The Effects of MVCO Injections and Conventional Fuel Injections in a High Speed Direction Injection Engine

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Abstract

Modifications to the KIVA code are introduced to the code for better capability with biodiesel simulations for an optically accessible engine. These include the extended Z'eldovich mechanism for describing the formation of nitrogen oxide. The Hiroyasu model and the Nagle-Strickland-Constable model are combined for evaluating soot emissions. The Shell model, with adjustment appropriate for biodiesel simulations, is used for low temperature combustion. Blended fuels are simulated using a multi-component model. The fuel library is also expanded to include properties of soybean biodiesel using BDProp. The operations of a small bore high speed direct injection (HSDI) engine with a MVCO injector with various blends of biodiesel and diesel fuels is studied. The modified KIVA code is shown to predict the major combustion characteristics include the peak combustion temperature, heat release rate and ignition timing, so is nitrogen oxide emission, using a conventional common rail fuel injector very well for all the fuels considered. The fuel blends tend to have lower emission, consistent with the general observation for the later. due to the longer ignition delay for the initial injection of The cylinder, the cylinder is under lower temperature upon main injection with biodiesel and its blends. This might explain the lower nitrogen oxides emissions by biodiesel.

Introduction

Agricultural based fuels are one of the most viable alternatives due to their renewability and can be used in most of the DI engines [1], which has a high thermal efficiency. It has similar properties as diesel such as cetane number and produces less carbon monoxide, unburnt hydrocarbon and PM, and has the potential of meeting stricter emission regulations set by EPA [2]. However, studies show that biodiesel may produce up to 10% of extra NO_x. Multiple-injection can be used to emissions. Nehmer and Reitz [3] showed that NO_x emissions can be reduced by injecting less than 50% of fuel during pilot injection, with no effects on soot emissions. Concurrent reductions of NO_x and soot are observed by delaying the main injection [4]. Han et al. [5] reported that simultaneous reduction of NOx and soot can be achieved by deferring fuel injection. Choi et al. [6] reported that biodiesel NO_x emissions vary with engine load.

Conventional injector limits the range of injection time. Fuel injected at very early stage of the cycle will form a film on the engine wall liner. A micro variable circular orifice (MVCO) injector that features an adjustable spray angles can extend the range of injection time. The goal of this study is to analyze and compare the combustion and operating characteristics with multi-injection schemes, using simulations, for biodiesel, diesel and their blends using the MVCO injector.

Blowby Model

The circumferential flow is usually neglected during computation since the oil fill on cylinder wall acts as a seal, preventing leakage of fuel. It might be significant for an optical engine. The crevice flow model and dynamic ring pack model, developed by Namazian [7, 8], and the circumferential flow model by Zhao and Lee [9] are inserted into the KIVA code to account for mass flow through the crevice region.

The Shell Model for Low Temperature Ignition

The Shell model [10] is a general multi-step kinetics model simulating the initiation, propagation, branching and termination processes during ignition and combustion. Ricart et al. [11] successfully applied the model for low-temperature auto-ignition process in diesel engine. There are eight reactions in the mechanism. Previous researches [14, 15, 16] indicated that biodiesel and diesel have similar ignition characteristics. The optimized values for tetradecane [13], $C_{14}H_{30}$, widely used in modeling diesel combustion, are also applied for biodiesel simulations except the kinetic constant A_{f4} is enlarged to 2.40×10^6. Other modifications to the code include the including oxygen and correcting the oxygen depletion rate for biodiesel [14]. The heat release per cycle is adjusted [14] to account for different chemical structures and heating values between the two fuels,

$$\frac{q_d}{q_b} = \left(\frac{HV_b}{HV_d}\right)\left(\frac{MW_b}{MW_d}\right)\left(\frac{N_b^H}{N_d^H}\right), \quad (1)$$

where q is the heat release per cycle, HV is the heating value, MW represents the molecular mass in g/mole and N^H is the number of hydrogen atoms per molecule, subscript b represents biodiesel and d represents diesel fuel. One other modification is assigning molecular masses to the intermediate species, for satisfying the conservation of mass per suggestion by Schaperton and Lee [17].

