Burning Rate Constants and Microexplosion Phenomena Measurements of Droplet Combustion

Basthiyan Sidqi Fidari Rosyadi[1,2], I Nyoman Gede Wardana[2],
Shenqyang (Steven) Shy[1]
[1]Department of Mechanical Engineering, National Central University
[2]Department of Mechanical Engineering, Brawijaya University
Email: basthiyan.sidqi@gmail.com

Abstract

This study investigates experimentally droplet combustion in a quiescent atmosphere using diesel oil (DO), biodiesel oil (BO), and sunflower oil (SO). Symmetrically spherical droplets with diameters varying from 0.3 mm to 0.6 mm are generated by a home-built piezoelectrically-driven droplet generator. Before a run, the small droplet is suspended at the intersection of two very fine horizontally-positioned, perpendicularly-aligned ceramic fibers of 20 µm in diameter. A run begins at a time when a diffusional flame is just established to envelop the suspended droplet using an electrically-controlled and automatically-removed heating device. A high-speed camcorder is used to record the time evolution of droplet burning process. Results show that after flame envelope the droplet where initial diameter (d_0) is determined, DO and BO droplet instantaneous diameters (d) just shrink with increasing time, where plot for d^2-law give linear slope indicate that DO and BO can be assumed as single-component fuel with burning rate constants value, but SO which is multi-component fuels, give two kinds slope from d^2-law plot indicate that there are two value burning rate constants, namely K_1 for first stage of burning rate constant and K_2 for second stage of burning rate constant.

Keywords: *Droplet combustion, Burning Rate Constant, Microexplosion.*

INTRODUCTION

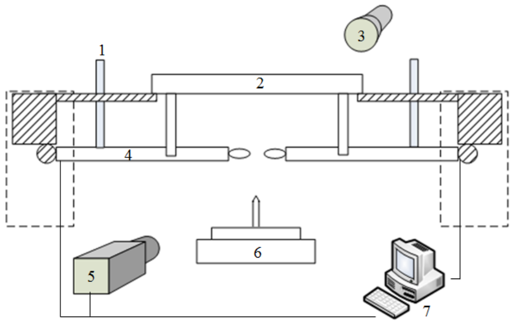
Nowadays, fossil fuel is still mostly favoured among many other sources of energy in the world. It is widely used as source of energy for transportation and machinery due to its high heating power, massive availability and good quality of combustion characteristic.

Unfortunately, the combustion of fossil fuel also takes the main part as contributor to the increase in the level of CO_2 in the atmosphere. The increase gas volume of CO_2 causes greenhouse effect that absorbs certain wave lengths of infrared radiation emitted from earth instead of radiated it out to space. It is directly associated with temperature increase which is called global warming. One of their main concerns is the development of biofuel as fuel source alternative. Many studies have pointed out that biofuel can help reduce emissions of carbon particulates and other harmful substances. The most promising bio-fuel to substitute fossil liquid fuel is vegetable oil which can make bio-diesel and bio-alcohol after a certain processing and their properties are close to petroleum diesel oil (DO). Studying combustion of droplets (single droplet combustion) is important because it can be used to reveal the fundamental characteristics of combustion. Thus, it is helpful to get a better understanding of complicated combustion phenomena, such as those occurred in IC engines. Biodiesel oil (BO) can be produced from straight vegetable oil, animal oil/fats, tallow and waste cooking oil. Biodiesel is biodegradable, nontoxic, and has significantly fewer emissions than petroleum-based diesel when burned. Biodiesel is an alternative fuel similar to conventional or “fossil/petroleum” diesel. Bartle et al. [1] found that the value of burning rate constant for diesel is greater than biodiesel. This result is contrast to study that has been conducted by [2-5] resulting heating value of biodiesel is greater than bio-diesel.

