Comparative Studies on Combustion Characteristics of Blended Crude Jatropha Oil with Magnetic Liquid Catalyst and DEX under Normal Gravity Condition

Hendry Y. Nanlohy

Department of Mechanical Engineering, Jayapura University of Science and Technology, Jayapura, 99351, Indonesia
Corresponding author:hynanlohy@gmail.com

ABSTRACT

A comparative study on the combustion characteristics of a single droplet fueled by DEX, crude jatropha oil (CJO), and a mixture of CJO with a magnetic liquid catalyst of rhodium trisulfate has been carried out under normal gravity conditions. The high viscosity of crude jatropha oil makes it difficult to burn under normal conditions (room temperature and atmospheric pressure), therefore the addition of a magnetic liquid catalyst rhodium trisulfate is needed to improve the properties of crude jatropha oil. As a catalyst, rhodium trisulfate has the potential to improve combustion performance while improving the physical properties of crude jatropha oil as an alternative fuel for the better. Furthermore, performance tests were also carried out with DEX fuel with a cetane number (CNs) 53. The results showed that compared to DEX, it was seen that the liquid metal catalyst rhodium trisulfate succeeded in making crude jatropha oil more charged so that the combustion process was better. This is evidenced by a significant change in the dimensions of the flame and an increase in the combustion temperature. Moreover, it is also seen that the burning rate increases and the ignition delay become faster.

Copyright © 2021. Journal of Mechanical Engineering Science and Technology.

Keywords: *Combustion characteristics, crude jatropha oil, DEX, rhodium trisulfate, single droplet*

I. Introduction

With the depletion of petroleum reserves, the increasing world population and energy consumption have a direct impact on the decreasing availability of fuel [1], [2]. Therefore, the need for alternative fuels (non-fossil fuel) is very important [3], and crude jatropha oil is one of the natural resources that can be converted into alternative fuels (biodiesel) to replace diesel oil [4]. Unfortunately, the sustainability of biodiesel use is hampered when it is found that the combustion products still contribute to greenhouse gases [5], and it is even worse with the addition of production equipment and the need for large costs to convert crude vegetable oil into biodiesel [6].

However, the crude jatropha oil compound, which is unsaturated, shows that there are C=C double bonds in the carbon chain [7], [8]. The presence of these double bonds has the potential to harm fuel combustion performance [9], where each double bond can reduce ignition properties such as CNs and others by a significant amount [10]. Due to the unfavorable effect of double bonds on ignition properties and fuel performance, some researchers use several catalysts such as Fe_2O_3, Al_2O_3, NaOH, and cobalt [11]–[15] including rhodium liquid catalyst [8], [16]–[20], which are used to reduce or even eliminate the negative impact of double bonds present in the fuel. On the other hand, the results of previous studies have found that the presence of C=C double bonds in the geometric

DOI: 10.17977/um016v5i22021p079

structure of the carbon chain of unsaturated oil does not reduce the ignition performance of vegetable oil fuels [18]. Therefore, this research is very important to produce new scientific information about the role of liquid metal catalysts on the combustion performance of vegetable oil (crude jatropha oil). In addition, the use of DEX to obtain other scientific information on the performance comparison of fuels containing catalysts.

On the other hand, the use of magnetic liquid catalyst rhodium trisulfate in crude jatropha oil also aims to determine the working principle of the catalyst in the fuel combustion process. In addition, with the complexity of the fuel combustion process that includes compression of combustion air, fuel injection, evaporation, mixing, ignition and chemical combustion reactions between fuel vapors and air, the role of catalysts in combustion is difficult to know through the applied research method. Therefore, the suspended single droplet method was chosen to reveal the role of metal-based catalysts and their impact on the combustion characteristics of crude jatropha oil.

II. Material and Methods

There are three types of fuel used in this study, i.e. DEX, crude jatropha oil, and a mixture of crude jatropha oil with a magnetic liquid catalyst of rhodium trisulfate $Rh_2(SO_4)_3$. The composition of the catalyst in blended CJO is 0.00% (pure CJO), 0.01% (CJOR 0.01 %), and 0.02% (CJOR 0.02 %). The test results on the main properties of the fuels are shown in Table 1. DEX, often called PERTAMINA DEX, is a fuel that has a cetane number 53 with a sulphur content of about 300 ppm or equivalent to EURO 3 to make the engine more durable and produce lower emissions and environmentally friendly [21]. While the magnetic liquid catalyst of rhodium trisulfate $Rh_2(SO_4)_3$ is a catalyst that has a 12 hydrogen acceptor, which results in a difference in electronegativity between the catalyst and the carbon chain. This difference causes the dipole-dipole interactions of the hydrocarbon chains to be pulled and attached to the catalyst surface. This causes the geometric structure of the carbon chain to change so that the viscosity and flashpoint of the CJO decrease, and it is easy to ignite [22].

