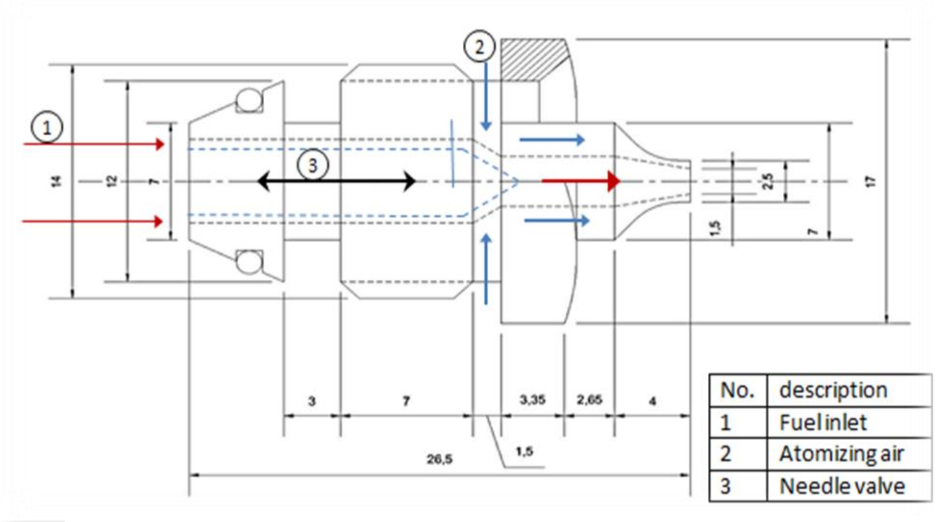


Fig.4: The atomizer geometry

Fig.5: Photo of atomization air flow meter, Photo of fuel flow meter.

2.3. The tested fuels

The biodiesel (Fatty acid methyl ester) used in this research produced from sunflower oil and methanol by transesterification process Fig.6, in combustion laboratory, mechanical engineering department, University of Technology by using the biodiesel reactor, made by the researcher. The tested Diesel and Kerosene supplied by Al-Dura refinery. The blending of biodiesel were prepared and most fuels tests was done in the fuels laboratory, University of Technology and GC mass in laboratory of Chemical science department –Mustansiriya University Table 1 shows the properties of biodiesel, diesel & kerosene according to ASTM.

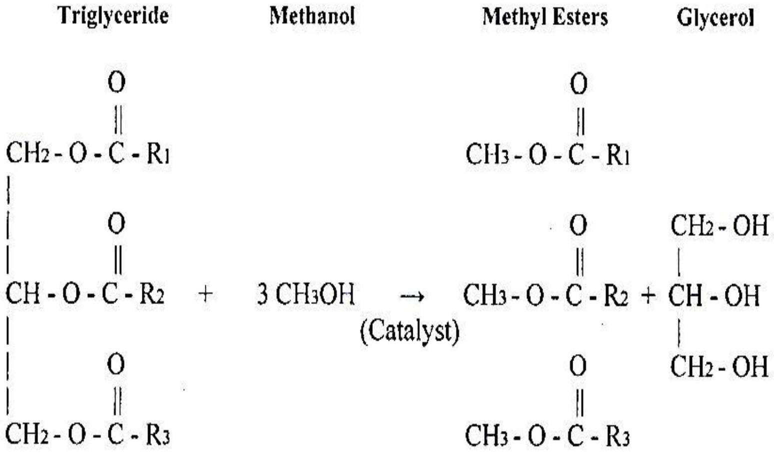


Fig. 6: Stoichiometry transesterification of triglyceride into a fatty acid and glycerol utilizing Methanol [11].

Table1: Properties of biodiesel, diesel and kerosene.

Property (unit)	*Test method*	*biodiesel*	*diesel*	*kerosene*
Approx. formula	GC mass	$C_{19}H_{36}O_2$	$C_{16}H_{34}$	$C_{11}H_{21}$
H/C	-	1.89	1.9	1.98
Viscosity cSt at (40 ^{0}C)	ASTM D445	4.92	2.8	1.38
Cloud point (^{0}C)	ASTM D2500	4	-	-
Pour point (^{0}C)	ASTM D97	2	-7	-9
Flash point (^{0}C)	ASTM D93	176	67	45
Density at (15^{0}C)(kg/m^3)	ASTM D1298	870	833	807
Cetane index	ASTM D976	67.4	53	-
Molecular weights g/mol	-	296	226	153
LHV (kJ/kg) [9]	-	37000	43090	43150

2.3. *Biodiesel blending*

The biodiesel blends prepared for the experiments by mixing the two fuels volumetrically. Biodiesel mixing with diesel and kerosene with no layer separation or emulsions was observed. The physicochemical properties of the blends tested in fuel laboratory, Tables 2and 3.