Compared to diesel oil, biodiesel has burning rate constant value greater than diesel oil. This occurs due to the evaporation rate of biodiesel which has a greater value than evaporation rate of diesel oil. Sunflower oil (SO) which is one of vegetable oils where the main composition is polyunsaturated fatty acids, can be assumed as multicomponent fuel because it contains many types of fatty acid. In case of combustion by using more than one components of the droplet (multicomponent), the result is strongly influenced by the evaporation point of each component. It is because some components within the droplets tend to be more volatile than the others. It will disrupt the process of switching diffusion inside the droplets and cause the occurrence of secondary atomization or commonly referred to as a microexplosion. Some experiments have been conducted to study pure vegetable oils droplet combustion. Wardana [6] found that there are two parts occur during combustion process of pure vegetable oil at low elevated temperature by analyse the temperature changes, and microexplosion phenomenon takes place just before the second stage combustion. These microexplosion phenomena lead to oscillation that makes evaporation rate constant hard to calculate [7]. Multicomponent droplet combustion becomes more complex because there are bubble formations, which eventually lead to a rupture in the droplet and microexplosion phenomena [8-11].

EXPERIMENTAL APPARATUS AND METHOD

Droplet experimental consisted of ceramic fiber, droplet generator, high speed camera, and heating system, as shown in Fig. 1. Droplet generated use piezoelectric generator that produce droplet with diameter 0.3~0.6 mm, and put in the horizontally-positioned, perpendicularly-aligned ceramic fibers which has 20 µm in diameter.



1. Magnetic holder.
2. Ceramic fiber holder.
3. Back light source.
4. Heating device
5. Red Lake high speed camera.
6. Droplet generator
7. Computer to control capturing process and heating time duration.

Fig.1 Schematics the experimental setup.

The simplest theoretical case of single-droplet evaporation consists of a liquid droplet surrounded by gas with no motion relative to the droplet with the droplet assumption. The following assumptions for droplet evaporation are [12]:

1. Spherical symmetry: Forced and natural convection are neglected. This reduces the analysis to one dimension.
2. The droplet is an isolated one immersed in an infinite oxidizing environment.
3. Isobaric process.
4. Constant gas-phase transport properties, such as thermal conductivity, density, and specific heat are constant, Lewis number is unity.
5. The chemical reaction rate is much larger than the gas phase diffusion rate , and therefore can be regarded as infinitely small thickness flame (flame-sheet combustion)
6. The droplet evaporation process is quasi-steady. This means that at any instant time, the process can be described as steady state.
7. The amount of fuel gasified at the surface is instantly consumed at the flame, or the instantaneous rate of gasification is equal to that of consumption.
8. Single component droplet.
9. Constant and uniform droplet temperature, with no heating phenomenon
10. Saturation vapor pressure at droplet surface. Gasification at the surface is

at equilibrium. Therefore fuel vapor that produce which is at its saturation vapor pressure corresponding to the droplet surface temperature.

11. Ignore Soret, dufour, and radiation effects.

From these assumptions, by the governing equations and boundary conditions derived d^2-Law, as follow

$$d^2 = d^2 - K\,t$$

This is the d^2-law of droplet vaporization where d_0 is the initial droplet diameter, d is instantaneous droplet diameter, and t is time. This indicates that during this combustion process square of the droplet diameter decrease constant with the reduced time.

RESULTS AND DISCUSSION

Diesel oil

0 Droplet combustion of DO gives linear slope from d^2-law plot. Droplet only shrinking with changing of times indicates that it can be assume as a single component fuels. In Fig. 2 show that direct measurements of droplet instantaneous diameter for d^2-law plot give small oscillations due to buoyancy effect, where MATLAB used to get best fitting line to calculate burning rate constant value with d 0.457 mm. From this d^2-law slope burning rate constant value can be obtained, for d_0 = 0.457 mm, 0.445 mm, 0.396 mm, and 0.339 mm, burning rate constant (K) value are 0.8033 mm²/s, 0.8180 mm²/s, 0.8255 mm²/s, and 0.8284 mm²/s respectively, shown in Fig. 3