Table 1. The main properties of fuels

Properties	DEX	Pure CJO	CJOR 0.01%	CJOR 0.02%
Flash Point (°C)	56	243	203	207
Viscosity at 40 °C (cSt)	5.181	35.52	32.38	34.29
Density at 15 °C (gr/ml)	0.827	0.917	0.916	0.936
Caloric value (cal/gr)	10600	9400	8939	8896

The research scheme can be seen in Figure 1. Droplets of crude jatropha oil are attached to the junction of a 13% wt. Pt/Rh type thermocouple with a diameter of 0.1 mm. This thermocouple is type R, is a precious metal thermocouple, and has a temperature range that can measure up to 1600 °C. Its has low sensitivity around 10 V/°C and high accuracy with an error tolerance of less than one-Celsius degree [23]. The distance between the droplet and the electric heating coil is about 0.5 mm to 0.7 mm. The droplets are ignited using an electric heating coil with a diameter of 0.7 mm and a wire length of 40 mm with a resistance of 1Ω. Temperature data is obtained from the thermocouple signal that is connected to the data logger, and ignition delay data is obtained from the recording of the high-speed camera. The testing process was carried out five times for each type of fuel.

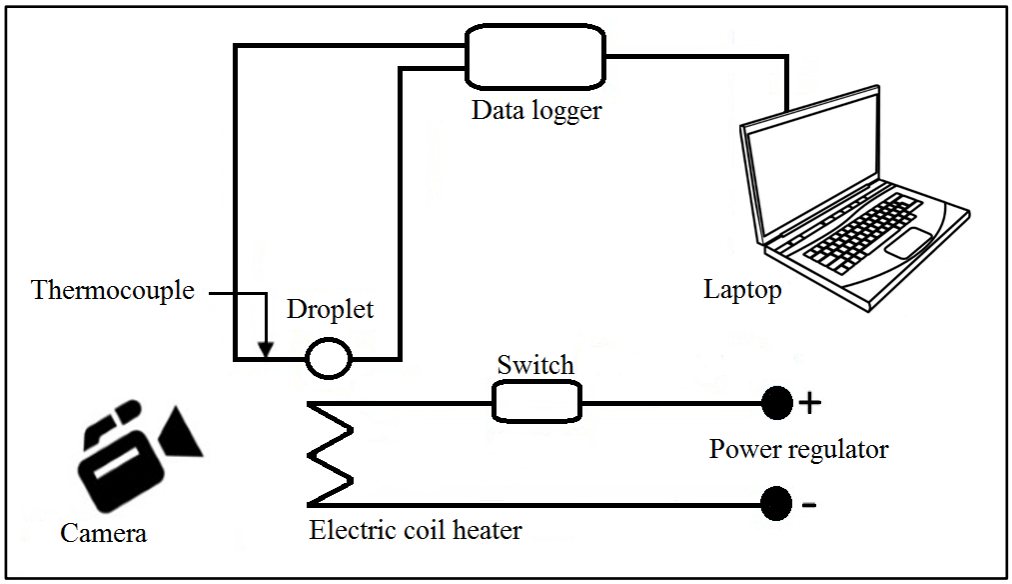

Fig. 1. Experimental scheme

III. Results and Discussions

The suspended single droplet combustion performance is known from four parameters, i.e. the dimension of the flame (height and width), ignition delay, burning rate, and combustion temperature. Figure 2 shows a comparison of the shape of the flame of the four types of fuel. The results show that with (see Figure 2b and 2c) and without rhodium trisulfate (see Figure 2a), the flame of crude jatropha oil appears to have the same shape, which is slightly wide and round, and for the DEX flame (see Figure 2d) looks more oval.

The results also show that without a catalyst, the CJO flame evolutions look longer, while with a catalyst are shorter. This phenomenon indicates that the catalyst can absorb more heat energy so that the droplets heat up faster, evaporate and burn. Furthermore, it is also seen that the flame of CJO droplets with and without a catalyst is more volatile than DEX that looks calmer. This phenomenon shows that saturated CJO compounds produce an imbalance in atomic composition and mass so that the droplet flame looks more reactive so that the viscosity and flash-point (see Table 1) decrease and the droplets ignite easily.

This analysis makes a lot of sense because saturated oil has a C=C double bond which creates an imbalance of bonding electron pairs. Where in that section, the CJO carbon chain lacks two hydrogen atoms so that the bonding electron pairs are not evenly distributed among the atoms carbon chain compounds. On the other hand, it appears that DEX has low volatility, and the flame looks calmer. This phenomenon indicates that the DEX constituent compounds are in a balanced state.

