Measuring Laminar Flame Speed of Lubrication Oil Mist in Air and CH_4-Air Mixtures

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1 Introduction

Lubrication oil combustion within engines has been experimentally linked to increased probability of fuel-air mixture preignition in spark ignition (SI) and gas turbine (GT) engines, causing erratic combustion, engine knock, and increasing unburned hydrocarbon emissions [1-3]. To improve engine high-load, low-speed performance, a better understanding of lubrication oil laminar flame speed is desirable [4, 5]. Other fundamental properties of oil combustion have been studied, such as ignition delay times [6-10], coking characteristics [9, 11, 12], and evaporation/boiling properties [8, 9, 13, 14]. However, no literature is available on a study into the laminar flame speed of lubrication oil in an air environment or in methane-oil-air and hydrogen-oil blends. A characterization of the laminar flame speed of lubrication oil would aid development of chemical kinetics models.

Lubrication oils encompass a broad class of heavy, long-chain hydrocarbons, which constitute the base oil of the lubricant. In terms of a simple alkane, most lubrication oils lie within the range of C_{15} – C_{30} for the carbon base, although heavier lubrication oils can contain base carbon chains up to C_{50} [15] [16]. Within that range, oils with higher viscosity and lower pour point properties generally have longer main carbon chains than lower-viscosity oils [16]. For the present study, an estimated molecule of $C_{30}H_{62}$ was used to represent Mobil DTE-732 and mineral oil, as these oils are relatively less viscous.

Originally, the existing method of liquid-fuel flame speed tests, developed by Keesee et al., was unsuccessfully used in an attempt to ignite the lubrication oil. Keesee et al.’s method involves injecting liquid fuel through an injection septum into a preheated combustion vessel, allowing the fuel to evaporate, and then adding oxidizer and igniting the mixture [17]. The entire rig is heated with a heating jacket, vaporizing the fuel upon introduction. Several issues with this method rendered it impractical for an oil laminar flame speed experiment. Lubrication oil vapor pressures are generally too low to be significant, even at elevated temperatures. While no data were directly available for gas turbine lubrication oil, Ndiaye et al. studied vapor pressures of castor oil and found them to be 1.950 kPa (14.62 torr) at a temperature of 354 K, which is not a level sufficient for gas-phase combustion to occur [18]. Further, due to their heterogeneous mixture compositions, the boiling point of lubrication oils ranges from 300 to 600˚C, which is outside of safe operating limits of the existing flame speed vessel [15, 19].

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Lubrication oils are less homogenous in composition than other liquid fuels. Often during vaporization of a lubrication oil, lighter components of the oil vaporize, while heavier components collect as a liquid. This preferential vaporization is evidenced by the fact that heavier components of lubricating oils often have boiling points more than 200˚C higher than the mixture as a whole [15]. Thus, the existing liquid flame speed method is unsuitable for accurately measuring laminar flame speed of lubrication oils. That is, the lubrication oil must be introduced as a liquid, preferable in the form of atomized droplets.

Atomized sprays present unique challenges when used to conduct a flame speed experiment. Among the largest is ensuring that the atomizer system produces fine droplets. These smaller droplets increase the quality of mixing between fuel and oxidizer, as well as being easier to vaporize than larger particles [20]. Another area of importance is maximizing the fuel-air ratio of mist leaving the atomizer nozzle, which is particularly challenging in an air-assisted pressure atomizer. As detailed later in this paper, the atomizer specifically utilized in this experiment uses a form of air-assist pressure atomization. Although it was originally designed to generate seed particles for use in an LDV system, the atomizer also works well for combustion applications, since it generates a fine mist of particles [16, 21]. As seen in Fig. 1, the oil reservoir has a tube that interfaces with the pressurized air. Pressurized air is passed over this tube, which causes particles of oil to atomize and exit the nozzle [21].