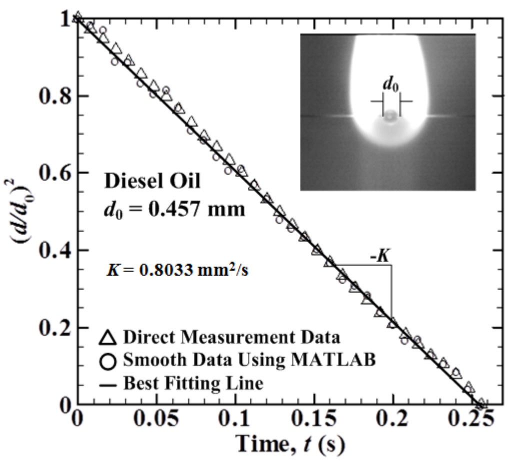


Fig. 2 A typical case showing the determination of the burning rate constant by the d^2-law.

The inset is an instantaneous image of diesel oil droplet enveloped by its flame just after the removal of ignition heating wires. With increasing d_0 burning rate value will decrease, due to diffusion process takes longer time to make droplet completely evaporated. However different initial droplet sizes do not strongly affect droplet burning in free convective environment.

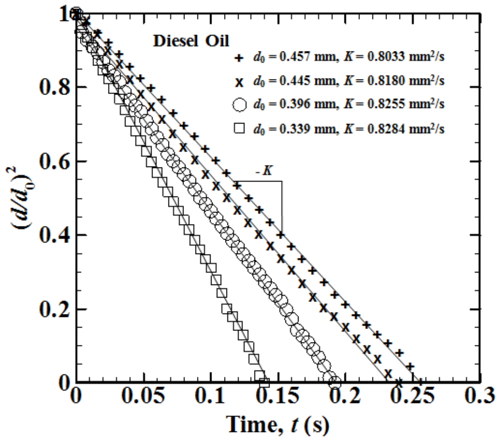
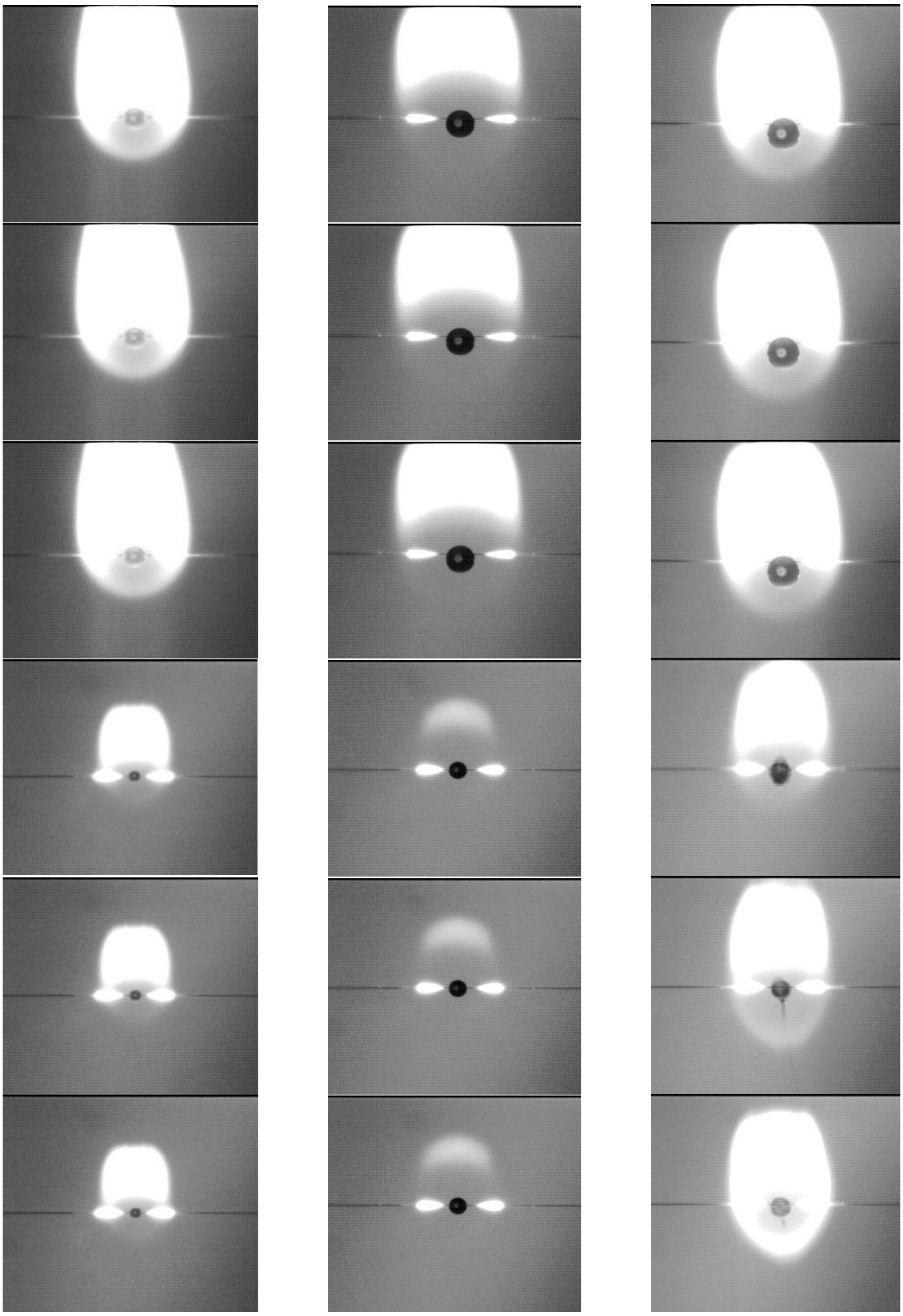