The Extended Z'eldovich Model for Nitrogen Oxides Emissions

The extended Z'eldovich mechanism [18] is included in KIVA for determining the formation of NO_x. Three reactions are involved in the mechanism:

$$O + N_2 \leftrightarrow NO + N, \quad (2)$$
$$N + O_2 \leftrightarrow NO + O, \quad (3)$$
$$N + OH \leftrightarrow NO + H, \quad (4)$$

Applying the steady state assumption on the radical species and Combining the forward and backward reaction rates, the transient variation of NO is obtained. Detailed discussion about the model can be found in Heywood [18]. No adjustments are made for nitrogen dioxides (NO_2) since nitrogen monoxide (NO) is the dominating species.

Computation Modelling of the HSDI Engine

The operation of the engine, built by Ford Motor Company, is simulated using the KIVA-3V Release 2 program, with the aforementioned adjustments. PM emission is calculated by the Hiroyasu's model for formation [19] and the Nagle and Strickland-Constable model for oxidation [20]. Details with the design and experimental specifications are reported by Mathews et al. [21] and Fang et al. [22]. Table 1 lists the engine configuration.

Table 1. Specifications of the DIATA research engine; the engine has four valves and six injectors.

Parameter	Value
Bore	7.0 cm
Stroke	7.8 cm
Connecting Rod Length	13.26 cm
Compression Ratio	19.5 : 1
Engine Speed	1500 rpm

Testing Conditions

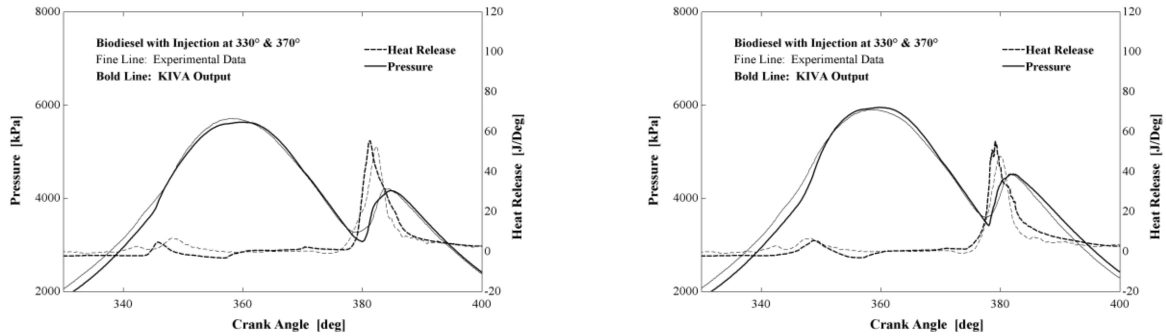
Table 2 shows the various injection schemes in this study. Three dual-injection schemes are considered for 500 kPa IMEP operations of the DIATA engine with the MVCO injector. The injection pressure remains constant at 100 MPa for all cases. A 1.3 mm3 of fuel is injected for the first injections, and fuel quantity is adjusted for the main injection for 500 kPa IMEP output. Diesel, soybean biodiesel and their blends are considered in this study. A equivalent chemical structure of $C_{19}H_{35}O_2$ is accepted for soybean biodiesel [14]. Tetradecane, $C_{14}H_{30}$, is used to represent European low-sulphur diesel in the simulations.

Table 2. Testing conditions considered in this study. Top-dead-center corresponds to 360º crank angle.

