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AN OVERVIEW OF EXPERIMENTAL TECHNIQUES OF THE INVESTIGATION OF WATER-DIESEL EMULSION CHARACTERISTICS DROPLETS MICRO-EXPLOSION

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ABSTRACT

Emulsified fuels considered as a promising alternative fuel that could solve and meet the increasingly stringent emission regulations for diesel engines due to their capability of reduction the harmful exhaust emission, such as carbon monoxide (CO), nitrogen oxides (NOx) and particulate matter (PM). The admission of water into the diesel fuel has significant advantages. One of these advantages is the possibility of occurrence of the so-called micro-explosion phenomena. There is a number of experimental techniques and visualization systems to investigate and analyse the uses of the water-diesel (W/D) emulsion fuel, especially regarding micro-explosion phenomena. Micro-explosion is the rapid breakup of fuel droplets and hence burst into smaller droplets which enhance fuel evaporation and hence improving the air-fuel mixing process. An investigation of micro-explosion of the smaller droplets is important. This review paper discussing the advantages of using the emulsion fuel and the different experimental techniques used to detect the micro-explosion phenomena in addition to the factors affecting the onset of micro-explosion processes and proposes potential research areas for W/D emulsion fuel studies. Most of the studies in the literature agree that W/D does result in a reduction in NOx and PM exhaust gas emissions. There is, however, some inconsistencies of the experimental techniques with respect to the heating process which affects the onset and the strength of the micro-explosion process. The factors that affect the micro-explosion phenomena consist of different parameters such as the distribution of the water in the emulsion, the size of the emulsion droplet, type and percentage of the surfactant, ambient temperature and pressure.

Keywords: water-diesel emulsion, micro-explosion, droplet, spray, surfactant.

INTRODUCTION

Diesel engines generally considered a useful in a variety of applications, such as power generation, transportation, agriculture, drilling machines, and elsewhere. This is mainly due to diesel engines poses the advantages of direct injection and compression ignition combustion system. The advantages of using direct injection compression ignition engines (DICIEs) can be traced to the high compression ratio and beside that it does not require air throttling to operate under part load operation [1]. The global air pollution deteriorated by the emissions coming from the internal combustion engines is very seriously. Correspondingly, interest is growing to develop and improve both the engines and the fuels to reduce the exhaust emissions of the regulated pollutants. especially gasses related to the diesel fuel combustion engines are nitrogen oxide (NOx), hydrocarbon (HC) and carbon monoxide (CO) which affect the environment [2][3]. Therefore, the development of alternative fuels such as an emulsion fuels to be used in the engines has been a major concern of the researchers and automotive centres since they are cleaner as compared to conventional fuels. This resulted in an increased interest to use alternative fuels in internal combustion engines. Strategies to reduce emissions from the combustion of diesel fuel such as improvement of the diesel fuel as it poses the requirement of the combustion characteristics. One of the possible and promising way for reducing both nitrogen oxides (NOx) and particulate matter (PM) in diesel engines, the uses of the water into the diesel engines have been investigated and developed by different researchers [2], [4], [5]. As an increase in the percentages of water in the diesel engines, will result in weakens luminous flames and decrease the peak temperature in combustion phase and hence lower NOx emission [2][4]. The possibility of inducing water to modify the combustion of diesel engines is via three common methods: (i) water injection into the pathway [6], (ii) direct injection of water into the combustion chamber [7] and (iii) emulsification of water and liquid diesel before injection into the chamber [3][8]. Emulsification of fuel is considered a favourable method, which can potentially solve this problem. This method is offering the capability of vaporization of the water inside the combustion chamber and hence reducing NOx emission. On the other hand, emulsion combustion is not only favourable to solve the problems of air pollution; it also provides an effective utilization of energy as the phenomena of micro-explosion take place. The micro-explosion phenomena occurrence during the combustion process of water emulsified diesel fuel (due to the drastic volatility difference between the different phases of the fuel) enhances their burnout by enhanced atomization and resulted in a reduction of the emitted hydrocarbons. Due to the differences in the density and hence evaporation rates of liquid diesel and water, the water molecules reach their superheated stage faster than the diesel, creating vapour expansion breakup. At this stage, two phenomena occur: micro-explosion and puffing [9]. The process of heat and mass transfer are completely responsible for the onset of puffing and/or micro-explosion of water admitted in the oil as well as the coalescence and phase separation. Experimental data is useful to characterize the spray combustion of the water emulsified diesel fuel, including the micro-explosion or puffing phenomena [10]. From this point of view, it is necessary to have an extensive review of the previous studies using different techniques to determine the emulsification characteristics of water in diesel and its effects on micro-explosion occurrence. The present review paper starts with the basic types of the emulsion, methods used for detecting the micro-explosion phenomena and the effect of the phenomena on the spray characteristics. These techniques are critically reviewed and analysed.