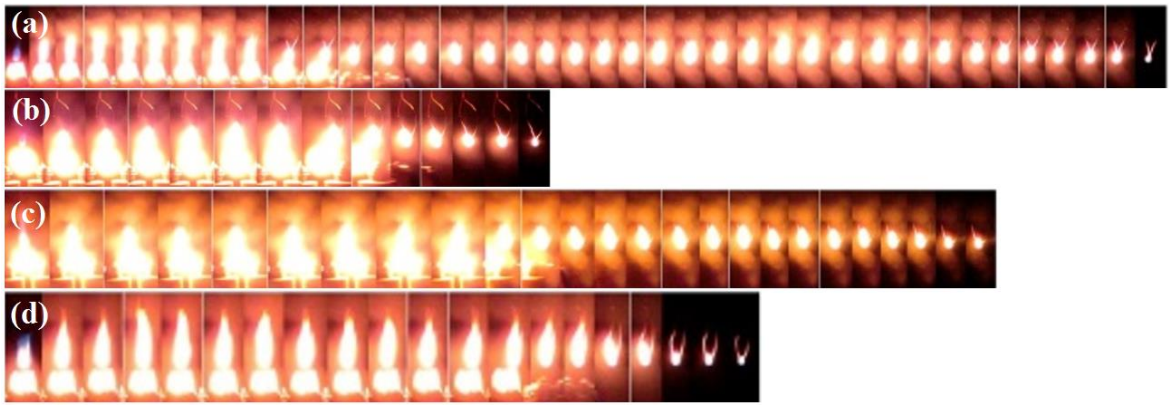

Fig. 2. Flame evolution comparison (a). Pure CJO, (b). CJOR 0.01%, (c). CJOR 0.02%, (d). DEX

Furthermore, Figure 3 shows the variation of the flame height of the four fuels. It can be seen that successively DEX has the highest flame, which is around 19.15 mm and is followed by pure CJO around 15.51 mm, then CJOR 0.02% is around 15.28, and the lowest is CJOR 0.01%, which is around 12.84 mm. The high flame indicates that DEX fuel has a faster evaporation rate than the three types of CJO fuel with and without a catalyst.

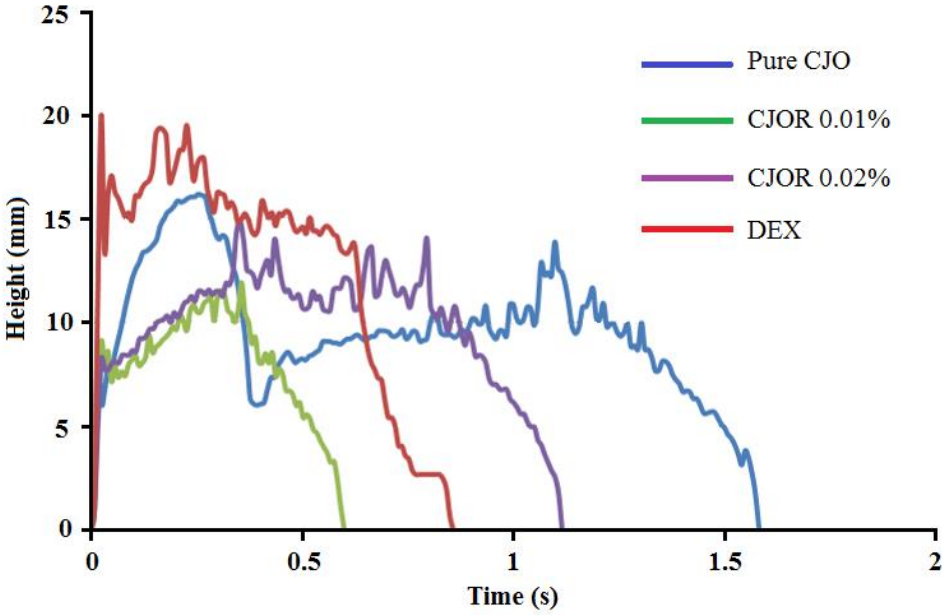

Fig. 3. Flame height evolution of fuels droplet

On the other hand, these results indicate that CJO droplets with and without a catalyst have a faster combustion rate than DEX, and this is because the addition of a rhodium trisulfate catalyst makes the mass of the fuel increase so that the distance between the fuel molecules gets closer, thus accelerating the interaction between the fuel molecules causing an effective collision have the potential to occur. This analysis is consistent with previous studies, which stated that the flame height was inversely related to the molecular diffusivity [24].

