Dimethyl Ether as the Next Generation Fuel to Control Nitrogen Oxides and Particulate Matter Emissions from Internal Combustion Engines: A Review

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ABSTRACT: Dimethyl ether (DME) is a new generation fuel produced from natural gas and coal. This fuel can be used directly to a conventional internal combustion (IC) engine without any significant modifications. The main advantage of DME combustion in IC engines is the low NOx and particulate emissions compared with the fossil liquid fuel. Thus, the usage of DME in IC engines is potentially to improve engine efficiency and reduce emissions in the future with minimum attempts. This paper offers a comprehensive review of some topics related to DME as an alternative fuel for IC engines and efforts to increase its utilization to meet high efficiency and low emissions regulations in the future.

1. INTRODUCTION

The DME is a promising alternative fuel for IC engines due to its combustion characteristic near-zero particulate emission influenced by the chemical structure CH₃−O−CH₃ and the oxygen content of about 35 wt %.¹ DME has a high cetane number and can easily undergo atomization. This advantage is very useful for combustion technologies such as homogeneous compression charge ignition (HCCI).² According to Azizi,³ the reason DME is considered an alternative and clean fuel is that it has safe storage. This is because the ether will not form explosive peroxide. Another reason is that DME contains only about 35% oxygen and only has CH and CO bonds and does not have CC bonds. In addition, combustion products such as CO and unburnt hydrocarbon emissions are smaller than natural gas.⁴ DME has a vapor pressure similar to LPG, so it can be used in infrastructure for transportation and storage. Because of the high cetane number, DME is considered a promising alternative fuel which when burned does not produce emissions of particulate matter and toxic gases.⁵

The disadvantages of DME are the problems in narrow working conditions and very poor anti-knock performance. This results in DME-fueled engines facing significant problems in new combustion technologies such as HCCI mode.² Other major problems faced by this type of fuel are the presence of low liquid density and viscosity, relatively low heating value, and the need for engine modification.⁶ The lower calorific value per unit volume is about half of that for diesel fuel, and it is necessary to double the injection quantity rate of fuel supply. Therefore, it is necessary to increase the capacity of the fuel tank.

This study will discuss the progress and recent trends of DME as an alternative fuel. Discussions cover the DME properties, the systems of fuel injection and strategies, spray characteristics and fuel atomization, combustion and engine emissions, the utilization of DME around the globe, and the current research and development of DME. This review is arranged in chronological order starting with a concept that has been defined by previous researchers to lay the foundation for

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subsequent studies, including this research effort. This review is compiled comprehensively so that future research efforts can be designed appropriately. Moreover, this review is expected to add to the body of literature and the scope and the direction of this research effort. For discussion, several recommendations were given to encourage DME as an alternative fuel for the development of CI engines in the future.

2. PROPERTIES OF DME

DME, as an alternative fuel, has properties that fulfill the requirement of the fuel. It has a cetane number of 55–60 that is higher than that of diesel fuel. The physical and chemical properties of DME compared with other fuels are shown in Table 1.

DME is a gas at room temperature and in 1 atm pressure condition; therefore, in the engine fuel injection arrangement, the fuel hoses were changed to the high-pressure type. As an interesting substitution fuel, DME has a high vapor pressure at the saturated condition that is 510 kPa at 293 K and a small boiling value of 248 K at 100 kPa. The other reference also mentioned the similar explanation that, at around 25 °C, dimethyl ether has a too high of a vapor pressure 510 kPa at 293.15 K, and there will be a powerful flash boiling tendency in the injection spray at small surrounding pressure, which can improve the dimethyl ether droplet breakup and also the evaporation process mechanism. Meanwhile, Pedersen explains that dimethyl ether is a gas form with the pressure of vapor around 6 bar at room temperature. There are two latent heats of DME, specifically latent heat of fusion in the condition of the phase change from solid to liquid and the latent heat of evaporation in the condition of the phase change from liquid to gas. The latent heat of fusion is about 4.94 kJ/mol and the latent heat of evaporation is about 21.5 kJ/mol.

DME has a lack of lubricity and very bad viscosity; thus, an injection strategy with lower injection pressures has to be applied and required to improve the injection method. Then, spray-induced air–fuel mixing should be obtained by using another strategy. Alternatively, the blending controlled combustion leads to a long delay, producing low engine efficiency, followed by huge CO emissions, high maximum chamber pressures, and extreme exhaust gas temperatures.