Fig. 3 Determination of the burning rate constants from diameter-square versus time for diesel oil with different initial diameters



a b c

Fig. 4 Droplet combustion sequences for (a) diesel oil (DO), (b) biodiesel oil (BO), and (c) sunflower oil (SO).

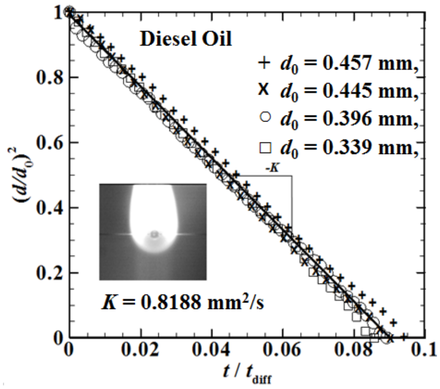


Fig. 5 Dimensionless droplet diameter-square versus time, normalize with time diffusion for diesel oil, where $t_{diff} = d^2/\alpha$ and α is thermal diffusivity of commercial diesel oil.

Droplet combustion sequences for DO, BO, and SO are shown in Fig. 4. Where DO have more bright color compare to BO and SO indicate that a lot of soot generated at combustion product. And Physical properties comparison for diesel, biodiesel and sunflowers oil showed at Table 1.

Table 1. Physical properties comparison for diesel and sunflowers oil from [13-16]

Properties	Diesel Oil	Biodiesel Oil	Sunflower Oil
Density at 15⁰C (g/cm³)	0.82	0.881	0.860 - 0.918
Boiling point (⁰C)	~162	204	~320
Flash point (⁰C)	52	177	274
Higher Heating Value (MJ/kg)	44.8	39.4	33.5
Cetane Number	52	51.2	37
Thermal Diffusivity (10^{-7} m²/s)	0.715	0.843	0.57

By dividing time with diffusion time (t_{diff}), where diffusion time (t_{diff}) defined as droplet initial diameter square (d^2) divided thermal diffusivity (α) of diesel oil. The diameter- square plot can be collapse together, indicate that diffusion process plays an important role on droplet combustion, shown in Fig. 5. slope burning rate constants value can be obtained, for d_0 = 0.542 mm, 0.496 mm, 0.428 mm, 0.323 mm burning rate constant (K) are 0.8851 mm²/s, 0.8911 mm²/s, 0.9028 mm²/s, and 0.9152 mm²/s respectively. By normalize time with diffusion time (t_{diff}), where diffusion time (t_{diff}) defined as droplet initial diameter square (d^2) divided thermal diffusivity (α) of biodiesel oil, the diameter-square plot.