Water–diesel emulsions

Emulsions, being liquids, mixtures of two or more substances immiscible in nature. In water in diesel (W/D) emulsions, water is present as droplets or dispersed phase and entrapped within larger diesel oil, distributed throughout the droplets that in turn are dispersed in a continuous water phase. The emulsion can be generated using a mechanical stirrer or homogenizer [11]. Figure-1 shows the water dispersed phase. The preparation of emulsion procedure involved mixing process depend on the dispersed water droplets, can be characterized to: macro-emulsions, micro-emulsions, and nano-emulsions. In a macro emulsion, the particles size of the dispersed phase are large compared to the others, and hence, the interfacial surface per unit volume is lower. In this category, the droplet size ranges between 0.4-1μm while in micro-emulsions and nano-emulsions they range between 0.4-0.1 and<0.1 μm respectively.

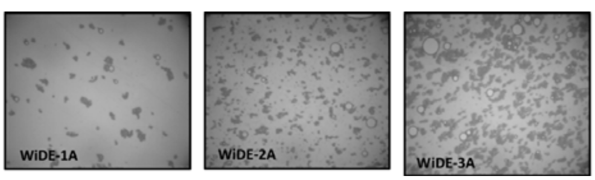

Figure-1. Images of W/D emulsion samples depicting droplet distribution [11].

Emulsion fuel stability

The phase separation of the emulsion plays an important role in the engine operation. Normally, W/D emulsions fuel can maintain their stability from 2 weeks [12] up to 6 months [13]. The emulsion stability can be defined as the process by which an emulsion completely separates into bulk oil and water phases. This process is governed by four mechanisms: creaming, disproportionation, Brownian flocculation and sedimentation flocculation. Figure-2 shows these process schematically. [14].

Micro-explosion phenomena

The micro-explosion phenomenon was first noticed by Michel A. Saad [15] in 1956 and later by Ivanov and Nefedov [16] in 1962. They reported that micro-explosion is the rapid breakup of fuel droplets and hence burst into smaller droplets which enhance fuel evaporation and hence improving the air-fuel mixing process. Enhances of the combustion process by present of water improving fuel atomization by micro-explosion phenomena as well as a reduction of the emitted hydrocarbons. [17], [18]. Beside the volatility of the base fuel, the type of surfactant, water content, the droplet size of the dispersed water and the ambient conditions surrounding the droplet i.e. pressure and temperature are play an important role in the occurrence of the micro-explosion phenomena [18]. Due to the difference in the density and hence evaporation rates of liquid diesel and water, the water molecules reach their superheated stage faster than the diesel, creating vapor expansion breakup by either micro-explosion and/or puffing [5, 6]. Furthermore, studies have already been visualizing the spray combustion, showing a decrease by half of the mean diameter of droplets compared to a non-emulsified liquid fuel [21]. Among a spray of droplets, the secondary atomization is the effect of puffing or micro-explosion phenomena individually.

Recently, a large scientific effort has been devoted to the visualization of the phenomenon of micro-explosion. However, in the literature, a number of techniques were used to detect the micro-explosion phenomena. In terms of visualizing the single droplet emulsion, the experimental techniques are several and are classified in terms of heating systems, droplet size and the visualization technique: Leidenfrost (droplet suspended on the thermocouple wire on a hot-plate), suspended droplets on a hot air and the dropping tower techniques.