DME is chosen as one of the most superior and valuable substitute fuels or oxygenated fuel additives, which contains oxygen around 34.8% by mass. Besides containing oxygen, DME molecular structure also lacks a C=C bond, which potentially promotes the low content of soot emissions, as this is the main consideration for a clean fuel.

DME is also appropriate for the HCCI engine mode using a compression ratio (CR) of at least 10. If a bigger CR is applied, several strategies for delaying the start of combustion should be utilized to obtain the best timing of the heat release. The lower heating value of dimethyl ether is about 28.9 MJ/kg and the value of the stoichiometric A/F ratio is 9.0. The comparison properties between DME and diesel fuel is presented in Table 2.

3. DME PRODUCTION

DME can be composed using various raw materials including natural gas, coal, and biomass (through dehydration reaction of methanol). The other technique to produce DME that was introduced is using synthetic gases produced of waste paper fluid from a paper factory (black liquor) and the wood-based biomass, for example, unused wood including thinned wood. From the natural gas or syngas, the DME can be produced conventionally through the two-step process or indirect method; specifically, first is the synthesis of methanol using syngas that is CO + H₂, and second, dimethyl ether is composed using the dehydration method of methanol. Both two-step reaction processes are summarized as follows:

**Synthesis of methanol**

\[
CO + 2H_2 \rightleftharpoons CH_3OH \quad \Delta H^\circ = -90.6 \text{ kJ/mol}
\]

**Dehydration of methanol**

\[
2CH_3OH \rightleftharpoons CH_3OCH_3 + H_2O \quad \Delta H^\circ = -23.4 \text{ kJ/mol}
\]

From the two-step part, dimethyl ether can also be produced by using syngas through a one-step process called the direct technique. This technique is associated with the water gas shift reaction (WSGR). The reaction is given as follows:

**Water and gas shift reaction**

\[
CO + H_2O \rightleftharpoons CO_2 + H_2 \quad \Delta H^\circ = -41.24 \text{ kJ/mol}
\]
The final reaction in the direct technique

$$3\text{CO} + 3\text{H}_2 \rightarrow \text{CH}_3\text{OCH}_3 + \text{CO}_2$$

$$\Delta H^0 = -245.8 \text{kJ/mol}$$

In the DME production process, chemical processes occur in many types of reactors, and were divided into two groups: conventional and innovative technologies reactions. The reactors included in conventional types are fixed-bed reactors, slurry stage reactors, and fluidized-bed reactors. Meanwhile, the reactors included in innovative technologies types are dual-type reactors; coupled reactors, coupling the reactor and separation units; microreactors; membrane reactors; and spherical reactors.

4. DME FOR IC ENGINE

Because dimethyl ether engines do not require a trade-off between NOx and particulate matter emissions, they can run at a greater exhaust gas recirculation (EGR).\textsuperscript{10} By optimizing the EGR rate, dimethyl ether engines have the possibility of fulfilling the NOx limit of EURO IV.\textsuperscript{9} Due to its high cetane number, dimethyl ether can also be used for future transportation fuel in the compression ignition engine.\textsuperscript{3} Inside a diesel engine, DME burns without soot, which is similar to an oxygenated fuel additive and also enhances a favorable air/fuel mixture inside the engine.\textsuperscript{3}

4.1. DME Fuel Systems for SI Engine. For SI engines, adding dimethyl ether can also improve fuel combustion and generate lower hydrocarbon and carbon monoxide emissions compared to the standard engine because of the high oxygen percentage in dimethyl ether.\textsuperscript{12} Furthermore, the stoichiometric quality of mixed fossil fuel and dimethyl ether can be ignited and burn very fast. Currently, the operation of SI engines is under a large range of load and speed, consuming a permanent octane number of fuels. However, for the best working results of SI engines to generate the achievable maximum thermal efficiency and cleanest emissions,\textsuperscript{13} SI engines must be operated using the various octane numbers of fuels for several engine working conditions. For working conditions such as a cold start, a low octane number fuel can be applied to promote the engine to begin running, and at high loads, a high octane number fuel can be applied to prevent knocking inside the cylinder of the engine.\textsuperscript{9}