Table 2: The physicochemical properties of the biodiesel, diesel and it's blends

Properties	Blending range					Limits
	0:100 B100	20:80 B20	35:65 B35	50:50 B50	100:0 D100	
Density kg/m^3	875	855	859	862	850	815-870
Viscosity cSt (40 ^{0}C)	4.92	3.22	3.54	3.86	2.8	2-5
Flash point ^{0}C	176	89	105	121	67	Min60 diesel Min100 biodiesel
Cloud point ^{0}C	4	-1	0	2	-	Max 18
Pour point	2	-3	-2	-1	-7	Max 18
Cetane index	67.4	57.4	59	60.3	53	48-67

Table 3: The physicochemical properties of the biodiesel, kerosene and it's blends

Proper.	Blending range					Limits
	0:100 Bk100	20:80 Bk20	35:65 Bk35	50:50 Bk50	100:0 K100	
Density kg/m^3	875	820	830	841	807	815-870
Viscosity cSt (40 ^{0}C)	4.92	2.1	2.6	3.15	1.38	2-5
Flash point ^{0}C	176	71.2	91	110.5	45	Min60 diesel Min100 biodiesel
Cloud point^{0}C	4	-2	0	2	-	Max 18
Pour point	2	-4	-3	-1	-7	Max 18
Cetane index	67.4	50.2	51.3	52.5	-	48-67

2.4. *The experiments data sheet*

Table 4 show data sheet of each test conditions of fuels and blending including $\dot{m}_{\text{atomiz-air}}$, $\dot{m}_{\text{fuel}}$, ALR and blending ratio for heating load=12.2kW. These values were repeated for five values of equivalence ratio (0.6, 0.8, 1.0, 1.2 and 1.4) during the testes.

Table 4: atomization-air to fuel mass flow rate ratio (ALR) according to the values of mass flow rate of each fuel =12.2kW as heat load.

	ALR=0.6		ALR=0.8		ALR=1.0	
Fuel type	$\dot{m}_{air}$ g/s	$\dot{m}_{fuel}$ g/s	$\dot{m}_{air}$ g/s	$\dot{m}_{fuel}$ g/s	$\dot{m}_{air}$ g/s	$\dot{m}_{fuel}$ g/s
B100	0.198	0.330	0.226	0.330	0.330	0.330
B20	0.175	0.292	0.233	0.292	0.292	0.292
B35	0.179	0.980	0.238	0.980	0.980	0.980
B50	0.183	0.305	0.245	0.305	0.305	0.305
D100	0.170	0.283	0.260	0.283	0.283	0.283
Bk20	0.175	0.290	0.237	0.290	0.290	0.290
Bk35	0.179	0.298	0.238	0.298	0.298	0.298
Bk50	0.183	0.300	0.244	0.300	0.300	0.300
K100	0.169	0.282	0.220	0.282	0.282	0.282

2.5. Burning velocity measurements

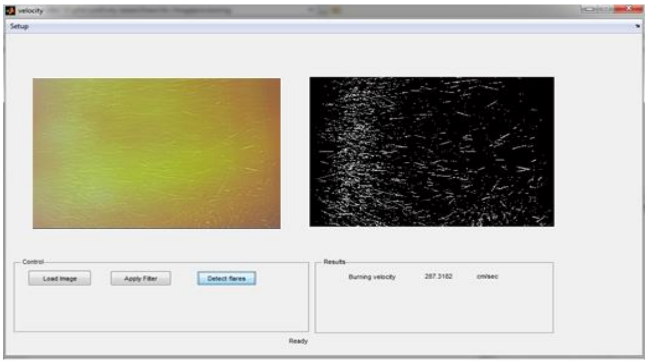
For each test, imaging more three captures to ensure the accuracy of experiments and using the case of low image density (Adrian, 1991) [12], in this case the images of individual particles can be detected clearly to determine the illumination of particles. For photographic and digital techniques the image of particles path had stored on a single image. The images transferred to the computer and analyzed to determine the burning velocities.