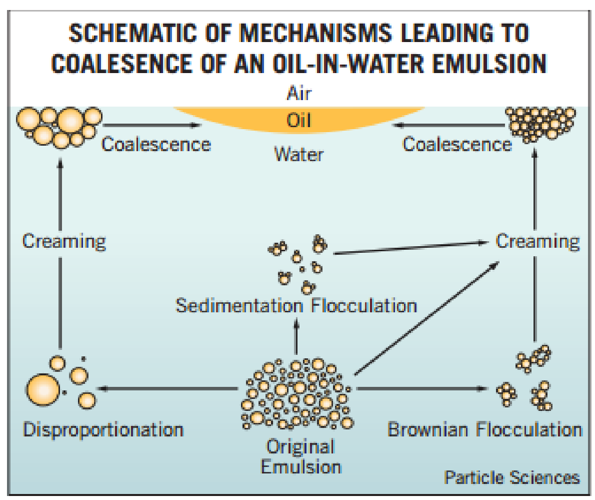

Figure-2. Different droplet loss mechanisms [14].

Leidenfrost technique

The technique of the heating surface is considered as a possible way to detect the micro explosion phenomena. In this technique, the droplet is suspended on a thermocouple over a hot plate, and due to the effect of the temperature, levitates on its own vapor and retains a spherical shape [22]. In order to get the micro-explosion phenomena of

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water emulsified oil, the droplet is disrupted after puffing occurs several times while the micro explosion does not always occur. Its occurrence depends on a number of parameters: distribution of droplet size, water content volume/ oil and the surfactant type and quantity that determines the repulsion forces between droplets of the dispersed phase [17]. An investigation on the effect of the size of the dispersed water droplets in the W/D emulsion were visualized to capture the micro-explosion phenomena using Leidenfrost technique was carried out by [23]. The droplets were placed using a syringe where the thermocouple was located at 0.25 mm at the center of the hot plate and it was maintained at 363 ^{o}C. The authors noticed that the size distribution of the dispersed water droplets had a significant effect on the temperature for micro-explosion, timing of the phenomenon and oil–water phase separation within the droplet that favours puffing and micro-explosion phenomena. When W/D emulsion is subjected to a heating process, the phase separation phenomena is accelerated because of the increased mass transfer, the decrease in viscosity of the continuous phase, and the loss of efficiency of the surfactant. If the emulsion is unstable enough, this phenomena can occur on the timescale of the evaporation and combustion of a droplet, leading to coalescence and micro explosion [24]. An investigation on the effect of the stability of emulsion on micro-explosion for water-in-oil emulsions using Leidenfrost effect was conducted by [25]. A micro-syringe was used to drop 0.700–1.10 mm diameter droplet on a thermocouple. The authors recommended that in order to attend a high frequency of micro-explosion phenomena, a narrow and small droplet size containing (0.1) water/volume fraction with a (0.75%) amount of surfactant must be used. The aggregation process of dispersed water droplets of W/D emulsion under a heating process was visualized and investigated by [26]. A micro-syringe as well as the thermocouple were used to suspend the droplet to address the effect of aggregation on secondary atomization as well as the characteristics of the micro-explosion. The temperature histories for micro-explosion, puffing, and evaporation of the emulsion was recorded as shown in Figure-3.

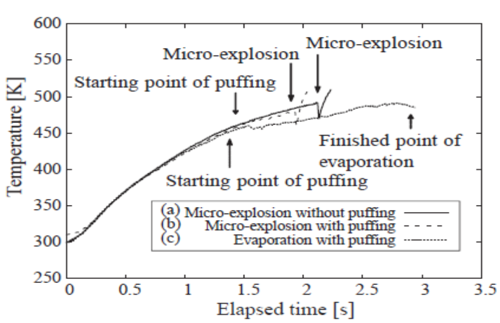

Figure-3. Temperature records of emulsified fuel droplets with secondary atomization [26].