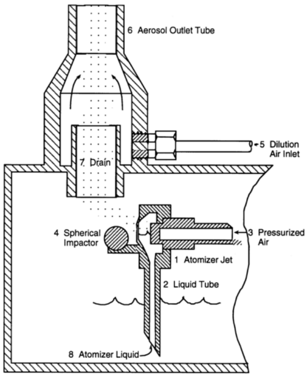

Figure 1: Schematic showing the operation of the atomizer used to mist oil particles into the flame speed vessel. Drawing courtesy of Agrawal et al. [21].

Diagnosing the amount of fuel being atomized also presents challenges. Particle size is often characterized by the mean aerodynamic diameter, which is the average diameter of a particle that moves with the same average velocity as the atomizer flow [18]. Mean aerodynamic diameters of particles emitted by atomizers relevant to this study are generally in the range of 0.6 to 0.8 microns, and thus cannot be easily filtered and measured on a mass basis [20, 21]. Agrawal et al. used an aerodynamic particle sizer [21], although a Malvern machine could be used to achieve similar results. A pressure atomizer setup suspends oil particles within the rig, allowing for a more homogenous composition.

3 Experimental Setup and Procedures

For this experiment, the 33.8-L turbulent flame speed vessel (TFSV) in the TEES Turbomachinery Laboratory at Texas A&M University was used [19]. A schlieren Z-type diagnostic system imaged the resulting flames. All experiments were conducted at room temperature. A new injection system (Fig. 2), consisting of a TSI 9306 Six-Jet atomizer and piping system was installed on the TFSV. This system utilizes an atomization method similar to that shown in Fig. 1. To test neat oil-air flame speeds, the TFSV was opened to atmospheric conditions, as operating the rig at vacuum did not allow for proper atomizer operation. The exhaust vent valve was slightly opened to avoid over pressure, while minimizing losses. After timing the injection duration, the mixture was ignited, following standard procedures [22]. For methane-oil and hydrogen-oil tests, oil mist was injected from the atomizer, after which a portion of the oil-air mixture was vacuumed into the exhaust manifold. This partial pressure amount was determined for each equivalence ratio [23]. Fuel was then added to the vessel, filling the chamber to 760.0 torr. The mixture was subsequently ignited.

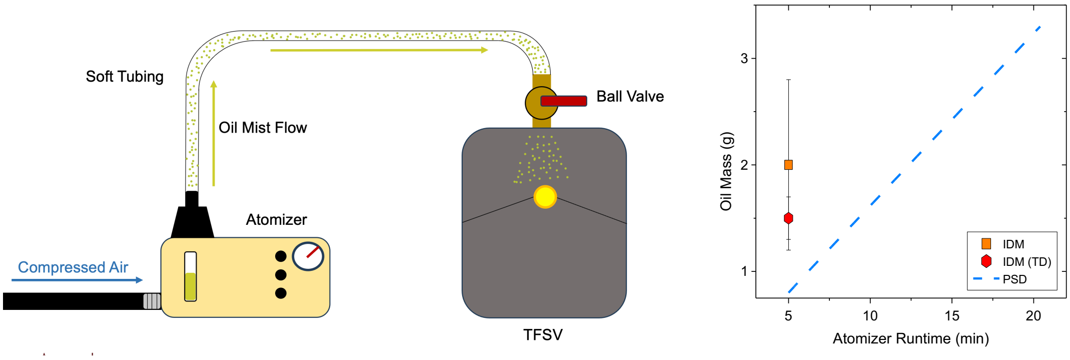

Figure 2: (a): Schematic of atomizer setup. (b): Atomized oil masses and uncertainties, dependent on atomizer run time. Results given with 95% confidence.