Moreover, it is also seen that the CJOR flame height of 0.02% exceeds the pure CJO and 0.01% CJOR flame height. This is due to the increase in the catalyst mass in the fuel causes the CJO molecules to be more charged, resulting in a potential difference between

the CJO molecules and the catalyst molecules, and this causes attractive interactions between atoms. The interaction between the fuel atoms makes the fuel molecules more reactive, so they are flammable and have the potential to facilitate microexplosion, which creates bulge geometry, and suddenly the height of the flame will increase like a needle [25].

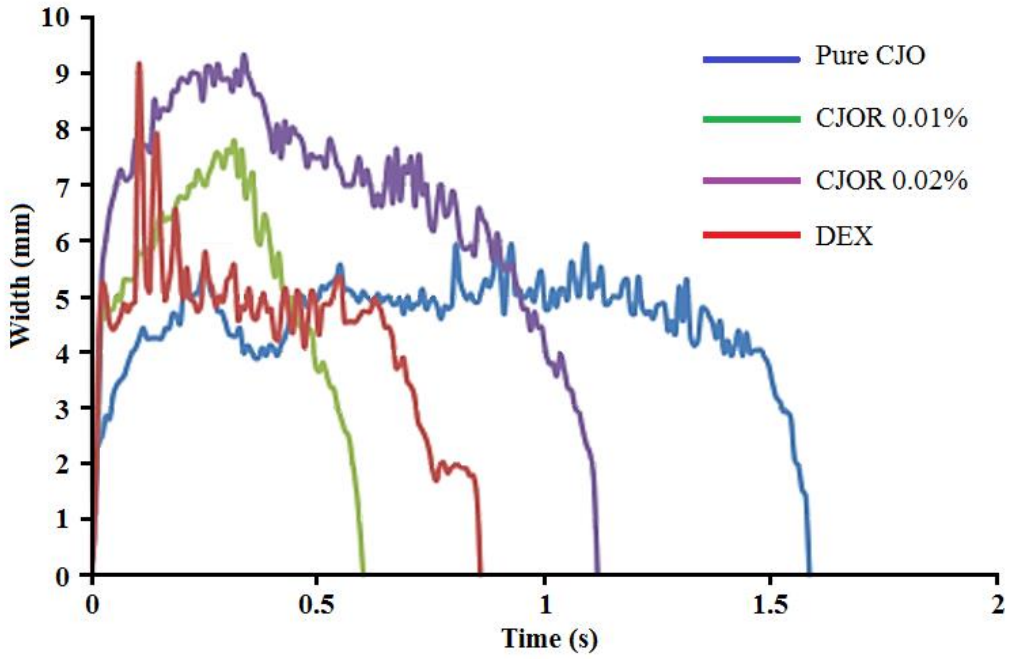

Fig. 4. Flame width evolution of fuels droplet

As for the flame width (see Figure 4), it can be seen that CJOR 0.02% of the catalyst was achieved, which was around 9.111 mm, DEX was around 7.97 mm, followed by CJOR 0.01% of 6.51 mm, and the smallest flame width was produced by pure CJO about 6.52 mm. These results indicate that the addition of rhodium trisulfate catalyst can produce faster combustion than evaporation. This is possible because of the CJO carbon chain structure, which is not balanced bonding electron pairs. It is made electrons have a larger space to move, and this is supported by the increase in atomic volume due to expansion due to atoms absorbing heat energy from the electric coil heater. This phenomenon also confirms the shape of the CJO flame with the catalyst, which looks more volatile and highly reactive (see Figure 2.).

Furthermore, Figure 3 and 4 also show the duration of the droplet flame of the four fuels and it can be seen that the longest flame time was produced by pure CJO, while the fastest flame was produced by CJOR 0.01%, followed by DEX and the next was CJOR 0.02%. A fast flame time indicates that the fuel produces more power or vice versa because power is inversely proportional to time. Moreover, Figure 3 and 4 show a change in the shape of the fire accompanied by a sudden increase in the height and width of the fire, indicating that there is a release of energy as evidenced by the occurrence of micro-explosion (see Figure 5). This result is in accordance with previous studies, which stated that the sudden change in the shape of the fire indicated that the satellite particles contained in the droplet were thrown out, resulting in micro-explosions [23], [26].