Biodiesel oil

Biodiesel droplet combustion give linear slope like diesel oil from d^2-law plot, indicate that it is can be assumed as single-component fuel with burning rate constants value. However there are small disturbance as it approached at the end of the combustion process, due to small amount of double bond or more concentration in this biodiesel leading swell and puff at nearly end of the combustion process.

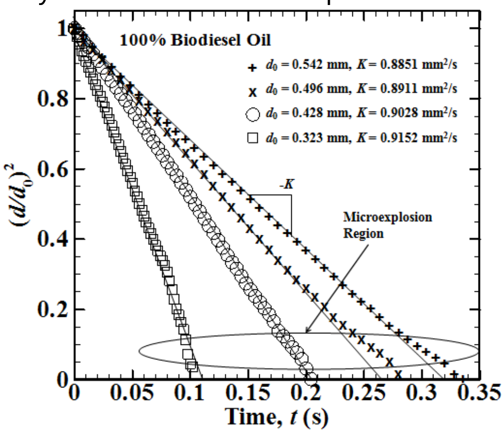


Fig. 6. Determination of the burning rate constants from diameter-square versus time for biodiesel oil with different initial diameters

From this d^2-law plot still can be collapsed together, indicate that diffusion process plays an important role on droplet combustion as shown in Fig. 7.

Nevertheless different initial droplet sizes do not strongly affect droplet burning in free-convective environment. Compare to DO, BO has higher burning rate value because there are no present of free fatty acids, only small concentration of double bond and methyl linoleic acid which has triple bound.

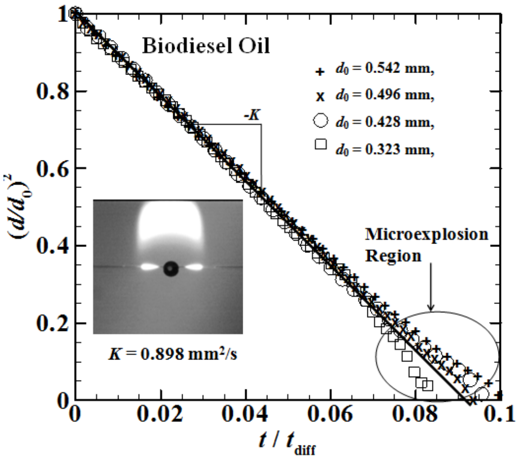


Fig. 7 Dimensionless droplet diameter-square versus time, normalize with time diffusion for diesel oil, where $t_{diff} = d_0^{2}/\alpha$ and α is thermal diffusivity of commercial biodiesel oil.

Sunflower oil

Combustion of pure sunflower gives more oscillation from direct measurement data shown in Fig. 8. Fats and oils are esters of the tri-alcohol, glycerol (or glycerin). Therefore, fats and oils are commonly called triglycerides and its make up the structure of sunflower oil. They are primarily composed of long chains of fatty acid esters. Triglyceride molecules contain mostly carbon and hydrogen atoms. They are similar to the hydrocarbons in petroleum. The properties of triglycerides depend on the fatty acid composition and relative location of fatty acids on the glycerol, so that sunflower oil called multi- component fuel. Fatty acids contain an even number of carbon atoms, from 4 to 36, bonded in an unbranched chain.

Table 2. Fatty acids in Sunflower oil.