4.2. DME Fuel Systems for CI Engine. The project of a new type of common rail for dimethyl ether injectors has been conducted by Xu et al.\textsuperscript{14} The test shows that the basic injector system is sufficient and its working results can fulfill the requirements of dimethyl ether fueled engines. The influences of the dimethyl ether supplement on the spray characteristics and atomization quality of diesel fuel were investigated by Yu et al.\textsuperscript{15} The test results show that the dimethyl ether portion in the dimethyl ether−diesel mixed fuels had an important effect on the macroscopic and microscopic spray characteristics because of the high explosion and flash boiling part. Park et al.\textsuperscript{14} reported a study on macroscopic spray characteristics and breakup performance of DME fuel at high fuel temperatures and ambient conditions which shows that the increase of the ambient gas temperature and fuel temperature induced the increase of DME overall droplet size. Another study on the spray characteristics of DME with a variation of ambient pressure reveals the answers of the dimethyl ether small heat release problem by increasing the diameter of the nozzle holes and the pressure of common rail.\textsuperscript{15} The spray wall impingement phenomenon in HCCI diesel engine was studied by Wang et al.\textsuperscript{16} which explained that the variations of the fuel−air mixture equivalence ratio distribution in the near-wall region were also controlled by four impact factors: impinged spray mass, mixing time, spreading/slashing resistance, and fuel−air containment strength in the near-wall region.

Mixing dimethyl ether in diesel fuel is one technique to apply dimethyl ether in CI engines without many modifications of fuel arrangement. However, the simple addition method of dimethyl ether into diesel fuel greatly decreases the viscosity of the blended fuel.\textsuperscript{17} Viscosity, as well as lubrication properties, may be a restricting aspect in applying dimethyl ether. The potential liquid fuel to increase lubricity is biodiesel. It was known that biodiesel is a fuel that appropriates for compression ignition (diesel) engines, which is produced from biological resources such as fassy oils of vegetable or animal fat. The main component of biodiesel is an ester.\textsuperscript{17}

The influence of various dimethyl ether pilot portions on combustion and emission behaviors in a one-cylinder direct-injection dimethyl ether engine and to investigate whether premixed charge compression ignition−direct injection is a feasible in-combustion chamber nitrogen oxide emission reduction technique was studied by Ying et al.\textsuperscript{18} The results reveal that the dimethyl ether engine works well at a large category of rpm and torques at a premixed charge compression ignition−direct injection method. Nitrogen oxide emission indicates a clear reduction with incremental addition of dimethyl ether pilot amount at low torques.

The influence of dimethyl ether fuel contaminants on the performance of a dimethyl ether fueled diesel engine was studied by Oguma and Goto.\textsuperscript{19} The 5% of propane and 5% of fatty acid methyl ester, whose contaminants have more C=C bonds, have a bigger condensation particle counter count because of the initiation of particulate matter during the maximum fuel-richness.

The experimental and kinetic investigation on autoignition timing of dimethyl ether-n-butane-O\textsubscript{2}−Ar blends with different dimethyl ether mixing portions at various pressures were studied with the shock tube method and also Chemkin package by Hu et al.\textsuperscript{20} Autoignition timings are faster exponentially with the increment addition of pressure and increasingly with the additional dimethyl ether mixing ratio.

An experiment to expand the operating category of an HCCI engine powered with dimethyl ether, direct injection, and EGR by exploring their influences on the shifting of combustion behaviors was conducted by Jang et al.\textsuperscript{21} The results exhibit that the indicated mean effective pressure (IMEP) was greater than that for inlet line injection because it retarded combustion obtained from lower-temperature combustion caused by evaporating the latent heat of injected dimethyl ether in the combustion chamber. The other work related to the compressed natural gas difficulties in homogeneous charge compression ignition engine utilization; important research activity has been done by adding dimethyl ether fuel into the natural gas blend and other fuel combinations.\textsuperscript{20} Controlling the combustion phasing in an HCCI engine fueled with DME using zero-dimensional commercial software in a detailed chemical kinetics model and continued experimentally using a single-cylinder compression ignition engine was conducted previously.\textsuperscript{22} The DME was supplied to the engine using a pneumatic-driven high-pressure pump as can be seen in Figure 1. Meanwhile, the optimum injection timing of DME which is higher IMEP and thermal efficiency with lower NO\textsubscript{x} were obtained at 120 °C A BTDC as can be seen in Figure 2. From the figures, it can be seen
that THC and CO emissions were maintained and did not increase.