Testing Condition	1A	1B	2A	2B	3A	3B
Injection Time [°CA]	280° 360°	280° 370°	300° 360°	300° 370°	320° 360°	320° 370°
Fuel	Biodiesel, Diesel, 20% Biodiesel blend, 50% Biodiesel blend					

KIVA Simulations MVCO Injections of Soybean Biodiesel

Simulations are done for the cases listed in Table 2. Figure 1 shows that KIVA prediction of the cylinder pressure and heat release rate and the comparison to experimental measurement for the 20% biodiesel and 50% biodiesel blends. KIVA predicted the ignition time, peak heat release and other combustion characteristics well. The small peak in heat release at about 350° is due to initial combustion for both experimental measurements and KVIA predictions. The dominant peak upon main injection is due to the quantity of fuel injected.

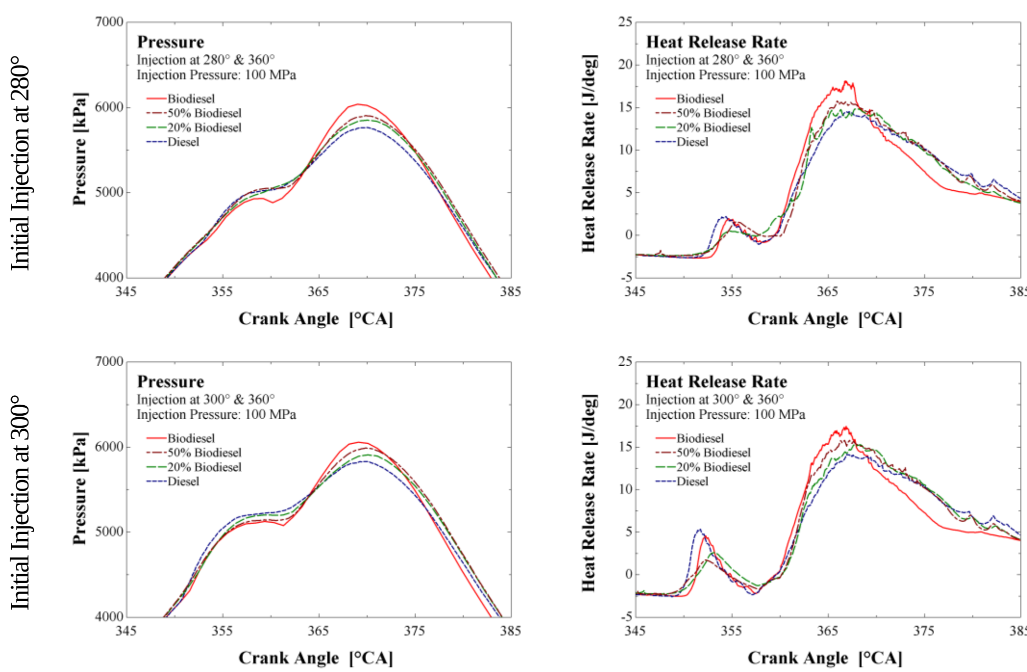


(I) (II)

Figure 1. Comparison of KIVA prediction and experimental measurement for the engine running with conventional injector for (I) B20 and (II) B50.

Simulations are conducted to study the operation of the DIATA engine with MVCO injectors. Figure 2 shows the predictions of cylinder pressure and heat release rate. The small peak in the heat release curve at about 350° to 355° corresponds to the heat release over the initial injection. Initial ignition is stronger and occurs earlier with later initial injection. The peak is almost twice as high for case 3 over case 1, where the initial injection is 40°earlier. A dominate peak is shown upon main injection due to larger amount of fuel injected during main injection. Consequently, two peak pressure peaks are observed: one at top-dead-centre and the other due to main injection. Comparing the heat release rate curves over the four fuels, higher biodiesel corresponds to longer ignition delay. In addition, biodiesel also causes higher heat release with shorter combustion duration. This indicates that biodiesel causes faster combustion. The extra oxygen might improve fuel oxidation and thus accelerating the combustion process. The long tail of the heat release curve indicates diffusion combustion for all the cases.