To calculate the burning velocity of liquid hydrocarbon fuel heterogeneous continues combustion in air-blast burner setting the mean axial velocity upstream of the turbulent flame brush equal to the burning velocity [14].

$$BV = L / S$$

BV: Burning velocity
L: length of particles path
S: shutter time of imaging

The length of particles path detected, by using laser sheet which clear the illumination of particles (TiO_2) on the frame of camera sensor. The shutter time of imaging is setting manually according to test conditions. The burning velocity calculated after using image processing technique (MATLAB) code on the particles paths images Fig.7 and 8.



Burning velocity 287.3182 cm/sec

Fig.7: PIP image (left) before processing, (right) after processing

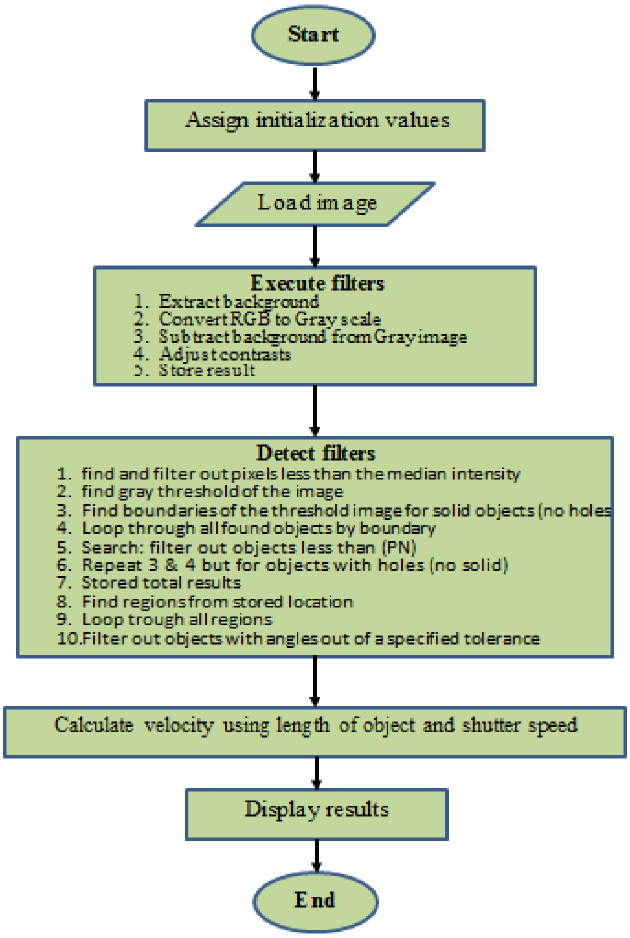


Fig.8: Flowchart of MATLAB program

3. Results and discussion

3.1. Effect of fuel types and blending on burning velocity

The effect of fuel type on burning velocity are illustrated in figures (9) to (17). The results trend of burning velocity generally decreases with biodiesel additives increasing in the blends for all ALR values until Φ=1.2. Figures (11) and (17) show the effect of fuel type on burning velocity at various equivalence ratio at ALR=1.0. It can be observed that the maximum burning velocity of blends observed are B20 and Bk20 at ALR=1.0, due to the low percentage of biodiesel in these blends.

The low volatility and high viscosity of biodiesel caused lower burning velocity, where is directly related to the function ln(1+B) where B is spalding's mass transfer number. The values of transfer number of biodiesel, Diesel and kerosene are 1.41, 2.8 and 3.8 respectively.

On the other hand the number of carbon atoms in biodiesel help to increase the burning velocity, that is the orange color of flame increase the flame radiation to unburned fuel which help to accelerate the evaporation rate of unburned fuel, that is makes the burning velocity of biodiesel and their blends is close to diesel and kerosene at Φ=1.2.

3.2. Effect of ALR on burning velocity

Figures (12) to (14) and (18) to (20) show effect of ALR on burning velocity of biodiesel and their blends at constant equivalence ratio (Φ). It can be observed that the burning velocity of all tested fuels are increases with ALR increase, because higher values of ALR which produced finer droplet size that help to reduce the resident time of evaporation which causes increasing of burning velocity.

The maximum value of burning velocity of blends at B20 and Bk20 are (4.04) and (4.04) m/s at (ALR=1, Φ=1.2) and (ALR=1, Φ=1.0) respectively. Also the results showed that the increasing of ALR is reducing the differences in burning velocity values between B100 and their blends with K100 and D100.

3.3. Effect of equivalence ratio on burning velocity.

Figures (9) to (11) and (15) to (17) show a set of results from the experimental work which summarizes the effect of equivalence ratio on the burning velocity for the experiments fuels at various ALRs.