The other study which concerns extending the range of the steady condition of engine performance and enhancing the thermal efficiency by utilizing supercharging and mixed fuels was conducted by Mochizuki et al.\textsuperscript{23} The results show that the quantities of dimethyl ether and propane injected regulate the autoignition delay; the engine torque value can be adjusted by using the quantity of propane to achieve combustion near the top dead center. Furthermore, combustion became moderate by supercharging.

The studies of DME-biodiesel blends and the effect of EGR application on the toxicity of particles, performance, and engine emission were investigated by Sun et al.\textsuperscript{24,25} Recently, the highlighted results reveal that the addition of biodiesel increases the total particle number, the peak of particle number concentration, and the particle size corresponding to the peak. Furthermore, fuel blends with biodiesel mass proportion $\leq 15\%$ can prevent abrasion and leakage in the engine, but there is no apparent increase in both particle emissions and the possibility of particle toxicity. Meanwhile, the EGR affects the engine’s combustion by changing the chemical reaction, the $O_2$ contents, and the specific heat capacities of the concentrations in the cylinders. The longer ignition delay, the retarded combustion phasing, and the longer combustion duration have resulted as the EGR increased. Therefore, the EGR application is practical for reducing NOx of the DME-biodiesel blend engine. However, EGR application does not have a better effect on the reduction of CO and HC emissions.

5. CURRENT DIFFICULTIES, FUTURE CHALLENGES, AND RECOMMENDATIONS

Currently, the dimethyl ether engine is still at the research and development level. There are big opportunities and outlooks to increase engine achievements and reduce exhaust emissions with dimethyl ether. It is necessary to carry out the following research studies to implement DME as a suitable alternative fuel for decreasing exhaust pipe emissions from CI engines.

- One of the major challenges with DME fuel is its bad viscosity compared to diesel petroleum-based fuel. This characteristic will increase the high rate of leakage through the small clearance of the injection pump plunger and injector nozzle. It is necessary to know the influences of elevated pressure and temperature on the viscosity of dimethyl ether. A viscometer can be used to perform the test.

- Lubricity is very relevant to the satisfactory operation of a diesel engine, which relies on the fuel to lubricate many of the moving parts of the fuel injection system. Viscosity is also directly related to lubricity, and DME has a lower lubricity compared to diesel. It is impossible to operate a DME CI engine without adding some lubricating additive for a long time. A suitable lubricating additive is also another concern for improving the lubrication of the plunger and nozzle of the fuel system. The additive should not have any detrimental effect on the in-cylinder combustion of DME and it will not increase engine-out exhaust emissions.

- A suitable fuel return system has to be developed to bring back the injector return into the fuel tank or need to check the performance of a NO\textsubscript{x} catalyst when return can be used as a reducing agent for producing a NO\textsubscript{x} reduction environment.

- The energy density of dimethyl ether is smaller compared to diesel petroleum-based fuel, and it is necessary to inject a large amount of dimethyl ether needed for a similar amount of power output. Using the same original pump plunger and orifice diameter will lengthen the diffusion combustion stage without affecting the start of combustion. Increasing the diameter of the orifice will enlarge both the coefficient of discharge of the orifice and the injection amount of dimethyl ether. Also, the whole mass of air entrainment of spray is bigger due to the larger injection amount of dimethyl ether. Therefore, it would be possible to reduce fuel consumption and obtain near-zero emissions of combustion.

- Spray formation, ignition delay, and heat release rate (HRR) suggest that the combustion phenomena of dimethyl ether should be dissimilar to diesel petroleum-based fuel, and it is important to study the combustion phenomena of dimethyl ether CI engine by in-cylinder visualization or spectroscopic method.

- Soot-less combustion of DME eliminates the trouble of extreme PM emissions, and more advanced autoignition timing of dimethyl ether in a lower-oxygen ambient condition reduces the loss of combustion. Moreover, there is an opportunity for formaldehyde development during the oxidation of unburned hydrocarbons, and careful observation or testing is necessary.