Recently, a visualization of W/D emulsion micro-explosion droplets using Liedenfrost effect was conducted by [11], the emulsion samples were prepared by blending (mechanical stirrer and homogenizer) distilled water into the commercial diesel fuel at water ratios of 5%, 10%, and 20% by/volume. The results showed that, a clear micro explosion was observed for all samples of mechanically stirred emulsions as shown in Figure-4. Concerning the influence of the characteristics of the dispersion of water droplets and droplet size, it was found that a larger particle had a faster rate of coalescence which led to micro-explosion initiation. Although, different studies focused on the investigation of the vaporization and burning behavior of individual emulsion droplets undergoing puffing or micro-explosion using Leidenfrost effect, another technique is to deposit the child emulsion drop onto a concave heated surface. This technique allows the emulsion droplet to avoid any contact with a solid surface promoting heterogeneous nucleation under a hot atmosphere as argued by [27]. In order to measure the child droplets, an IR camera and statistical methods were applied to both the child droplet on the plate and on the fly respectively. Their results showed that a normal thermal energy distribution was significant among all the droplets. From the previous studies it was clearly noticed that, the coalescence and/or phase separation of emulsion fuel during heating process was an important issue in the micro-explosion existence and brings about an indication of the role of emulsion stability on micro-explosion, in a free-falling droplet on a hot plate experiments. On the other hand, the suspended droplet experimental technique is completely different from those experiments in which the droplets fall on a hot plate in terms of droplet size and heating system.

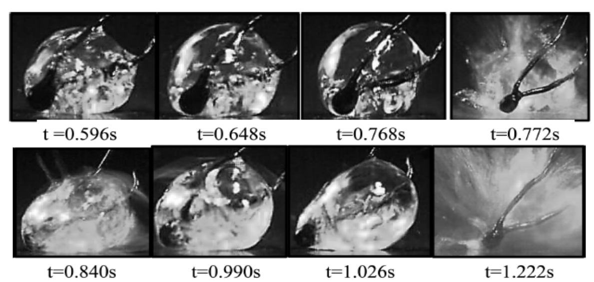

Figure-4. Sequence of images showing micro-explosion behavior of case A WiDE [11].

SUSPENDED DROPLET EXPERIMENTS

Suspended droplet experiments were performed in a number of different cylindrical single drop combustion chamber using optical systems [20, 21]. Studies on a hot-air chamber reflecting the real diesel engine condition using the suspended droplets is not new, Michel 1956 [15] was the first to propose this technique and developed a furnace to visualize the freely suspended droplet of kerosene, hydrocarbon, n-heptane and isooctane with the diameters of between 1.5 and 0.3 mm on a hot air up to 926 ^{o}C. Wang [30] designed a high-temperature furnace which was maintained at 1000 ^{o}C. An emulsion of water and n-heptane, n-decane, n-dodecane, n-hexadecane, and isooctane to investigate the micro-explosion phenomena.

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Droplets with a diameter of 0.33 and 0.43 mm were generated using a steam generator and were freely induced into the furnace. The captured images showed that a clear micro-explosion was observed for fuels whose boiling points were sufficiently higher than that of water. In contrast, the surfactants had significant effect to drive up the droplet temperature to exceed the limit of superheat of water. An investigation of water/oil emulsion droplet by D. Segawa *et al.,* [31], argued that the occurrence of the micro-explosion Phenomena affected by the coalescence or phase separation factor, with an increase in the droplet temperature, a clear phase separation and resulted in the micro-explosion phenomena.

An electrical furnace maintained at 860 ºC at atmospheric ambient pressure was used to visualize micro-explosion phenomena argued by [32]. In their experiment, a single droplet was suspended and placed manually, quickly into the electric furnace chamber using a quartz bar 0.6 mm diameter. Their results showed a clear micro-explosion as well as an increase in the combustion speed. The design of the chamber is as shown in Figure-5.

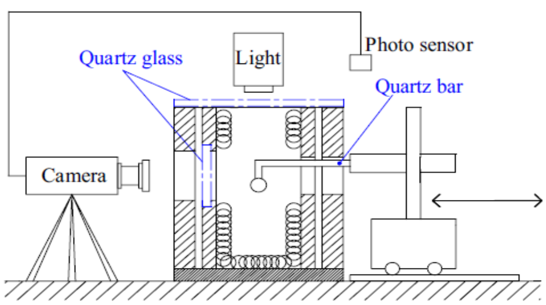

Figure-5. Experimental apparatus for suspended droplet combustion [32].