Similar results are observed for deferred main injections (at 370°), see Figure 3, albeit with a less obvious trend. Both B20 and B50 blend behaves more closely to diesel fuel.



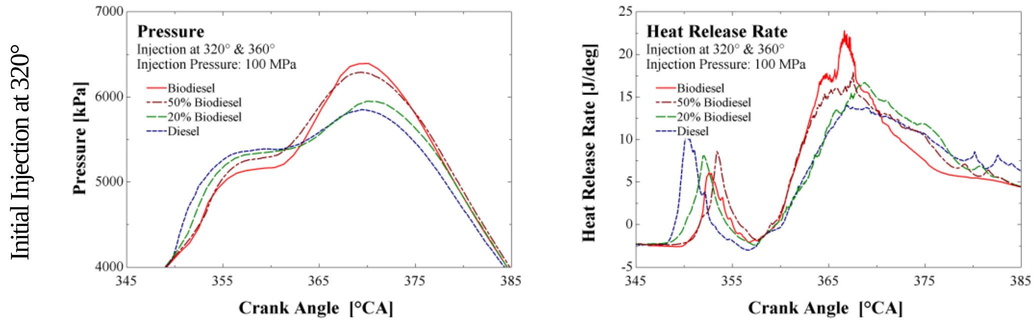


Figure 2. Pressure and heat release rate variation with main injection at 360°.