- Less THC emission with a dimethyl ether engine demonstrates declining NO\textsubscript{x} performance with alumina-based NO\textsubscript{x} reduction catalyst. The shortage of decreasing agents on the NO\textsubscript{x} reduction reaction, which is a basic behavior of dimethyl ether engines. By adding more dimethyl ether into the sampled exhaust gas, a bigger NO\textsubscript{x} reduction amount is achievable just by adjusting the
catalyst temperature. A common-rail dimethyl ether injection system might be suitable where a double injection into the exhaust gas pipe makes it less agent rich.

6. SUMMARY

Various studies have exposed the necessity of dimethyl ether fuel in CI engines in the automotive area. However, very few investigations on the factors of pure dimethyl ether and the mixing of dimethyl ether with the other fuels have been conducted. Therefore, there is considerable reason to utilize dimethyl ether fuel in IC engines to fulfill future emission regulations. However, there are several restrictions to using dimethyl ether fuel in IC engines to fulfill the rigid emission regulations. Furthermore, pure dimethyl ether fuel with a high-pressure storage system is very risky for leakage problems. Then, maintaining the dimethyl ether in the liquid phase and requiring an adequate amount flow rate in the fuel system are the main problems. Therefore, it is beneficial to mix the high oxygen content of dimethyl ether with diesel fuel without any engine conversions. Hence, the relation “advantage” of every fuel might be applied. The mixed fuel maintains the required physical characteristics of diesel fuel. However, this involves the zero-emission ability of dimethyl ether. The 5% of propane and 5% of fatty acid methyl ester, which have many C−C bonds, have a bigger condensation particle count because of the initiation of particulate matter during the maximum fuel-rich stage. The total condensation particle counts for an experimental sample of 5% of propane and 5% of fatty acid methyl ester are higher compared to the other fuels. This is a crucial level for the dimethyl ether and diesel mixed fuel to operate perfectly in the CI engine with a few conversions to the fuel arrangement by offering the best results in reducing soot, particulate matter, and nitrogen oxide emissions of CI engines.

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Notes

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■ REFERENCES

(1) Arcoumanis, C.; Bae, C.; Crookes, R.; Kinoshita, E. The Potential of Di-Methyl Ether (DME) as an Alternative Fuel for Compression-Ignition Engines: A Review. Fuel 2008, 87, 1014−1030.

(2) Yan, Y.; Yu-sheng, Z.; Yong-tian, C.; Zu-di, C.; Ge, X. Study on HCCI Combustion and Emission Characteristics of Diesel Engine Fueled with Methanol/DME. SAE Tech. Pap. Ser. 2010, 1.

(3) Azizi, Z.; Rezaeimanesh, M.; Tohidian, T.; Rahimpour, M. R. Dimethyl Ether: A Review of Technologies and Production Challenges. Chem. Eng. Process. 2014, 82, 150−172.

(4) Cung, K.; Lee, S. Numerical Study on Emission Characteristics of High-Pressure Dimethyl Ether (DME) under Different Engine Ambient Conditions. SAE Tech. Pap. Ser. 2013, 1 DOI: 10.4271/2013-01-0319.

(5) Lee, D. Spray Characteristics of DME-LPG Blended Fuel in a High-Pressure Diesel Injection System. SAE Tech. Pap. Ser. 2013, 1 DOI: 10.4271/2013-01-0105.

(6) Bhattacharya, S.; Kabir, K. B.; Hein, K. Dimethyl Ether Synthesis from Victorian Brown Coal through Gasification Current Status, and Research and Development Needs. Prog. Energy Combust. Sci. 2013, 39, 577−605.

(7) Xu, S.; Wang, Y.; Zhang, X.; Zhen, X.; Tao, C. Development of a Novel Common-Rail Type Dimethyl Ether (DME) Injector H. Appl. Energy 2012, 94, 1−12.

(8) Yu, J.; Zhang, Y.; Jiang, G.; Kui, Q. An Experimental Study on Steady Flash Boiling Spray Characteristics of DME/Diesel Blended. SAE Tech. Pap. Ser. 2010, 1 DOI: 10.4271/2010-01-0879.

(9) Pedersen, T. D.; Schramm, J. Reduction of HCCI Combustion Noise Through Piston Crown Design. SAE Tech. Pap. Ser. 2010, 1 DOI: 10.4271/2010-01-1487.