Fatty Acid	wt %	Structure	Formula	Boiling Point (^{0}C)
Linoleic	74	18:2	$C_{18}H_{32}O_2$	230
Oleic	17	18:1	$C_{18}H_{34}O_2$	360
Palmitic	6	16:0	$C_{16}H_{32}O_2$	350
Stearic	3	18:0	$C_{18}H_{36}O_2$	382

Most of the bonds between carbon atoms are single bonds. If all of these bonds are single bonds, the fatty acid is said to be saturated, because the number of atoms attached to each carbon atom is the maximum of four. If some of the bonds between carbon atoms are double bonds, then the fatty acid is unsaturated. When burned unsaturated fatty acids give higher value compare to the saturated fatty acids. The fatty acid compositions of sunflower oil are shown in table 2. Where the high concentration is linoleic 74 wt.%, oleic 17 wt.%, palmitic 6 wt.%, stearic 3 wt.%.

MATLAB give best fitting line to calculate burning rate constant. Sunflower oil give two kinds of slope from d^2-law plot, namely first stage burning rate constant (K_1) and second stage burning rate constant (K_2), where K_2 value is greater than K_1 due to swell puff and microexplosion phenomenon occur at the later stage of droplet combustion. During heating process high volatile component or linoleic fatty acids evaporate at the first place then ignite and generated flame that envelope the droplet, because linoleic fatty acids has small boiling point and greater percentages of weight in sunflower oil. Low level of volatile component uses the temperature from flame to increase it temperature up to a superheating state, form bubble inside the droplet. When heated to superheated, bubbles will be formed in the nearly center of the droplet, increase the volume of the droplet this process is called homogeneous nucleation. On the other side sunflower oil is a triglyceride base fuel, where 3 different fatty acids attach to glycerin molecule. During combustion process droplet triglycerides will absorb water vapor product from combustion process to break it become fatty acid and glycerin which is the well-known the hydrolysis process. Due to flame that envelope the droplet, temperature inside droplet increase lead to.

When glycerin breaks from fatty acid, glycerin can rapidly absorb water even at room temperature. Water that absorb by glycerin evaporated together with low level of volatile component begin to evaporate. Water bubble and low level of volatile component move inside droplet not only because the buoyancy but also ceramic fiber effect. When bubble reach the surface of the droplet, it break up droplet surface and ejecting amount fuel including vapor of low level volatile component, that burn quickly called microexplosion. This phenomena lead to second stage burning rate constant has higher value than first stage burning rate constant (K_2>K_1). The initial droplet diameter (d_0) for pure sunflower oil case is 0.621 mm, 0.592 mm, 0.533 mm, 0.459 mm, and 0.408 mm, In Fig. 9 show increasing droplet initial diameter first stage burning rate constant (K_1) decrease, this is refer to diesel oil where diffusion process takes longer time to make droplet evaporate completely. But for second stage of burning rate constants increasing droplet initial diameter will increasing burning rate constants value due to increasing low volatile component inside the droplet lead to swell, puff, and microexplosion rapidly occurs.

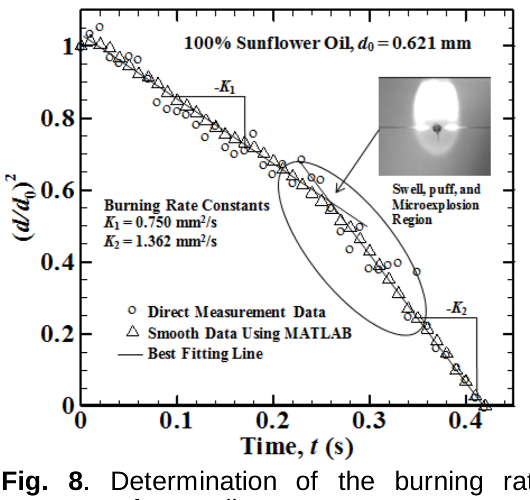


Fig. 8. Determination of the burning rate constant from direct measurement and smooth data using MATLAB of d^2-law for sunflower oil case at d_0 = 0.621 mm