It can be observed that the burning velocity increases with increasing of the equivalence ratio on the lean side where reaches the maximum value at equivalence ratio (1.0) for blends of K100, D100, Bk50, B50, Bk35 and B35. But for B100, Bk35 and B20 the maximum value of burning velocity where equivalence ratio reach to 1.2. Afterwards it starts to decrease on the rich side of the mixture with increasing of equivalence ratio.

This behavior of burning velocity results depends on the chemical reaction rate and the increasing of partial evaporation that is occurs during the flow of main air stream, as it behaves like temperature in their variation with equivalence ratio.

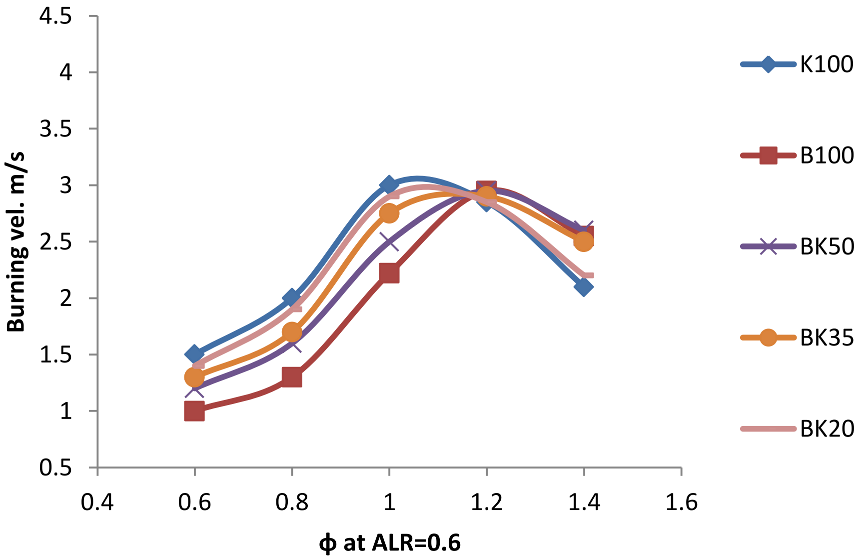


Fig.(9): Variation of Burning velocity (BV) with equivalence ratio (Φ)
at atomization ratio ALR=0.6 of Bk blend.

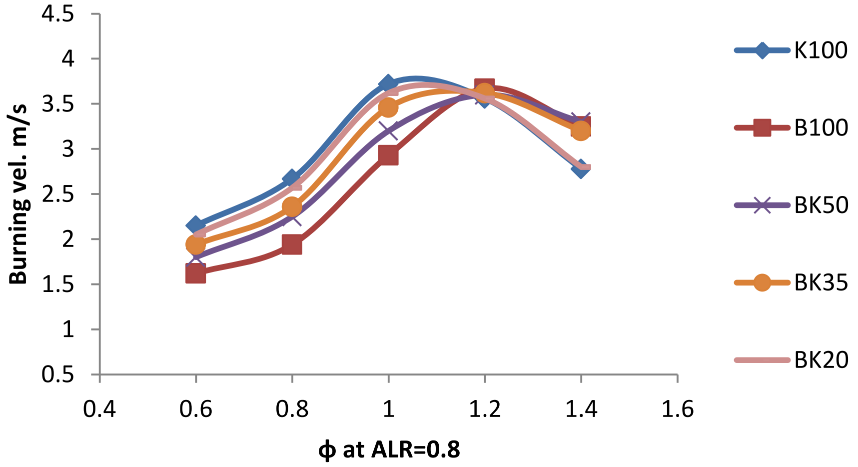


Fig.(10): Variation of Burning velocity (BV) with equivalence ratio (Φ) at atomization ratio ALR=0.8 of Bk blend.