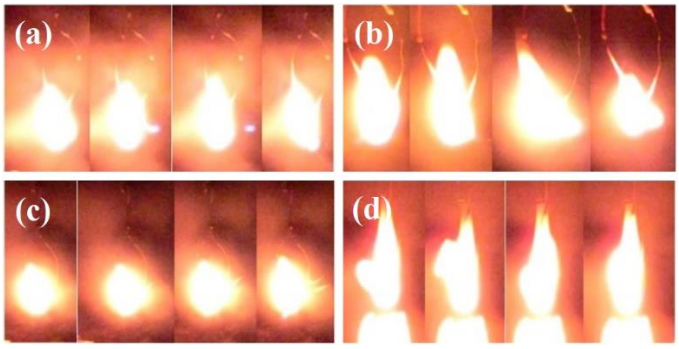

Fig. 5. Microexplosion phenomena. (a) Pure CJO, (b) CJOR 0.01 %, (c) CJOR 0.02 %, and (d) DEX

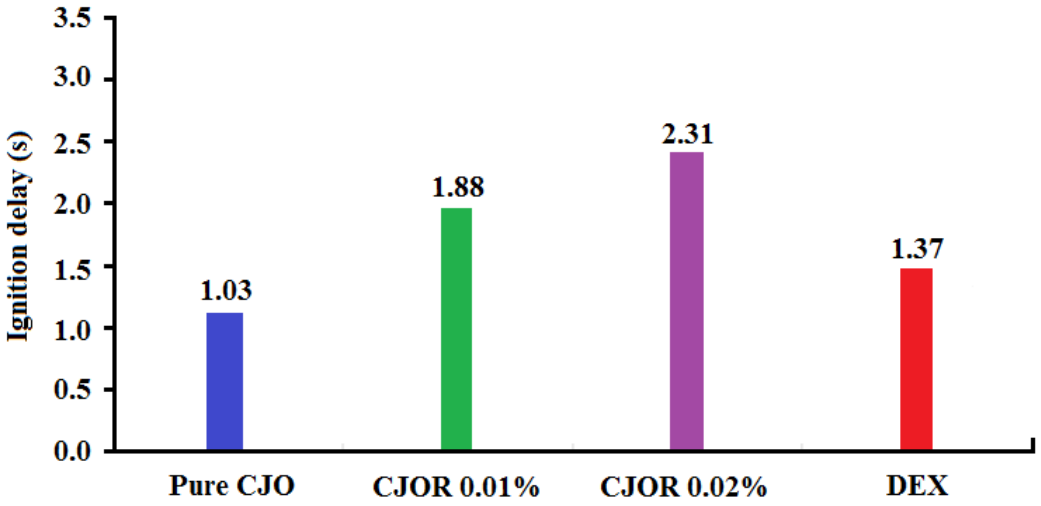

Fig. 6. Ignition delay time of CJO droplet with and without catalyst vs DEX

Figure 6 shows the ignition delay of the four types of fuel. It can be seen successively that CJOR 0.02% has the longest ignition delay time, which is around 2.31 seconds, the next is CJOR 0.01%, then DEX 1.37 seconds and the fastest is pure CJO which is around 1.03 seconds. These results indicate that the magnetic liquid catalyst rhodium trisulfate has not been able to produce a faster ignition delay time. This is very reasonable because the working principle of rhodium catalyst is to lower its high activation energy in addition reactions by converting double bonds into single bonds. This has the potential to reduce the dissociation energy value of the CJO fuel molecules so that the fuel is easy to heat and ignite.

Moreover, from Figure 6, it can also be seen that when compared to DEX fuel, the ignition delay time of CJOR 0.01% and CJOR 0.02% is longer. This phenomenon is very possible because, with the increase in the mass of the fuel molecules due to the addition of rhodium trisulfate, the fuel molecules need a longer time to absorb heat energy from the electric coil heater. Another reason is that the operating temperature of the rhodium trisulfate liquid catalyst is at 400-500 °C, so with the addition of a catalyst, the time needed to reach the working temperature is longer. This causes the value of heat of evaporation of CJO to increase, where the heat of evaporation of CJO is 210 kJ/kg, and rhodium is 4564.81 kJ/kg.

Figure 7 shows the effect of variations in the addition of catalysts on the burning rate of CJO droplet combustion compared to DEX. Sequentially, it can be seen that the highest burning rate was achieved by CJOR 0.02%, then CJOR 0.01%, DEX, and pure CJO had the

lowest burning rate. This result proves that the catalyst can make the fuel molecules more charged, making it easier for them to interact with oxygen. This analysis is very reasonable because with the number of protons greater than the protons of the atoms of the CJO compounds (Carbon, Hydrogen, and Oxygen), the catalyst becomes more positive, causing a potential difference with the CJO carbon chain.