4 Results and Discussion

4.1 Characterization of Oil Mist from Atomizer

The resulting equivalence ratio of the oil mist from the atomizer was characterized via an indirect mass measurement (IDM), which involved measuring the tank reservoir mass before and after atomization, with the difference being the atomized mass. Oil amounts can also be estimated with a particle size data method (PSD), which relies on manufacturer data (6 µm particle diameter) to calculate a theoretical mass flow rate [21]. The results plotted in Fig. 2c were found to be time dependent, resulting in lower uncertainty when collection time was held constant. Approximately 1.5 grams of oil were atomized into the rig for these tests. Additionally, errors associated with the experimental venting and filling procedures were characterized on a per-equivalence-ratio basis. These oil losses are incorporated in the final oil measurement, with oil amounts ranging from 0 to 1.5 grams, depending on equivalence ratio.

4.2 Oil-Air Laminar Flame Speeds

The first mixture that was tested was lubrication oil as the fuel in air. Ignition of the lubrication oil (both mineral oil and Mobil DTE-732) was attempted to obtain a flame speed. Oil mist was atomized into the TFSV from durations of 30 seconds to two minutes of atomizer run time in regular, 10-second intervals. One ignition attempt consisted of a 32-minute injection period, while repeatedly sparking the mixture at regular intervals every 30 s for 30 min. During the two-minute tests, flame kernels were seen developing at run times of 60 s upwards but were unable to propagate past the electrode tips. An increased 30 V primary circuit supply was used rather than the standard, 15-V power supply to increase ignition energy. The oil mixture within the rig was also pressurized up to 50 psig. While pressurized, the mixture was sparked with air as an oxidizer, as well as one test which used oxygen in an attempt to increase the mixture's reactivity. Ignition was not observed during any of these tests.

Several factors may account for difficulties igniting the neat oil-air mixture. The most likely reason is the spark supplied by the 15- and 30-V primary circuit in the TFSV ignition system does not provide the oil with enough energy to reach its activation energy, including local vaporization of the droplets. Additionally, unlike most liquid fuels, the oil mix was not heated. Thus, it is likely that a stronger spark or pilot fuel is necessary to provide the mixture with energy to vaporize and propagate a spherical flame.

Another factor that likely contributes to the inability of the oil to ignite is the combustion-inhibiting antioxidant additives within the oil. The Mobil DTE-732 oil was new, synthetic, and sparked at room temperature. Antioxidant additives and synthetic properties of the oil may have inhibited combustion further. The mineral oil mixture does not have these additives and was tested to provide insight on this theory. More frequent flame kernels were observed, but none propagated past the electrode tips.

4.3 Methane-Oil-Air Laminar Flame Speeds

To obtain ignition using the present setup while still utilizing the oil-mist system, hybrid methane-oil-air blends (60-30% oil content) were tested, and these mixtures did ignite. For all experiments, the run time of the atomizer was 7 min (around 1.6 g of oil using the IDM method), except the experiment at $\phi = 0.8$, which had a run time of 5 min (around 1.5 g). Fig. 3a shows the results of the methane-oil-air flame speeds compared to the Aramco Mech 1.3 kinetics mechanism [24] results for methane-air at 298.15 K and 1 atm (14.7 psia), as well as experimental methane-air laminar flame speeds from Turner et al. [25] at the same conditions. Oil-air experimental results are reported based on the unadjusted methane-air equivalence ratio (what was experimentally controlled in the lab).