The captive droplet technique was used by [33], it has the advantages to present the droplets behavior over the whole period where radiation is the dominant mode of heat transfer. A set-up consisting of a furnace and visualization system, and an image processing were used to study the single suspended droplet combustion. A visualization system was used to capture the breakup behavior of water-emulsified diesel fuel droplet under the secondary atomization argued by [34]. A ceramic fiber wire and an R-type thermocouple with a diameter of 10 and 50 µm respectively were used as suspending wires. A clear micro-explosion phenomena were observed using an electric furnace maintained up to 1073K. The puffing occurrence depending on the suspended wire position (as far as the wire position). The superheat temperature had a significant effect on the speed of the micro-explosion behaviour.

Micro explosion during the spray experiment

Experimental studies on such characteristics (spray, spray wall impingement, droplets size, and evaporation) either under engine conditions or non-combusting sprays and how they enhance the atomization as well as mixture process is well known [27, 28]. The observation of micro-explosion characteristics in a real engine environment is completely different from those conducted in a single droplet experiments. Therefore, the hypothesis of water-emulsified diesel droplet under a real diesel engine temperature conditions that micro-explosion occurs in spray characteristics which enhance the secondary breakup and hence mixture formation resulted in reduces the hydrocarbon is completely different. The occurrence of the micro-explosion in spray combustion is sensitive to the injection pressure and ambient conditions that also need more explanation.

Different studies on micro-explosion in atomized sprays have been carried out using visualization systems. Studies on non-combusting sprays, Y. Yoshimoto [32] used a shadowgraph visualization method to capture the emulsion fuel spray characteristics.

Emulsified fuels (water droplets and n-dodecane) were injected separately into a hot temperature inert gas [37]. A shadowgraphy imaging technique was used for the visualization while the spray droplet size was measured using image processing. In their experiment, a complete micro-explosion rarely was observed but partially occurred. While [38] captured the micro-explosion phenomena of different fuels (butanol, n-butan, biodiesel and diesel) spray under ambient and combusting conditions. It was found that the micro-explosion observed in the case of a butanol-biodiesel-diesel. In contrast, in the case of n-butan with biodiesel, the micro-explosion was observed at relatively low initial ambient temperatures. The occurrence micro-explosion was advanced with an increase the ambient temperature. Ref. [39] Used a shadowgraphy visualization system to capture the spray behavior (break-up, droplets penetration, droplet size) in an optical combustion vessel in ambient air condition 850 K and 50 bar. It was found that with an increase the water led to longer spray tip penetration compared to the diesel fuel. The evidence of the micro-explosion phenomena was demonstrated by different studies [40] , [35].

Recently, an optical visualization system used to visualize the spray and combustion behavior of W/D in a constant volume chamber was conducted by Huo *et al*. [42]. At low ambient temperatures, a longer initial liquid penetration for emulsified diesel was observed, while at higher ambient temperatures the trend was reversed. Micro-explosion was observed just at the beginning of combustion under high ambient temperatures. W/D emulsion fuel visualized in a good engine environment under different W/D ratios ware argued by [43]. As shown in Figure-6 strong micro-explosions were noticed at the spray tip. At 40 percent W/D fuel emulsion, a reduction in the flame luminosity was observed compared to 20 percentages W/D fuel emulsion.

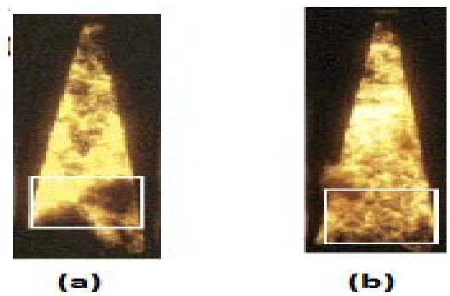

Figure-6. (a) diesel fuel (b) W/D fuel emulsion [43]

In another study [44], the onset of the micro-explosion speed is directly proportional to the ambient temperature.