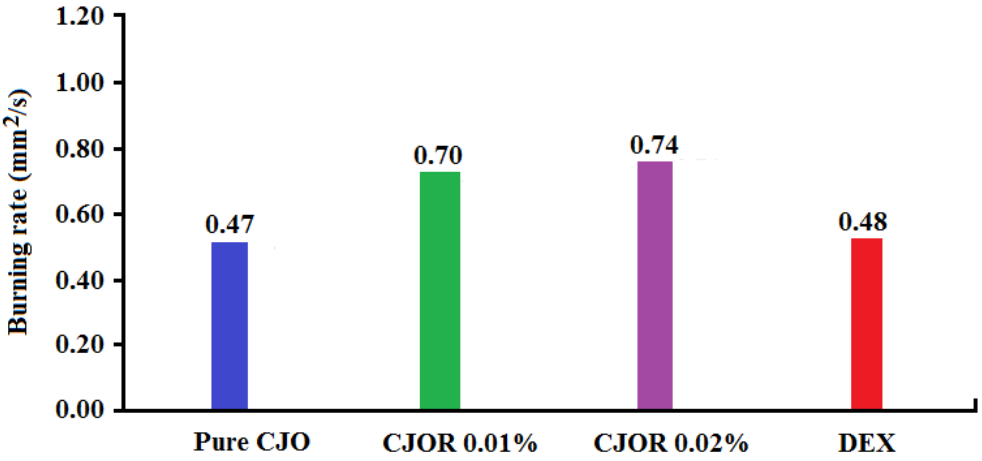

Fig. 7. Burning rate comparison of CJO droplet with and without catalyst vs DEX

Furthermore, the unbalance of bonding electron pairs in the C=C double bond makes it a weak point in the arrangement of the carbon chain. This causes the catalyst to be able to attract electrons in the phi orbitals from the carbon atoms in the C=C double bond so that the CJO has the potential to lose electrons and is positively charged. Because the CJO is positively charged while the oxygen around the droplet is negatively charged, there is an attractive interaction that generates the reactivity of the fuel molecules. This is what causes the burning rate of the CJO fuel mixture with a catalyst to be higher than pure CJO and DEX, where the attraction between the fuel molecules increases the reactivity of the molecules so that the fuel easily absorbs heat and burns fast.

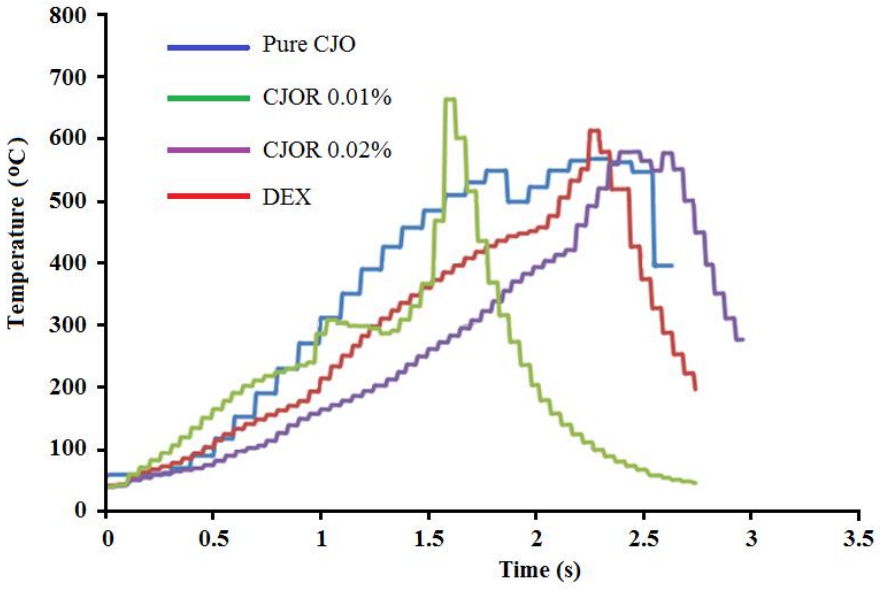

Fig. 8. Temperature evolution of fuel droplet

Figure 8 shows the temperature evolution of the four fuel types. Especially for CJO, it can be seen that the highest temperature was achieved by CJOR 0.01% at 606.70 °C, followed by CJOR 0.02% at around 590.92 °C, and pure CJO at 578.87 °C. These results indicate that the catalyst can increase the enthalpy of the fuel, which is a function of the effective collisions between charged molecules and the random motion of the atoms.

On the other hand, it can be seen that there is a decrease in the temperature value at CJOR 0.02%, and this phenomenon indicates that at certain compositions, the catalyst work is not optimal [14]. This is because the presence of an excessive amount of catalyst mass has the potential to reduce the calorific value of CJO (see Table 1) fuel which has a heating value of 39662.48 kJ/kg, while rhodium is 5148.14815 kJ/kg. In addition, with more mass, the time required for CJOR0.02 fuel molecules to absorb heat and burn becomes longer, resulting in a longer burning lifetime compared to CJOR 0.01%.