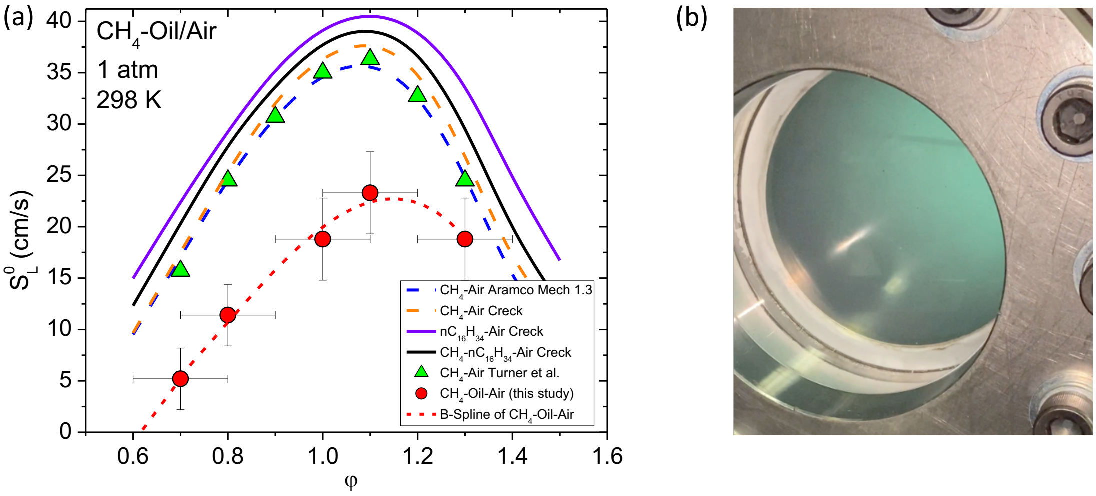

Figure 3: (a) Methane-oil-air flame speed results. The error bars on the methane-oil-air data are ±0.1 for equivalence ratio and ±3 to 4 cm/s for flame speed, based on uncertainty in the mixture composition and uncertainty in the gas density ratio used for conservation of mass in the flame speed analysis. (b) The oil mist fog creates diagnostic issues by scattering the Schlieren light source.

Additionally shown in Fig. 3a are three simulations using the Creck Mechanism [26-29]: a pure methane-air simulation for comparison purposes with the Aramco Mech 1.3 kinetics model, a methane and n-hexadecane blended fuel (based on the ratios of methane to oil). The n-hexadecane model and blended methane n-hexadecane model are of particular interest, as these correlate with the mixtures predicted by perfect-mixing and perfect-displacement mass models respectively.

Fig. 3a shows that the methane-oil-air flame speeds are anywhere from 23-39% slower than the methane-air chemical kinetics models. Both the perfect-mixing ($n\text{-}C_{16}H_{34}$) and perfect-displacement ($CH_4\text{-}nC_{16}H_{34}$) models also do not capture the experimental behavior. The model underpredictions are likely a result of the assumption that the oil (n-hexadecane) is gaseous, whereas in actuality, the flame is likely having to expend additional energy towards vaporizing the oil droplets in the fuel mix. It is also interesting to note that when the equivalence ratio is adjusted to account for the oil content in the fuel mixture, the peak measured laminar flame speed is closer to an equivalence ratio of 1.2. The vaporization of the oil seemed to slow the flame momentum down significantly at peak flame speeds compared to the Aramco mechanism, as evidenced by the flattened curve. This negative effect on laminar flame speed may result from higher amounts of oil being vaporized at methane equivalence ratios closer to stoichiometric, since the methane adiabatic flame temperature is higher.

Diagnostic issues were encountered during the methane-oil-air test runs, particularly for the lean flame speeds (Fig. 3b). Due to the oil-mist particles, after an atomizer run time of around one minute, the particles scattered and diffused the light from the schlieren power source. After an atomizer run time of around two minutes, the light was obscured almost completely by the particles. The exposure time and shutter speed were adjusted to try to compensate. On methane-oil-air blends, the images were noticeably brighter towards the end of the experiment because of this adjustment, and edge detection was often poor. The effect of exposure changes was less noticeable in the rich regime of equivalence ratios tested.

5 Conclusion

A new atomizer injection system was developed to test laminar flame speeds of lubrication oils and oil-fuel hybrid mixtures in air. Mixtures of oil-air and oil with elevated oxygen content were tested under a variety of atomizer run times, as well as at elevated pressures, but did not ignite. This outcome is likely due to insufficient spark voltage not providing the mixture with ample energy to surpass the reaction activation energy. Methane-oil-air hybrid blends did ignite and showed significantly lower flame speeds when compared with methane-air results calculated from Aramco Mech 1.3 at atmospheric conditions. This outcome likely results from a combination of factors, most significantly the energy requirement to first vaporize the oil prior to ignition. The lower flame speed of methane-oil-air compared to methane-air also validates the claim that the spark ignition system failed to provide sufficient energy to the oil for ignition in the pure oil tests. Future work will focus on the particle loading produced by the atomizer, reduction of the uncertainty in equivalence ratio, and continuing work with hydrogen-oil-air blends.