CONCLUSIONS

From all the previous studies that were argued in this review paper, it is clearly understood that the W/D emulsion fuel has a significant effect on the environment emissions particularly NO_x and PM. Since the studies on the micro-explosion behavior were discovered in the 1956, up-to-date, different studies have been conducted using different techniques to study the impact and behave the W/D emulsion fuel. The most known experiments for detecting the single droplet micro-explosion are lidenfrost technique and the suspended droplet in a high temperature environment. A brief comparison can be summarized as follows:

In the lidenfrost technique (the droplet suspended on a thermocouple wire), the micro-explosion droplet temperature can be controlled. While in the suspended droplet method only the temperature of the air can be controlled.

In terms of the droplet size and heat distribution in lidenfrost experiment is approximately double that of the suspended droplet experiments.

In lidenfrost approach, a clear emulsion separation by creaming is possible which is does appear in the suspended droplet because of the higher temperature.

In term of metastability of the heat transfer process to the droplet of emulsion, with the suspended droplet experiment can be achieved while in lidenfrost is not dominant.

On the other hand, studies on the micro-explosion during the spray have been conducted with investigations of the spray chrematistics, the effect of micro-explosion on the W/D emulsion fuel. However, to date, studies on spray characteristics of water emulsified diesel fuel such as spray cone angle, spray tip penetration and glowing spots were detected as micro-explosion occurrence, whereas direct visualization techniques as much less reported. The challenge of determining the micro-explosion phenomena and its measurements, in addition to the hardware requirements for high temporal and spatial resolution, but also from the nature of the phenomenon itself, as micro-explosion is a highly transient process and it is completely depending on the fuel properties as well as ambient conditions. Micro-explosion behavior in a burning spray is also much less reported.

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REFERENCES

[1] K. A. Subramanian, "A comparison of water-diesel emulsion and timed injection of water into the intake manifold of a diesel engine for simultaneous control of NO and smoke emissions," Energy Convers. Manag., vol. 52, no. 2, pp. 849–857, 2011.

[2] K. Kannan and M. Udayakumar, "Nox And Hc Emission Control Using Water Emulsified Diesel In Single Cylinder Diesel Engine," vol. 4, no. 8, pp. 59–62, 2009.

[3] A. M. A. Attia and A. R. Kulchitskiy, "Influence of the structure of water-in-fuel emulsion on diesel engine performance," Fuel, vol. 116, pp. 703–708, 2014.

[4] D. Ogunkoya, S. Li, O. J. Rojas, and T. Fang, "Performance, combustion, and emissions in a diesel engine operated with fuel-in-water emulsions based on lignin," Appl. Energy, vol. 154, pp. 851–861, 2015.

[5] K. Kannan and M. Udayakumar, "NOx and HC emission control using water emulsified diesel in single cylinder diesel engine," J. Eng. Appl. Sci., vol. 4, no. 8, pp. 59–62, 2009.

[6] X. Tauzia, A. Maiboom, and S. R. Shah, "Experimental study of inlet manifold water injection on combustion and emissions of an automotive direct injection Diesel engine," Energy, vol. 35, no. 9, pp. 3628–3639, 2010.

[7] F. Bedford, C. Rutland, P. Dittrich, and F. Wirbeleit, "Effects of Direct Water Injection on DI Diesel Engine Combustion," SAE Pap. 01-2938, 2000.

[8] K. a. Subramanian, "A comparison of water-diesel emulsion and timed injection of water into the intake manifold of a diesel engine for simultaneous control of NO and smoke emissions," Energy Convers. Manag., vol. 52, no. 2, pp. 849–857, 2011.

[9] J. Shinjo, J. Xia, L. C. Ganippa, and A. Megaritis, "Physics of puffing and microexplosion of emulsion fuel droplets," Phys. Fluids, vol. 26, no. 10, p. 103302, 2014.

[10] H. Watanabe, Y. Matsushita, H. Aoki, and T. Miura, "Numerical simulation of emulsified fuel spray combustion with puffing and micro-explosion," Combust. Flame, vol. 157, no. 5, pp. 839–852, 2010.