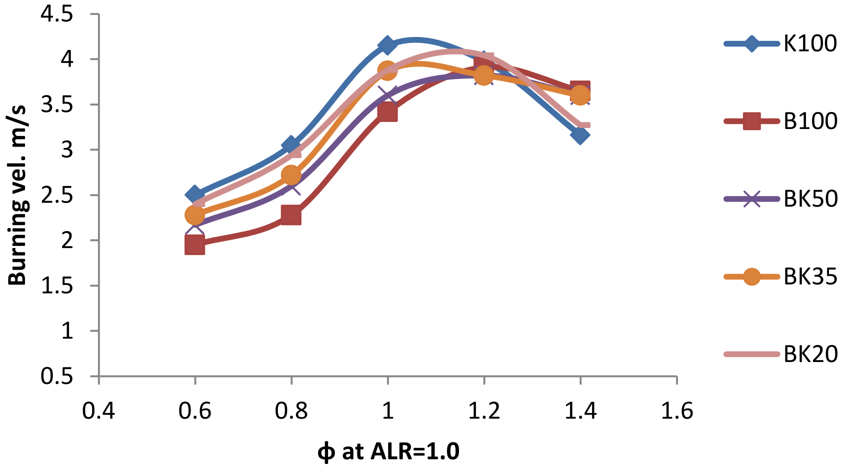


Fig.(11): Variation of Burning velocity (BV) with equivalence ratio (Φ) at atomization ratio ALR=1.0 of Bk blend

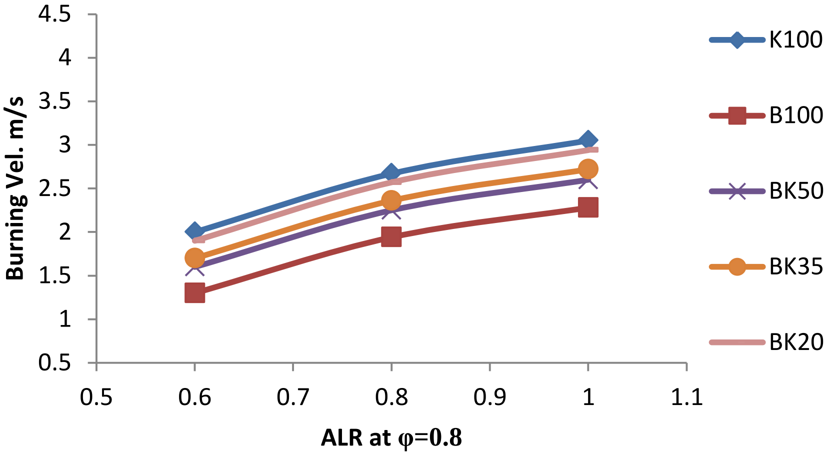


Fig.(12): Variation of Burning velocity (BV) with atomization ratio ALR at (Φ)= 0.8 of Bk blend

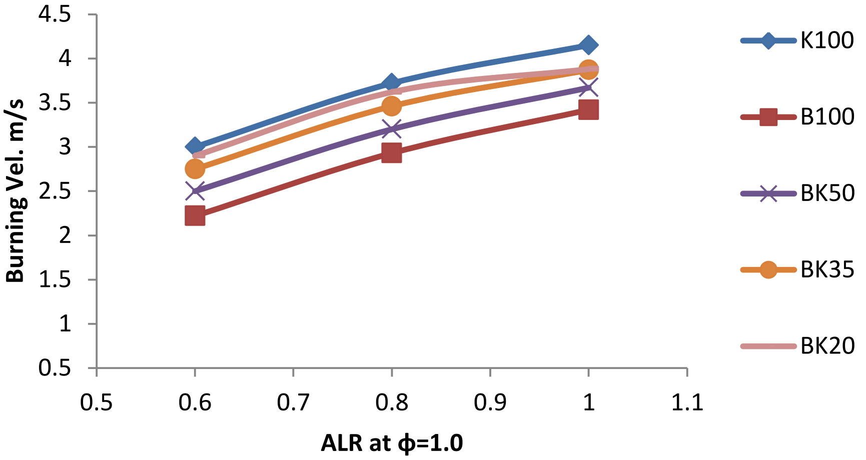


Fig.(13): Variation of Burning velocity (BV) with atomization ratio ALR at (Φ)= 1.0 of Bk blend

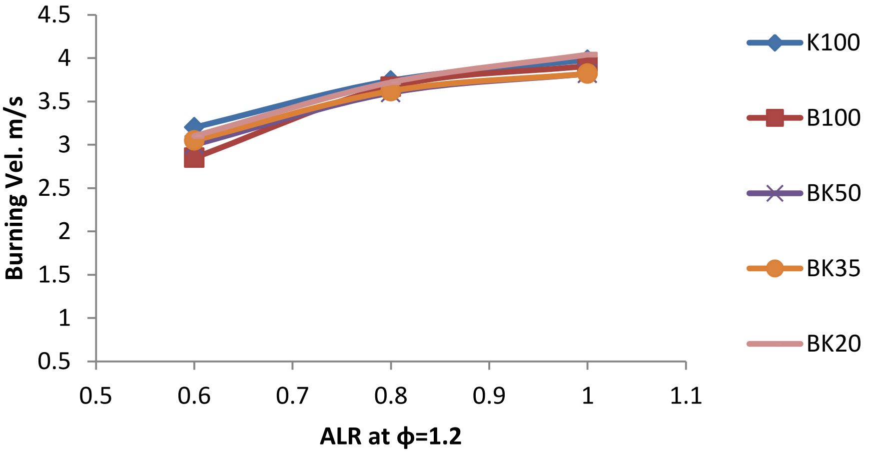


Fig.(14): Variation of Burning velocity (BV) with atomization ratio ALR at (Φ)= 1.2 of Bk blend