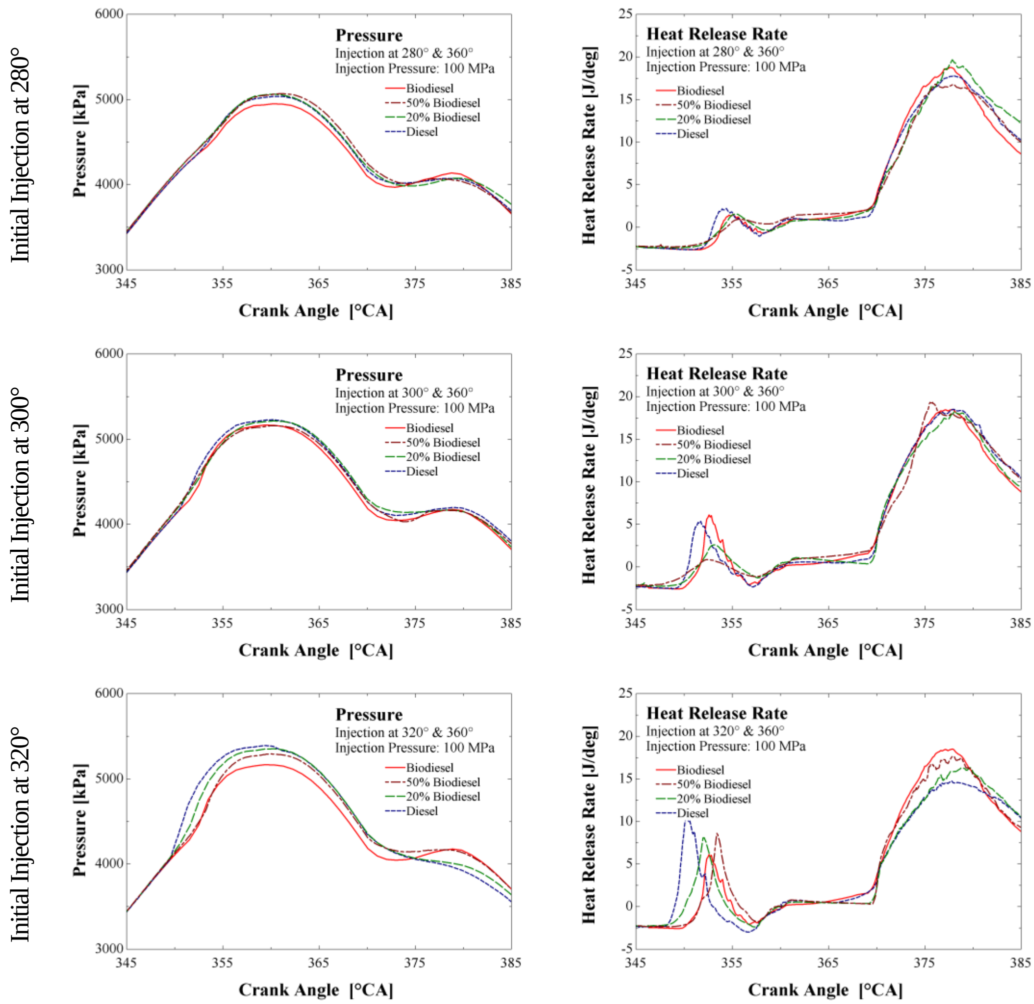


Figure 3. Pressure and heat release rate variation with main injection at 370°.

Numerical Predictions of Engine Performance and Emissions

The indicated thermal efficiency is shown in Figure 4. Thermal efficiency is a more appropriate scale for comparison of engine performance since it accounts for the different energy contents between the fuels. Note that the heating value of biodiesel is about 15% lower than that of regular diesel [14]. Biodiesel and fuel blends show higher ISFCs over diesel for a given IMEP output. The DIATA engine sees better thermal efficiency when pure biodiesel is used, with almost 10% improvements in thermal efficiency in certain cases. This improvement is likely because of the oxygen in biodiesel that assist the overall combustion process. Deferring the injection, either the initial injection or the main injection, lowers the thermal efficiency when the engine is operated with biodiesel, but this is not observed with diesel. Different trends are observed for fuel blends. With main injection at top-dead-centre, both B20 and B50 blend results with lower efficiency than the pure fuels. However, B50 is as efficient as pure biodiesel and B20 is as efficient as pure diesel for late main injection (at 370°), despite the combustion process for both fuels closely resemble that of diesel.

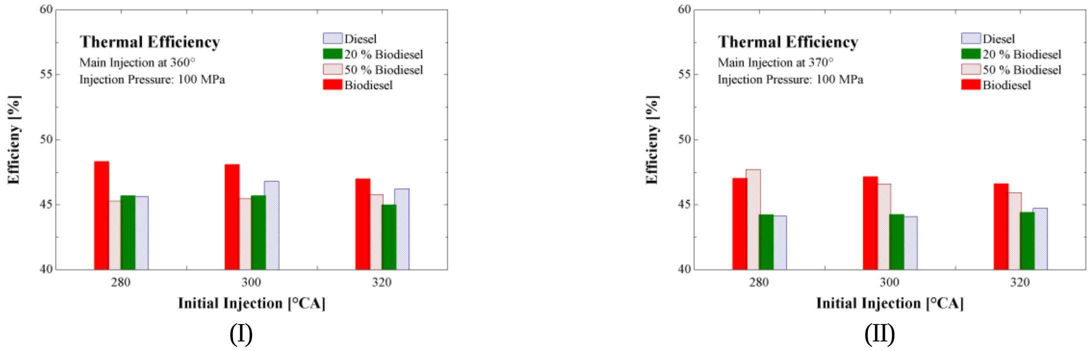


Figure 4. Comparison of thermal efficiency using MVCO injections between biodiesel and diesel with main injection at (I) 360° CA and (II) 370° CA.

KIVA predictions of NO are shown in Figure 5. Biodiesel and B50 produce fewer emissions. Due to longer ignition delay for biodiesel and blends, during main injections, the fuel is injected into a cooler ambient. As NOx formation is sensitive at high temperature, a cooler ambient upon main injection is very favorable. B50 consistently, showing lower NOx emission level over pure biodiesel. However, there is no such clear trend for B20 fuel. There are cases that B20 is causing the highest emission level among the fuels. It is probable that biodiesel is causing the extra NOx emission, since this has been reported in the literature.