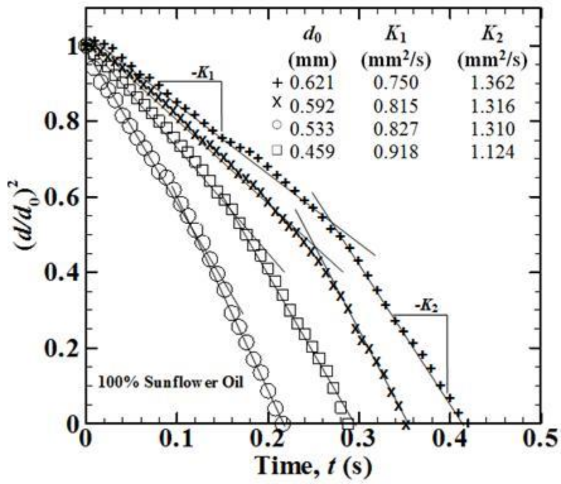


Fig. 9. Determination of the burning rate constants from diameter-square versus time for sunflower oil with different initial diameters.

MATLAB give best fitting line to calculate burning rate constant. Sunflower oil give two kinds of slope from d^2-law plot, namely first stage burning rate constant (K_1) and second stage burning rate constant (K_2), where K_2 value is greater than K_1 due to swell puff and microexplosion phenomenon occur at the later stage of droplet combustion. During heating process high volatile component or linoleic fatty acids evaporate at the first place then ignite and generated flame that envelope the droplet, because linoleic fatty acids has small boiling point and greater percentages of weight in sunflower oil. Low level of volatile component uses the temperature from flame to increase it temperature up to a superheating state, form bubble inside the droplet. When heated to superheated, bubbles will be formed in the nearly center of the droplet, increase the volume of the droplet this process is called homogeneous nucleation. On the other side sunflower oil is a triglyceride base fuel, where 3 different fatty acids attach to glycerin molecule. During combustion process droplet triglycerides will absorb water vapor product from combustion process to break it become fatty acid and glycerin which is the well-known the hydrolysis process. Due to flame that envelope the droplet, temperature inside droplet increase lead to.

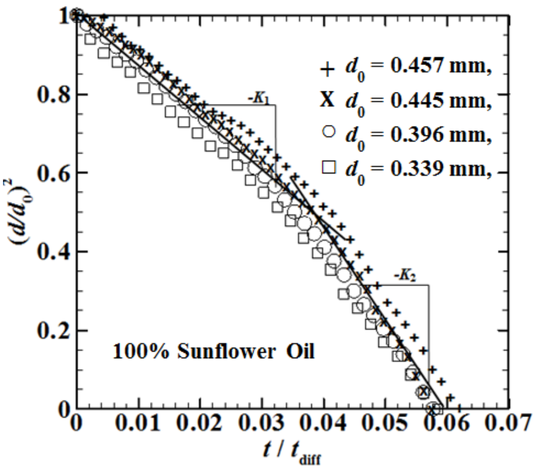


Fig. 10. Dimensionless droplet diameter-square versus time, normalize with time diffusion for diesel oil, where $t_{diff} = d_0 / \alpha$ and α is thermal diffusivity of commercial sunflower oil.

When glycerin breaks from fatty acid, glycerin can rapidly absorb water even at room temperature. Water that absorb by glycerin evaporated together with low level of volatile component begin to evaporate. Water bubble and low level of volatile component move inside droplet not only because the buoyancy but also ceramic fiber effect. When bubble reach the surface of the droplet, it break up droplet surface and ejecting amount fuel including vapor of low level volatile component, that burn quickly called microexplosion. This phenomena lead to second stage burning rate constant has higher value than first stage burning rate constant ($K_2 > K_1$). The initial droplet diameter (d_0) for pure sunflower oil case is 0.621 mm, 0.592 mm, 0.533 mm, 0.459 mm, and 0.408 mm, In Fig.9 show increasing droplet initial diameter first stage burning rate constant (K_1) decrease, this is refer to diesel oil where diffusion process takes longer time to make droplet evaporate completely. But for second stage of burning rate constants increasing droplet initial diameter will increasing burning rate constants value due to increasing low volatile component inside the droplet lead to swell, puff, and microexplosion rapidly occurs.