6 References

[1] O.A. Kuti, S.Y. Yang, N. Hourani, N. Naser, W.L. Roberts, S.H. Chung, S.M. Sarathy, A fundamental investigation into the relationship between lubricant composition and fuel ignition quality, Fuel 160 (2015) 605-613.

[2] T. Rockstroh, C.P. Kolodziej, S.S. Goldsborough, T. Wallner, M.C. Jespersen, Insights into Engine Knock - Comparison of Knock Metrics across Ranges of Intake Temperature and Pressure in the CFR Engine, SAE International Journal of Fuels and Lubricants 11 (2018) 545-562.

[3] M. Amann, T. Alger, Lubricant Reactivity Effects on Gasoline Spark Ignition Engine Knock, SAE International Journal of Fuels and Lubricants 5 (2012) 760-771.

[4] E. Distaso, R. Amirante, G. Calò, P. De Palma, P. Tamburrano, R.D. Reitz, Predicting lubricant oil induced pre-ignition phenomena in modern gasoline engines: The reduced GasLube reaction mechanism, Fuel 281 (2020) 118709.

[5] J.B.a. Heywood, Internal combustion engine fundamentals, New York : McGraw-Hill Book Company, [1988] ©19881988.

[6] S.P. Cooper, Z.K. Browne, S.A. Alturaifi, O. Mathieu, E.L. Petersen, Auto-Ignition of Gas Turbine Lubricating Oils in a Shock Tube Using Spray Injection, Journal of Engineering for Gas Turbines and Power 143 (2021).

[7] W. Vera-Tudela, P. Süess, P. Albrecht, S. Wüthrich, K. Herrmann, Experimental study of lube oil pre-ignition in an optical gas engine test rig, International Journal of Engine Research 25 (2024) 1037-1049.

[8] C. Tao, K. Miao, F. Tang, Y. Qian, Y. Zhang, S. Meng, C. Wang, B. Jiang, Evaporation and combustion characteristics for a droplet of lubricating oil and gasoline, International Communications in Heat and Mass Transfer 127 (2021) 105513.

[9] E.L. Petersen, O. Mathieu, J.C. Thomas, S.P. Cooper, D.S. Teitge, R. Juárez, N. Gutierrez, C.V. Mashuga, Combustion and Oxidation of Lube Oils at Gas Turbine Conditions: Experimental Methods, 2021.

[10] S.P. Cooper, E.L. Petersen, High-Temperature Ignition Kinetics of Gas Turbine Lubricating Oils, Journal of Engineering for Gas Turbines and Power 143 (2021).

[11] R. Juárez, N. Gutierrez, E.L. Petersen, Characterization of an Apparatus to Study Solid Deposit Formation in Lubricating Oils at High Temperatures, Journal of Turbomachinery 145 (2022).

[12] P.F. Grigor'ev, Y.A. Tyurin, M.G. Trusenev, M.M. Vakhmyanina, Resistance of lubrication oils to coke formation, Chemistry and Technology of Fuels and Oils 13 (1977) 815-817.

[13] Y. Qian, S. Bian, P. Zhao, T. Wang, Y. Hua, Y. Liu, Q. Teng, C. Tao, The investigation of evaporation behavior of lubricating oil droplet at high ambient temperature, International Communications in Heat and Mass Transfer 117 (2020) 104689.

[14] M. Soejima, Y. Harigaya, T. Hamatake, Y. Wakuri, Study on Lubricating Oil Consumption from Evaporation of Oil-Film on Cylinder Wall for Diesel Engine, SAE International Journal of Fuels and Lubricants 10 (2017) 487-501.