IV. Conclusions

A study of the combustion characteristics of pure CJO with a blended CJO with magnetic liquid catalyst and a comparison with DEX has been carried out. The results showed that the catalyst was able to increase the reactivity of the fuel molecules to increase the performance of CJO combustion. The catalyst increases the mass of fuel molecules and the distance between atoms, thereby facilitating attractive interactions between the fuel molecules. This makes CJOR 0.01% capable of producing good performance, as indicated by a high combustion temperature and burning rate, as well as a shorter burning lifetime. Determination of the correct composition of the catalyst volume is very important to produce good fuel performance because the excessive amount of catalyst mass reduces the calorific value of CJOR 0.02%.

To reveal the role of platinum group metal catalysts in improving the performance of crude vegetable oil fuels, further research is needed using the same or different magnetic liquid catalysts such as ruthenium or platinum. Moreover, an in-depth study is also needed of the role of catalysts on the performance of crude vegetable oil fuels composed of saturated or polyunsaturated compounds.

Acknowledgment

The authors express grateful thanks to the Institute for Research and Community Service, Jayapura University of Science and Technology for financial support, and the Fuel and Combustion Laboratory of the Department of Mechanical Engineering for their support of materials and research equipment.

References

[1] M. A. Aktar, M. M. Alam, and A. Q. Al-Amin, “Global economic crisis, energy use, CO_2 emissions, and policy roadmap amid COVID-19,” *Sustain. Prod. Consum.*, vol. 26, pp. 770–781, 2021, doi: 10.1016/j.spc.2020.12.029.

[2] O. Andreev, O. Lomakina, and A. Aleksandrova, “Diversification of structural and crisis risks in the energy sector of the ASEAN member countries,” *Energy Strateg. Rev.*, vol. 35, p. 100655, 2021, doi: 10.1016/j.esr.2021.100655.

[3] Y. Bai and C. Dahl, “Evaluating the management of U.S. Strategic Petroleum Reserve during oil disruptions,” *Energy Policy*, vol. 117, pp. 25–38, 2018, doi: 10.1016/j.enpol.2018.02.034.

[4] Digambar Singh, Dilip Sharma, S.L. Soni., "A comprehensive review of physicochemical properties, production process, performance and emissions characteristics of 2nd generation biodiesel feedstock: Jatropha curcas," *Fuel*, vol. 285, p. 119110, 2021, doi: 10.1016/j.fuel.2020.119110.

[5] G. A. Ewunie, O. I. Lekang, J. Morken, and Z. D. Yigezu, "Characterizing the potential and suitability of Ethiopian variety Jatropha curcas for biodiesel production: Variation in yield and physicochemical properties of oil across different growing areas," *Energy Reports*, vol. 7, pp. 439–452, 2021, doi: 10.1016/j.egyr.2021.01.007.

[6] M. Alherbawi, G. McKay, H. R. Mackey, and T. Al-Ansari, "Jatropha curcas for jet biofuel production: Current status and future prospects," *Renew. Sustain. Energy Rev.*, vol. 135, p. 110396, 2021, doi: 10.1016/j.rser.2020.110396.

[7] Yu Zhang, Ronghua Huang, Xi Chen., "Experimental study on auto-ignition characteristics of a butanol-hexadecane droplet under elevated pressures and temperatures," *Energy*, vol. 171, pp. 654–665, 2019, doi: 10.1016/j.energy.2019.01.046.

[8] H. Y. Nanlohy, I. N. G. Wardana, N. Hamidi, and L. Yuliati, "Combustion characteristics of crude jatropha oil droplets using rhodium liquid as a homogeneous combustion catalyst," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 299, no. 1, pp. 0–7, 2018, doi: 10.1088/1757-899X/299/1/012090.

[9] J. Wang, X. Wang, H. Chen, Z. Jin, and K. Xiang, "Experimental study on puffing and evaporation characteristics of jatropha straight vegetable oil (SVO) droplets," *Int. J. Heat Mass Transf.*, vol. 119, pp. 392–399, 2018, doi: 10.1016/j.ijheatmasstransfer.2017.11.130.

[10] A. Sankaranarayanan, S. Lal, I. N. N. Namboothiri, R. Sasidharakurup, A. Chowdhury, and N. Kumbhakarna, "Droplet combustion studies on two novel energetic propellants, an RP-1 surrogate fuel, and their blends," *Fuel*, vol. 255, 2019, doi: 10.1016/j.fuel.2019.115836.

[11] B. Ashok, K. Nanthagopal, Ong Hwai Chyuan., "Multi-functional fuel additive as a combustion catalyst for diesel and biodiesel in CI engine characteristics," *Fuel*, vol. 278, p. 118250, 2020, doi: 10.1016/j.fuel.2020.118250.