Normalize of sunflower oil burning time by dividing time with diffusion time (t_{diff}), that shown in Fig. 10, where diffusion time (t_{diff}) defined as droplet initial diameter square (d_0^{2}) divided thermal diffusivity (α) of sunflower oil. The diameter-square plot nearly can be collapse together. Due to oscillation from bubble motion and microexplosion phenomena, indicate that diffusion process still plays an important role on droplet combustion.

Conclusions

1. Diesel oil (DO) and biodiesel oil (BO) droplet combustion give single linear slope from d^2-law plot indicated these oils can be assuming as a single component fuel.
2. Biodiesel oil has higher burning rate constants than diesel oil because there are no present of free fatty acids, only small concentration of double bond and methyl linoleic acid which has triple bound.
3. Sunflower oil (SO) is triglycerides fuels. When triglycerides react with water from combustion product, it will break become fatty acids and glycerine which is the well-known the hydrolysis process. When glycerine is formed it will absorb more water that produce from combustion product. Lead to water vapour form inside the droplet. Burning pure sunflower oil give two kinds of slope from d^2-law determination, because sunflower oil can be assume as multi-component fuels, which has different volatility of free fatty acids component, lead to swell, puff, and burn quickly that called microexplosion.

References

[1] Bartle, K.D., Fitzpatrick, E.M., Jones, J.M., Kubacki, M.L., Plant, R., Pourkashanian, M., Ross, A.B., and Williams, A., 2011, “The combustion of droplets of liquid fuels and biomass particles”, *Fuel*, Vol.90, 1113–1119.

[2] Boteroa, M.L., Huanga, Y., Zhu, D.L., Molina, A., and Law, C.K., 2012, "Synergistic combustion of droplets of ethanol, diesel and biodiesel mixtures", *Fuel*, Vol.94, 342–347.

[3] Pan, K.L, and Chiu, M.C., 2013, “Droplet combustion of blended fuels with alcohol and biodiesel/diesel in microgravity condition”, *Fuel*, Vol.113, 757–765.

[4] Zhu, M., Ma, Y., and Zhang, D., 2013, “Effect of a homogeneous combustion catalyst on combustion characteristics of single droplets of diesel and biodiesel” *Proceedings of the Combustion Institute*, Vol.34, 1537–1544.

[5] Li, T.X., Zhu, D.L., Akafuah, N.K., Saito, K., and Law, C.K., 2011, "Synthesis, droplet combustion, and sooting characteristics of biodiesel produced from waste vegetable oils", *Proceedings of the Combustion Institute*, Vol.33, 2039–2046.
[6] Wardana, I.N.G., 2010,"Combustion characteristics of jatropha oil droplet at various oil temperatures", *Fuel*, Vol.89, 659–664.
[7] Daho, T., Vaitilingom, G., Sanogo, O., Ouiminga, S.K., Segda, B.G., Valette, J., Higelin, P., and Koulidiati, J., 2012, "Study of droplet vaporization of various vegetable oils and blends of domestic fuel oil cottonseed oil under different ambient temperature conditions", *Biomass and Bioenergy*, Vol.46, 653-66.
[8] Hou, S.S., Rizal F.M., Lin T.H., Yang T.Y., and Wan H.P., 2013, "Microexplosion and ignition of droplets of fuel oil/bio-oil (derived from lauan wood) blends", *Fuel*, Vol.113, 31–42.
[9] Mishra, D.P., and Patyal, A., 2012, "Effects of initial droplet diameter and pressure on burning of ATF gel propellant", *Fuel*, Vol.95, 226-233.
[10] Nam, H., and Alvarado, J.L., 2012, "Microexplosion detection hexadecane and vegetable oil blend", Spring technical meeting of the central states section of the combustion institute, 22-24.