(10) Salsing, H.; Golovitchev, V.; Denbratt, I. Numerical Analysis of Combustion and Emissions Formation in a Heavy Duty DME Engine. SAE Tech. Pap. Ser. 2012, 1 DOI: 10.4271/2012-01-0156.

(11) Chen, W.; Lin, B.; Lee, H.; Huang, M. One-Step Synthesis of Dimethyl Ether from the Gas Mixture Containing CO 2 with High Space Velocity. Appl. Energy 2012, 98, 92−101.
(12) Zubel, M.; Lehrheuer, B.; Pischinger, S. Impact of Increased Injector Nozzle Hole Diameters on Engine Performance, Exhaust Particle Distribution and Methane and Formaldehyde Emissions during Dimethyl Ether Operation. *Int. J. Engine Res.* 2021, 22, 503.

(13) Liang, C.; Ji, C.; Gao, B. Load Characteristics of a Spark-Ignited Ethanol Engine with DME Enrichment. *Appl. Energy* 2013, 112 (x), 500–506.

(14) Park, S. H.; Kim, H. J.; Lee, C. S. Macroscopic-Spray-Characteristics-and-Breakup-Performance-of-Dimethyl-Ether-DME-Fuel-at-High-Fuel-Temperatures-and-Ambient-Conditions.Pdf. *Fuel* 2010, 89, 3001.

(15) Lee, S.; Lim, O. An Investigation on the Spray Characteristics of DME with Variation of Ambient Pressure Using the Common Rail Fuel Injection System. *Transactions of the Korean Society of Automotive Engineers* 2013, 21, 1.

(16) Wang, J.; Yu, H.; Li, M.; Liang, X.; Liu, H. Experimental and Numerical Study on Effects of Impingement Parameters on Fuel-Air Mixture Formation in the Near Wall Region for Diesel-DME Blended Fuels. *SAE Tech. Pap. Ser.* 2018, 1–10.

(17) Putrasari, Y.; Praptijanto, A.; Santoso, W. B.; Lim, O. Resources, Policy, and Research Activities of Biofuel in Indonesia: A Review. *Energy Reports* 2016, 2, 237–245.

(18) Ying, W.; Longbao, Z.; Wei, L. Effects of DME Pilot Quantity on the Performance of a DME PCCI-DI Engine. *Energy Convers. Manage.* 2010, 51 (4), 648–654.

(19) Oguma, M.; Goto, S. Investigation of Fuel Impurities Effect on DME Powered Diesel Engine System. *SAE Tech. Pap. Ser.* 2010, 1.

(20) Hu, E.; Huang, Z.; Jiang, X.; Zhang, J. Study on Ignition Delay Times of DME and n-Butane Blends. *SAE Tech. Pap. Ser.* 2013, DOI: 10.4271/2013-01-1146.

(21) Jang, J.; Lee, Y.; Cho, C.; Woo, Y.; Bae, C. Improvement of DME HCCI Engine Combustion by Direct Injection and EGR. *Fuel* 2013, 113, 617–624.

(22) Putrasari, Y.; Jamsran, N.; Lim, O. An Investigation on the DME HCCI Autoignition under EGR and Boosted Operation. *Fuel* 2017, 200, 447–457.

(23) Mochizuki, K.; Shima, T.; Suzuki, H.; Ishikawa, Y.; Iijima, A.; Yoshida, K.; Shoji, H. A Study of Supercharged HCCI Combustion Using Blended Fuels of Propane and DME. *SAE Tech. Pap. Ser.* 2014, DOI: 10.4271/2014-32-0005.

(24) Sun, C.; Qiao, X.; Ju, D.; Tang, Q.; Fang, X.; Zhou, F. Composition and Toxicity of Particulate Matter Emitted from Turbocharged Common Rail DME–Biodiesel Engine. *Environ. Sci. Pollut. Res.* 2020, 27 (10), 10700–10714.

(25) Sun, C.; Liu, Y.; Qiao, X.; Ju, D.; Tang, Q.; Fang, X.; Zhou, F. Experimental Study of Effects of Exhaust Gas Recirculation on Combustion, Performance, and Emissions of DME-Biodiesel Fueled Engine. *Energy* 2020, 197, 117233.