[11] M. Y. Khan, Z. A. Abdul Karim, A. R. A. Aziz, and I. M. Tan, "Experimental investigation of microexplosion occurrence in water in diesel emulsion droplets during the Leidenfrost effect," Energy & Fuels, vol. 28, no. 11, pp. 7079–7084, 2014.

[12] S. A. Issaka, A. H. Nour, and R. M. Yunus, "20-80 % water-in-diesel emulsion fuel formulations and stability study for duration of two weeks," vol. 3, no. 7, pp. 1394–1398, 2015.

[13] J. Jiao and D. J. Burgess, "Rheology and stability of water-in-oil-in-water multiple emulsions containing Span 83 and Tween 80.," AAPS PharmSci, vol. 5, no. 1, p. E7, 2003.

[14] Particle Sciences: drug development services, "Emulsion Stability and Testing," Tech. Br., vol. 2, 2011.

[15] Michel A. Saad, "Evaporation and combustion of single fuel deoplet in a hot atmosphere," University of Michigan, 1956.

[16] V. Me Ivanov and P. I. Nefedov, "Experimental Investigation Of Ths Combustion Process Of Natural And Emulsified Liquid Fuels," NASA Techincal Transl., vol. 19, pp. 35–45, 1962.

[17] D. Tarlet, J. Bellettre, M. Tazerout, and C. Rahmouni, "Prediction of micro-explosion delay of emulsified fuel droplets," Int. J. Therm. Sci., vol. 48, no. 2, pp. 449–460, 2009.

[18] M. Tsue, H. Yamasaki, T. Kadota, and D. Segawa, "Effect of Gravity on Onset of Microexplosion for an Oil-in-Water Emulsion Droplet," Twenty-Seventh Symp. Combust. Combust. Inst., pp. 2587–2593, 1998.

[19] M. M. Avulapati, L. C. Ganippa, J. Xia, and A. Megaritis, "Puffing and micro-explosion of diesel–biodiesel–ethanol blends," Fuel, vol. 166, pp. 59–66, 2016.

[20] J. Shinjo, J. Xia, A. Megaritis, and L. C. Ganippa, "Secondary atomization and vapor mixing characteristics of diesel / biodiesel / bioethanol fuel droplets due to puffing / microexplosion," pp. 1–8, 2015.

[21] O. Armas, R. Ballesteros, F. Martos, and J. Agudelo, "Characterization of light duty Diesel engine pollutant emissions using water-emulsified fuel," Fuel, vol. 84, no. 7–8, pp. 1011–1018, 2005.

[22] T. Kadota, H. Tanaka, D. Segawa, S. Nakaya, and H. Yamasaki, "Microexplosion of an emulsion droplet during Leidenfrost burning," Proc. Combust. Inst., vol. 31 II, pp. 2125–2131, 2007.

[23] E. Mura, P. Massoli, C. Josset, K. Loubar, and J. Bellettre, "Study of the micro-explosion temperature of water in oil emulsion droplets during the Leidenfrost effect," Exp. Therm. Fluid Sci., vol. 43, pp. 63–70, 2012.

[24] G. Chen and D. Tao, "An experimental study of stability of oil-water emulsion," Fuel Process. Technol., vol. 86, no. 5, pp. 499–508, 2005.

[25] V. Califano, R. Calabria, and P. Massoli, "Experimental evaluation of the effect of emulsion stability on micro-explosion phenomena for water-in-oil emulsions," Fuel, vol. 117, pp. 87–94, 2014.

[26] Y. Suzuki, T. Harada, H. Watanabe, M. Shoji, Y. Matsushita, H. Aoki, and T. Miura, "Visualization of aggregation process of dispersed water droplets and the effect of aggregation on secondary atomization of emulsified fuel droplets," Proc. Combust. Inst., vol. 33, no. 2, pp. 2063–2070, 2011.

[27] D. Tarlet, E. Mura, C. Josset, J. Bellettre, C. Allouis, and P. Massoli, "Distribution of thermal energy of child-droplets issued from an optimal micro-explosion," Int. J. Heat Mass Transf., vol. 77, pp. 1043–1054, 2014.

[28] C. Jeong and K. H Lee, "Auto-Ignition And Micro-Explosion Behaviors Of Droplet Arrays Of Water-In-Fuel Emulsion," Int. J. Automot. Technol., vol. 139, no. 6, p. 735−740, 2008.