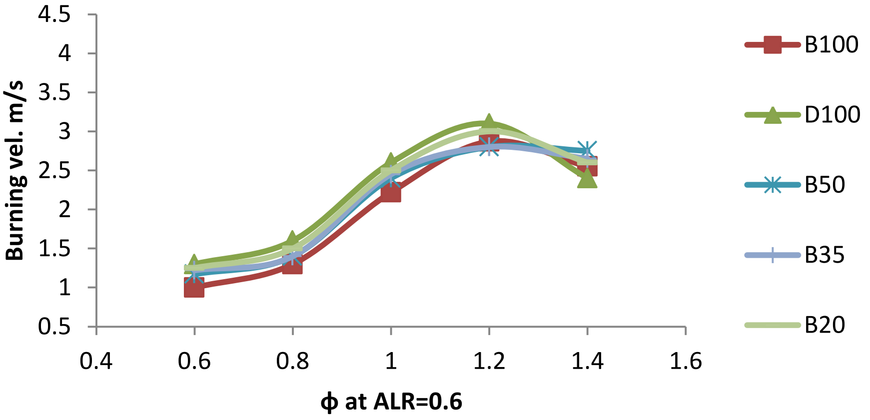


Fig.(15): Variation of Burning velocity (BV) with equivalence ratio (Φ) at atomization ratio ALR=0.6 of B blend

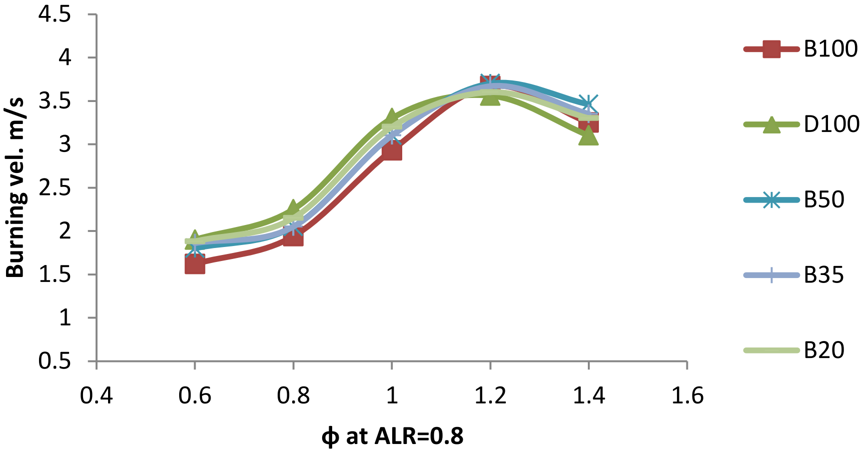


Fig.(16): Variation of Burning velocity (BV) with equivalence ratio (Φ) at atomization ratio ALR=0.8 of B blend

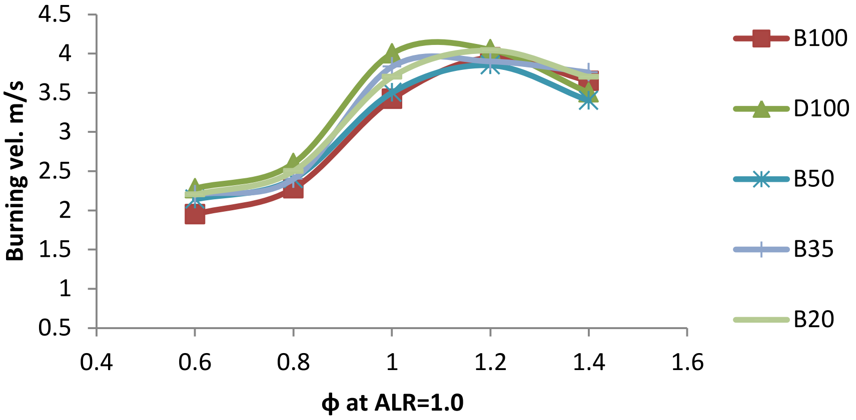


Fig.(17): Variation of Burning velocity (BV) with equivalence ratio (Φ) at atomization ratio ALR=1.0 of B blend