The prediction of soot emissions from KIVA is presented in Figure 6. These results are showing consistent trend with general observations that biodiesel has lower soot emission. There are cases where the soot emission from biodiesel is over 50% less than that from regular diesel. Lower PM emission is always encountered with fuel blends, either B20 or B50. The oxygen content in biodiesel is thought to assist oxidation of soot, resulting in lower emission.

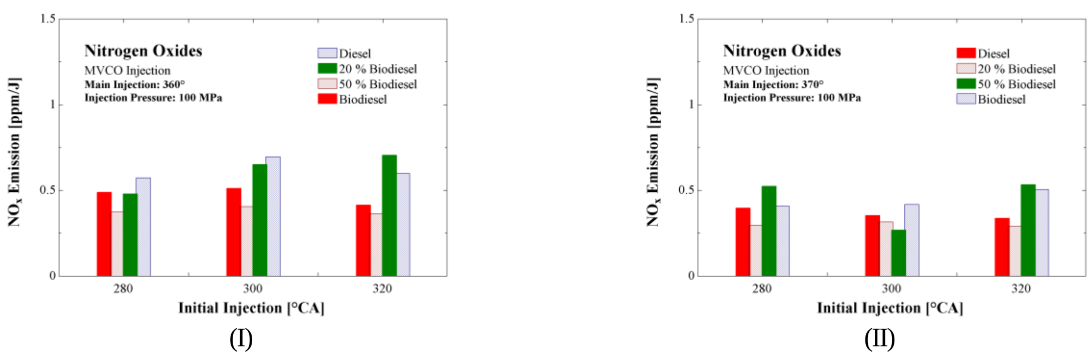


Figure 5. Comparison of NO_x emissions with MVCO injections for main injections at (I) 360° and (II) 370°.

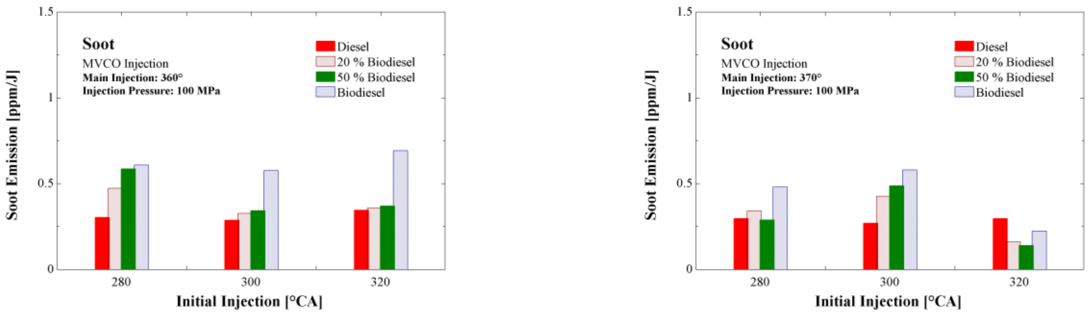


Figure 6. Comparison of soot emissions with MVCO injections for main injections at (I) 360° and (II) 370°.

Conclusion

Several amendments and improvements are incorporated into the KIVA 3V release 2 code for improving its compatibility with biodiesel simulations with a small bore, HSDI optical engine. Simulations are completed to study the operation characteristics of the DIATA engine with MVCO injector. Various schemes are considered, with simulations conducted over blends of biodiesel and diesel. The MVCO injector extends the range of injection timings over conventional injectors by allowing very early injection. This is not advised with conventional injectors as the fuel is more likely to form a film on engine wall liner.