[29] M. L. Botero, Y. Huang, D. L. Zhu, A. Molina, and C. K. Law, "Synergistic combustion of droplets of ethanol, diesel and biodiesel mixtures," Fuel, vol. 94, pp. 342–347, 2012.

[30] C.-H. Wang and J.-T. Chen, "An experimental investigation of the burning characteristics of water-oil emulsions," Int. Commun. Heat Mass Transf., vol. 23, no. 6, pp. 823–834, 1996.

[31] D. Segawa, H. Yamasaki, T. Kadota, H. Tanaka, H. Enomoto, and M. Tsue, "Water-coalescence in an oil-in-water emulsion droplet burning under Microgravity," Proc. Combust. Inst., vol. 28, pp. 985–990, 2000.

[32] Y. Yoshimoto, "Performance of DI Diesel Engines Fueled by Water Emulsions with Equal Proportions of

Gas Oil-Rapeseed Oil Blends and the Characteristics," SAE Tech. Pap. 2006-01-3364, no. 724, 2006.

[33] R. Villasenor and F. Garcia, "Experimental study of the effects of asphaltenes on heavy fuel oil droplet combustion," Fuel, vol. 78, no. 8, pp. 933–944, 1999.

[34] H. Watanabe, Y. Suzuki, T. Harada, and Y. Matsushita, "An experimental investigation of the breakup characteristics of secondary atomization of emulsified fuel droplet," Energy, vol. 35, no. 2, pp. 806–813, 2010.

[35] M. A. Ismael, M. R. Heikal, and M. B. Baharom, "Spray Characteristics of a Diesel-CNG Dual Fuel Jet Using The Schlieren Imaging Technique," Int. J. Mater. Mech. Manuf., vol. 3, no. 3, pp. 145–151, 2015.

[36] S. Sazhin, C. Crua, D. Kennaird, and M. Heikal, "The initial stage of fuel spray penetration," Fuel, vol. 82, no. 8, pp. 875–885, 2003.

[37] H. Watanabe and K. Okazaki, "Visualization of secondary atomization in emulsified-fuel spray flow by shadow imaging," Proc. Combust. Inst., vol. 34, no. 1, pp. 1651–1658, 2013.

[38] Y. Liu, W. L. Cheng, M. Huo, C. F. Lee, J. Li, C. C. City, and J. L. Province, "Effects of Micro-Explosion on Butanol-Biodiesel-Diesel Spray and Combustion," in Annual Confernce on Liquid and Spray systems, Cincinnati, OH, 2010, no. May, pp. 1–8.

[39] R. Ochoterena, A. Lif, M. Nydén, S. Andersson, and I. Denbratt, "Optical studies of spray development and combustion of water-in-diesel emulsion and microemulsion fuels," Fuel, vol. 89, no. 1, pp. 122–132, 2010.

[40] H. Sheng, X. Li, X. Wei, and D. Wu, "Paper ID ILASS06-160 The Droplet Group Micro-Explosions, Viscosity and Atomization Characteristics of W / O Emulsions," Water, pp. 2–7, 2006.

[41] L. Ferrante, M. Miccio, F. Miccio, and R. Solimene, "Fluidized Bed Combustion of Liquid Biofuels: Application of Integrated Diagnostics for Micro-explosions Characterization," Energy & Fuels, vol. 22, no. 6, pp. 4213–4222, 2008.

[42] M. Huo, S. Lin, H. Liu, and C. F. Lee, "Study on the spray and combustion characteristics of water–emulsified diesel," Fuel, vol. 123, no. May, pp. 218–229, 2014.

[43] W. Park, K. Y. Huh, and K. H. Park, "Experimental Study on the Combustion Characteristics of Emulsified Diesel in a RCEM," Seoul 2000 FISITA World Automot. Congr., no. 6, pp. 1–6, 2000.

[44] W. B. Fu, L. Y. Hou, L. Wang, and F. H. Ma, "A unified model for the micro-explosion of emulsified droplets of oil and water," vol. 79, pp. 107–119, 2002.