[15] R. Vazquez-Duhalt, Environmental impact of used motor oil, Science of The Total Environment 79 (1989) 1-23.

[16] T. Yao, N. Zhang, J. Hu, X. Liao, Y. Shen, Z. Gan, Effect of Temperature on the Chemical Composition and Physicochemical Properties of Diester Aviation Lubrication Oil, International Journal of Chemical Engineering 2020 (2020) 8829206.

[17] C.L. Keesee, B. Guo, E.L. Petersen, Proper interpretation and overall accuracy of laminar flame speed measurements of single- and multi-component liquid fuels, Proceedings of the Combustion Institute 38 (2021) 2225-2234.

[18] P.M. Ndiaye, F.W. Tavares, I. Dalmolin, C. Dariva, D. Oliveira, J.V. Oliveira, Vapor Pressure Data of Soybean Oil, Castor Oil, and Their Fatty Acid Ethyl Ester Derivatives, Journal of Chemical & Engineering Data 50 (2005) 330-333.

[19] A. Morones, M.A. Turner, V. León, K. Ruehle, E.L. Petersen, Validation of a New Turbulent Flame Speed Facility for the Study of Gas Turbine Fuel Blends at Elevated Pressure, 2019.

[20] C. Liu, F. Liu, J. Yang, Y. Mu, C. Hu, G. Xu, Experimental investigations of spray generated by a pressure swirl atomizer, Journal of the Energy Institute 92 (2019) 210-221.

[21] E.M.J. J.K. Agarwal, Generating Aerosol for Laser Velocimeter Seeding, TSI, NASA, 1981.

[22] Y. Kochar, J. Seitzman, T. Lieuwen, W. Metcalfe, S.a. Burke, H. Curran, M. Krejci, W. Lowry, E. Petersen, G. Bourque, Laminar Flame Speed Measurements and Modeling of Alkane Blends at Elevated Pressures With Various Diluents, 2011, pp. 129-140.

[23] Y.M. Almarzooq, I. Schoegl, E.L. Petersen, Laminar flame speed measurements of a gasoline surrogate and its mixtures with ethanol at elevated pressure and temperature, Fuel 343 (2023) 128003.

[24] W.K. Metcalfe, S.M. Burke, S.S. Ahmed, H.J. Curran, A Hierarchical and Comparative Kinetic Modeling Study of C1 − C2 Hydrocarbon and Oxygenated Fuels, International Journal of Chemical Kinetics 45 (2013) 638-675.

[25] M.A. Turner, T.T. Paschal, P. Parajuli, W.D. Kulatilaka, E.L. Petersen, Application of high-speed, species-specific chemiluminescence imaging for laminar flame speed and Markstein length measurements in spherically expanding flames, Experimental Thermal and Fluid Science 129 (2021) 110477.

[26] G. Bagheri, E. Ranzi, M. Pelucchi, A. Parente, A. Frassoldati, T. Faravelli, Comprehensive kinetic study of combustion technologies for low environmental impact: MILD and OXY-fuel combustion of methane, Combustion and Flame 212 (2020) 142-155.

[27] E. Ranzi, C. Cavallotti, A. Cuoci, A. Frassoldati, M. Pelucchi, T. Faravelli, New reaction classes in the kinetic modeling of low temperature oxidation of n-alkanes, Combustion and Flame 162 (2015) 1679-1691.

[28] E. Ranzi, A. Frassoldati, R. Grana, A. Cuoci, T. Faravelli, A.P. Kelley, C.K. Law, Hierarchical and comparative kinetic modeling of laminar flame speeds of hydrocarbon and oxygenated fuels, Progress in Energy and Combustion Science 38 (2012) 468-501.

[29] E. Ranzi, A. Frassoldati, A. Stagni, M. Pelucchi, A. Cuoci, T. Faravelli, Reduced Kinetic Schemes of Complex Reaction Systems: Fossil and Biomass-Derived Transportation Fuels, International Journal of Chemical Kinetics 46 (2014) 512-542.