Combustion from the initial injection is always observed for all the fuel blends using MVCO injection. Initial combustion consists of low temperature combustion and the breakdown of the fuel molecules into smaller radicals, generating a favorable environment for fuel evaporation and ignition for the main injection. This is reflected as an improvement in fuel economy. MVCO injections may lead to up to 10% in indicated thermal efficiency Improvements. Biodiesel (and its blends) is shown to lengthen the ignition delay over diesel for initial injection. Ignition delay for main injection is negligible in all the cases studied due to the cylinder condition upon main injection. The magnitude of the initial heat release for biodiesel and its blends tends to be lower than that of diesel. Therefore, main combustion occurs at a lower ambient temperature within the combustion chamber upon main injection. Consequatnly, lower NOx emission is realized. Soot emissions from biodiesel blends and this is consistent with the general observation. Diffusion combustion is observed in all the cases considered. However, faster burning rate and shorter combustion duration are found to be proportionally varying with the amount of biodiesel in the blends. With better fuel economy and lower emissions, further investigation of operating the engine using MVCO injectors and blends of biodiesel can be conducted for possible low-emission operations.

References

1. Knothe, G., Krahl, J., and Van Gerpen, J., *The Biodiesel Handbook*, AOCS Press, 2005, p. 76.
2. *A Comprehensive Analysis of Biodiesel Impacts on Exhaust Emissions*, EPA420-P-02-001. October 2002.
3. Nehmer, D. A. and Reitz, R. D., *SAE Paper 940668*, 1994.
4. Tow, T. C., Pierpont, D. A., and Reitz, R. D., *SAE Paper 940897*, 1994.
5. Han, Z., Uludogan, A., Hapmson, G. J., and Reitz, R. D., *SAE Paper 960633*, 1996.
6. Choi, C. Y., Bower, G. R. and Reitz, R. D., *SAE Paper 970218*, 1997.
7. Namazian, M., Ph.D. Thesis, Massachusetts Institute of Technology, Mechanical Engineering, 1981.
8. Namazian, M. and Heywood, J. B., *SAE Paper No. 820088*, Warrendale, PA, 1982.
9. Zhao, J. and Lee. C.F., *SAE Paper No. 2006-01-0649*, Warrendale, PA, 2006.
10. Halstead, M.P., Kirsch, L.J., and Quinn, C.P., *Combustion and Flame* 30:1 pp. 45-60, 1977.
11. Ricart, L.M., Xin, J., Bower, G.R., and Reitz. R.D., *SAE Paper No. 971591*, Warrendale, PA, 1997.
12. Amsden, A. A., *KIVA-3V, Release 2, Improvements to KIVA-3V*, Los Alamos National Laboratory Report LA-13608-MS, 1999.
13. Hamosfakidis, C., and Reitz, R.D., *Combustion and Flame* 132, pp. 433-450, 2003.
14. Yuan, W., *Ph.D. Thesis*, University of Illinois, Agricultural Engineering, 2005.
15. Choi, C.Y., *Ph.D. Thesis*, University of Wisconsin at Maidson, Mechanical Engineering, 1998.
16. Tat, M.E., and Van Gerpen, J.H., *ASAE Paper No. 20036034*, St. Joseph, MI, 2003.
17. Schaperton, H., and Lee, W., *SAE Paper No. 850502*, Warrendale, PA, 1985.
18. Heywood, J.B., *Internal Combustion Engine Fundamentals*, McGrawHill, 1988, pp. 572-578.

19. Hiroyasu, H. and Nishida, K., *SAE paper 890269*, 1989.
20. Nagle, J. and Strickland-Constable, R. F., *Proceedings of the Fifth Carbon Conference* 1, 1962.
21. Mathews, W.S., Coverdill, R.E., and Lee, C.F., *J. of Fuels and Lubricants* 111(4): pp. 1059-1071 (2002).
22. Fang, T., Coverdill, R. E., Lee, C.F., and White, R.A., *SAE Paper No. 2005-01-0919*, 2005.

Nomenclatures

HV heating value of fuel
MW molecular weight
N^H number of hydrogen atoms
q heat release per engine cycle
r radial distance
V molar volume
x mole fraction

Subscripts

b biodiesel
d diesel fuel
i component index
l liquid
mix mixture