[12] Zhiqing Zhang, Jiedong Ye, Dongli Tan, "The effects of Fe2O3 based DOC and SCR catalyst on the combustion and emission characteristics of a diesel engine fueled with biodiesel," *Fuel*, vol. 290, p. 120039, 2021, doi: 10.1016/j.fuel.2020.120039.

[13] S. Piazzi, S. S. Ail, V. Benedetti, F. Patuzzi, and M. Baratieri, "Fuel-lean combustion synthesized cobalt catalysts for Fischer-Tropsch reaction," *Catal. Today*, pp. 0–1, 2020, doi: 10.1016/j.cattod.2020.06.088.

[14] S. Lopatin, A. Elyshev, and A. Zagoruiko, "Catalytic device for environmentally friendly combustion of liquid fuels on the base of structured glass-fiber catalyst," *Catal. Today*, 2021, doi: 10.1016/j.cattod.2021.02.010.

[15] R. Sui, J. Mantzaras, and R. Bombach, "H_2 and CO heterogeneous kinetic coupling during combustion of H2/CO/O_2/N_2 mixtures over rhodium," *Combust. Flame*, vol. 202, pp. 292–302, 2019, doi: 10.1016/j.combustflame.2019.01.021.

[16] V.A. Shilov, V.N. Rogozhnikov, N.V. Ruban., "Biodiesel and hydrodeoxygenated biodiesel autothermal reforming over Rh-containing structured catalyst," *Catal. Today*, vol. 379, pp. 42–49, 2021, doi: 10.1016/j.cattod.2020.06.080.

[17] Weili Jiang, Yaqi Chen, Lijie Gao., "Hydroformylation for reducing the olefin content in the FCC light gasoline with magnetic rhodium-catalysts," *Fuel*, vol. 279, p. 118508, 2020, doi: 10.1016/j.fuel.2020.118508.

[18] H. Y. Nanlohy, I. N. G. Wardana, N. Hamidi, L. Yuliati, and T. Ueda, "The effect of Rh^{3+} catalyst on the combustion characteristics of crude vegetable oil droplets," *Fuel*, vol. 220, 2018, doi: 10.1016/j.fuel.2018.02.001.

[19] M. S. Leguizamón Aparicio, M. A. Ocsachoque, E. Rodríguez-Castellón, D. Gazzoli, M. L. Casella, and I. D. Lick, "Promoting effect of rhodium on Co/ZnAl2O4 catalysts for the catalytic combustion of hydrocarbons," *Catal. Today*, vol. 372, pp. 2–10, 2021, doi: 10.1016/j.cattod.2020.10.006.

[20] S. Neuberg, H. Pennemann, V. Shanmugam, R. Zapf, and G. Kolb, "Promoting effect of Rh on the activity and stability of Pt-based methane combustion catalyst in microreactors," *Catal. Commun.*, vol. 149, p. 106202, 2021, doi: 10.1016/j.catcom.2020.106202.

[21] E. Elfiano, M. N. Darin, and R. H. Panjaitan, "Analisa penggunaan bahan bakar pertamina dex, dexlite dan campuran pertamina dex dengan dexlite terhadap performance mesin diesel 4 silinder," Proceeding of Seminar Nasional "Mitigasi Dan Strategi Adaptasi Dampak Perubahan Iklim Di Indonesia" pp. 235–240. 2020.

[22] H. Y. Nanlohy, "Automotive Experiences," *Automot. Exp.*, vol. 3, no. 2, pp. 39–45, 2020, doi: https://doi.org/10.31603/ae.v3i1.3039.

[23] M. Ikegami, G.Xu, K. Ikeda, S. Honma., "Distinctive combustion stages of single heavy oil droplet under, microgravity," Fuel, vol. 82, pp. 293–304, 2003.

[24] H. Y. Nanlohy, I. N. G. Wardana, M. Yamaguchi, and T. Ueda, "The role of rhodium sulfate on the bond angles of triglyceride molecules and their e ff ect on the combustion characteristics of crude jatropha oil droplets," *Fuel*, vol. 279, 2020.

[25] X. Wang, M. Dai, J. Yan, C. Chen, G. Jiang, and J. Zhang, "Experimental investigation on the evaporation and micro-explosion mechanism of jatropha vegetable oil (JVO) droplets," *Fuel*, vol. 258, p. 115941, 2019, doi: 10.1016/j.fuel.2019.115941.

[26] K. Meng, W. Fu, Y. Lei, D. Zhao, Q. Lin, and G. Wang, "Study on micro-explosion intensity characteristics of biodiesel, RP-3 and ethanol mixed droplets," *Fuel*, vol. 256, 2019, doi: 10.1016/j.fuel.2019.115942.