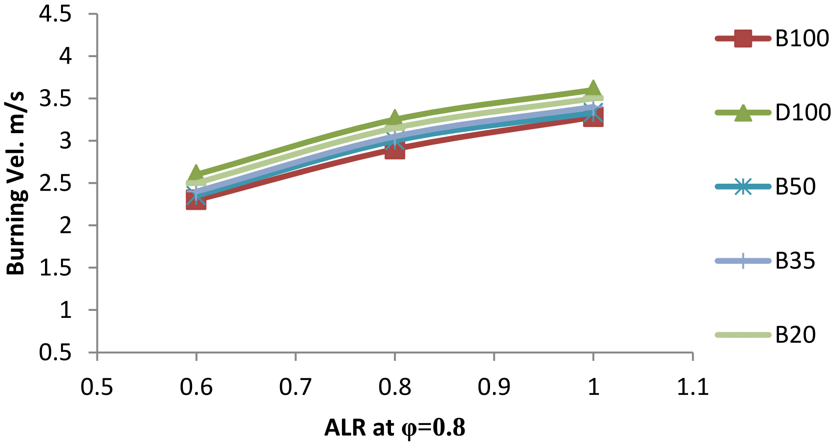


Fig.(18): Variation of Burning velocity (BV) with atomization ratio ALR at (Φ)= 0.8 of B blend

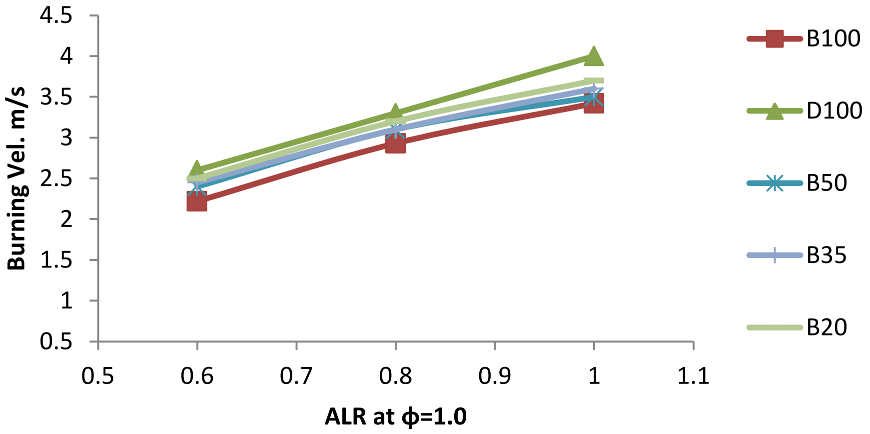


Fig.(19): Variation of Burning velocity (BV) with atomization ratio ALR= at (Φ)= 1.0 of B blend

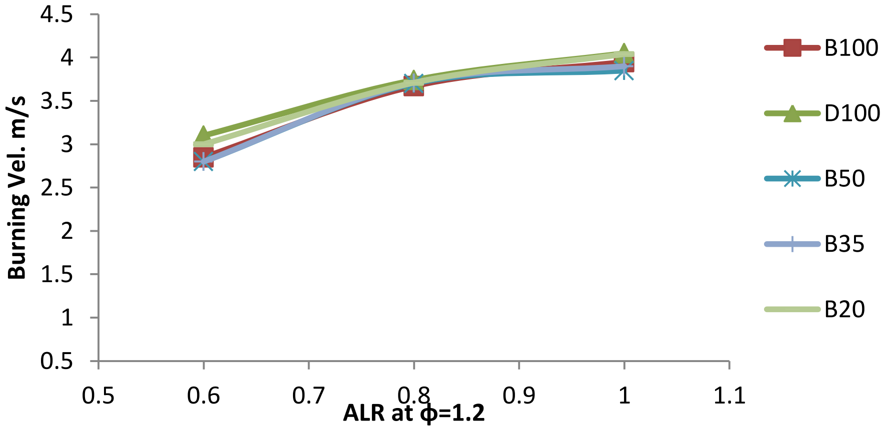


Fig.(20): Variation of Burning velocity (BV) with atomization ratio ALR at (Φ)= 1.2 of B blend

4. Comparisons with the Other Works

In order to verify the validity of the experimental results, the results of the present work plotted together with the published data .

Figures (21) and (22) compares the burning velocity results of B50, Bk50 and B20, Bk20 with other published results of Cheng [9], where the Cheng burning velocity results, convert from laminar burning velocity to turbulent burning velocity by using Balla1 and Lefebvre relation S_T=4S_L [13].

The comparison of results observed that the peak burning velocity of Cheng [9] are 3.34 and 3.32 m/s at equivalence ratio =1.1 for Bk50 and B50. But the maximum burning velocity of present work 3.84 m/s at equivalence ratio= 1.2 for same blends. Also the comparison show, the burning velocity of Cheng is lower than the present work about 0.5 m/s.

The maximum burning velocity of B20 and Bk20 is occurring at same equivalence ratios 1.1 and 1.2 for Cheng [9] and present work respectively.

The maximum burning velocity of B20 and Bk20 are 4.04 m/s, which is higher than Cheng about 0.56 m/s.

Generally, it can be observed that the agreement is well and this ensure the validity of the measurement method and calculations used in this work. These figures show same differences in the values of burning velocity according to the different techniques.

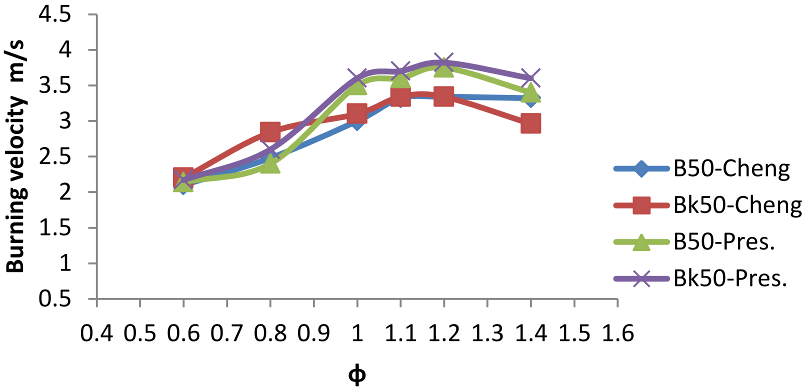


Fig.(21): Comparison of present results (exp.) of burning velocity with the published results.

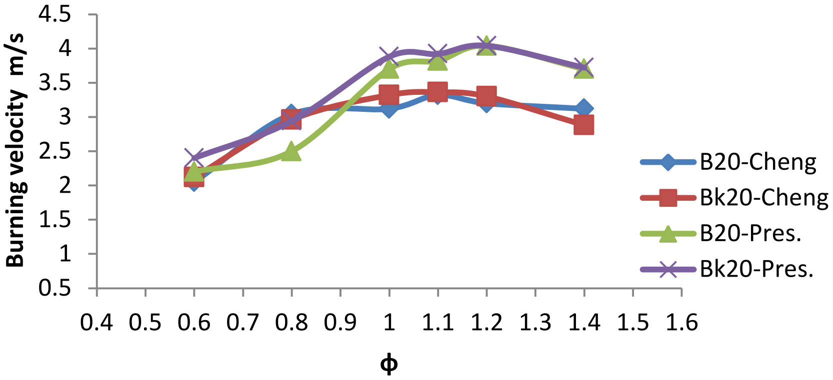


Fig.(22): Comparison of present results (exp.) of burning velocity with the published results.

5. Conclusions

The particles image path (PIP) technique was used to measure the burning velocity of higher hydrocarbon liquid fuels. The results showed good compatibility with literature data. The burning velocity of sunflower methyl esters (SME), kerosene and diesel measurements were performed. Also the burning velocity of (SME) blends with kerosene and diesel at 20%, 35% and 50% by volume at 1 atm. and 301K over a range of equivalence ratios were performed.

Based on the results obtained, the study concluded the following:

1. The results showed a decrease in the burning velocity on the lean side and an increase on the rich side, at the location close the stoichiometric region (Φ=1). Also the reductions of biodiesel percent in the blends increase the burning velocity.
2. The burning velocity of kerosene and its reaction is affected more by the blending of SME than diesel. The lower heating value and higher viscosity of

SME are led to the contradiction of burning velocity and reactivity, compared to kerosene and diesel flame.

3. The investigation above have shown that SME can be used as substitute fuel for boilers and industrial furnaces. SMEs reactivity was found to be comparable to diesel fuel. Despite the slight variation in size of droplets, the biodiesel flame shows an almost same flame shape and length compared to the conventional liquid fuel (kerosene and diesel).

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